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DETERMINATION OF A COEFFICIENT MODEL FOR A HYDROSTATIC TRANSMISSION

by

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CHAPTER I

INTRODUCTION

Introduction

The constantly increasing use of automatic controls to enhance performance, efficiency, function, and convenience has brought forth the need to more fully understand the controlled processes. Analytic or laboratory studies of a process can be used to determine a mathematical model that describes a process such that the output variables can be determined from given input variables.

A computer analysis of a draft vehicle was conducted by Ibrahim [1] as his Ph.D. research at Kansas State University. The study determined that the overall cost of operation of the vehicle could be minimized through the use of automatic controls. Ibrahim's work was the initial phase of a long-term study aimed at improving the performance of the man-machine tillage system. The research presented in this thesis is a continuation of that work.

Ibrahim chose to study a vehicle equipped with a hydrostatic transmission because its infinite variable speed ratio capability lends it readily to automatic control techniques. A hydrostatic transmission consists of a hydraulic pump and hydraulic motor coupled by a closed-loop oil circuit. Power is transmitted through the transmission by the oil at relatively low speed and high pressure. Variable speed ratios are accomplished by changing the displacements of either the pump or motor or both.

For purposes of analysis, it was necessary for Ibrahim to develop or assume mathematical descriptions, or models, for the engine, transmission, tractive mechanism, and tillage mechanism. Since his work was basically a feasability study, it was important to have representative models but not necessarily precise models. For the hydrostatic transmission a coefficient model and typical coefficient values were assumed but not experimentally verified in much detail.

The next major phase of the research is to experimentally verify the conclusions of Ibrahim's analytical study. For this phase the transmission model must accurately predict actual performance.

Objective

The objective of the research presented in this thesis was to experimentally determine and verify a mathematical model for a hydrostatic transmission.

Literature Review

Much of the original work in the area of hydrostatic transmission modeling was done by Dr. Warren Wilson [2]. His work was based on coefficient models. This type of model has the deviations from the ideal expressed as functions of coefficients and variables in the system.

Ibrahim chose to use the following basic equations of Wilson's Model for his research.

$$Qp = Dp\ Np - \frac{Csp\ \Delta P\ Dpm}{2\pi\ \mu}$$

$$Tp = \frac{\Delta P\ Dp}{2\pi} + \frac{Cfp\ \Delta P\ Dpm}{2\pi} + Cdp\ \mu\ Np\ Dpm$$

$$Qm = Dm\ Nm + \frac{Csm\ \Delta P\ Dmm}{2\pi\ \mu}$$

$$Tm = \frac{\Delta P\ Dm}{2\pi} - \frac{Cfm\ \Delta P\ Dmm}{2\pi} - Cdm\ \mu\ Nm\ Dmm$$

Examination of the flow equations reveals that the first term on the right of each equation is the ideal flow. However, leakage decreases the flow output of a pump and increases the flow requirement of a motor. The leakage is accounted for by a coefficient term much in the same manner that the coefficient of friction is used to calculate friction force as a function of normal force. The leakage is shown to be a function of the variables pressure differential and viscosity. The maximum displacement and 2π terms are constants present only for dimensional consideration.

The first term on the right of the torque equations is the ideal torque term. The torque required to drive a pump is greater than the ideal; likewise, the torque output of a motor is less than the ideal. The torque losses are grouped as dry friction losses and viscous friction losses. The dry friction losses are a function of pressure differential. The viscous friction losses are a function of speed and viscosity.

In a study of fluidic control of a hydrostatic transmission, Reid [3] also used the basic model of Wilson. In that study the equations were arranged in matrix form to calculate motor speed and pump torque as functions of the other system variables as follows:

$$\begin{bmatrix} Nm \\ Tp \end{bmatrix} = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \begin{bmatrix} Np \\ Tm \end{bmatrix}$$

The symbols a, b, c, and d represent expressions involving the coefficients, viscosity, and displacements.

A modified form of Wilson's Model was used in a simulation of a hydraulic hybrid vehicle power train by Elder and Otis [4]. The flow and torque equations follow.

$$Tm = \frac{(Ps - Pc)\ Dm}{2\pi} - \frac{Cfm\ (Ps + Pc - 2\ Pd)}{2\pi\ (1 - \tan \alpha m)} - \frac{Cdm\ Nm\ Dmm\ \mu}{(1 - \tan \alpha m)}$$

$$Qm = Dm\ Nm + \frac{(Dmm - Dm)\ Nm}{2}\left[\exp\left(\frac{Ps - Pc}{\beta}\right) - 1\right] + Csm1\ Nm\ Dmm \tan \alpha m + \frac{Csm2\ (Ps - Pd)\ Dmm}{2\pi} + \frac{Csm3\ (Ps - Pc)\ Dmm}{2\pi}$$

$$Tp = \frac{(Ps - Pc)\ Dp}{2\pi} + \frac{Cfp\ (Ps + Pc - 2\ Pd)\ Dmm}{2\pi\ (1 - \tan \alpha p)} + \frac{Cdp\ Np\ Dpm\ \mu}{(1 - \tan \alpha p)}$$

$$Qp = Dp\ Np\left[\frac{1.0}{\exp\left(\frac{Ps - Pc}{\beta}\right)}\right] - \frac{(Dpm - Dp)\ Np}{2}\left[\exp\left(\frac{Ps - Pc}{\beta}\right) - 1\right] + Csp1\ Np\ Dpm \tan \alpha p - \frac{Csp2\ (Ps - Pd)\ Dpm}{2\pi} - \frac{Csp3\ (Ps - Pc)\ Dpm}{2\pi}$$

Although Elder and Otis do not present a formal development of the modified model, observations can be made. The flow equations are more complex than the basic Wilson Model. The model acknowledges leakage paths from system pressure to charge pressure as the basic model does. It also acknowledges a leakage path from system pressure to drain pressure which the basic model does not. The flow equation also has a term relating to the compressibility of the fluid. Another term in the flow equation shows a component of the leakage as a function of speed and displacement.

The torque equations are similar to those of Wilson's basic model except the denominator of the coefficient terms contains the 1 - tan α term. This causes the torque losses to be a function of displacement whereas in the basic model they remain constant relative to changing displacement.

Blackburn, Reethof, and Shearer [5] give thorough coverage of coefficient models in Fluid Power Control. Wilson's model is developed and a practical method of experimental determination is given. The basic equations are as follows:

$$Qp = Dp\ Np - \frac{Csp\ \Delta P\ Dpm}{2\pi\ \mu}$$

$$Tp = \frac{\Delta P\ Dp}{2\pi} + \frac{Cfp\ \Delta P\ Dpm}{2\pi} + Cdp\ \mu\ Np\ Dpm + Tcp$$

$$Qm = Dm\ Nm + \frac{Csm\ \Delta P\ Dmm}{2\pi\ \mu}$$

$$Tm = \frac{\Delta P\ Dm}{2\pi} - \frac{Cfm\ \Delta P\ Dmm}{2\pi} - Cdm\ \mu\ Nm\ Dmm - Tcm$$

The model presented in Fluid Power Control is the same as the model used by Ibrahim except for the addition of the constant torque term to the torque equations in the former. Due to its relative simplicity and thorough coverage in the literature, the model presented by Blackburn was selected for the initial investigation in this research. The modified model used by Elder and Otis was used as a background for modifications to improve the basic model.

CHAPTER II

DEVELOPMENT OF THE MODEL

Reformulation of Equations

The basic equations of the selected form of Wilson's Model are given below.

$$Qp = Dp\ Np - \frac{Csp\ \Delta P\ Dpm}{2\ \pi\ \mu}$$

$$Tp = \frac{\Delta P\ Dp}{2\ \pi} + \frac{Cfp\ \Delta P\ Dpm}{2\ \pi} + Cdp\ \mu\ Np\ Dpm + Tcp$$

$$Qm = Dm\ Nm + \frac{Csm\ \Delta P\ Dmm}{2\ \pi\ \mu}$$

$$Tm = \frac{\Delta P\ Dm}{2\ \pi} - \frac{Cfm\ \Delta P\ Dmm}{2\ \pi} - Cdm\ \mu\ Nm\ Dmm - Tcm$$

To be useful for the computer analysis conducted by Ibrahim [1], the model must be arranged to calculate pump speed and pump torque as functions of motor speed and motor torque and conversely.

The procedure for reformulation of the equations is given in Appendix B. The resulting equations are as follows.

$$Np = \frac{Dm\ Nm}{Dp} + \frac{K\ (Tm + Cdm\ \mu\ Nm\ Dmm + Tcm)}{\mu\ (Dm - Cfm\ Dmm)\ Dp}$$

$$Tp = (Tm + Tcm)\left[\frac{(Dp + Cfp\ Dpm)}{(Dm - Cfm\ Dmm)} + \frac{Cdp\ Dpm\ K}{Dp\ (Dm - Cfm\ Dmm)}\right]$$
$$+ Nm\left[Cdm\ \mu\ Dmm\ \frac{(Dp + Cfp\ Dpm)}{(Dm - Cfm\ Dmm)} + \frac{Cdp\ \mu\ Dpm}{Dp}\left(Dm + \frac{K\ Cdm\ Dmm}{(Dm - Cfm\ Dmm)}\right)\right]$$
$$+ Tcp$$

$$Nm = \frac{Dp\ Np}{Dm} - \frac{K\ (Tp - Cdp\ \mu\ Np\ Dpm - Tcp)}{\mu\ (Dp + Cfp\ Dpm)\ Dm}$$

$$Tm = (Tp - Tcp)\left[\frac{(Dm - Cfm\ Dmm)}{(Dp + Cfp\ Dpm)} + \frac{K\ Cdm\ Dmm}{Dm\ (Dp + Cfp\ Dpm)}\right]$$

$$- Np\left[Cdp\ \mu\ Dpm\ \frac{(Dm - Cfm\ Dmm)}{(Dp + Cfp\ Dpm)} + \frac{Cdm\ \mu\ Dmm}{Dm}\left(Dp + \frac{K\ Cdp\ Dpm}{(Dp + Cfp\ Dpm)}\right)\right]$$

$$- Tcm$$

Determination of Coefficients

Fluid Power Control [5] covers the procedure for experimentally determining the coefficients of the selected model. The procedure requires measurements of pump speed, motor speed, pump torque, motor torque, system pressure, and charge pressure at various operating conditions. All tests for determination of the coefficients are conducted with both the pump and motor at full displacement. The oil temperature must be held constant to maintain the same oil viscosity throughout the tests.

It is interesting to note that development of a model for a hydrostatic transmission does not require flow rate measurement. However, flow rate measurement is necessary for development of a model for either a pump or a motor as a single unit.

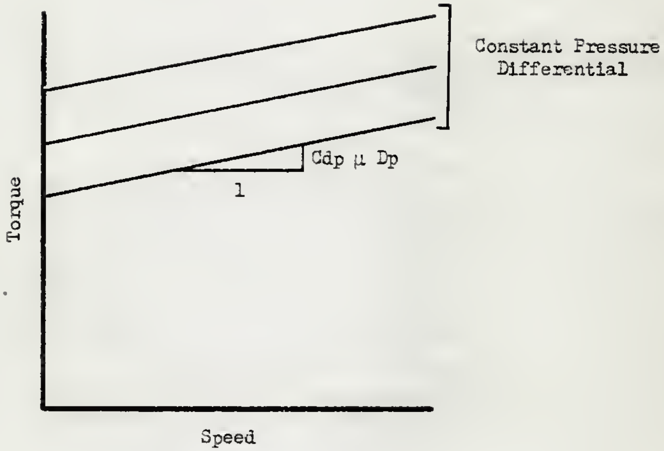
The composite slip factor, K, can be calculated from the data by the relationship

$$K = \frac{(Dp\ Np - Dm\ Nm)\ 2\ \pi\ \mu}{\Delta P}$$

Determination of the other coefficients requires plotting graphs or using linear regression analysis. The coefficient of viscous drag for the pump, Cdp, is related to the slope of the constant pressure differential lines of the torque vs. speed graph as shown in Figure 2.1. The coefficient of viscous drag for the motor, Cdm, can be determined in a similar manner as shown in Figure 2.2.

The lines of constant pressure on the torque vs. speed graph can be extrapolated to zero speed to determine the zero-speed torque values. These values are then plotted as zero-speed torque vs. pressure differential. The coefficient of dry friction for the pump, Cfp, is related to the slope, and the constant friction torque of the pump, Tcp, is the zero-pressure differential torque as shown in Figure 2.1. The coefficient of dry friction for the motor, Cfm, and the constant friction torque of the motor, Tcm, can be determined in a similar manner as shown in Figure 2.2.

As stated in Chapter I, determination of the coefficients requires only measurements to be taken with both the pump and motor at full displacement. The approach chosen for this research was to determine the coefficients at full displacement according to the prodecure, and then evaluate the model at full displacement and various partial displacements.



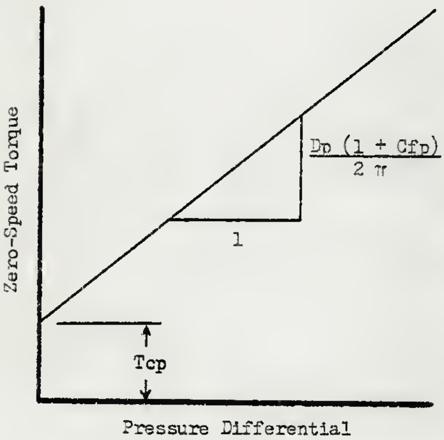


Figure 2.1. Graphical Illustration of Determination of Pump Coefficients

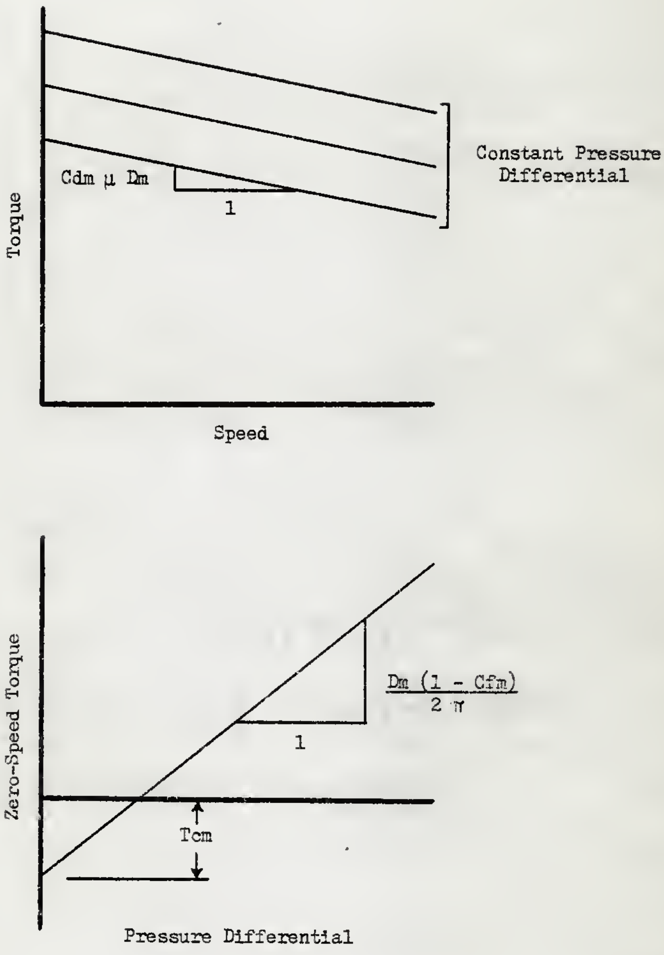


Figure 2.2. Graphical Illustration of Determination of Motor Coefficients

CHAPTER III

TEST EQUIPMENT

Hydrostatic Transmission

The hydrostatic transmission test stand used in this research is pictured in Plates 1 and 2 and is diagrammed in Figure 3.1.

Sundstrand Hydro-Transmission [6] of Ames, Iowa manufactures the transmission used in this research. It consists of their Model 22 variable displacement pump and Model 24 variable displacement motor. The pump displacement is variable from 0 to 4.26 in^3/rev which corresponds to a swashplate angle variation from 0 to 18°. The motor displacement is variable from 2.73 to 7.24 in^3/rev which corresponds to a swashplate angle variation from 7 to 18°. The transmission is rated for 3000 psi continuous working pressure at maximum shaft speeds. Normal relief valve setting is 5000 psi.

A 0.75 in^3/rev fixed displacement charge pump is mounted on the main pump. It provides a flow of oil through the transmission for cooling purposes and provides sufficient oil under pressure for control purposes and to replace internal leakage. The main pump supply oil and motor return oil are maintained at charge pressure. The charge pressure relief valve setting is 160 to 180 psi.

The pump displacement and motor displacement are controlled by Moog controllers. Moog Model 62-600 controllers are mounted on the pump and motor and are used in conjunction with Moog Model 122-105 Servoamplifiers. These units control displacement proportional to an operator determined input voltage.

EXPLANATION OF PLATE 1

Item	Description
1	Engine
2	Pump Torque Transducer
3	Pump Speed Transducer
4	HST Pump
5	Pump Moog Controller
6	Charge Pump (integral with HST pump)
7	HST Motor
8	Motor Moog Controller
9	Motor Torque Transducer
10	Motor Speed Transducer
11	Load Pump
12	Load Valve
13	Load Circuit Heat Exchanger
14	Inlet Temperature Transducer
15	Charge Pressure Port
16	System Pressure Port

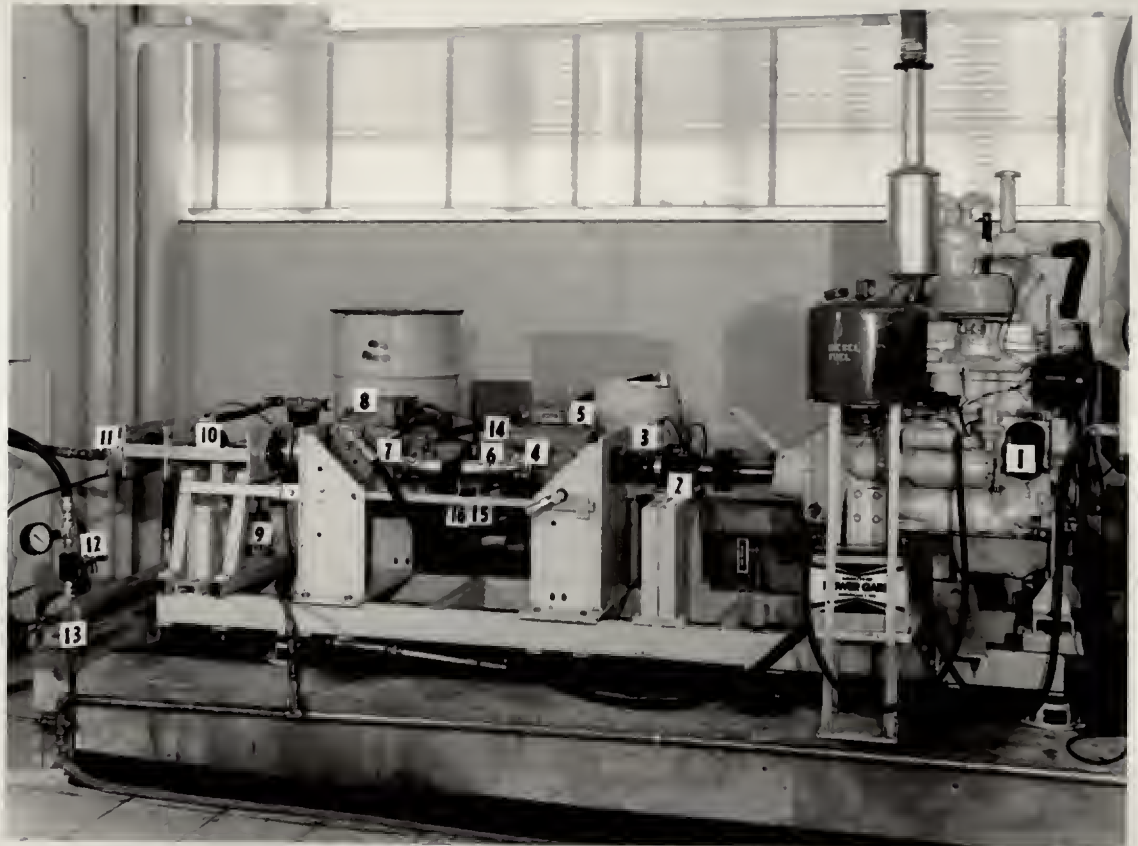


Plate 1. Test Stand From Right-Hand Side

EXPLANATION OF PLATE 2

Item	Description
1	Outlet Temperature Transducer
2	Transmission Oil Reservoir
3	Transmission Heat Exchanger
4	Cooling Water Control Solenoid
5	Charge Pressure Transducer
6	System Pressure Transducer
7	Load Circuit Oil Reservoir
8	Microcomputer (protective cover removed)
9	Interface (protective cover removed)
10	Moog Electronics (protective cover removed)
11	Pump Displacement Control
12	Motor Displacement Control
13	Signal Conditioners
14	Teletype

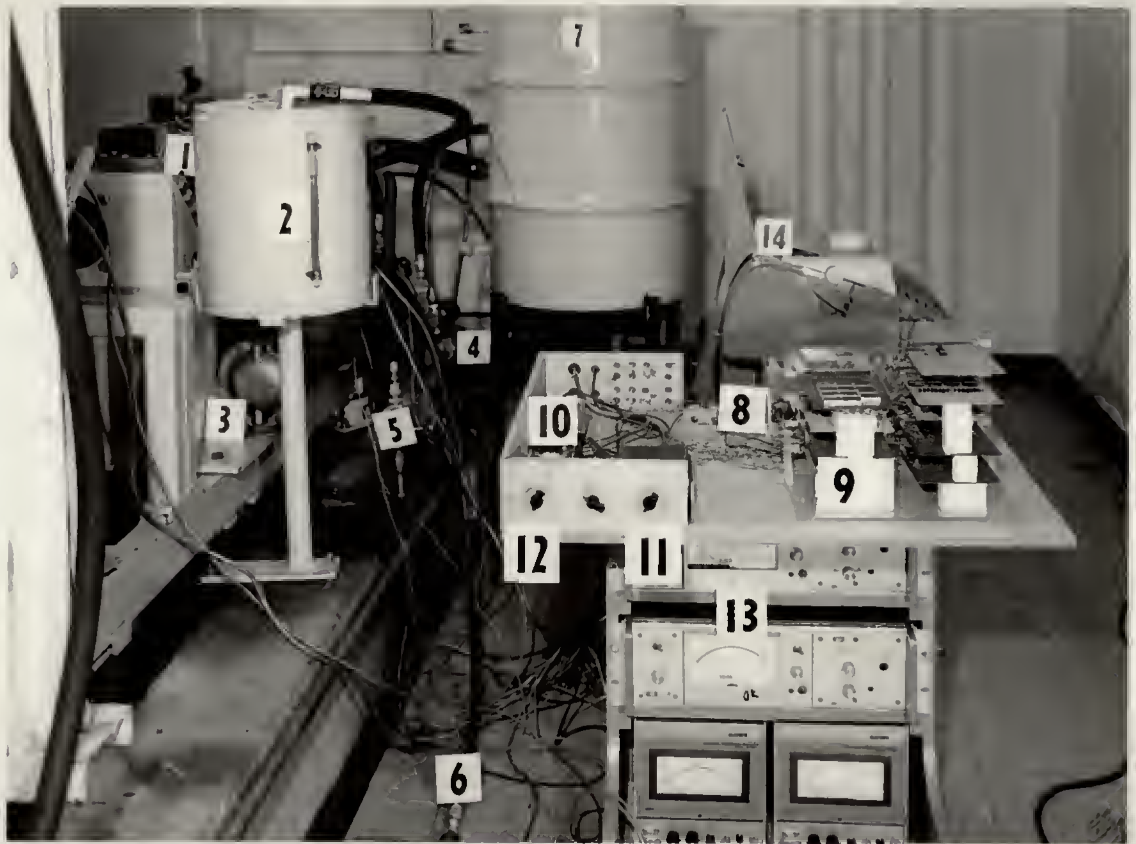


Plate 2. Test Stand From Left-Hand Foreground

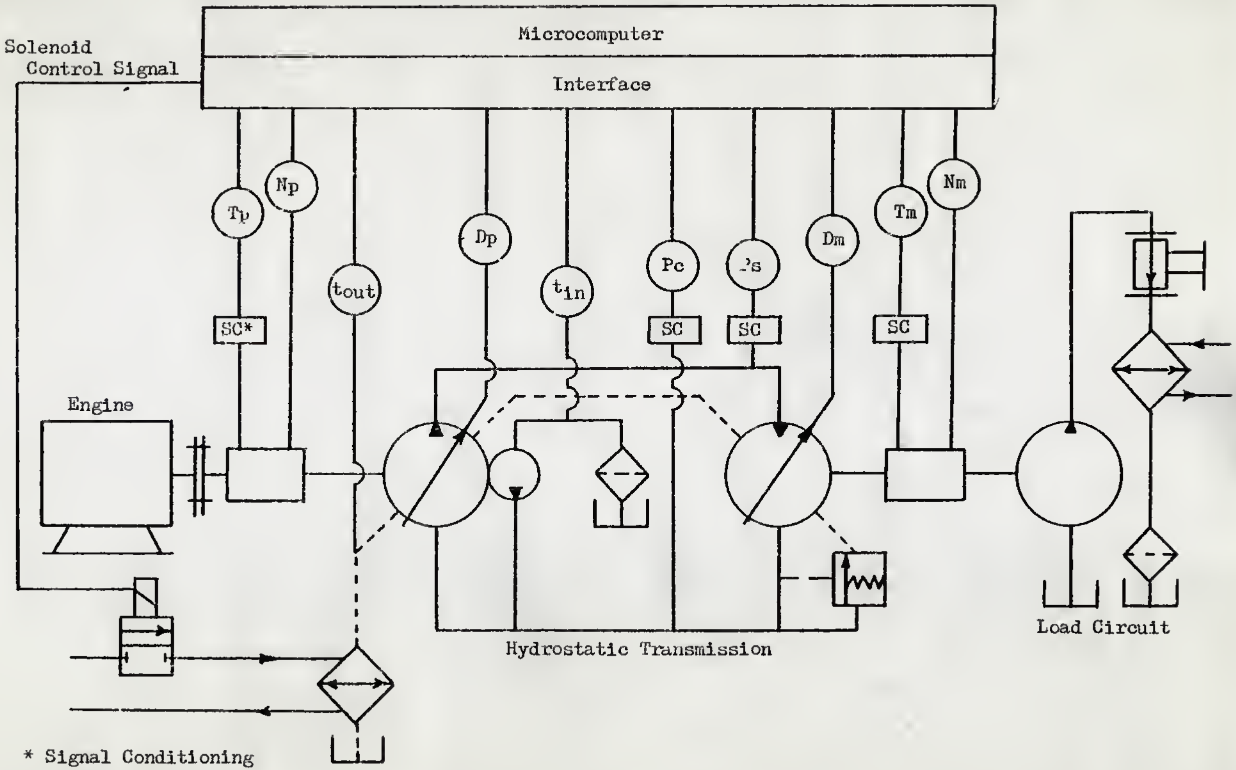


Figure 3.1. Diagram of Test Stand

For this research the transmission oil was cooled by a Thermxchanger heat exchanger, Number 530-BFX, manufactured by E. C. Cooley Company. The transmission oil temperature was regulated by a microcomputer controlled solenoid valve that initiated or terminated the flow of cooling water through the heat exchanger. The microcomputer is discussed in a subsequent section of this chapter.

The transmission oil temperature control scheme was an on-off nonlinearity with hysteresis as shown in Figure 3.2. Temperature measurement locations at the charge pump inlet and case drain outlet were selected to avoid placing transducers in high pressure lines or passages of the transmission. The average of these two temperatures was used as representative of the average oil temperature in the transmission. The lower and upper temperature settings were 51.2°C and 52.0°C giving a total hysteresis band of 0.8°C. This gave a nominal control temperature of 51.6°C or 125°F.

Engine

The engine used to supply power to the transmission in this research was a John Deere Model 3164 DT. This three cylinder diesel engine displaces 164 in^3. Raw performance data provided by John Deere indicate it has maximum brake torque of 134 ft.lb at 1400 rpm and maximum brake power of 56.7 hp at 2400 rpm. The torque curve is relatively flat with a rise of about 10 ft.lb between 2400 rpm and 1400 rpm.

Load Unit

The output of the transmission was coupled directly to a Cessna 24600 Series gear pump with fixed displacement of 3.78 in^3/rev. The

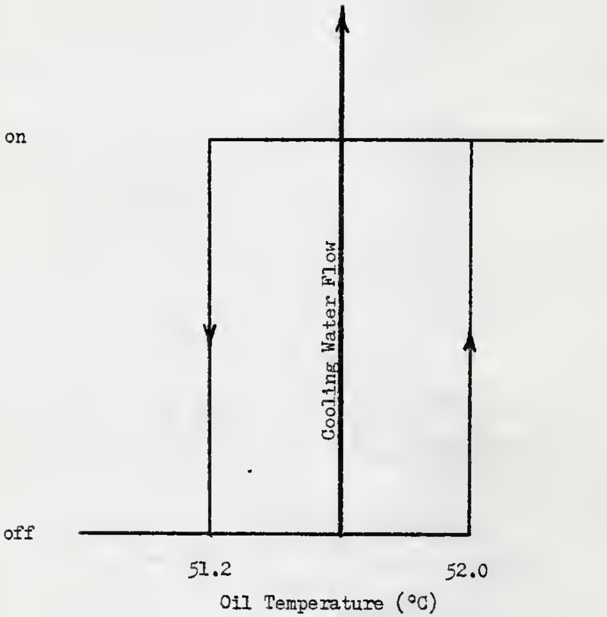


Figure 3.2. Transmission Oil Temperature Control

output flow of the load pump was throttled across a needle valve to dissipate the energy. The load circuit oil then entered a Model F-303-EY-4P heat exchanger manufactured by Young Radiator Company. The needle valve setting was used to control the load on the transmission.

The load pump was mounted in a frame that allowed the pump free rotation about its shaft centerline. The rotation was restrained by the load cell used to measure the transmission output torque.

Microcomputer and Interface

A microprocessor based system was used for data acquisition and transmission oil temperature control. The KIM-1 Microcomputer manufactured by MOS Technology, Inc. [7] was selected for its versatility and low cost. It uses an 8-bit MCS 6502 microprocessor array operating in conjunction with two MCS 6530 arrays. The basic system plus an additional 8K of RAM (random-access-memory) gives 2048 bytes of ROM (read-only-memory) and 9344 bytes of RAM. The unit has an address range of 65536 bytes.

A Teletype Model 33 teletypewriter was connected to the microcomputer. The teletypewriter provided an alternative to the microcomputer keyboard and display for communication with the microcomputer. It also provided printed hard copy and punched paper tape. The paper tape could be used for subsequent re-entry of the program.

The interface provided the link between the transmission, the microcomputer, and the operator. The major functions of the interface were to control input signals, control output signals, provide timekeeping, and display measured parameter values. Major components in the interface were an analog-to-digital converter, a multiplexer, an interface adapter, and the display.

The analog-to-digital converter used was an ADC-8S manufactured by Analog Devices. This 8-bit converter uses the staircase conversion technique. Its range is 0 to 10 volts and a full scale conversion is accomplished in one millisecond.

The multiplexer allowed the eight analog signals to be converted by one A/D converter. An AD7501 Multiplexer manufactured by Analog Devices was used in the interface.

The interface adapter was a MCS 6522 manufactured by MOS Technology. This device provided much of the control of the input and output signals and also included the timekeeping function.

The display consisted of 24 units of 7-segment light emitting diodes. Each unit was individually addressable.

Transducers and Signal Conditioning

Pump speed and motor speed were measured by an Airpax 4-0008 magnetic pickup with pulses generated from a 60 tooth gear. The pump speed gear was mounted in the Lebow torque meter. The motor speed gear was mounted on the shaft coupling the motor and the load unit pump. The microcomputer and interface recorded pulses for one second with the result being the shaft speed in rpm.

Pump torque was measured by a Lebow Model 1104-2K strain gage torque transducer installed between the engine and the pump. Motor torque was measured by a Transducers, Inc. Model BTC-FF63-CS-200# strain gage force transducer attached to a 9 inch lever arm restraining the rotation of the load unit pump mounting cradle.

Daytronic Type 91 Strain Gage Transducer Input Modules and Type P

Galvanometer Driver Output Modules were used for signal conditioning of the torque signals. The Daytronic units provided an output voltage compatible with the 0 to 10 volt range of the A/D converter.

The raw torque signal exhibited extreme variation probably due to engine induced torsional vibrations. The Daytronic output signals were filtered with a low-pass R-C filter. The filter configuration and frequency response characteristics are shown in Figure 3.3.

Pressures were sensed with Statham Model UGP4 Pressure Accessories with interchangeable diaphragms used in conjunction with Gould Statham Model UC3 Universal Transducing Cells. A 2000 psi diaphragm was used for the system pressure transducer, and a 200 psi diaphragm was used for the charge pressure transducer.

Statham Model SC1001 Universal Transducer Readout units were used for pressure signal conditioning. The output signal of each pressure indicator was filtered with the same type filter used for the torque signals and illustrated in Figure 3.3. The 0 to 5 volt output range was amplified to the 0 to 10 volt A/D converter range by an amplifier in the interface.

Pump displacement and motor displacement were sensed from the feed-back signal from the Moog Model 62-600 Controllers mounted on the transmission. The signals were in the 0 to 10 volt range and thereby were directly compatible with the A/D converter.

Transmission inlet and outlet oil temperatures were measured by Analog Devices AD590 Temperature Transducers. Their output is a current that is proportional to absolute temperature. A circuit built into the interface converted the temperature signal into the A/D converter compatible range of 0 to 10 volts.

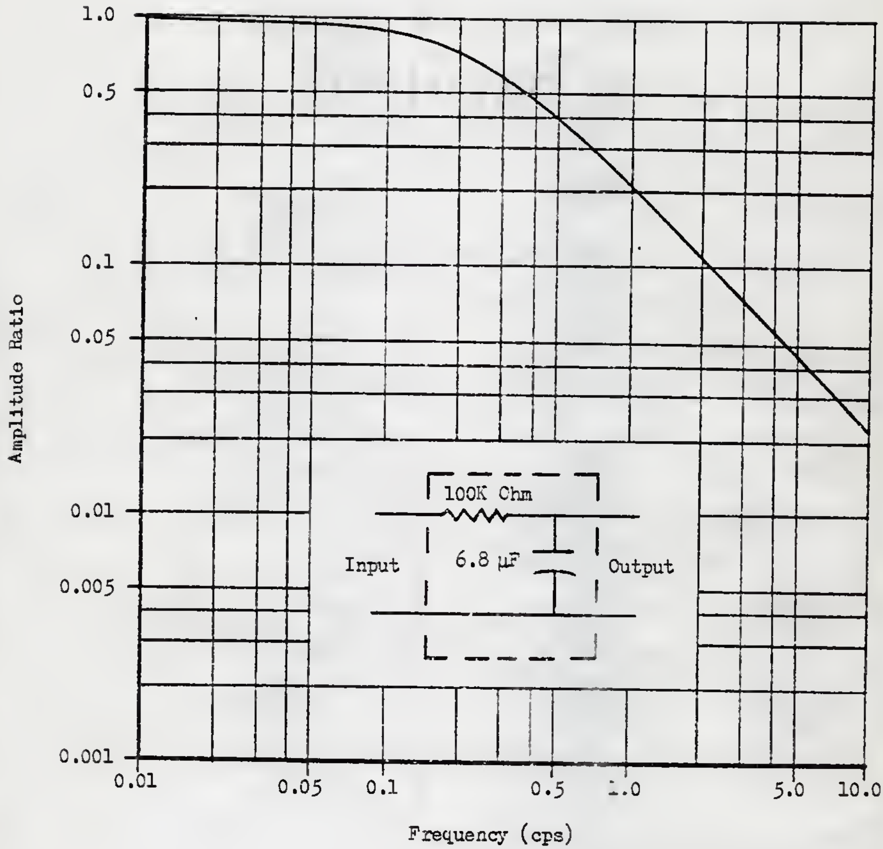


Figure 3.3. R-C Low-Pass Filter

<u>Software</u>

The software developed for this research had the tasks of data acquisition and transmission oil temperature control. The programming of the microcomputer was done in hexadecimal machine language code. MOS Technology publications [7, 8, 9, 10] detail the microcomputer and the program code. The program is listed in Appendix C.

A structured programming technique was used in developing the software. The main feature of structured programming is that the program is composed of numerous segments with each segment having a narrowly defined function. This keeps the segments short and enhances program debugging and component trouble-shooting. It also improves understanding of the program by persons other than the programmer. The program is also versatile in that the main program can easily be revised to call only one or several of the subroutines for reduced program scope.

The Main Program as illustrated in Figure 3.4 is solely a sequence of Jump to Subroutine statements. Upon commencing the Main Program, control is immediately transferred to the Initialization Subroutine where upon its completion control is transferred back to the Main Program and then immediately to the Pump Speed Subroutine. This sequence continues until program control is returned from the Temperature Control Subroutine to the Main Program. The Main Program then loops back to the Pump Speed Subroutine. The program continues in this infinite loop that each cycle determines and displays ten separate data values and provides for transmission oil temperature control. Execution can be halted by pressing the STOP key.

The Initialization Subroutine, Figure 3.5, is a sequence that defines and stores constants required for proper program execution. The first

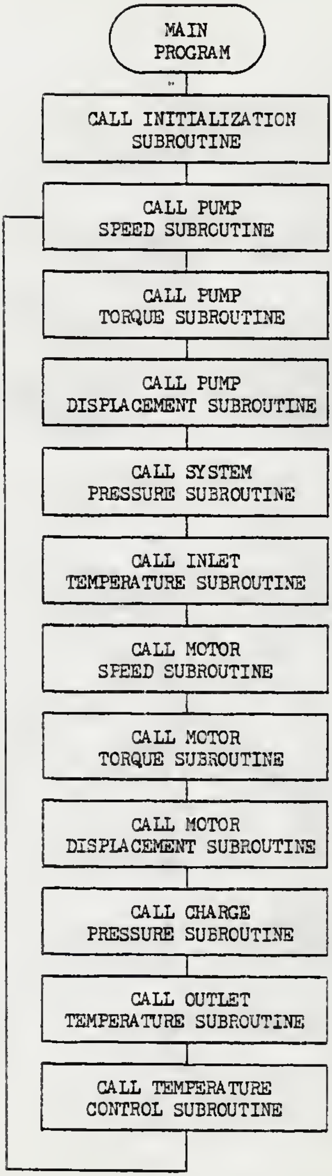


Figure 3.4. Main Program

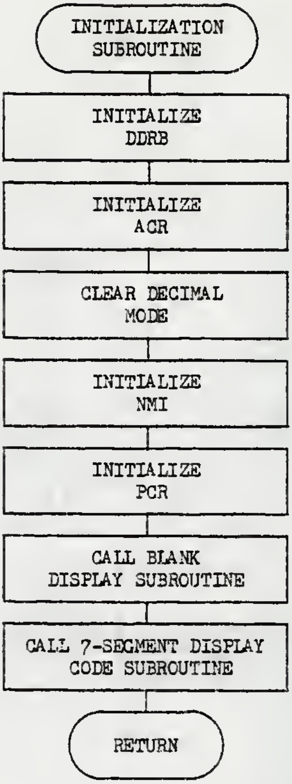


Figure 3.5. Initialization Subroutine

step is to initialize the Data Direction Register B to specify the pins as either inputs or outputs. Port B pins are all outputs with the exception of PB6 which is the shaft speed input pin. DDRB is therefore initialized to HEX BF or BIN 1011 1111.

The Auxilary Control Register is initialized to HEX 60 or BIN 0110 0000. This sets up Timer 2 as a pulse counter on PB6 and puts Timer 1 in the free-running mode.

The next step of the Initialization Subroutine clears the decimal mode. This sets up the microprocessor for binary arithmetic operations.

The two bytes of the Non-Maskable Interrupt must be initialized to HEX 1C00 so that the program can be terminated by pressing the STOP key.

The Peripheral Control Register is initialized to HEX 00. This step is possibly unnecessary in that the PCR is redefined in the Temperature Control Subroutine. However, it does provide a convenient check on the operation of the cooling water solenoid when the oil is cold. When the PCR is defined as HEX 00 it allows CB2 to go high which energizes the solenoid. The solenoid is subsequently de-energized as the Temperature Control Subroutine is executed.

The Initialization Subroutine then calls the Blank Display Subroutine to clear the interface display and the 7-Segment Display Code Subroutine to store the code for the symbols 0 to F.

The Pump Speed Subroutine and Motor Speed Subroutine are identical except for the address of the input channel and the display addresses. The Pump Speed Subroutine is illustrated in Figure 3.6. The first step is to specify the input channel address. Control is then transferred to the RPM Subroutine which determines and stores the rpm value in memory as a high and low byte.

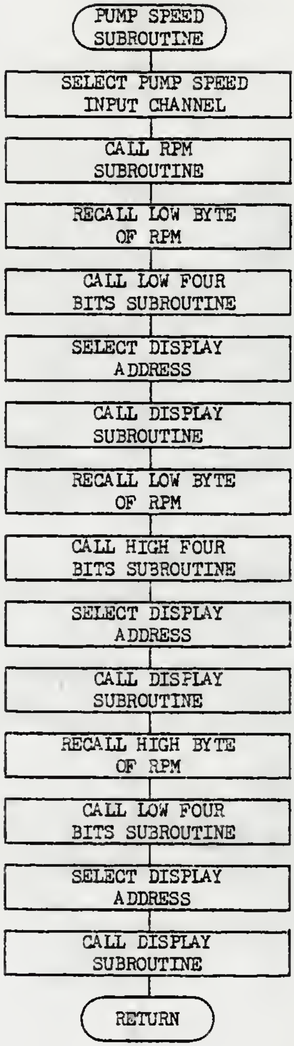


Figure 3.6. Pump Speed Subroutine

The remainder of the RPM Subroutine is dedicated to displaying the result. First the low byte is recalled and the low four bits are separated, decoded, and displayed as a hexadecimal digit. Next the high four bits of the low byte are separated, decoded, and displayed. Finally, the low four bits of the high byte are separated, decoded, and displayed. Only the lower 12 bits of the 16 bits total are actually used for the speed value. This gives a range of 0 to 4095 rpm with a resolution of one rpm.

The subroutines that determine and display the values of the eight analog channels consisting of torque, displacement, pressure, and temperature are similar with only the channel and display address differing. The Pump Torque Subroutine is shown in Figure 3.7.

First the subroutine specifies the appropriate analog input channel. Control is then transferred to the analog to digital conversion subroutine. The remainder of the subroutine separates, decodes, and displays the four low bits and four high bits of the eight bit digital value.

The RPM Subroutine, Figure 3.8, determines the selected shaft speed by activating the appropriate input channel and counting pulses for one second. The pulses are generated by a magnetic pickup on a 60 tooth gear so the number of pulses counted in one second is the shaft speed in rpm. The pulses are counted by Timer 2 which decrements for each negative-going pulse of PB6. The one second time period is determined by Timer 1 in the free-running mode used in conjunction with a loop counter.

The RPM Subroutine first activates the input channel specified by the calling routine. It then initializes the loop counter to HEX 11 or DEC 17. Since the pulse counter decrements, it is initialized to the large number

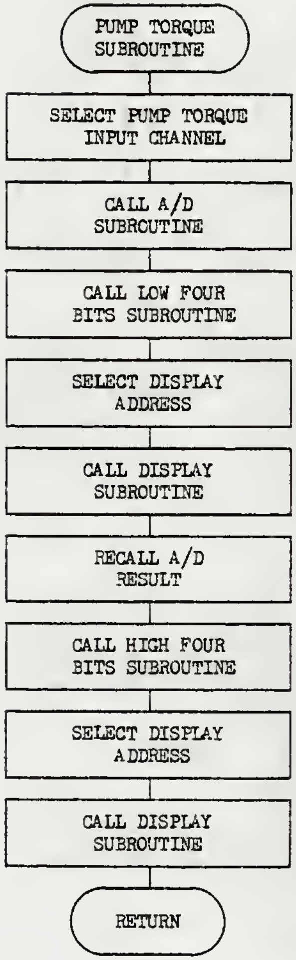


Figure 3.7. Pump Torque Subroutine

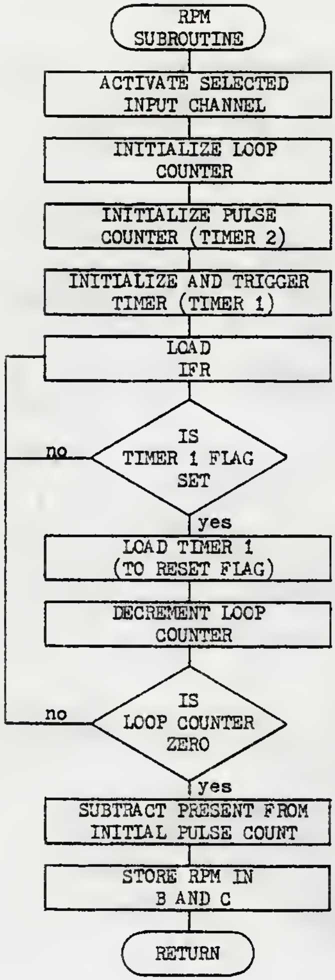


Figure 3.8. RPM Subroutine

HEX FFFF and the final count will be subtracted from it to determine rpm. The timer is initialized to HEX E5C8 or DEC 58824. Loading the timer also triggers the count-down which is at system clock rate of 1 MHz.

The program then enters a loop that keeps checking if the timer has timed-out. When the timer reaches zero it sets a flag and also reloads the initial value, HEX E5C8, and continues to decrement. When the time-out occurs, the timer flag is reset by reading the timer value. The loop counter is decremented and the program loops back to the loop that checks the timer flag. This sequence continues until the loop counter reaches zero. The counting down of the timer 17 times from 58824 at 1 MHz clock rate gives an elapsed time of one second.

The pulse counter is then read and subtracted from the initial value. The resulting value is stored in memory and program control is returned to the calling routine.

The A/D Subroutine, Figure 3.9, determines the digital representation of the analog value on the input channel specified by the calling routine. The channel address is passed to the subroutine in the X-register. The digital result is loaded into the Accumulator for use by the calling routine. It also remains in memory location 0400.

The subroutine first adds the A/D control bit PB4 to the A/D enable and channel address in the Accumulator. The result is then stored in ORB which activates the selected input channel and clears the previous conversion result. The following twenty-five NOP commands are to allow time for the multiplexor to switch and settle. The A/D control bit is then driven low to initiate the conversion.

The subroutine then enters a loop where the IFR is loaded and checked

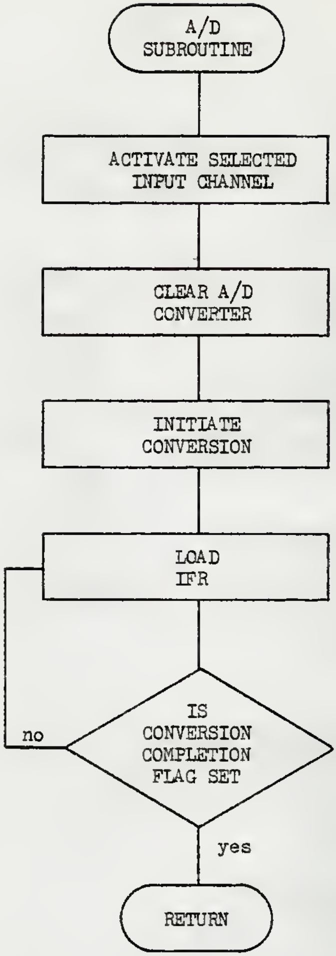


Figure 3.9. A/D Subroutine

to determine if the conversion is complete. Upon completion of the conversion, the result is loaded into the Accumulator and control is returned to the calling routine.

The Low Four Bits Subroutine, Figure 3.10, and High Four Bits Subroutine, Figure 3.11, serve to prepare data for the display. Each eight bit number must be separated into two four bit numbers to be represented as two hexadecimal digits. The Display Subroutine requires the four bits being displayed to be the low four bits. The incoming eight bit number must be in the Accumulator. The resulting number is returned to the calling routine in the Y-register along with the original number being restored in the Accumulator.

The Low Four Bits Subroutine masks the high four bits by an AND operation with the number HEX OF. The High Four Bits Subroutine places the high four bits in the low four bit locations and zeros in the high four bit locations by using a logical shift right four times.

The data is displayed in hexadecimal form to provide efficient use of the display units. The simultaneous presentation of eight two-digit parameters and two three-digit parameters uses 22 of the 24 available digits. Conversion to base ten would require one additional digit for each parameter or a total of 32. Scaling to appropriate units would require 39 digits.

The Display Subroutine, Figure 3.12, displays the selected hexadecimal number at a selected display address. The low byte of the display address must be in the X-register and the digit to be displayed must be in the Y-register.

The subroutine determines the 7-segment code for the digit to be

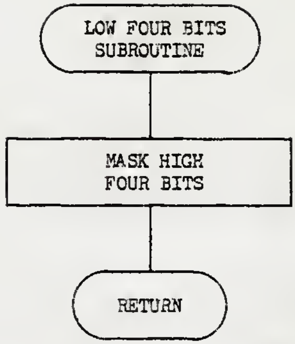


Figure 3.10. Low Four Bits Subroutine

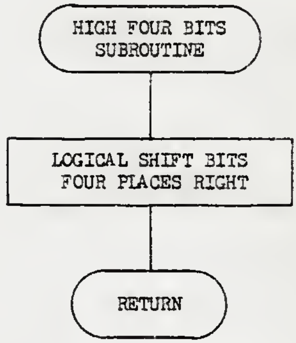


Figure 3.11. High Four Bits Subroutine

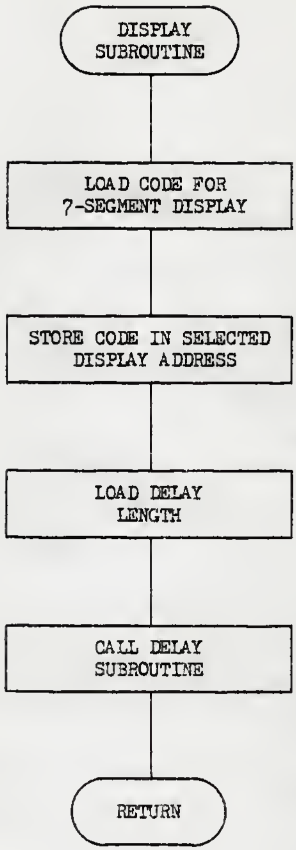


Figure 3.12. Display Subroutine

displayed by using the digit to specify the address where the code is stored by the 7-Segment Display Code Subroutine. The code is then stored at the selected display address.

The subroutine then must delay for a period to allow the display multiplexer to sweep before addressing another display address. The delay length is loaded in the Y-register and the Delay Subroutine is then called.

The Delay Subroutine, Figure 3.13, causes a delay of approximately one millisecond for each unit in the Y-register. The inner loop consists of operations requiring 7 machine cycles and is executed 143 times for a total of approximately 1000 cycles or about 1 millisecond at the one MHz clock rate. The subroutine executes the outer loop once for each unit initially in the Y-register.

The subroutine first initializes the inner loop counter to HEX 8F. The routine then enters the inner loop. The inner loop counter is decremented and then checked for zero. When the inner loop counter reaches zero, the outer loop counter is then decremented and checked for zero. If the outer loop counter is not zero, the routine then loops back and initializes and executes the inner loop again. When the outer loop counter reaches zero, control is returned to the calling routine.

The Blank Display Subroutine, Figure 3.14, is used in the Initialization Subroutine to clear all display memory locations. This could be to remove garbage present when the machine woke up or to remove previous data from display memory locations not currently being used by the routines called by the Main Program.

The first step is to load HEX 00 which is the code for a blank display

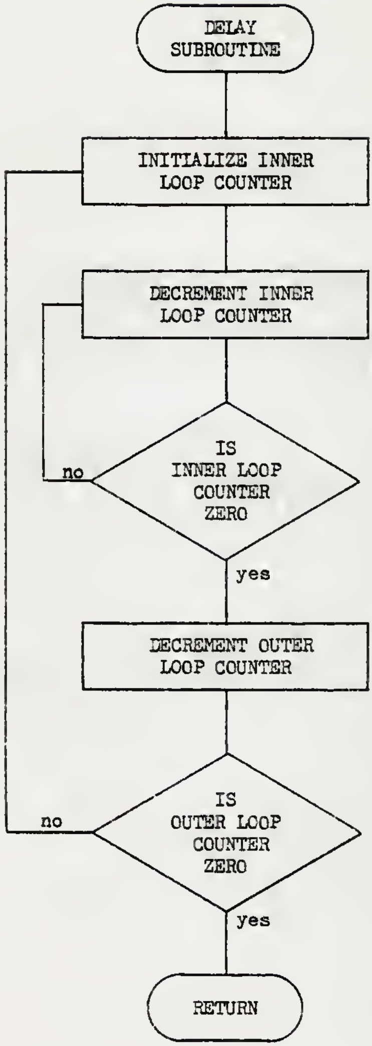


Figure 3.13. Delay Subroutine

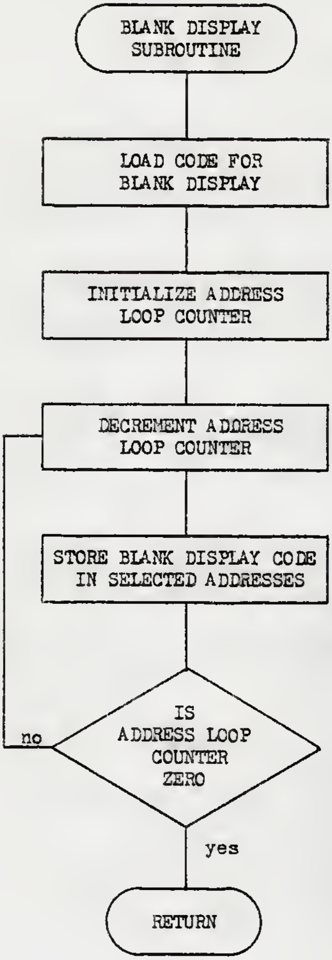


Figure 3.14. Blank Display Subroutine

digit. The next step is to initialize the loop counter to count down the four low bits of the address location. The subroutine then enters a loop where the loop counter is first decremented and then the result is combined with the values HEX 0600 and HEX 0640 to address the display memory locations. When the loop counter reaches zero, control is transferred back to the calling routine.

The 7-Segment Display Code Subroutine, Figure 3.15, is a sequence of steps that loads and stores the 7-segment code for each of the hexadecimal digits.

The Temperature Control Subroutine, Figure 3.16, regulates the transmission oil temperature by controlling the flow of cooling water to the transmission oil heat exchanger. The subroutine first determines and stores the inlet oil temperature. Next, the outlet oil temperature is determined and averaged with inlet oil temperature.

The average temperature is first compared to the high temperature limit. If the average temperature exceeds the high temperature limit, the value HEX E0 is stored in the PCR to cause CB2 to go or remain high and energize the solenoid to initiate or maintain the flow of cooling water.

If the average temperature is not above the high temperature limit, it is then compared to the low temperature limit. If the average temperature is below the low temperature limit, the value HEX C0 is stored in the PCR to cause CB2 to go or remain low and de-energize the solenoid to terminate the flow of cooling water or keep it off if previously off.

If the average temperature is less than or equal to the high limit and greater than or equal to the low limit, no action is taken and control is returned to the Main Program.

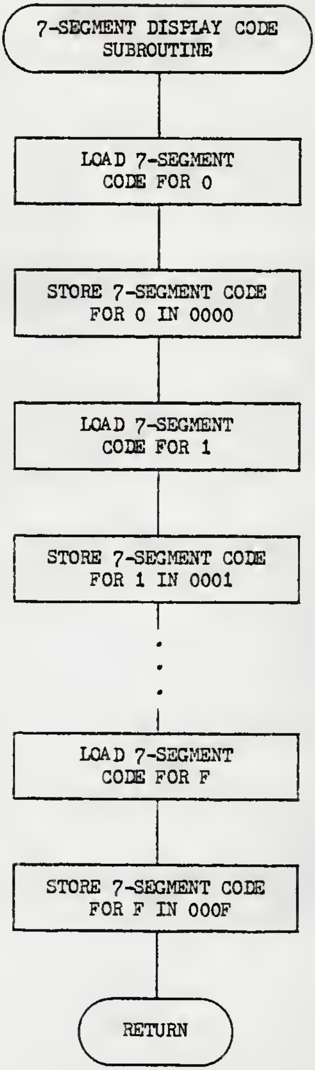


Figure 3.15. 7-Segment Display Code Subroutine

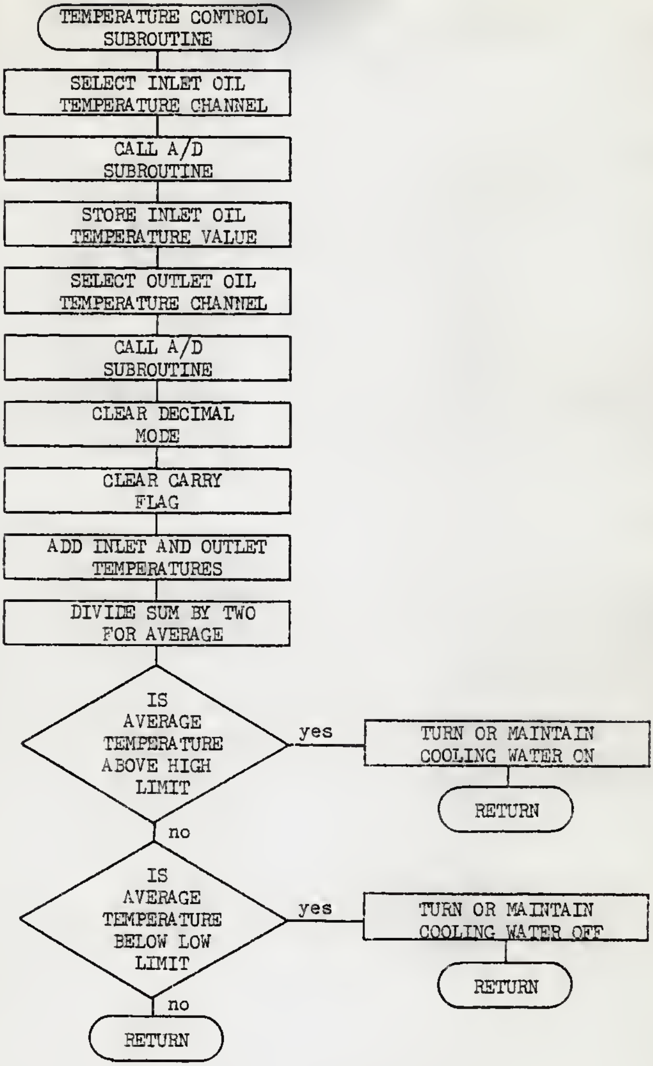


Figure 3.16. Temperature Control Subroutine

CHAPTER IV

EXPERIMENTAL PROCEDURES

Calibration

Pump speed and motor speed were determined from pulses generated by a magnetic pickup on a 60 tooth gear. A one second period was selected so that the number of pulses during that period would give rpm directly. The one second interval was timed by the microcomputer and its crystal controlled 1 MHz clock. The time period was written into the software and required no further calibration.

The torque, displacement, pressure, and temperature signals entered the interface as voltage levels. These voltage signals were converted to a digital representation by the analog to digital converter. The digital representation was a 8-bit number which was displayed as two hexadecimal digits. This gave 256 distinct values for the 0 to 10 volt range of the A/D converter.

The zero point of the input signal was hard to detect because the A/D converter would indicate zero for all negative voltages. It was therefore found convenient to use a digital voltmeter during calibration procedure. With the voltmeter set to read in increments of 0.01 volt, it also provided better resolution than the 0.04 volt per increment of the 8-bit A/D converter.

A small amount of input voltage bias was caused by the A/D input buffers. This required a small positive voltage in the input signal to represent the zero value of the A/D converter. Therefore the zero parameter value condition was actually represented by a small positive voltage signal but due to the input bias was still represented as zero by the A/D converter.

The pump torque and motor torque were calibrated by shunt resistance. The equivalent torque of the shunt was determined by comparison to a known torque generated by dead weight. A scaling factor of 7.2 in.lb per increment of the 8-bit A/D converter was used. The zero and calibration values are given in Table 4.1.

The pump displacement and motor displacement were assumed to be linear with the feedback signal from the Moog controllers. The A/D digital values for minimum and maximum displacements were determined and straight line coefficients were calculated.

The A/D digital value HEX 11 corresponded to the 0 in^3/rev minimum pump displacement and HEX F8 corresponded to the 4.26 in^3/rev maximum pump displacement. Pump displacement could then be calculated from the relationship

$$Dp = 0.018442\ Vdpa/d - 0.31351$$

where Vdpa/d is the digital representation of the pump displacement voltage as determined by the A/D converter.

To illustrate the use of the pump displacement equation, consider the value HEX F8 being read from the pump displacement display. Convert HEX F8 to DEC 248 and then calculate pump displacement as

$$Dp = (0.018442)\ (248) - 0.31351 = 4.26\ in^3/rev$$

The A/D digital value HEX 4B corresponded to the 2.73 in^3/rev minimum motor displacement and HEX D7 corresponded to the 7.24 in^3/rev

TABLE 4.1

ZERO AND CALIBRATION VALUES

	Zero	Calibration
Pump Speed	none	none
Motor Speed	none	none
Pump Torque	0 = 0.09 V = HEX 00	shunt = 8.09 V = HEX CD
Motor Torque	0 = 0.09 V = HEX 00	shunt = 8.00 V = HEX CA
Pump Displacement	none	none
Motor Displacement	none	none
System Pressure	0 = 0.11 V = HEX 00	2020 psi = 4.05 V = HEX CA
Charge Pressure	0 = 0.11 V = HEX 00	205 psi = 4.09 V = HEX CD
Inlet Temperature	0° C = HEX 00	99.6° C = HEX FF
Outlet Temperature	0° C = HEX 00	99.6° C = HEX FF

maximum motor displacement. Motor displacement could then be determined from the relationship

$$Dm = 0.032214\ Vdma/d + 0.31395$$

where Vdma/d is the digital representation of the motor displacement voltage as determined by the A/D converter.

System pressure and charge pressure were calibrated with a dead weight pressure tester. A scaling factor of 10 psi per increment of the 8-bit A/D converter was used for system pressure, and a scaling factor of 1 psi per increment was used for charge pressure. The zero and calibration values are listed in Table 4.1.

The temperature measurements were calibrated to read HEX 00 for 0°C and HEX FF for 99.6°C. This gave 1/2.56 or 0.3906°C per increment of the 8-bit A/D converter.

Test Procedure

The test procedure followed for data acquisition at full displacement is listed below.

1. Turn on all electronic equipment at least thirty minutes prior to calibration.
2. Perform calibration procedure.
3. Check engine and transmission oil levels.
4. Turn on exhaust fan, cooling water, and fuel.
5. Start engine and allow brief warm-up period without load.
6. Completely open load circuit valve.
7. Engage clutch to activate transmission.

8. Slowly increase the load and speed to near the first data point.

9. Allow ample warm-up time (normally twenty minutes or greater)

10. Turn pump to zero displacement and set no-load speed on engine.

11. Turn pump to full displacement and set load circuit valve for the highest system pressure to be included in the run.

12. Allow a several minute stabilization period.

13. Record three sets of data at one minute intervals.

14. Change the load circuit valve setting to the next lower system pressure to be run.

15. Allow five minutes from the time data was initially read at the previous load setting.

16. Repeat steps 13, 14, and 15 until the test run is completed.

17. Shut down and check calibration.

Essentially the same procedure given above was also followed for data taken at partial displacement except step 13 was changed so that six sets of data were read at one-half minute intervals. The number of data sets at each load setting was increased because the partial displacement data had more scatter than the full displacement data. This was possibly due to minor changes in the displacements during partial displacement operation that did not occur during full displacement operation because of the swashplate angle being fixed by internal stops.

CHAPTER V

PRESENTATION OF RESULTS

Temperature Control Analysis

The internal leakage and viscous drag are both functions of oil viscosity which is a function of temperature. The procedure for determination of the model coefficients required the transmission oil temperature to be held constant throughout the tests so that the viscosity would remain constant.

As discussed in Chapter III, the transmission oil temperature control scheme was an on-off nonlinearity with hysteresis. The input temperature was the average of the inlet oil temperature and outlet oil temperature. The lower and upper temperature settings were 51.2°C and 52.0°C giving a total hysteresis band of 0.8°C. This gave a nominal control temperature of 51.6°C.

A detailed analysis of the temperature controller was not conducted. However, it was observed that the controller exhibited a stable limit cycle at all transmission operating conditions.

A summary of the transmission oil temperature is given in Table 5.1. These data were taken when the tests for determination of the coefficients were run and are listed in Appendix D. The operating conditions covered a wide range of torques and speeds with the pump and motor both at full displacement.

TABLE 5.1

TRANSMISSION OIL TEMPERATURE ANALYSIS

	$\bar{x}$	s	n
t_{in}	47.78	1.11	135
t_{out}	55.66	1.41	135
t_{avg}	51.72	1.05	135

The average temperature of 51.72° C was reasonably close to the control temperature of 51.6° C. The standard deviation of 1.05° C of the average temperature gave an indication of the amount of variation in the average temperature. The temperature controller was considered acceptable for its application in this research.

Amoco 1000 oil was used in the transmission during this research. The Amoco specification sheet [11] for this oil lists its viscosity as 315 SSU at 100° F and 59 SSU at 210° F. From a standard viscosity vs. temperature graph, the viscosity was determined to be 180 SSU at the average transmission oil temperature of 51.72° C or 125° F. Using the standard conversion formula [5] for t greater than 100 SSU the kinematic viscosity was converted to cm^2/sec.

$$\nu = 0.0022t - \frac{1.35}{t} = (0.0022)\ (180) - \frac{1.35}{180} = 0.3885\ cm^2/sec$$

The Amoco specification sheet lists the specific gravity of the oil as 0.8911 at 60° F. From information in the Petroleum Measurement Tables [12], the specific gravity at the average transmission oil temperature of 125° F was determined to be 0.868.

The absolute viscosity was determined as follows.

$$\mu = \frac{(0.3885\ cm^2/sec)\ (0.868)\ (1.94\ slug/ft^3)\ (lb\ sec^2/slug\ ft)}{(2.54\ cm/in)^2\ (12\ in/ft)^4\ (60\ sec/min)}$$

$$\mu = 8.15 \times 10^{-8}\ lb.min/in^2$$

Development of Model A

The model selected in Chapter I for initial investigation will be referred to as Model A to distinguish it from modified versions to be considered later in this chapter.

Speed, torque, and pressure data were recorded over a wide range of operating conditions for determination of the coefficients of Model A. The raw data are listed in Appendix D. System pressures from 600 to 1600 psi in increments of 200 psi and no-load engine speeds from 1000 to 2400 rpm in increments of 200 rpm were considered. Every system pressure setting was used at every no-load engine speed setting except only system pressures of 1000 psi and less could be run at 1000 rpm no-load engine speed. This gave a total of 45 distinct load and speed settings.

From the three readings taken at each setting, the average of each measured parameter was determined. This information is listed in Appendix E. From the average values, the value of K/μ was found from the relationship developed in Appendix B.

$$\frac{K}{\mu} = \frac{2\pi\,(Dp\ Np - Dm\ Nm)}{\Delta P}$$

Ideally, this value would be the same for all data points. However, observation of the calculated values of K/μ listed in Appendix E reveals it to be quite variable. The mean value of K/μ of 42 data pcints was determined to be 2.135 with a standard deviation of 0.895. The data at 1000 rpm no-load engine speed were not included in this calculation since they didn't include the full range of system pressures. Since only one number could be used for K/μ in the model, the mean of the values was used. The value of K for model A was determined as follows.

$$K = (2.135)\ (8.15 \times 10^{-8}) = 1.740 \times 10^{-7}$$

Determination of the remainder of the coefficients required a plot of torque vs. speed at constant pressure differential for various pressure levels. When the data were recorded, system pressure was held constant but charge pressure varied somewhat as a function of pump speed. It was therefore necessary to adjust the measured torque for a common charge pressure.

The charge pressure data recorded at the 45 load settings used for determination of the coefficients is listed in Appendix E. Analysis of this data determined the mean charge pressure to be 170.8 psi with a standard deviation of 6.4 psi. For convenience, the value of 170 psi was chosen for use as the standard charge pressure.

The torque values were adjusted for the standard charge pressure by multiplying the measured torque value by the ratio of the standard pressure differential value to the measured pressure differential value. This can be illustrated by an example. The first data point listed in Appendix E lists a measured pump torque of 1147 in.lb with system pressure of 1600 psi and charge pressure of 183 psi. The adjusted pump torque value is calculated by

$$1147\ (1600 - 170)\ /\ (1600 - 183) = 1158$$

The adjusted torque values are listed in Appendix F.

The graph of torque at constant pressure differential vs. speed for the pump is given in Figure 5.1 and for the motor is given in Figure 5.2. Least-squares regression analysis was used to determine the slope, intercept, and correlation coefficient of the best fitting straight line for each set of data at constant pressure differential. This information is summarized in Table 5.2.

The coefficients of viscous drag were determined from the average slope as follows.

$$Cdp = \frac{m}{Dpm\ \mu} = \frac{0.049021}{(4.26)\ (8.15 \times 10^{-8})} = 141194$$

$$Cdm = \frac{-m}{Dmm\ \mu} = \frac{0.075469}{(7.24)\ (8.15 \times 10^{-8})} = 127901$$

The next step in the determination of the coefficients required the value of the zero-speed torque as a function of pressure differential. Graphically this was determined as the torque value at the zero-speed intercept of the constant pressure differential lines for the pump and motor given in Figures 5.1 and 5.2. These values are listed in Table 5.2 as b, or intercept.

The graph of zero-speed torque vs. pressure differential is given in Figure 5.3 for the pump and Figure 5.4 for the motor. Least-squares

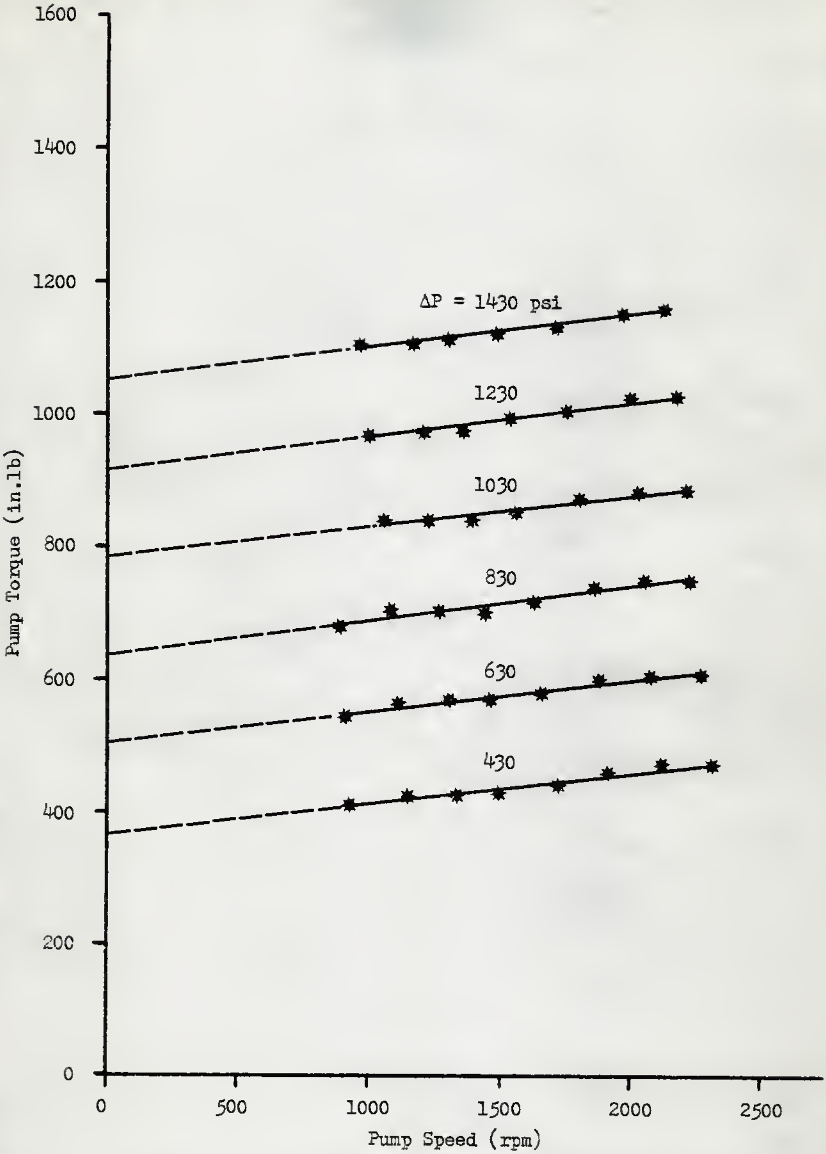


Figure 5.1. Pump Torque at Constant Pressure Differential vs. Speed - Model A

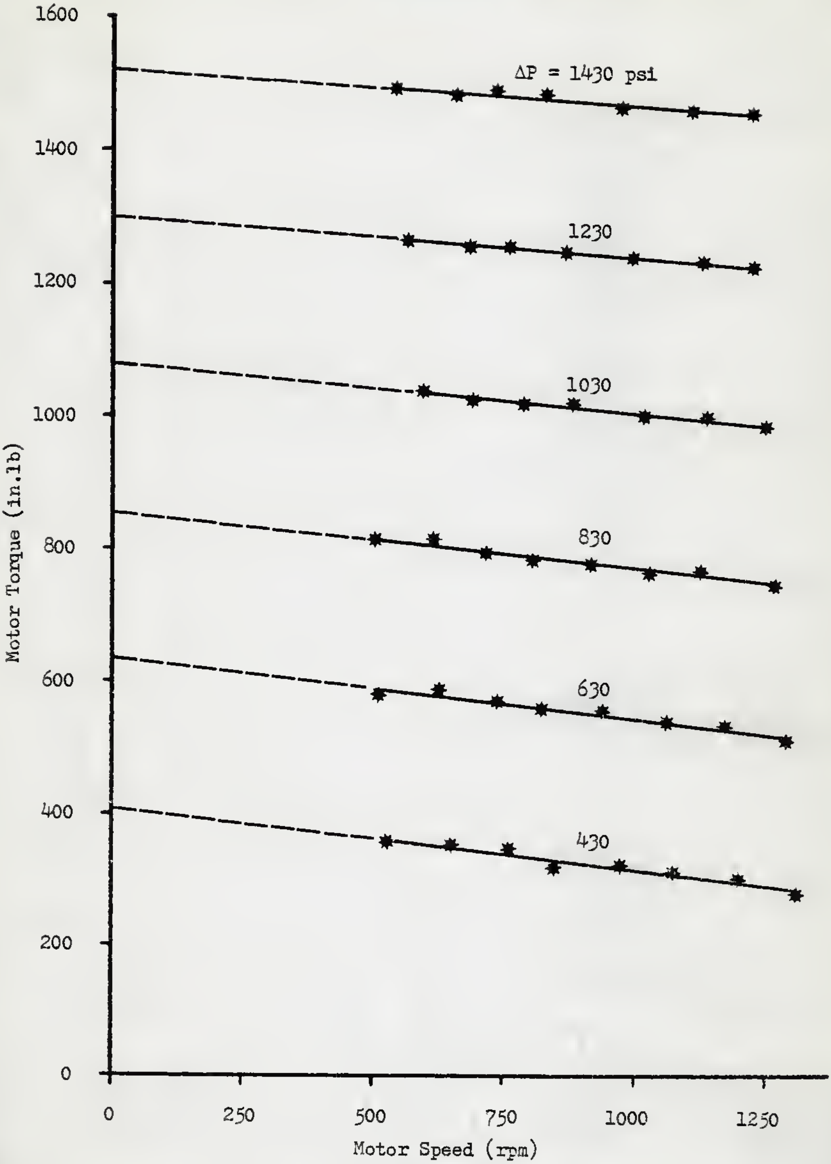


Figure 5.2. Motor Torque at Constant Pressure Differential vs. Speed - Model A

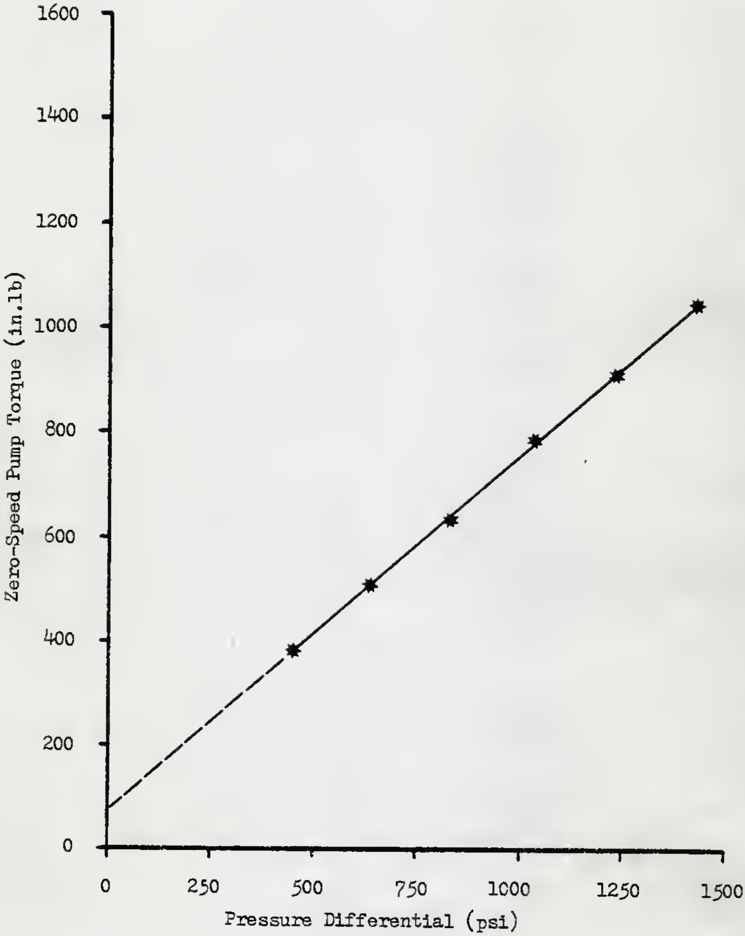


Figure 5.3. Pump Zero-Speed Torque vs. Pressure Differential - Model A

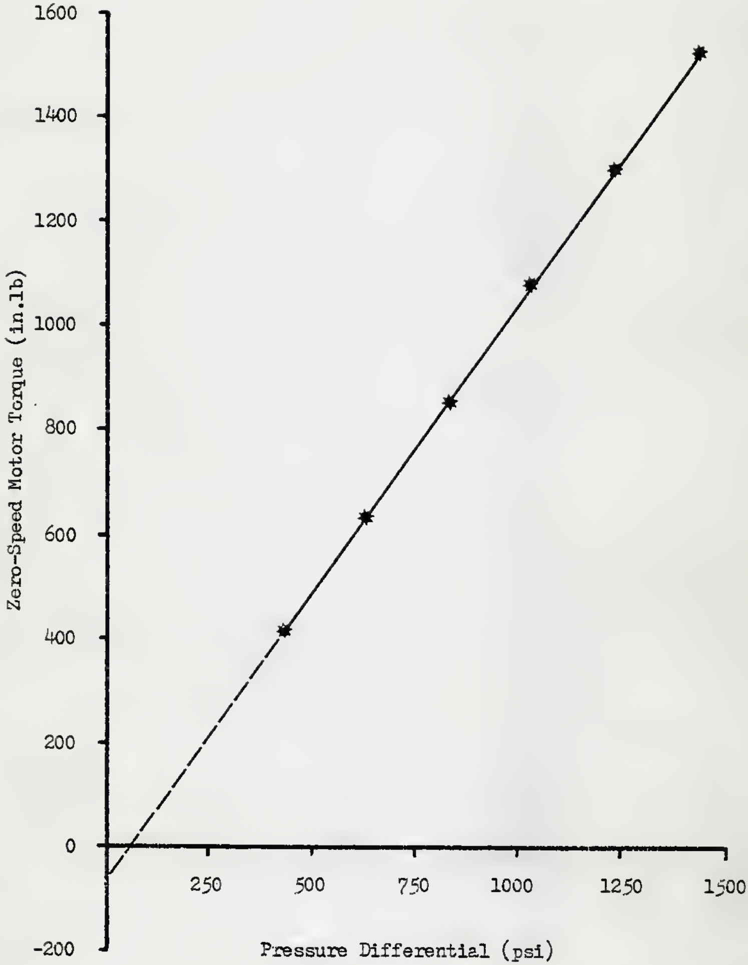


Figure 5.4. Motor Zero-Speed Torque vs.
Pressure Differential - Model A

TABLE 5.2

LINEAR REGRESSION COEFFICIENTS FOR TORQUE AT CONSTANT PRESSURE VS. SPEED FOR MODEL A

ΔP	Pump m	Pump b	Pump r^2	Motor m	Motor b	Motor r^2
1430	0.050122	1050.2	0.959	-0.056604	1526.3	0.880
1230	0.051573	914.4	0.953	-0.059172	1299.9	0.968
1030	0.047818	783.6	0.914	-0.072966	1080.1	0.927
830	0.051884	638.2	0.914	-0.082110	857.2	0.935
630	0.047354	506.1	0.940	-0.088267	634.7	0.927
430	0.045373	370.8	0.934	-0.093692	412.8	0.931

Pump: $\bar{x}$ = 0.049021, s = 0.002587

Motor: $\bar{x}$ = -0.075469, s = 0.015282

TABLE 5.3

LINEAR REGRESSION COEFFICIENTS FOR ZERO SPEED TORQUE VS. PRESSURE FOR MODEL A

Pump m	Pump b	Pump r^2	Motor m	Motor b	Motor r^2
0.681043	77.18	0.99986	1.112286	-65.93	0.99999

regression analysis was used to determine the slope, intercept, and correlation coefficient of the best fitting straight line. This information is summarized in Table 5.3.

The coefficients of dry friction were determined from the slope as follows.

$$Cfp = \frac{2\pi m}{Dpm} - 1 = \frac{2\pi(0.681043)}{4.26} - 1 = 0.004488$$

$$Cfm = 1 - \frac{2\pi(-m)}{Dmm} = 1 - \frac{2\pi(1.112286)}{7.24} = 0.034710$$

The constant friction torques for Model A were determined from the intercepts in Table 5.3 as follows.

$$Tcp = b = 77.18$$

$$Tcm = -b = 65.93$$

Evaluation of Model A at Full Displacement

The method chosen to evaluate a model was to compare a value calculated by the model to a value measured under the same input conditions. The model was used to calculate pump speed and pump torque from the inputs of measured values of motor speed and motor torque for which measured values of pump speed and pump torque were also known. From the values of torque and speed, power was also calculated for comparison.

Comparisons were made on both a ratio basis and a difference basis to give an indication of relative and absolute error between the calculated and measured values. For example, if for one of the points considered the calculated speed from the model was 1010 rpm and the measured value was

1000 rpm the ratio of calculated to measured speed would be 1.0100 and the difference would be +10 rpm. If the model speed was 2020 rpm and the measured value was 2000 rpm the ratio would also be 1.0100 but the difference would then be +20 rpm. Both types of comparison were considered important as evaluation tools for the models.

The main evaluation of the model was based on the speed and torque calculations. Power calculations were also made and compared but were only of secondary importance as they were only a combined reflection of the speed and torque comparison.

Model A was evaluated by comparing its calculated values to all the measured values used for determination of its coefficients. This information is listed in Appendix G.

Model A on the average predicted the pump speed to be 1.0094 of the measured pump speed with a standard deviation of 0.0199. In other words, the model predicted pump speed about 1% high on the average with a standard deviation of about 2%. This corresponded to the model predicting 9.0 rpm high on the average with a standard deviation of 26.2 rpm.

Model A on the average predicted the pump torque to be 0.9986 of the measured pump torque with a standard deviation of 0.0098. This corresponded to the model predicting 0.6 in.lb high on the average with a standard deviation of 7.6 in.lb. In this case the ratio basis indicated the average prediction was low while the difference basis indicated the average prediction was high. This was due to the ratio terms at the lower parameter values dominating the ratio terms at the higher parameter values but yet on the difference basis the difference terms at the higher parameter values dominated the difference terms at the lower parameter values.

The pump power predicted by Model A was on the average 1.0081 of the measured power with a standard deviation of 0.0253. This corresponded to the model predicting 0.20 hp high on the average with a standard deviation of 0.50 hp.

Development of Model B

On the average, Model A did a relatively good job of predicting actual pump speed, pump torque, and pump power. The variability of the predictions as compared to the measured values was indicated by the standard deviation. Although the variations were at an acceptable level, two modifications to possibly improve the model were determined and evaluated as Model B.

The first modification involves the leakage term in the flow equation. Model A recognizes leakage as a constant times pressure differential for a given oil viscosity. The variability in the K/μ terms evaluated for Model A suggested the need for a more comprehensive accounting of the leakage.

Leakage values were determined for each data point and are given in Appendix E. This information is plotted in Figure 5.5 as leakage vs. pressure differential. The leakage values from the 1000 rpm no-load speed runs were not included as they didn't cover the full pressure range of the remainder of the data. Although there was considerable scatter in the data in Figure 5.5, it appeared that leakage could be better approximated by a constant leakage component plus a component that is a constant times pressure differential.

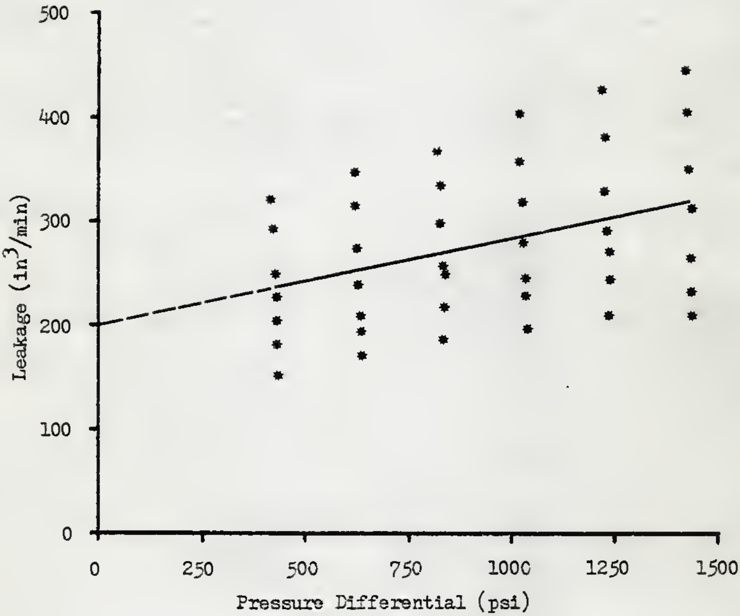


Figure 5.5. Leakage Flow vs. Pressure Differential - Model B

The flow and torque equations for Model B are given below. Only the flow equations are changed from Model A.

$$Qp = Dp\ Np - \frac{Csp\ \Delta P\ Dpm}{2\ \pi\ \mu} - \frac{Lcp}{\mu}$$

$$Tp = \frac{\Delta P\ Dp}{2\ \pi} + \frac{Cfp\ \Delta P\ Dpm}{2\ \pi} + Cdp\ \mu\ Np\ Dpm + Tcp$$

$$Qm = Dm\ Nm + \frac{Csm\ \Delta P\ Dmm}{2\ \pi\ \mu} + \frac{Lcm}{\mu}$$

$$Tm = \frac{\Delta P\ Dm}{2\ \pi} - \frac{Cfm\ \Delta P\ Dmm}{2\ \pi} - Cdm\ \mu\ Nm\ Dmm - Tcm$$

The procedure for rearranging the flow and torque equations to get the speed and torque equations needed to use the model was the same for Model B as that for Model A given in Appendix B. The resulting equations are given below.

$$Nm = \frac{Dp\ Np}{Dm} - \frac{K\ (Tp - Cdp\ \mu\ Np\ Dpm - Tcp)}{\mu\ (Dp + Cfp\ Dpm)\ Dm} - \frac{K'}{\mu\ Dm}$$

$$Np = \frac{Dm\ Nm}{Dp} + \frac{K\ (Tm + Cdm\ \mu\ Nm\ Dmm + Tcm)}{\mu\ (Dm - Cfm\ Dmm)\ Dp} + \frac{K'}{\mu\ Dp}$$

$$\begin{aligned} Tm = {} & (Tp - Tcp)\left[\frac{(Dm - Cfm\ Dmm)}{(Dp + Cfp\ Dpm)} + \frac{K\ Cdm\ Dmm}{(Dp + Cfp\ Dpm)\ Dm}\right] \\ & - Np\left[\frac{Cdp\ \mu\ Dpm\ (Dm - Cfm\ Dmm)}{(Dp + Cfp\ Dpm)} + \frac{Cdm\ \mu\ Dmm}{Dm}\left(Dp + \frac{K\ Cdp\ Dpm}{(Dp + Cfp\ Dpm)}\right)\right] \\ & + \frac{K'\ Cdm\ Dmm}{Dm} - Tcm \end{aligned}$$

$$Tp = (Tm + Tcm)\left[\frac{(Dp + Cfp\ Dpm)}{(Dm - Cfm\ Dmm)} + \frac{Cdp\ Dpm\ K}{(Dm - Cfm\ Dmm)\ Dp}\right]$$

$$+ Nm\left[\frac{Cdm\ \mu\ Dmm\ (Dp + Cfp\ Dpm)}{(Dm - Cfm\ Dmm)} + \frac{Cdp\ \mu\ Dpm}{Dp}\left(Dm + \frac{K\ Cdm\ Dmm}{(Dm - Cfm\ Dmm)}\right)\right]$$

$$+ \frac{K'\ Cdp\ Dpm}{Dp} + Tcp$$

where $K' = Lcp + Lcm$

Least-squares regression analysis was conducted on the leakage vs. pressure differential data presented in Figure 5.5. The slope was determined to be 0.084124, the intercept was 201.30, and the correlation coefficient was 0.1563. The composite slip factor, K, was determined from the slope as follows.

$$K = 2\ \pi\ \mu\ m = 2\ \pi\ (8.15 \times 10^{-8})\ (0.084124) = 4.3078 \times 10^{-8}$$

The constant leakage coefficient, K', was determined from the intercept as follows.

$$K' = \mu\ b = (8.15 \times 10^{-8})\ (201.30) = 1.6406 \times 10^{-5}$$

The second modification to be included in Model B was a modification in the method of determination of the coefficients and was not a change in the model equations. According to the model, the slope of all the pump torque at constant pressure differential vs. pump speed lines should have been the same. Likewise, all the motor torque at constant pressure differential vs. motor speed lines should have had the same slope. The slopes of all the lines are listed in Table 5.2 as m and are seen to be somewhat variable.

For Model B each line was rotated about its mean speed value so that all the pump lines had slope equivalent to the average slope of the pump lines and each motor line had slope equivalent to the average of the motor lines. The mean speed of each line, the average slope, and the resulting zero-speed torque value are listed in Table 5.4.

The coefficients of viscous drag were determined from the average slope for Model A and are therefore the same for Model B: Cdp = 141194 and Cdm = 127901.

Least-squares regression analysis was used to determine the slope, intercept, and correlation coefficients of the revised zero-speed torque vs. pressure differential data. This information is summarized in Table 5.5.

The coefficients of dry friction for Model B were determined from the slope as follows.

$$Cfp = \frac{2 \pi m}{Dpm} - 1 = \frac{2 \pi (0.688400)}{4.26} - 1 = 0.015339$$

$$Cfm = 1 - \frac{2 \pi (-m)}{Dmm} = 1 - \frac{2 \pi (1.148043)}{7.24} = 0.003679$$

The constant friction torques for Model B were determined from the intercepts in Table 5.5 as follows.

$$Tcp = b = 70.29$$

$$Tcm = -b = 99.40$$

<u>Comparison of Model A and Model B at Full Displacement</u>

Model B was evaluated on the same basis as Model A was in an earlier section. Model B was used to calculate pump speed and pump torque from the inputs of motor speed and motor torque of actual data. The values of

TABLE 5.4

STRAIGHT LINE COEFFICIENTS FOR TORQUE AT CONSTANT PRESSURE VS. SPEED FOR MODEL B

	Pump			Motor		
ΔP	$\overline{N}p$	m	b	$\overline{N}m$	m	b
1430	1530	0.049021	1051.9	856	-0.075469	1542.4
1230	1571	0.049021	918.4	882	-0.075469	1314.3
1030	1604	0.049021	781.7	904	-0.075469	1082.4
830	1550	0.049021	642.6	876	-0.075469	851.4
630	1581	0.049021	503.5	898	-0.075469	623.2
430	1616	0.049021	364.9	920	-0.075469	396.0

TABLE 5.5

LINEAR REGRESSION COEFFICIENTS FOR ZERO SPEED TORQUE VS. PRESSURE FOR MODEL B

Pump			Motor		
m	b	r^2	m	b	r^2
0.688400	70.29	0.99994	1.148043	-99.40	0.99999

pump speed, torque, and power were then compared on a ratio basis and difference basis involving the calculated and measured values. This information is listed in Appendix H.

Table 5.6 provides a comparison of Model A and Model B at full displacement. Model B on the average predicts speed closer to the actual value and also with less variability. The average ratio of calculated to measured value for Model B was 1.0042 compared to 1.0094 for Model A. The standard deviation on the ratio basis was significantly less for Model B at 0.0124 compared to 0.0199 for Model A. Speed comparison on the difference basis also indicates substantial improvement with Model B.

The average pump torque prediction was changed very little between Model A and Model B. However a slight reduction in the standard deviation on both the ratio basis and difference basis showed Model B to have less variation from the measured values.

Model B gave improved predictions for pump power mostly as a result of the model's improved speed prediction capability.

It was concluded that Model B provided the better model at full displacement and should be evaluated at partial displacements.

Evaluation of Model B at Partial Displacement

Sets of data were taken at partial displacements to determine the transmission performance and provide a basis for further evaluation of Model B. Appendix I contains raw data taken with both the pump and motor set at approximately three-fourths displacement. Appendix J gives the averaged data at approximately three-fourths displacement. Appendix K contains raw data taken with both the pump and motor set at approximately one-half displacement and is followed by Appendix L with the averaged data.

TABLE 5.6

COMPARISON OF MEASURED AND CALCULATED VALUES AT FULL DISPLACEMENT FOR MODEL A AND MODEL B

		Model A full disp	Model B full disp
Np/Np calc/meas	$\bar{x}$	1.0094	1.0042
	s	0.0199	0.0124
Tp/Tp calc/meas	$\bar{x}$	0.9986	1.0016
	s	0.0098	0.0081
HPp/HPp calc/meas	$\bar{x}$	1.0081	1.0058
	s	0.0253	0.0133
ΔNp calc - meas	$\bar{x}$	+ 9.0	+ 1.7
	s	26.2	16.7
ΔTp calc - meas	$\bar{x}$	+ 0.6	+ 0.7
	s	7.6	5.4
ΔHPp calc - meas	$\bar{x}$	+0.20	+0.03
	s	0.50	0.24

Values calculated by Model B were compared to the actual measured data. This information is listed in Appendices M and N and is summarized in Table 5.7. Comparison of any parameter on either the ratio basis or difference basis showed that the model became progressively less accurate as displacement was decreased. This was especially apparent in the torque comparison. This indicated that the torque losses were probably not constant relative to changing displacement and therefore needed to be accounted for as functions of displacement.

Development of Model C

The evaluation of Model B at partial displacement suggested that the torque losses are probably not constant relative to displacement. The model used by Elder and Otis [4] that was discussed in Chapter I used the term 1 - tan α, where α is the swashplate angle, in the denominators of the viscous drag and dry friction torque terms. These losses then become a function of displacement rather than being constant relative to displacement as in Model B.

The only modification beyond Model B to obtain Model C was the inclusion of the 1 - tan α term in the denominator of the viscous drag and dry friction torque terms. The model evaluated as Model C is given below.

$$Qp = Dp\ Np - \frac{Csp\ \Delta P\ Dpm}{2\ \pi\ \mu} - \frac{Lcp}{\mu}$$

$$Tp = \frac{\Delta P\ Dp}{2\ \pi} + \frac{Cfp\ \Delta P\ Dpm}{2\ \pi\ (1 - \tan \alpha p)} + \frac{Cdp\ \mu\ Np\ Dpm}{(1 - \tan \alpha p)} + Tcp$$

$$Qm = Dm\ Nm + \frac{Csm\ \Delta P\ Dmm}{2\ \pi\ \mu} + \frac{Lcm}{\mu}$$

TABLE 5.7

COMPARISON OF MEASURED AND CALCULATED VALUES AT FULL AND PARTIAL DISPLACEMENT FOR MODEL B

		Model B full disp	Model B 3/4 disp	Model B 1/2 disp
Np/Np calc/meas	$\bar{x}$	1.0042	1.0204	1.0325
	s	0.0124	0.0133	0.0163
Tp/Tp calc/meas	$\bar{x}$	1.0016	1.0310	1.0753
	s	0.0081	0.0183	0.0338
HPp/HPp calc/meas	$\bar{x}$	1.0058	1.0520	1.1102
	s	0.0133	0.0233	0.0376
ΔNp calc - meas	$\bar{x}$	+ 1.7	+29.2	+50.0
	s	16.7	16.3	16.1
ΔTp calc - meas	$\bar{x}$	+ 0.7	+20.8	+37.3
	s	5.4	6.6	6.1
ΔHPp calc - meas	$\bar{x}$	+0.03	+0.89	+1.47
	s	0.24	0.17	0.21

$$Tm = \frac{\Delta P\ Dp}{2\ \pi} - \frac{Cfm\ \Delta P\ Dmm}{2\ \pi\ (1 - \tan \alpha m)} - \frac{Cdm\ \mu\ Nm\ Dmm}{(1 - \tan \alpha m)} - Tcm$$

The procedure for rearranging the flow and torque equations to get the speed and torque equations needed to use the model was the same for Model C as that used for Model A given in Appendix B. The resulting equations are given below.

$$Nm = \frac{Dp\ Np}{Dm} - \frac{K\left(Tp - \dfrac{Cdp\ \mu\ Np\ Dpm}{(1 - \tan \alpha p)} - Tcp\right)}{\mu\ \left(Dp + \dfrac{Cfp\ Dpm}{(1 - \tan \alpha p)}\right) Dm} - \frac{K'}{\mu\ Dm}$$

$$Np = \frac{Dm\ Nm}{Dp} - \frac{K\left(Tm + \dfrac{Cdm\ \mu\ Nm\ Dmm + Tcm}{(1 - \tan \alpha m)} + Tcm\right)}{\mu\ \left(Dm - \dfrac{Cfm\ Dmm}{(1 - \tan \alpha m)}\right) Dp} + \frac{K'}{\mu\ Dp}$$

$$\begin{aligned} Tm = (Tp - Tcp) & \left[\frac{\left(Dm - \dfrac{Cfm\ Dmm}{(1 - \tan \alpha m)}\right)}{\left(Dp + \dfrac{Cfp\ Dpm}{(1 - \tan \alpha p)}\right)} + \frac{\dfrac{K\ Cdm\ Dmm}{(1 - \tan \alpha m)}}{\left(Dp + \dfrac{Cfp\ Dpm}{(1 - \tan \alpha p)}\right) Dm}\right] \\ & - Np\left[\frac{Cdp\ \mu\ Dpm\left(Dm - \dfrac{Cfm\ Dmm}{(1 - \tan \alpha m)}\right)}{(1 - \tan \alpha p)\left(Dp + \dfrac{Cfp\ Dpm}{(1 - \tan \alpha p)}\right)} \right. \\ & \qquad \left. + \frac{Cdm\ \mu\ Dmm}{Dm\ (1 - \tan \alpha m)}\left(Dp + \frac{\dfrac{K\ Cdp\ Dpm}{(1 - \tan \alpha p)}}{\left(Dp + \dfrac{Cfp\ Dpm}{(1 - \tan \alpha p)}\right)}\right)\right] \\ & + \frac{K'\ Cdm\ Dmm}{Dm\ (1 - \tan \alpha m)} - Tcm \end{aligned}$$

$$Tp = (Tm + Tcm)\left[\frac{\left(Dp + \frac{Cfp\ Dpm}{(1 - \tan \alpha p)}\right)}{\left(Dm - \frac{Cfm\ Dmm}{(1 - \tan \alpha m)}\right)} + \frac{\frac{K\ Cdp\ Dpm}{(1 - \tan \alpha p)}}{\left(Dm - \frac{Cfm\ Dmm}{(1 - \tan \alpha m)}\right) Dp}\right]$$

$$+ Nm\left[\frac{Cdm\ \mu\ Dmm\left(Dp + \frac{Cfp\ Dpm}{(1 - \tan \alpha p)}\right)}{(1 - \tan \alpha m)\left(Dm - \frac{Cfm\ Dmm}{(1 - \tan \alpha m)}\right)} + \frac{Cdp\ \mu\ Dpm}{Dp\ (1 - \tan \alpha p)}\left(Dm + \frac{\frac{K\ Cdm\ Dmm}{(1 - \tan \alpha m)}}{\left(Dm - \frac{Cfm\ Dmm}{(1 - \tan \alpha m)}\right)}\right)\right]$$

$$+ \frac{K'\ Cdp\ Dpm}{Dp\ (1 - \tan \alpha p)} + Tcp$$

The terms K and K' determined for Model B remain the same for Model C and are relisted below.

$$K = 4.3078 \times 10^{-8}$$

$$K' = 1.6406 \times 10^{-5}$$

The coefficients of viscous drag and coefficients of dry friction can be determined from those found for Model B by multiplying by the term $1 - \tan \alpha$ and using the swashplate angle at full displacement which was 18° for both the pump and the motor used in this research. The coefficients for Model C are determined below.

$$Cdp = (141194)\ (1 - \tan 18°) = 95317$$

$$Cdm = (127901)\ (1 - \tan 18°) = 86343$$

$$Cfp = (0.015339)\ (1 - \tan 18°) = 0.010355$$

$$Cfm = (0.003679)\ (1 - \tan 18°) = 0.002484$$

The constant torque terms for Model C are the same as those determined for Model B and are relisted below.

Tcp = 70.29

Tcm = 99.40

Comparison of Model B and Model C at Partial Displacement

Model C and Model B are equivalent at full displacement so the evaluation of Model B at full displacement applies to Model C. Appendices O and P list the comparison of values calculated by Model C and actual measured data at partial displacement. This information is summarized in Table 5.8.

Comparison of the Model C data summary in Table 5.8 and the Model B data summary in Table 5.7 showed that Model C gave calculated values of torque significantly closer to the measured values. At one half displacement Model C predicted torque on the average to be 1.0202 of the measured value compared to 1.0753 for Model B. This reduction was also accompanied by a reduction in standard deviation to 0.0191 from 0.0338. Speed calculations were relatively unchanged between Model B and Model C. The power calculations reflected the improved torque predictions.

Comparison of Model C and Sundstrand Data

Sundstrand publishes full displacement performance information in their Engineering Applications Manual [6]. The data are given for 3000 psi and 5000 psi pressure differential across the pumps and motors. Sundstrand uses Mobil 300 oil at 180° F during their tests. The oil viscosity at that temperature is 65 SSU and the density is 7.30 lb/gal. Absolute viscosity was determined to be 2.47×10^{-8} lb.min/in^2.

TABLE 5.8

COMPARISON OF MEASURED AND CALCULATED VALUES AT FULL AND PARTIAL DISPLACEMENT FOR MODEL C

		Model C full disp	Model C 3/4 disp	Model C 1/2 disp
Np/Np calc/meas	$\bar{x}$	1.0042	1.0202	1.0318
	s	0.0124	0.0133	0.0163
Tp/Tp calc/meas	$\bar{x}$	1.0016	1.0095	1.0202
	s	0.0081	0.0137	0.0191
HPp/HPp calc/meas	$\bar{x}$	1.0058	1.0299	1.0527
	s	0.0133	0.0216	0.0282
ΔNp calc - meas	$\bar{x}$	+ 1.7	+28.8	+48.9
	s	16.7	16.2	16.2
ΔTp calc - meas	$\bar{x}$	+ 0.7	+ 5.6	+ 8.9
	s	5.4	7.4	6.6
ΔHPp calc - meas	$\bar{x}$	+0.03	+0.48	+0.66
	s	0.24	0.29	0.23

Model C calculations and Sundstrand data for the pump power are compared in Figure 5.6. This information is listed in Appendix Q. On the average, Model C predicts the pump power to be 0.9803 of the Sundstrand pump power data at 3000 psi and 0.9915 of the Sundstrand pump power data at 5000 psi. On the difference basis, Model C predicts pump power to be 1.27 hp lower on the average than the Sundstrand data at 3000 psi and 1.00 hp lower than the Sundstrand data at 5000 psi.

Model C calculations and Sundstrand data for motor torque are compared in Figure 5.7. This information is listed in Appendix R. On the average, Model C predicts the motor torque to be 1.0247 of the Sundstrand motor torque data at 3000 psi and 1.0244 of the Sundstrand motor torque data at 5000 psi. On the difference basis, Model C predicts motor torque to be 79 in.lb higher on the average than the Sundstrand data at 3000 psi and 113 in.lb higher than the Sundstrand data at 5000 psi.

Model C calculations and Sundstrand data for volumetric and overall efficiency are compared at 3000 psi in Figure 5.8 and 5000 psi in Figure 5.9. This information along with torque efficiency is listed in Appendices S, T, and U. Model C does not provide a very accurate prediction of volumetric efficiency which is also reflected in the overall efficiency.

The Sundstrand tests were conducted with much less viscous oil than the tests in this research. It appeared that the model did not accurately account for the differences in viscosity which were substantially reflected in the difference between Sundstrand volumetric efficiencies and Model C volumetric efficiencies.

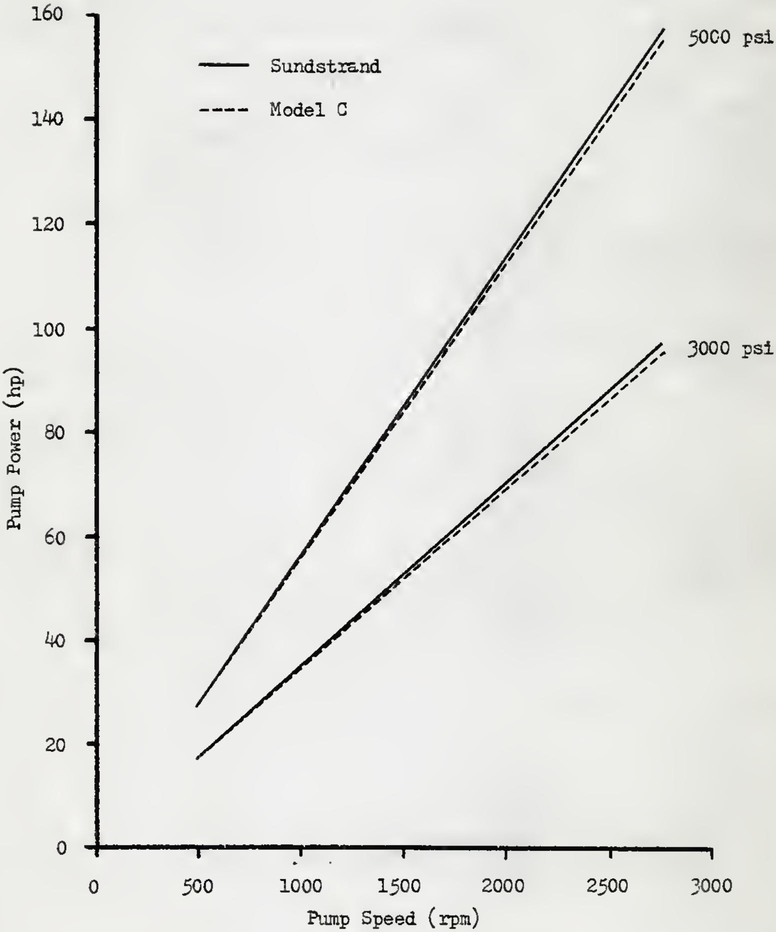


Figure 5.6. Pump Power at Constant Pressure Differential vs. Speed - Sundstrand and Model C

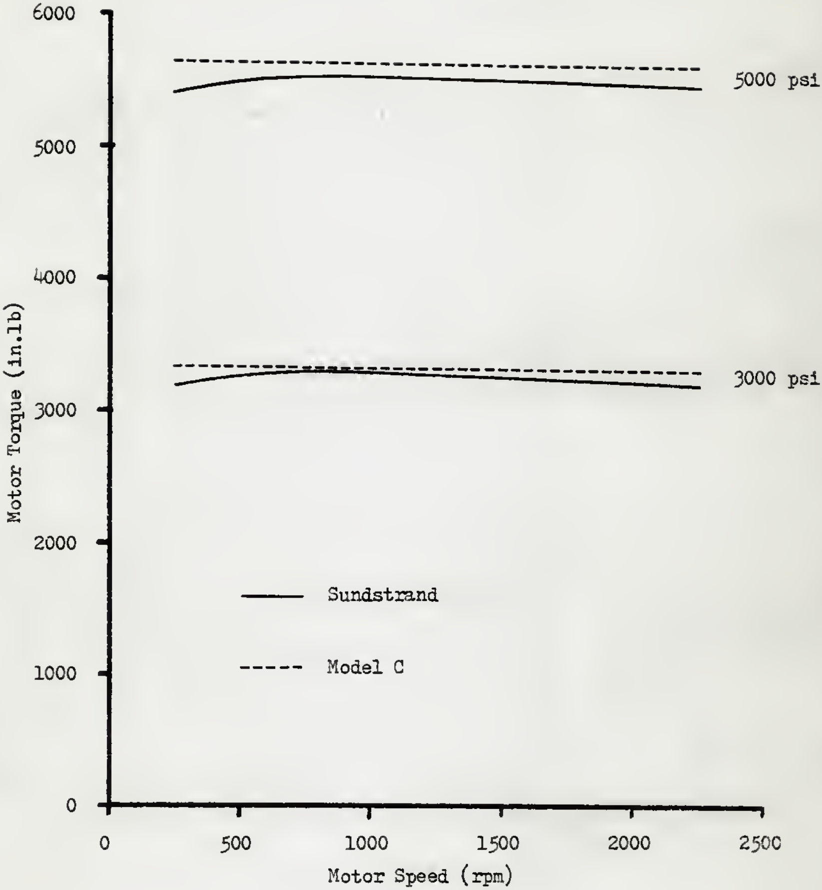


Figure 5.7. Motor Torque at Constant Pressure Differential vs. Speed - Sundstrand and Model C

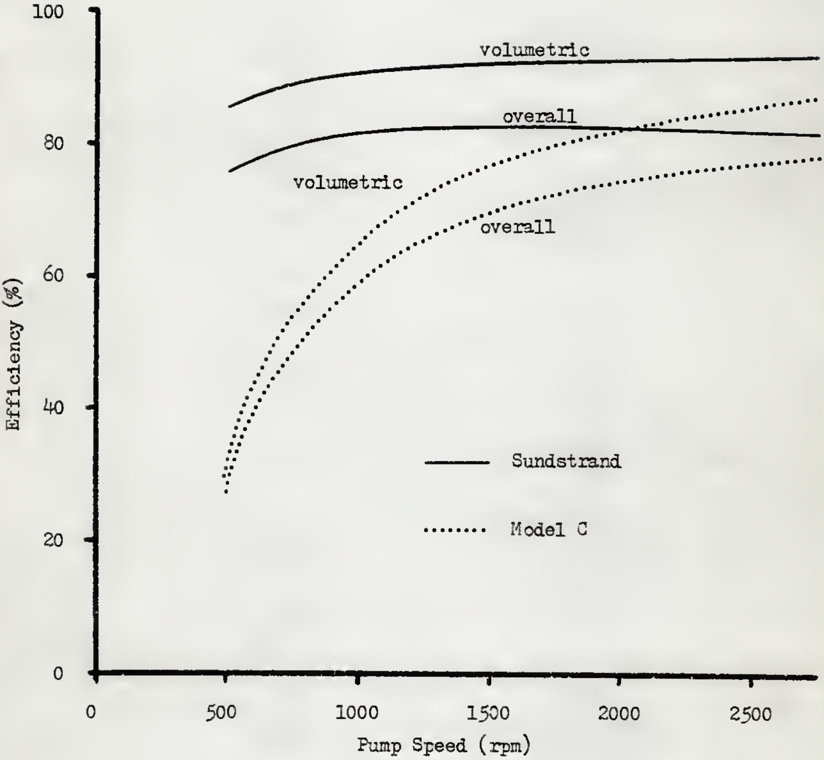


Figure 5.8. Transmission Efficiency at 3000 psi Pressure Differential vs. Speed - Sundstrand and Model C

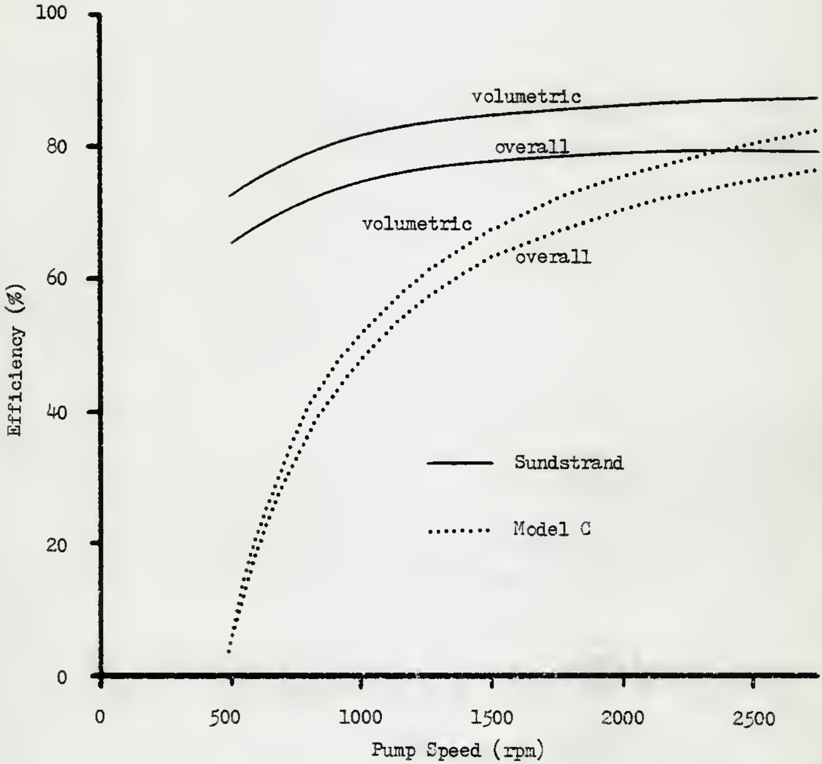


Figure 5.9. Transmission Efficiency at 5000 psi Pressure Differential vs. Speed - Sundstrand and Model C

<u>Comparison of Model C Without Viscosity Allowance and Sundstrand Data</u>

In an effort to verify the inadequacy of Model C relative to viscosity allowance, a comparison of Model C and Sundstrand data was made using the viscosity of the oil used in this research rather than that used in Sundstrand's tests. This is termed Model C Without Viscosity Allowance and is indicated as Model C*.

Model C* calculations and Sundstrand data for the pump power are compared in Figure 5.10. This information is listed in Appendix V. Model C and Model C* provide about the same accuracy in pump power prediction with Model C* predicting power about as much high as Model C predicted low.

Model C* calculations and Sundstrand data for motor torque are compared in Figure 5.11. This information is listed in Appendix W. Comparison of Figures 5.11 and 5.7 showed Model C* to provide somewhat better motor torque prediction than Model C.

Model C* calculations and Sundstrand data for volumetric and overall efficiency are compared at 3000 psi in Figure 5.12 and at 5000 psi in Figure 5.13. This information along with torque efficiency is listed in Appendices S, X, and Y. Comparison of Figures 5.12 and 5.13 and Figures 5.8 and 5.9 show Model C* to provide much better efficiency prediction than Model C.

Table 5.9 summarizes the comparison of Model C and Model C*. Comparison of pump power, motor torque, volumetric efficiency, torque efficiency, and overall efficiency shows Model C* to be better than Model C in every case. The main improvement is in prediction of volumetric efficiency which is then reflected in overall efficiency.

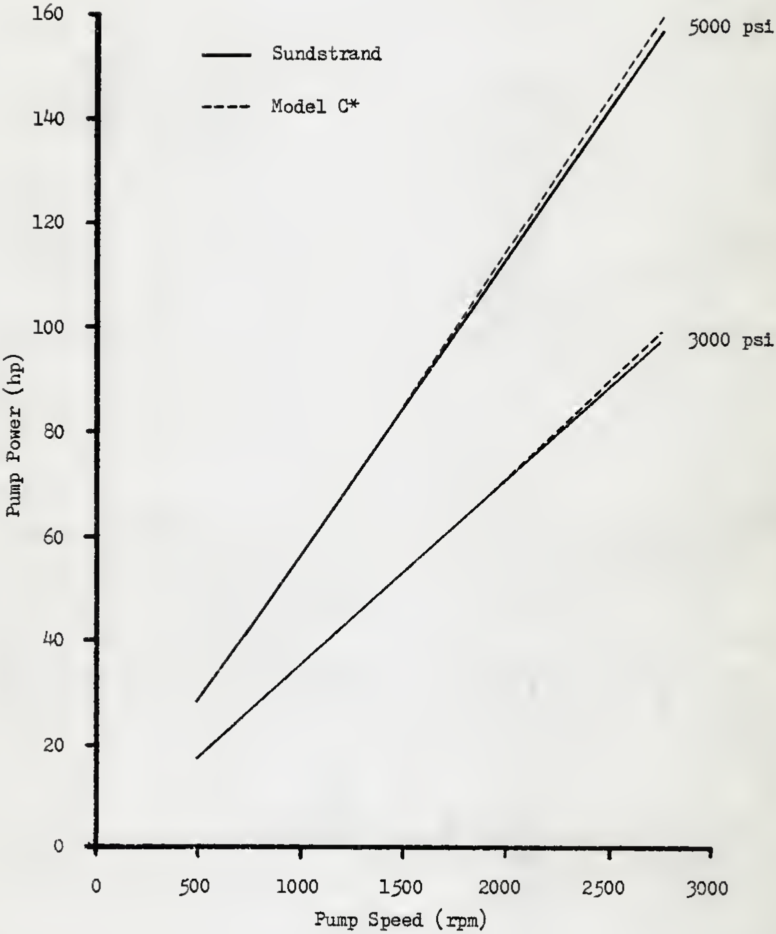


Figure 5.10. Pump Power at Constant Pressure Differential vs. Speed - Sundstrand and Model C*

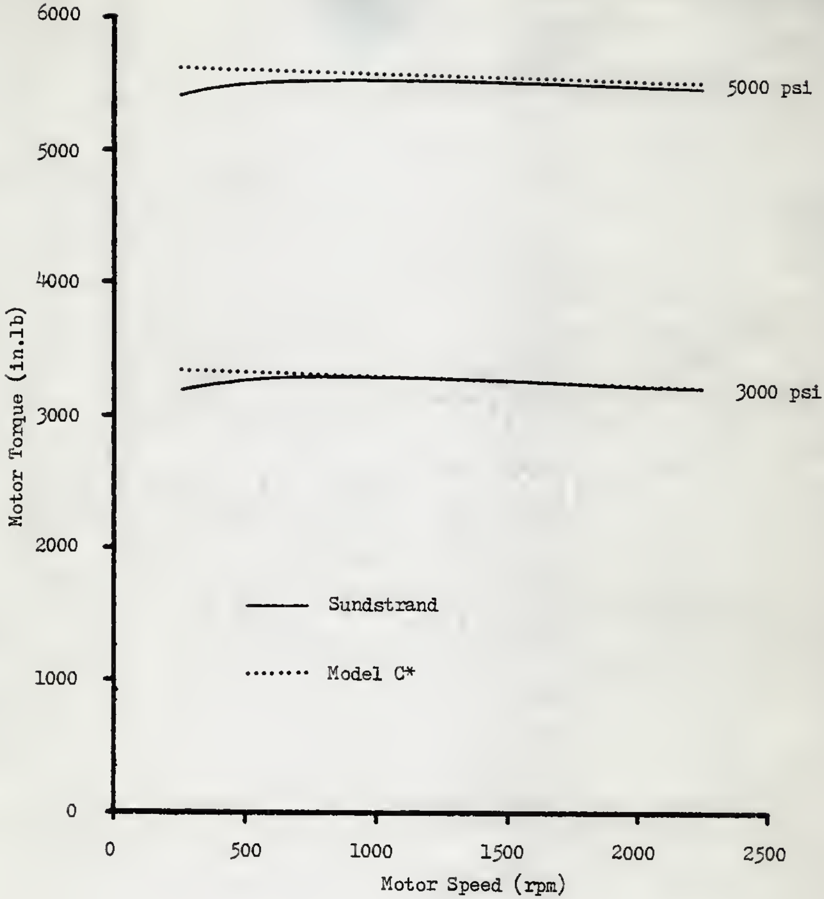


Figure 5.11. Motor Torque at Constant Pressure Differential vs. Speed - Sundstrand and Model C*

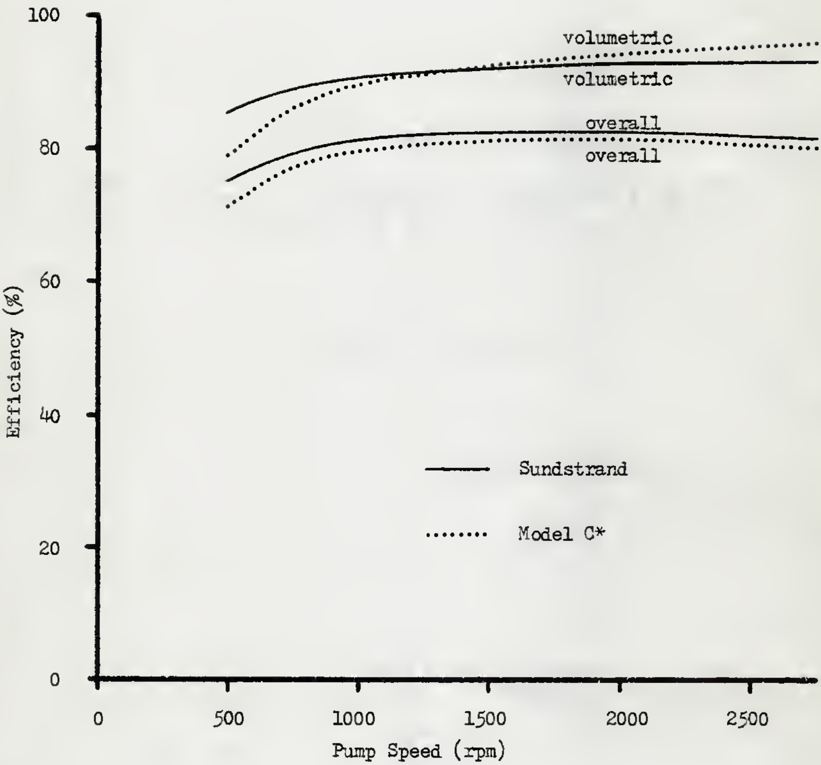


Figure 5.12. Transmission Efficiency at 3000 psi Pressure Differential vs. Speed - Sundstrand and Model C*

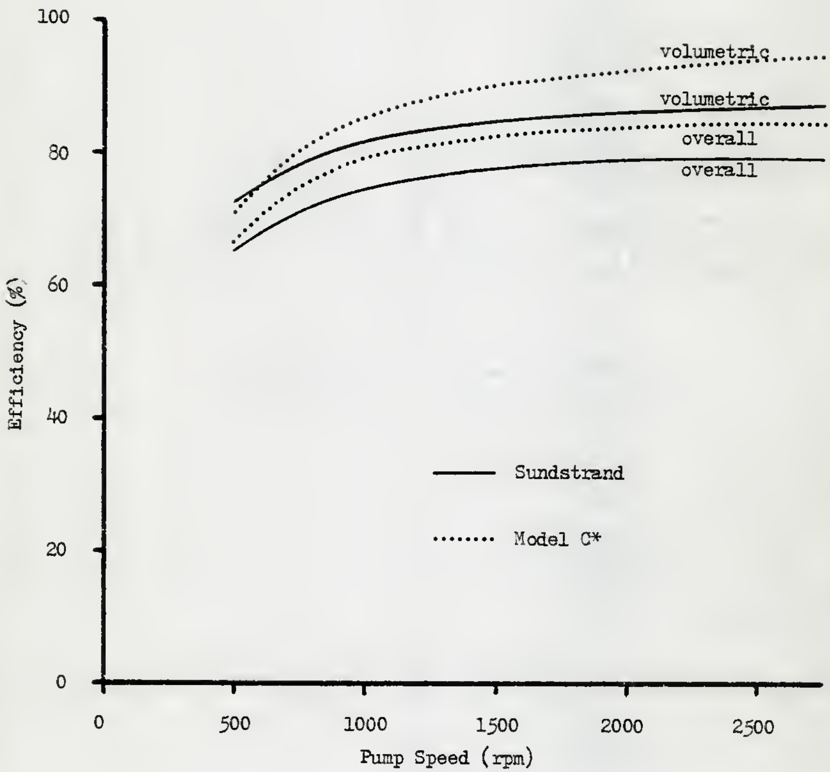


Figure 5.13. Transmission Efficiency at 5000 psi Pressure Differential vs. Speed - Sundstrand and Model C*

TABLE 5.9

COMPARISON OF SUNSTRAND DATA AND CALCULATED VALUES AT FULL DISPLACEMENT FOR MODEL C AND MODEL C WITHOUT VISCOSITY ALLOWANCE

		Model C	Model C*	Model C	Model C*
		-----3000	psi-----	-----5000	psi-----
HPp/HPp calc/Sund	$\bar{x}$	0.9803	1.0054	0.9915	1.0070
	s	0.0080	0.0076	0.0068	0.0044
Tm/Tm calc/Sund	$\bar{x}$	1.0247	1.0043	1.0244	1.0120
	s	0.0118	0.0154	0.0070	0.0113
ηv/ηv calc/Sund	$\bar{x}$	0.7783	0.9983	0.7180	1.0553
	s	0.1847	0.0341	0.2795	0.0339
ηt/ηt calc/Sund	$\bar{x}$	1.0204	0.9800	1.0253	1.0004
	s	0.0091	0.0221	0.0098	0.0187
η/η calc/Sund	$\bar{x}$	0.7932	0.9777	0.7337	1.0550
	s	0.1866	0.0120	0.2838	0.0162
ΔHPp calc - Sund	$\bar{x}$	-1.27	+0.50	-1.00	+0.71
	s	0.77	0.67	0.74	0.69
ΔTm calc - Sund	$\bar{x}$	+79	+14	+113	+68
	s	37	49	37	59
Δηv calc - Sund	$\bar{x}$	-0.1990	-0.0009	-0.2237	+0.0475
	s	0.1573	0.0301	0.2017	0.0289
Δηt calc - Sund	$\bar{x}$	+0.0180	-0.0177	+0.0230	+0.0003
	s	0.0078	0.0195	0.0087	0.0169
Δη calc - Sund	$\bar{x}$	-0.1648	-0.0179	-0.1914	+0.0426
	s	0.1411	0.0090	0.1861	0.0135

* Model C Without Viscosity Allowance

Summary of Model C Performance

Model C was determined to provide the best hydrostatic transmission performance model of the three considered. The evaluation summary given in Table 5.8 gives an indication of its performance.

At full displacement, pump speeds were predicted on the average to be 1.0042 of the measured values with a standard deviation of 0.0124. This corresponded to speed being predicted 1.7 rpm high on the average with a standard deviation of 16.7 rpm. Pump torque values were predicted on the average to be 1.0016 of the measured values with a standard deviation of 0.0081. This corresponded to torque being predicted 0.7 in.lb high on the average with a standard deviation of 5.4 in.lb.

The pump power predictions at full displacement were on the average 1.0058 of the measured values with a standard deviation of 0.0133. This corresponded to power being predicted 0.03 hp high on the average with a standard deviation of 0.24 hp.

With the pump and motor each at approximately one-half displacement, pump speeds were predicted on the average to be 1.0318 of the measured values with a standard deviation of 0.0163. This corresponded to speed being predicted 48.9 rpm high on the average with a standard deviation of 16.2 rpm. Pump torque values were predicted on the average to be 1.0202 of the measured values with a standard deviation of 0.0191. This corresponded to torque being predicted 8.9 in.lb high on the average with a standard deviation of 6.6 in.lb.

The pump power predictions at one-half displacement were on the average 1.0527 of the measured values with a standard deviation of 0.0282. This corresponded to power being predicted 0.66 hp high on the average with a standard deviation of 0.23 hp.

The model performance at three-fourths displacement was between the full displacement and one-half displacement performances.

Model C was determined and verified with Amoco 1000 oil at 125° F. It must be restricted to use with oil of the same viscosity until it is confirmed or modified for use with other oil viscosities.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

1. Model C, a modified form of the basic Wilson's Model, was determined to provide a good steady state performance model for the hydrostatic transmission at full and partial displacements with constant oil temperature.
2. A microcomputer based system was successfully used for data acquisition and control of transmission oil temperatures in this research.
3. Internal leakage can be represented as a constant component and a component that is a constant times pressure differential to obtain improved model accuracy.
4. Viscous drag and dry friction torque terms must be represented as functions of displacement to obtain an accurate partial displacement model.
5. Further research is needed to evaluate Model C at various oil viscosities. Preliminary comparison with Sundstrand's data showed the model did not accurately account for changing oil viscosity.

Recommendations

Model C as determined in this research will provide a good performance model at constant oil temperature to be used for further computer simulation and laboratory studies relating to automatic control of hydrostatic transmissions.

More research will be necessary to account for the effect of oil viscosity on transmission performance and how to represent it in the model if the model is to be used with different oil temperatures. The present models do not appear to accurately account for viscosity changes, especially as they affect speed calculations.

Further microcomputer programming could ease the task of data acquisition by providing the data in base ten and converted to the appropriate units. The 24-unit display will limit flexibility in this area but one possibility would be to have a user controlled toggle switch to select the set of parameters to be displayed. For example, have pump parameters of speed, torque, and displacement displayed in one switch position and the same motor parameters displayed with the switch in its alternate position.

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APPENDIX A

NOMENCLATURE

NOMENCLATURE

Symbol	Definition
A/D	Analog-to-digital
b	Intercept from equation of a straight line
calc	Calculated from a model
Cdm	Coefficient of viscous drag of HST motor
Cdp	Coefficient of viscous drag of HST pump
Cfm	Coefficient of dry friction of HST motor
Cfp	Coefficient of dry friction of HST pump
Csm	Coefficient of slip of HST motor (also Csm1, Csm2, and Csm3 used by Elder and Otis)
Csp	Coefficient of slip of HST pump (also Csp1, Csp2, and Csp3 used by Elder and Otis)
Dm	HST motor displacement (in^3/rev)
Dmm	Maximum HST motor displacement (in^3/rev)
Dp	HST pump displacement (in^3/rev)
Dpm	Maximum HST pump displacement (in^3/rev)
HPcp	HST charge pump shaft power (hp)
HPm	HST motor shaft power (hp)
HPmp	HST main pump shaft power (hp)
HPp	HST pump (charge + main) shaft power (hp)
HST	Hydrostatic transmission
K	Composite slip factor
K'	Composite constant leakage coefficient
L	Internal HST leakage (in^3/min)
Lcm	Coefficient of constant leakage of HST motor

Lcp	Coefficient of constant leakage of HST pump
m	Slope from equation of a straight line
meas	Measured
n	Number of data used in statistical analysis
no-load	Engine no-load condition
Nm	HST motor shaft speed (rpm)
$\overline{Nm}$	Average HST motor shaft speed for a set of data (rpm)
Np	HST pump shaft speed (rpm)
$\overline{Np}$	Average HST pump shaft speed for a set of data (rpm)
Pc	HST charge pump pressure (psi)
Pd	HST drain pressure (psi)
Ps	HST system pressure (psi)
Qm	Fluid flow rate into HST motor (in^3/min)
Qp	Fluid flow rate from HST pump (in^3/min)
r^2	Correlation coefficient from linear regression analysis
s	Standard deviation
SSU	Seconds Saybolt Universal
Sund	Sundstrand
t	Viscometer efflux time (sec)
t_{avg}	Average of HST inlet and outlet oil temperatures (°C)
t_{in}	HST inlet oil temperature (°C)
t_{out}	HST outlet oil temperature (°C)
$\bar{x}$	Arithmetic average or mean
Tcm	HST motor constant friction torque (in.lb)
Tcp	HST pump constant friction torque (in.lb)
Tm	HST motor shaft torque (in.lb)

T_p	HST pump shaft torque (in.lb)
α	Swashplate angle
α_m	HST motor swashplate angle (°)
α_p	HST pump swashplate angle (°)
β	Bulk modulus (psi)
ΔP	Pressure differential between system pressure and charge pressure (psi)
η	Overall HST efficiency
η_m	Overall HST motor efficiency
η_p	Overall HST pump efficiency
η_t	Composite HST torque efficiency
η_{tm}	Torque efficiency of HST motor
η_{tp}	Torque efficiency of HST pump
η_v	Composite HST volumetric efficiency
η_{vm}	Volumetric efficiency of HST motor
η_{vp}	Volumetric efficiency of HST pump
μ	Absolute viscosity of HST oil ($lb.min/in^2$)
ν	Kinematic viscosity

APPENDIX B

REARRANGEMENT OF MODEL A EQUATIONS

One form of the basic equations used for Wilson's Model is given below. The equations are solved for flow and torque and contain the pressure differential term on the right hand side. To be useful as a hydrostatic transmission performance model, the equations must be solved for pump torque and pump speed as functions of motor torque and motor speed and vice versa. The rearrangement of the equations follows.

$$Qp = Dp\ Np - \frac{Csp\ \Delta P\ Dpm}{2\ \pi\ \mu} \tag{1}$$

$$Tp = \frac{\Delta P\ Dp}{2\ \pi} + \frac{Cfp\ \Delta P\ Dpm}{2\ \pi} + Cdp\ \mu\ Np\ Dpm + Tcp \tag{2}$$

$$Qm = Dm\ Nm + \frac{Csm\ \Delta P\ Dmm}{2\ \pi\ \mu} \tag{3}$$

$$Tm = \frac{\Delta P\ Dm}{2\ \pi} - \frac{Cfm\ \Delta P\ Dmm}{2\ \pi} - Cdm\ \mu\ Nm\ Dmm - Tcm \tag{4}$$

Since Qm = Qp, then from (1) and (3),

$$Dp\ Np - \frac{Csp\ \Delta P\ Dpm}{2\ \pi\ \mu} = Dm\ Nm + \frac{Csm\ \Delta P\ Dmm}{2\ \pi\ \mu} \tag{5}$$

Solving (5) for Nm and Np,

$$Nm = \frac{1}{Dm}\left[Dp\ Np - \frac{Csp\ \Delta P\ Dpm}{2\ \pi\ \mu} - \frac{Csm\ \Delta P\ Dmm}{2\ \pi\ \mu}\right] \tag{6}$$

$$Np = \frac{1}{Dp}\left[Dm\ Nm + \frac{Csp\ \Delta P\ Dpm}{2\ \pi\ \mu} + \frac{Csm\ \Delta P\ Dmm}{2\ \pi\ \mu}\right] \tag{7}$$

Define K,

$$K = Csp\ Dpm + Csm\ Dmm \tag{8a}$$

Also, from (5),

$$K = \frac{2\ \pi\ \mu\ (Dp\ Np - Dm\ Nm)}{\Delta P} \tag{8b}$$

Substitute (8a) into (6) and (7),

$$Nm = \frac{Dp\ Np}{Dm} - \frac{K\ \Delta P}{2\ \pi\ \mu\ Dm} \tag{9}$$

$$Np = \frac{Dm\ Nm}{Dp} + \frac{K\ \Delta P}{2\ \pi\ \mu\ Dp} \tag{10}$$

Solving (2) and (4) for ΔP,

$$\Delta P = \frac{2\ \pi\ (Tp - Cdp\ \mu\ Np\ Dpm - Tcp)}{Dp + Cfp\ Dpm} \tag{11}$$

$$\Delta P = \frac{2\ \pi\ (Tm + Cdm\ \mu\ Nm\ Dmm + Tcm)}{Dm - Cfm\ Dmm} \tag{12}$$

Substituting (11) into (9),

$$Nm = \frac{Dp\ Np}{Dm} - \frac{K\ (Tp - Cdp\ \mu\ Np\ Dpm - Tcp)}{\mu\ (Dp + Cfp\ Dpm)\ Dm} \tag{13}$$

Substituting (12) into (10),

$$Np = \frac{Dm\ Nm}{Dp} + \frac{K\ (Tm + Cdm\ \mu\ Nm\ Dmm + Tcm)}{\mu\ (Dm - Cfm\ Dmm)\ Dp} \tag{14}$$

Substituting (11) and (13) into (4),

$$Tm = \frac{(Dm - Cfm\ Dmm)\ (Tp - Cdp\ \mu\ Np\ Dpm - Tcp)}{(Dp + Cfp\ Dpm)}$$
$$- Cdm\ \mu\ Dmm \left[\frac{Dp\ Np}{Dm} - \frac{K\ (Tp - Cdp\ \mu\ Np\ Dpm - Tcp)}{\mu\ (Dp + Cfp\ Dpm)\ Dm}\right] - Tcm \qquad (15)$$

Rearranging (15),

$$Tm = (Tp - Tcp)\left[\frac{(Dm - Cfm\ Dmm)}{(Dp + Cfp\ Dpm)} + \frac{K\ Cdm\ Dmm}{Dm\ (Dp + Cfp\ Dpm)}\right]$$
$$- Np\left[\frac{Cdp\ \mu\ Dpm\ (Dm - Cfm\ Dmm)}{(Dp + Cfp\ Dpm)} + \frac{Cdm\ \mu\ Dmm}{Dm}\left(Dp + \frac{K\ Cdp\ Dpm}{(Dp + Cfp\ Dpm)}\right)\right]$$
$$- Tcm \qquad (16)$$

Substituting (12) and (14) into (2),

$$Tp = \frac{(Dp + Cfp\ Dpm)\ (Tm + Cdm\ \mu\ Nm\ Dmm + Tcm)}{(Dm - Cfm\ Dmm)}$$
$$+ Cpd\ \mu\ Dpm\left[\frac{Dm\ Nm}{Dp} + \frac{K\ (Tm + Cdm\ \mu\ Nm\ Dmm + Tcm)}{\mu\ (Dm - Cfm\ Dmm)\ Dp}\right] + Tcp \qquad (17)$$

Rearranging (17),

$$Tp = (Tm + Tcm)\left[\frac{(Dp + Cfp\ Dpm)}{(Dm - Cfm\ Dmm)} + \frac{K\ Cdp\ Dpm}{Dp\ (Dm - Cfm\ Dmm)}\right]$$
$$+ Nm\left[\frac{Cdm\ \mu\ Dmm\ (Dp + Cfp\ Dpm)}{(Dm - Cfm\ Dmm)} + \frac{Cdp\ \mu\ Dpm}{Dp}\left(Dm + \frac{K\ Cdm\ Dmm}{(Dm - Cfm\ Dmm)}\right)\right]$$
$$+ Tcp \qquad (18)$$

APPENDIX C

MICROCOMPUTER NON-PROGRAM AND PROGRAM MEMORY

NON-PROGRAM MEMORY

MEMORY LOCATION	COMMENTS
0000	7-SEGMENT DISPLAY CODE FOR 0
0001	7-SEGMENT DISPLAY CODE FOR 1
0002	7-SEGMENT DISPLAY CODE FOR 2
0003	7-SEGMENT DISPLAY CODE FOR 3
0004	7-SEGMENT DISPLAY CODE FOR 4
0005	7-SEGMENT DISPLAY CODE FOR 5
0006	7-SEGMENT DISPLAY CODE FOR 6
0007	7-SEGMENT DISPLAY CODE FOR 7
0008	7-SEGMENT DISPLAY CODE FOR 8
0009	7-SEGMENT DISPLAY CODE FOR 9
000A	7-SEGMENT DISPLAY CODE FOR A
000B	7-SEGMENT DISPLAY CODE FOR B
000C	7-SEGMENT DISPLAY CODE FOR C
000D	7-SEGMENT DISPLAY CODE FOR D
000E	7-SEGMENT DISPLAY CODE FOR E
000F	7-SEGMENT DISPLAY CODE FOR F
0010	B (USER DEFINED REGISTERS)
0011	C (USER DEFINED REGISTERS)
0400	A/D CONVERSION RESULT (READ ONLY)
0480	D/A CONVERTER 1 (WRITE ONLY)
0500	D/A CONVERTER 2 (WRITE ONLY)
	0580 TO 058F ARE IN MCS6522
0580	OUTPUT REGISTER B (ORB)
0581	OUTPUT REGISTER A (ORA)
0582	DATA DIRECTION REGISTER B (DDRB)
0583	DATA DIRECTION REGISTER A (DDRA)
0584	TIMER 1 LATCH (WRITE) OR COUNTER (READ)-LOW (T1L-L OR T1C-L)
0585	TIMER 1 COUNTER-HIGH (T1C-H)
0586	TIMER 1 LATCH-LOW (T1L-L)
0587	TIMER 1 LATCH-HIGH (T1L-H)
0588	TIMER 2 LATCH (WRITE) OR COUNTER (READ)-LOW (T2L-L OR T2C-L)
0589	TIMER 2 COUNTER-HIGH (T2C-H)
058A	SHIFT REGISTER (SR)
058B	AUXILIARY CONTROL REGISTER (ACR)
058C	PERIPHERAL CONTROL REGISTER (PCR)
058D	INTERRUPT FLAG REGISTER (IFR)
058E	INTERRUPT ENABLE REGISTER (IER)
058F	OUTPUT REGISTER A (ORA)

	0600 TO 060B AND 0640 TO 064B ARE DISPLAY ADDRESSES
0600	DISPLAY DIGIT 1,1
0601	DISPLAY DIGIT 1,3
0602	DISPLAY DIGIT 1,5
0603	DISPLAY DIGIT 2,1
0604	DISPLAY DIGIT 2,3
0605	DISPLAY DIGIT 2,5
0606	DISPLAY DIGIT 3,1
0607	DISPLAY DIGIT 3,3
0608	DISPLAY DIGIT 3,5
0609	DISPLAY DIGIT 4,1
060A	DISPLAY DIGIT 4,3
060B	DISPLAY DIGIT 4,5
0640	DISPLAY DIGIT 1,2
0641	DISPLAY DIGIT 1,4
0642	DISPLAY DIGIT 1,6
0643	DISPLAY DIGIT 2,2
0644	DISPLAY DIGIT 2,4
0645	DISPLAY DIGIT 2,6
0646	DISPLAY DIGIT 3,2
0647	DISPLAY DIGIT 3,4
0648	DISPLAY DIGIT 3,6
0649	DISPLAY DIGIT 4,2
064A	DISPLAY DIGIT 4,4
064B	DISPLAY DIGIT 4,6

PROGRAM MEMORY

MEMORY LOCATION	OP CODE	MNEMONIC	COMMENTS
			MAIN PROGRAM
2000	20 40 20	JSR	JUMP TO INITIALIZATION SUBROUTINE
2003	EA	NOP	
2004	EA	NOP	
2005	EA	NOP	
2006	20 80 20	JSR	JUMP TO PUMP SPEED SUBROUTINE
2009	20 C0 20	JSR	JUMP TO PUMP TORQUE SUBROUTINE
200C	20 F0 20	JSR	JUMP TO PUMP DISPLACEMENT SUBROUTINE
200F	20 20 21	JSR	JUMP TO SYSTEM PRESSURE SUBROUTINE
2012	20 50 21	JSR	JUMP TO INLET TEMPERATURE SUBROUTINE
2015	EA	NOP	
2016	EA	NOP	
2017	EA	NOP	
2018	20 80 21	JSR	JUMP TO MOTOR SPEED SUBROUTINE
201B	20 C0 21	JSR	JUMP TO MOTOR TORQUE SUBROUTINE
201E	20 F0 21	JSR	JUMP TO MOTOR DISPLACEMENT SUBROUTINE
2021	20 20 22	JSR	JUMP TO CHARGE PRESSURE SUBROUTINE
2024	20 50 22	JSR	JUMP TO OUTLET TEMPERATURE SUBROUTINE
2027	20 00 24	JSR	JUMP TO TEMPERATURE CONTROL SUBROUTINE
202A	4C 06 20	JMP-ABS	JUMP TO 2006 IN MAIN PROGRAM
			INITIALIZATION SUBROUTINE
2040	A9 BF	LDA-IMM	
2042	8D 82 05	STA-ABS	INITIALIZE DDRB
2045	A9 60	LDA-IMM	
2047	8D 8B 05	STA-ABS	INITIALIZE ACR
204A	D8	CLD	CLEAR DECIMAL MODE
204B	EA	NOP	
204C	EA	NOP	
204D	EA	NOP	
204E	EA	NOP	
204F	EA	NOP	
2050	A9 00	LDA-IMM	
2052	8D FA 17	STA-ABS	INITIALIZE NMI-L
2055	A9 1C	LDA-IMM	
2057	8D FB 17	STA-ABS	INITIALIZE NMI-H
205A	EA	NOP	
205B	EA	NOP	
205C	EA	NOP	
205D	EA	NOP	
205E	EA	NOP	
205F	EA	NOP	
2060	A9 00	LDA-IMM	
2062	8D 8C 05	STA-ABS	INITIALIZE PCR

```
2065   20 70 23   JSR       JUMP TO BLANK DISPLAY SUBROUTINE
2068   20 90 23   JSR       JUMP TO 7-SEGMENT DISPLAY CODE SUBROUTINE
206B   60         RTS       RETURN FROM SUBROUTINE

                            ***PUMP SPEED SUBROUTINE***
2080   A2 80      LDX-IMM   SELECT PUMP SPEED INPUT CHANNEL
2082   20 80 22   JSR       JUMP TO RPM SUBROUTINE
2085   EA         NOP
2086   EA         NOP
2087   EA         NOP
2088   AD 10 00   LDA-ABS   LOAD A WITH B
208B   20 10 23   JSR       JUMP TO LOW FOUR BITS SUBROUTINE
208E   A2 01      LDX-IMM   SELECT DISPLAY ADDRESS 0601
2090   20 30 23   JSR       JUMP TO DISPLAY SUBROUTINE
2093   AD 10 00   LDA-ABS   LOAD A WITH B
2096   20 20 23   JSR       JUMP TO HIGH FOUR BITS SUBROUTINE
2099   A2 40      LDX-IMM   SELECT DISPLAY ADDRESS 0640
209B   20 30 23   JSR       JUMP TO DISPLAY SUBROUTINE
209E   AD 11 00   LDA-ABS   LOAD A WITH C
20A1   20 10 23   JSR       JUMP TO LOW FOUR BITS SUBROUTINE
20A4   A2 00      LDX-IMM   SELECT DISPLAY ADDRESS 0600
20A6   20 30 23   JSR       JUMP TO DISPLAY SUBROUTINE
20A9   60         RTS       RETURN FROM SUBROUTINE

                            ***PUMP TORQUE SUBROUTINE***
20C0   A2 08      LDX-IMM   SELECT PUMP TORQUE INPUT CHANNEL
20C2   20 E0 22   JSR       JUMP TO A/D SUBROUTINE
20C5   EA         NOP
20C6   EA         NOP
20C7   EA         NOP
20C8   EA         NOP
20C9   EA         NOP
20CA   20 10 23   JSR       JUMP TO LOW FOUR BITS SUBROUTINE
20CD   A2 42      LDX-IMM   SELECT DISPLAY ADDRESS 0642
20CF   20 30 23   JSR       JUMP TO DISPLAY SUBROUTINE
20D2   AD 00 04   LDA-ABS   LOAD A WITH A/D RESULT
20D5   20 20 23   JSR       JUMP TO HIGH FOUR BITS SUBROUTINE
20D8   A2 02      LDX-IMM   SELECT DISPLAY ADDRESS 0602
20DA   20 30 23   JSR       JUMP TO DISPLAY SUBROUTINE
20DD   60         RTS       RETURN FROM SUBROUTINE

                            ***PUMP DISPLACEMENT SUBROUTINE***
20F0   A2 0A      LDX-IMM   SELECT PUMP DISPLACEMENT INPUT CHANNEL
20F2   20 E0 22   JSR       JUMP TO A/D SUBROUTINE
20F5   EA         NOP
20F6   EA         NOP
20F7   EA         NOP
20F8   EA         NOP
20F9   EA         NOP
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20FA    20 10 23   JSR        JUMP TO LOW FOUR BITS SUBROUTINE
20FD    A2 43      LDX-IMM    SELECT DISPLAY ADDRESS 0643
20FF    20 30 23   JSR        JUMP TO DISPLAY SUBROUTINE
2102    AD 00 04   LDA-ABS    LOAD A WITH A/D RESULT
2105    20 20 23   JSR        JUMP TO HIGH FOUR BITS SUBROUTINE
2108    A2 03      LDX-IMM    SELECT DISPLAY ADDRESS 0603
210A    20 30 23   JSR        JUMP TO DISPLAY SUBROUTINE
210D    60         RTS        RETURN FROM SUBROUTINE

                              ***SYSTEM PRESSURE SUBROUTINE***
2120    A2 0E      LDX-IMM    SELECT SYSTEM PRESSURE INPUT CHANNEL
2122    20 E0 22   JSR        JUMP TO A/D SUBROUTINE
2125    EA         NOP
2126    EA         NOP
2127    EA         NOP
2128    EA         NOP
2129    EA         NOP
212A    20 10 23   JSR        JUMP TO LOW FOUR BITS SUBROUTINE
212D    A2 44      LDX-IMM    SELECT DISPLAY ADDRESS 0644
212F    20 30 23   JSR        JUMP TO DISPLAY SUBROUTINE
2132    AD 00 04   LDA-ABS    LOAD A WITH A/D RESULT
2135    20 20 23   JSR        JUMP TO HIGH FOUR BITS SUBROUTINE
2138    A2 04      LDX-IMM    SELECT DISPLAY ADDRESS 0604
213A    20 30 23   JSR        JUMP TO DISPLAY SUBROUTINE
213D    60         RTS        RETURN FROM SUBROUTINE

                              ***INLET TEMPERATURE SUBROUTINE***
2150    A2 0C      LDX-IMM    SELECT INLET TEMPERATURE INPUT CHANNEL
2152    20 E0 22   JSR        JUMP TO A/D SUBROUTINE
2155    EA         NOP
2156    EA         NOP
2157    EA         NOP
2158    EA         NOP
2159    EA         NOP
215A    20 10 23   JSR        JUMP TO LOW FOUR BITS SUBROUTINE
215D    A2 45      LDX-IMM    SELECT DISPLAY ADDRESS 0645
215F    20 30 23   JSR        JUMP TO DISPLAY SUBROUTINE
2162    AD 00 04   LDA-ABS    LOAD A WITH A/D RESULT
2165    20 20 23   JSR        JUMP TO HIGH FOUR BITS SUBROUTINE
2168    A2 05      LDX-IMM    SELECT DISPLAY ADDRESS 0605
216A    20 30 23   JSR        JUMP TO DISPLAY SUBROUTINE
216D    60         RTS        RETURN FROM SUBROUTINE

                              ***MOTOR SPEED SUBROUTINE***
2180    A2 20      LDX-IMM    SELECT MOTOR SPEED INPUT CHANNEL
2182    20 80 22   JSR        JUMP TO RPM SUBROUTINE
2185    EA         NOP
2186    EA         NOP
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2187   EA         NOP
2188   AD 10 00   LDA-ABS    LOAD A WITH B
218B   20 10 23   JSR        JUMP TO LOW FOUR BITS SUBROUTINE
218E   A2 07      LDX-IMM    SELECT DISPLAY ADDRESS 0607
2190   20 30 23   JSR        JUMP TO DISPLAY SUBROUTINE
2193   AD 10 00   LDA-ABS    LOAD A WITH B
2196   20 20 23   JSR        JUMP TO HIGH FOUR BITS SUBROUTINE
2199   A2 46      LDX-IMM    SELECT DISPLAY ADDRESS 0646
219B   20 30 23   JSR        JUMP TO DISPLAY SUBROUTINE
219E   AD 11 00   LDA-ABS    LOAD A WITH C
21A1   20 10 23   JSR        JUMP TO LOW FOUR BITS SUBROUTINE
21A4   A2 06      LDX-IMM    SELECT DISPLAY ADDRESS 0606
21A6   20 30 23   JSR        JUMP TO DISPLAY SUBROUTINE
21A9   60         RTS        RETURN FROM SUBROUTINE


                             ***MOTOR TORQUE SUBROUTINE***
21C0   A2 09      LDX-IMM    SELECT MOTOR TORQUE INPUT CHANNEL
21C2   20 E0 22   JSR        JUMP TO A/D SUBROUTINE
21C5   EA         NOP
21C6   EA         NOP
21C7   EA         NOP
21C8   EA         NOP
21C9   EA         NOP
21CA   20 10 23   JSR        JUMP TO LOW FOUR BITS SUBROUTINE
21CD   A2 48      LDX-IMM    SELECT DISPLAY ADDRESS 0648
21CF   20 30 23   JSR        JUMP TO DISPLAY SUBROUTINE
21D2   AD 00 04   LDA-ABS    LOAD A WITH A/D RESULT
21D5   20 20 23   JSR        JUMP TO HIGH FOUR BITS SUBROUTINE
21D8   A2 08      LDX-IMM    SELECT DISPLAY ADDRESS 0608
21DA   20 30 23   JSR        JUMP TO DISPLAY SUBROUTINE
21DD   60         RTS        RETURN FROM SUBROUTINE


                             ***MOTOR DISPLACEMENT SUBROUTINE***
21F0   A2 0B      LDX-IMM    SELECT MOTOR DISPLACEMENT INPUT CHANNEL
21F2   20 E0 22   JSR        JUMP TO A/D SUBROUTINE
21F5   EA         NOP
21F6   EA         NOP
21F7   EA         NOP
21F8   EA         NOP
21F9   EA         NOP
21FA   20 10 23   JSR        JUMP TO LOW FOUR BITS SUBROUTINE
21FD   A2 49      LDX-IMM    SELECT DISPLAY ADDRESS 0649
21FF   20 30 23   JSR        JUMP TO DISPLAY SUBROUTINE
2202   AD 00 04   LDA-ABS    LOAD A WITH A/D RESULT
2205   20 20 23   JSR        JUMP TO HIGH FOUR BITS SUBROUTINE
2208   A2 09      LDX-IMM    SELECT DISPLAY ADDRESS 0609
220A   20 30 23   JSR        JUMP TO DISPLAY SUBROUTINE
220D   60         RTS        RETURN FROM SUBROUTINE
```

```
                                  ***CHARGE PRESSURE SUBROUTINE***
2220   A2 0F      LDX-IMM      SELECT CHARGE PRESSURE INPUT CHANNEL
2222   20 E0 22   JSR          JUMP TO A/D SUBROUTINE
2225   EA         NOP
2226   EA         NOP
2227   EA         NOP
2228   EA         NOP
2229   EA         NOP
222A   20 10 23   JSR          JUMP TO LOW FOUR BITS SUBROUTINE
222D   A2 4A      LDX-IMM      SELECT DISPLAY ADDRESS 064A
222F   20 30 23   JSR          JUMP TO DISPLAY SUBROUTINE
2232   AD 00 04   LDA-ABS      LOAD A WITH A/D RESULT
2235   20 20 23   JSR          JUMP TO HIGH FOUR BITS SUBROUTINE
2238   A2 0A      LDX-IMM      SELECT DISPLAY ADDRESS 060A
223A   20 30 23   JSR          JUMP TO DISPLAY SUBROUTINE
223D   60         RTS          RETURN FROM SUBROUTINE

                                  ***OUTLET TEMPERATURE SUBROUTINE***
2250   A2 0D      LDX-IMM      SELECT OUTLET TEMPERATURE INPUT CHANNEL
2252   20 E0 22   JSR          JUMP TO A/D SUBROUTINE
2255   EA         NOP
2256   EA         NOP
2257   EA         NOP
2258   EA         NOP
2259   EA         NOP
225A   20 10 23   JSR          JUMP TO LOW FOUR BITS SUBROUTINE
225D   A2 4B      LDX-IMM      SELECT DISPLAY ADDRESS 064B
225F   20 30 23   JSR          JUMP TO DISPLAY SUBROUTINE
2262   AD 00 04   LDA-ABS      LOAD A WITH A/D RESULT
2265   20 20 23   JSR          JUMP TO HIGH FOUR BITS SUBROUTINE
2268   A2 0B      LDX-IMM      SELECT DISPLAY ADDRESS 060B
226A   20 30 23   JSR          JUMP TO DISPLAY SUBROUTINE
226D   60         RTS          RETURN FROM SUBROUTINE

                                  ***RPM SUBROUTINE***
2280   8E 80 05   STX-ABS      STORE X IN ORB TO ACTIVATE INPUT CHANNEL
2283   A0 11      LDY-IMM      INITIALIZE Y AS LOOP COUNTER
2285   A9 FF      LDA-IMM
2287   8D 88 05   STA-ABS      INITIALIZE T2L-L
228A   8D 89 05   STA-ABS      INITIALIZE T2C-H
228D   A9 C8      LDA-IMM
228F   8D 84 05   STA-ABS      INITIALIZE T1L-L
2292   A9 E5      LDA-IMM
2294   8D 85 05   STA-ABS      INITIALIZE T1C-H AND INITIATE COUNTDOWN
2297   EA         NOP
2298   EA         NOP
2299   EA         NOP
229A   AD 8D 05   LDA-ABS      LOAD A WITH IFR
```

```
229D   29 40      AND-IMM    ISOLATE TIMER 1 FLAG
229F   F0 F9      BEQ        BRANCH TO 229A IF FLAG NOT SET
22A1   AD 84 05   LDA-ABS    LOAD A WITH T1C-L TO CLEAR FLAG
22A4   EA         NOP
22A5   EA         NOP
22A6   88         DEY        DECREMENT LOOP COUNTER
22A7   98         TYA        TRANSFER Y TO A
22A8   D0         BNE        BRANCH TO 229A IF LOOP COUNTER NOT ZERO
22AA   EA         NOP
22AB   EA         NOP
22AC   EA         NOP
22AD   EA         NOP
22AE   EA         NOP
22AF   EA         NOP
22B0   38         SEC        SET CARRY FLAG
22B1   A9 FF      LDA-IMM    LOAD A WITH INITIAL T2L-L VALUE
22B3   ED 88 05   SBC-ABS    SUBTRACT PRESENT T2C-L FROM INITIAL T2L-L
22B6   8D 10 00   STA-ABS    STORE RESULT IN B
22B9   A9 FF      LDA-IMM    LOAD A WITH INITIAL T2C-H VALUE
22BB   ED 89 05   SBC-ABS    SUBTRACT PRESENT T2C-H FROM INITIAL T2C-H
22BE   8D 11 00   STA-ABS    STORE RESULT IN C
22C1   60         RTS        RETURN FROM SUBROUTINE


                             ***A/D SUBROUTINE***
                             LOW FOUR BITS OF INPUT CHANNEL ADDRESS IN X
                             A/D RESULT IN A AND 0400
22E0   8A         TXA        TRANSFER INPUT CHANNEL ADDRESS FROM X TO A
22E1   18         CLC        CLEAR CARRY FLAG
22E2   69 10      ADC-IMM    ADD A/D CONTROL BIT TO INPUT CHANNEL ADDRESS
22E4   8D 80 05   STA-ABS    STORE A IN ORB TO ACTIVATE INPUT CHANNEL AND
                                CLEAR A/D CONVERTER
22E7   EA         NOP
22E8   EA         NOP
22E9   EA         NOP
22EA   EA         NOP
22EB   EA         NOP
22EC   EA         NOP
22ED   EA         NOP
22EF   EA         NOP
22F0   EA         NOP
22F1   EA         NOP
22F2   EA         NOP
22F3   EA         NOP
22F4   EA         NOP
22F5   EA         NOP
22F6   EA         NOP
22F7   EA         NOP
22F8   EA         NOP
22F9   EA         NOP
22FA   EA         NOP
22FB   EA         NOP
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22FC   EA         NOP
22FD   EA         NOP
22FE   EA         NOP
22FF   EA         NOP
2300   8E 80 05   STX-ABS      STORE X IN ORB TO INITIATE CONVERSION
2303   AD 8D 05   LDA-ABS      LOAD A WITH IFR
2306   29 10      AND-IMM      ISOLATE A/D CONVERSION COMPLETION FLAG
2308   F0 F9      BEQ          BRANCH TO 2303 IF FLAG NOT SET
230A   AD 00 04   LDA-ABS      LOAD A WITH A/D RESULT
230D   60         RTS          RETURN FROM SUBROUTINE

                               ***LOW FOUR BITS SUBROUTINE***
                               INCOMING DATA IN A
                               OUTGOING DATA IN Y
                               ORIGINAL INCOMING DATA RESTORED IN A
2310   AA         TAX          TRANSFER DATA TO X FOR STORAGE
2311   29 0F      AND-IMM      MASK HIGH FOUR BITS
2313   A8         TAY          TRANSFER RESULT TO Y
2314   8A         TXA          TRANSFER ORIGINAL DATA BACK TO A
2315   60         RTS          RETURN FROM SUBROUTINE

                               ***HIGH FOUR BITS SUBROUTINE***
                               INCOMING DATA IN A
                               OUTGOING DATA IN Y
                               ORIGINAL INCOMING DATA RESTORED IN A
2320   AA         TAX          TRANSFER DATA TO X FOR STORAGE
2321   4A         LSR          SHIFT DATA RIGHT ONE BIT
2322   4A         LSR          SHIFT DATA RIGHT ONE BIT
2323   4A         LSR          SHIFT DATA RIGHT ONE BIT
2324   4A         LSR          SHIFT DATA RIGHT ONE BIT
2325   A8         TAY          TRANSFER RESULT TO Y
2326   8A         TXA          TRANSFER ORIGINAL DATA BACK TO A
2327   60         RTS          RETURN FROM SUBROUTINE

                               ***DISPLAY SUBROUTINE***
                               LOW BYTE OF DISPLAY ADDRESS IN X
                               DIGIT TO BE DISPLAYED IN Y
2330   B9 00 00   LDA-ABS,Y    LOAD A WITH 7-SEGMENT CODE FOR Y
2333   9D 00 06   STA-ABS,X    STORE A IN SELECTED DISPLAY ADDRESS
2336   A0 08      LDY-IMM      LOAD Y WITH DELAY TIME
2338   20 50 23   JSR          JUMP TO DELAY SUBROUTINE
233B   60         RTS          RETURN FROM SUBROUTINE

                               ***DELAY SUBROUTINE***
                               MILLISECONDS DELAY IN Y
2350   A2 8F      LDX-IMM      LOAD X WITH INITIAL INNER LOOP COUNTER VALUE
2352   CA         DEX          DECREMENT INNER LOOP COUNTER
2353   8A         TXA          TRANSFER INNER LOOP COUNTER TO A
```

```
2354   D0 FC      BNE          BRANCH TO 2352 IF INNER LOOP COUNT NOT ZERO
2356   88         DEY          DECREMENT OUTER LOOP COUNTER
2357   98         TYA          TRANSFER OUTER LOOP COUNTER TO A
2358   D0 F6      BNE          BRANCH TO 2350 IF OUTER LOOP COUNT NOT ZERO
235A   60         RTS          RETURN FROM SUBROUTINE


                               ***BLANK DISPLAY SUBROUTINE***
2370   A9 00      LDA-IMM      LOAD A WITH 7-SEGMENT CODE FOR BLANK DISPLAY
2372   A0 0C      LDY-IMM      LOAD LOOP COUNTER
2374   88         DEY          DECREMENT LOOP COUNTER
2375   99 00 06   STA-ABS,Y    STORE BLANK DISPLAY CODE IN DISPLAY ADDRESSES
2378   99 40 06   STA-ABS,Y    STORE BLANK DISPLAY CODE IN DISPLAY ADDRESSES
237B   D0 F7      BNE          BRANCH TO 2374 IF LOOP COUNT NOT ZERO
237D   60         RTS          RETURN FROM SUBROUTINE


                               ***7-SEGMENT DISPLAY CODE SUBROUTINE***
2390   A9 3F      LDA-IMM      LOAD A WITH 7-SEGMENT CODE FOR 0
2392   85 00      STA-Z,PAGE   STORE A IN 0000
2394   A9 06      LDA-IMM      LOAD A WITH 7-SEGMENT CODE FOR 1
2396   85 01      STA-Z,PAGE   STORE A IN 0001
2398   A9 5B      LDA-IMM      LOAD A WITH 7-SEGMENT CODE FOR 2
239A   85 02      STA-Z,PAGE   STORE A IN 0002
239C   A9 4F      LDA-IMM      LOAD A WITH 7-SEGMENT CODE FOR 3
239E   85 03      STA-Z,PAGE   STORE A IN 0003
23A0   A9 66      LDA-IMM      LOAD A WITH 7-SEGMENT CODE FOR 4
23A2   85 04      STA-Z,PAGE   STORE A IN 0004
23A4   A9 6D      LDA-IMM      LOAD A WITH 7-SEGMENT CODE FOR 5
23A6   85 05      STA-Z,PAGE   STORE A IN 0005
23A8   A9 7D      LDA-IMM      LOAD A WITH 7-SEGMENT CODE FOR 6
23AA   85 06      STA-Z,PAGE   STORE A IN 0006
23AC   A9 07      LDA-IMM      LOAD A WITH 7-SEGMENT CODE FOR 7
23AE   85 07      STA-Z,PAGE   STORE A IN 0007
23B0   A9 7F      LDA-IMM      LOAD A WITH 7-SEGMENT CODE FOR 8
23B2   85 08      STA-Z,PAGE   STORE A IN 0008
23B4   A9 6F      LDA-IMM      LOAD A WITH 7-SEGMENT CODE FOR 9
23B6   85 09      STA-Z,PAGE   STORE A IN 0009
23B8   A9 77      LDA-IMM      LOAD A WITH 7-SEGMENT CODE FOR A
23BA   85 0A      STA-Z,PAGE   STORE A IN 000A
23BC   A9 7C      LDA-IMM      LOAD A WITH 7-SEGMENT CODE FOR B
23BE   85 0B      STA-Z,PAGE   STORE A IN 000B
23C0   A9 39      LDA-IMM      LOAD A WITH 7-SEGMENT CODE FOR C
23C2   85 0C      STA-Z,PAGE   STORE A IN 000C
23C4   A9 5E      LDA-IMM      LOAD A WITH 7-SEGMENT CODE FOR D
23C6   85 0D      STA-Z,PAGE   STORE A IN 000D
23C8   A9 79      LDA-IMM      LOAD A WITH 7-SEGMENT CODE FOR E
23CA   85 0E      STA-Z,PAGE   STORE A IN 000E
23CC   A9 71      LDA-IMM      LOAD A WITH 7-SEGMENT CODE FOR F
23CE   85 0F      STA-Z,PAGE   STORE A IN 000F
23D0   60         RTS          RETURN FROM SUBROUTINE
```

```
                                 ***TEMPERATURE CONTROL SUBROUTINE***
2400   A2 0C      LDX-IMM        SELECT INLET TEMPERATURE INPUT CHANNEL
2402   20 E0 22   JSR            JUMP TO A/D SUBROUTINE
2405   8D 10 00   STA-ABS        STORE INLET TEMPERATURE IN B
2408   EA         NOP
2409   EA         NOP
240A   EA         NOP
240B   A2 0D      LDX-IMM        SELECT OUTLET TEMPERATURE INPUT CHANNEL
240D   20 E0 22   JSR            JUMP TO A/D SUBROUTINE
2410   D8         CLD            CLEAR DECIMAL MODE
2411   18         CLC            CLEAR CARRY FLAG
2412   6D 10 00   ADC-ABS        ADD INLET AND OUTLET TEMPERATURES
2415   2A         ROL-A          ROTATE SUM ONE BIT LEFT
2416   2A         ROL-A          ROTATE SUM ONE BIT LEFT
2417   2A         ROL-A          ROTATE SUM ONE BIT LEFT
2418   2A         ROL-A          ROTATE SUM ONE BIT LEFT
2419   2A         ROL-A          ROTATE SUM ONE BIT LEFT
241A   2A         ROL-A          ROTATE SUM ONE BIT LEFT
241B   2A         ROL-A          ROTATE SUM ONE BIT LEFT
241C   2A         ROL-A          ROTATE SUM ONE BIT LEFT
241D   C9 85      CMP-IMM        COMPARE AVERAGE TEMPERATURE TO HIGH LIMIT
241F   10 0F      BPL            BRANCH TO 2430 IF AVERAGE TEMPERATURE IS
                                    ABOVE HIGH LIMIT
2421   EA         NOP
2422   EA         NOP
2423   EA         NOP
2424   EA         NOP
2425   EA         NOP
2426   C9 83      CMP-IMM        COMPARE AVERAGE TEMPERATURE TO LOW LIMIT
2428   30 0F      BMI            BRANCH TO 2439 IF AVERAGE TEMPERATURE IS
                                    BELOW LOW LIMIT
242A   EA         NOP
242B   4C 3E 24   JMP-ABS        JUMP TO 243E
242E   EA         NOP
242F   EA         NOP
2430   A9 E0      LDA-IMM        LOAD A FOR PCR TO HOLD CB2 HIGH
2432   8D 8C 05   STA-ABS        STORE A IN PCR TO TURN ON COOLING WATER
2435   4C 3E 24   JMP-ABS        JUMP TO 243E
2438   EA         NOP
2439   A9 C0      LDA-IMM        LOAD A FOR PCR TO HOLD CB2 LOW
243B   8D 8C 05   STA-ABS        STORE A IN PCR TO TURN OFF COOLING WATER
243E   60         RTS            RETURN FROM SUBROUTINE
```

APPENDIX D

RAW DATA AT FULL DISPLACEMENT

Np no load	Np	Tp	Dp	Ps	t_{in}	Nm	Tm	Dm	Pc	t_{out}	t_{avg}
2400	2127	1152	4.26	1600	47.3	1191	1454	7.24	183	56.6	52.0
2400	2133	1145	4.26	1600	47.3	1193	1440	7.24	183	56.3	51.8
2400	2135	1145	4.26	1600	48.0	1194	1447	7.24	182	57.4	52.7
2400	2172	1015	4.26	1400	48.0	1219	1210	7.24	180	58.2	53.1
2400	2172	1022	4.26	1400	48.0	1219	1217	7.24	180	58.2	53.1
2400	2171	1022	4.26	1400	48.0	1220	1217	7.24	180	58.2	53.1
2400	2201	878	4.26	1200	48.4	1239	979	7.24	181	58.2	53.3
2400	2201	878	4.26	1200	48.0	1240	979	7.24	180	58.2	53.1
2400	2201	878	4.26	1200	48.4	1239	972	7.24	180	58.2	53.3
2400	2227	742	4.26	1000	48.0	1259	742	7.24	180	58.2	53.1
2400	2230	742	4.26	1000	48.0	1260	742	7.24	181	58.2	53.1
2400	2228	742	4.26	1000	48.0	1260	742	7.24	181	58.2	53.1
2400	2268	598	4.26	800	48.0	1286	504	7.24	181	58.2	53.1
2400	2269	598	4.26	800	48.0	1287	504	7.24	181	58.2	53.1
2400	2270	598	4.26	800	48.4	1288	504	7.24	181	58.2	53.3
2400	2309	461	4.26	600	48.0	1314	274	7.24	181	58.2	53.1
2400	2308	461	4.26	600	48.4	1314	274	7.24	181	58.2	53.3
2400	2311	461	4.26	600	48.4	1313	274	7.24	181	58.6	53.5
2200	1959	1152	4.26	1600	47.7	1096	1454	7.24	176	55.9	51.8
2200	1955	1145	4.26	1600	48.8	1096	1462	7.24	176	56.6	52.7
2200	1959	1145	4.26	1600	47.7	1096	1454	7.24	176	56.6	52.1
2200	1989	1015	4.26	1400	48.4	1118	1231	7.24	178	57.0	52.7
2200	1992	1008	4.26	1400	47.3	1120	1224	7.24	178	57.0	52.1
2200	1991	1015	4.26	1400	46.9	1118	1224	7.24	178	56.6	51.8
2200	2020	878	4.26	1200	46.9	1138	994	7.24	179	57.0	52.0
2200	2017	878	4.26	1200	46.9	1138	994	7.24	178	56.6	51.8
2200	2018	878	4.26	1200	48.8	1137	994	7.24	177	57.0	52.9
2200	2052	742	4.26	1000	46.9	1161	756	7.24	177	56.6	51.8
2200	2053	742	4.26	1000	48.0	1162	763	7.24	177	57.0	52.5
2200	2052	742	4.26	1000	48.0	1160	763	7.24	177	57.0	52.5
2200	2080	598	4.26	800	47.3	1179	526	7.24	178	55.1	51.2
2200	2076	598	4.26	800	47.3	1179	533	7.24	178	56.6	52.0
2200	2078	598	4.26	800	47.7	1179	533	7.24	178	57.0	52.3
2200	2107	468	4.26	600	47.3	1200	302	7.24	179	56.3	51.8
2200	2106	461	4.26	600	47.7	1198	302	7.24	179	56.6	52.1
2200	2107	461	4.26	600	48.8	1200	302	7.24	179	57.0	52.9

Np no load	Np	Tp	Dp	Ps	t_{in}	Nm	Tm	Dm	Pc	t_{out}	t_{avg}
2000	1714	1138	4.26	1600	47.7	960	1462	7.24	173	55.1	51.4
2000	1714	1130	4.26	1600	49.6	960	1462	7.24	172	55.9	52.7
2000	1714	1130	4.26	1600	48.8	961	1469	7.24	172	55.9	52.3
2000	1754	1001	4.26	1400	48.4	986	1238	7.24	173	55.9	52.1
2000	1756	1001	4.26	1400	47.3	987	1238	7.24	173	55.9	51.6
2000	1754	1008	4.26	1400	48.0	987	1246	7.24	173	56.3	52.1
2000	1795	871	4.26	1200	48.4	1013	1001	7.24	174	56.3	52.3
2000	1795	871	4.26	1200	48.4	1011	1001	7.24	174	56.6	52.5
2000	1794	871	4.26	1200	44.1	1013	1001	7.24	174	56.3	50.2
2000	1846	734	4.26	1000	47.7	1046	763	7.24	175	56.3	52.0
2000	1846	734	4.26	1000	47.3	1044	763	7.24	175	56.3	51.8
2000	1845	734	4.26	1000	48.8	1045	763	7.24	174	56.6	52.7
2000	1874	598	4.26	800	48.4	1065	533	7.24	174	56.3	52.3
2000	1874	598	4.26	800	48.8	1064	540	7.24	176	56.3	52.5
2000	1872	598	4.26	800	47.3	1063	540	7.24	176	56.3	51.8
2000	1894	454	4.26	600	48.4	1080	310	7.24	176	56.6	52.5
2000	1894	454	4.26	600	47.3	1080	310	7.24	176	56.3	51.8
2000	1895	461	4.26	600	46.9	1080	310	7.24	176	56.3	51.6
1800	1483	1123	4.26	1600	50.0	829	1490	7.24	166	55.1	52.5
1800	1485	1123	4.26	1600	48.4	830	1490	7.24	166	54.3	51.4
1800	1484	1123	4.26	1600	46.5	831	1490	7.24	166	53.9	50.2
1800	1527	994	4.26	1400	48.0	859	1267	7.24	169	55.5	51.8
1800	1529	986	4.26	1400	46.9	859	1246	7.24	169	55.1	51.0
1800	1527	994	4.26	1400	48.4	858	1253	7.24	167	56.3	52.3
1800	1563	850	4.26	1200	47.7	880	1022	7.24	168	55.1	51.4
1800	1563	857	4.26	1200	49.2	881	1022	7.24	167	56.3	52.7
1800	1562	857	4.26	1200	48.0	881	1022	7.24	168	56.3	52.1
1800	1617	720	4.26	1000	48.8	916	785	7.24	169	56.6	52.7
1800	1617	720	4.26	1000	47.7	915	792	7.24	169	56.3	52.0
1800	1617	720	4.26	1000	46.9	917	785	7.24	170	55.1	51.0
1800	1660	583	4.26	800	47.7	942	554	7.24	171	55.9	51.8
1800	1658	583	4.26	800	46.9	943	554	7.24	171	55.1	51.0
1800	1660	576	4.26	800	49.2	944	554	7.24	170	56.3	52.7
1800	1715	446	4.26	600	48.0	977	324	7.24	172	55.1	51.6
1800	1717	439	4.26	600	49.2	978	324	7.24	172	56.3	52.7
1800	1716	439	4.26	600	47.3	979	324	7.24	172	55.5	51.4

Np no load	Np	Tp	Dp	Ps	t_{in}	Nm	Tm	Dm	Pc	t_{out}	t_{avg}
1600	1301	1116	4.26	1600	45.7	728	1498	7.24	162	53.9	49.8
1600	1302	1123	4.26	1600	46.9	729	1498	7.24	163	54.3	50.6
1600	1302	1116	4.26	1600	48.4	730	1498	7.24	163	55.1	51.8
1600	1352	979	4.26	1400	47.7	758	1260	7.24	165	55.1	51.4
1600	1349	979	4.26	1400	49.2	756	1260	7.24	163	56.3	52.7
1600	1350	986	4.26	1400	48.0	758	1260	7.24	165	56.3	52.1
1600	1384	842	4.26	1200	48.8	780	1022	7.24	165	56.3	52.5
1600	1383	842	4.26	1200	47.3	778	1022	7.24	166	55.1	51.2
1600	1380	850	4.26	1200	46.1	779	1022	7.24	165	55.1	50.6
1600	1427	706	4.26	1000	47.3	805	785	7.24	167	55.1	51.2
1600	1425	706	4.26	1000	47.7	806	785	7.24	168	55.1	51.4
1600	1422	698	4.26	1000	49.2	802	785	7.24	168	56.3	52.7
1600	1451	569	4.26	800	49.2	824	554	7.24	169	56.3	52.7
1600	1452	569	4.26	800	48.8	823	562	7.24	170	56.3	52.5
1600	1450	569	4.26	800	46.5	826	554	7.24	171	55.1	50.8
1600	1494	432	4.26	600	48.4	847	324	7.24	168	55.1	51.8
1600	1490	432	4.26	600	46.9	851	324	7.24	169	55.1	51.0
1600	1496	425	4.26	600	46.1	852	324	7.24	169	54.3	50.2
1400	1160	1102	4.26	1600	46.1	647	1483	7.24	166	53.9	50.0
1400	1162	1109	4.26	1600	48.0	649	1490	7.24	166	54.3	51.2
1400	1159	1109	4.26	1600	49.2	650	1490	7.24	166	55.1	52.1
1400	1201	979	4.26	1400	44.9	674	1260	7.24	167	53.9	49.4
1400	1201	979	4.26	1400	46.9	673	1260	7.24	167	54.3	50.6
1400	1201	979	4.26	1400	48.8	673	1260	7.24	167	55.1	52.0
1400	1226	842	4.26	1200	46.5	692	1030	7.24	169	54.3	50.4
1400	1231	842	4.26	1200	48.0	691	1022	7.24	168	55.1	51.6
1400	1227	842	4.26	1200	49.2	690	1030	7.24	168	55.1	52.1
1400	1267	706	4.26	1000	48.0	716	792	7.24	169	55.1	51.6
1400	1268	706	4.26	1000	49.2	718	799	7.24	169	55.5	52.3
1400	1268	706	4.26	1000	47.3	715	799	7.24	169	55.1	51.2
1400	1302	569	4.26	800	48.8	740	569	7.24	169	55.1	52.0
1400	1303	569	4.26	800	48.8	739	569	7.24	169	55.1	52.0
1400	1301	569	4.26	800	46.9	739	569	7.24	170	54.3	50.6
1400	1330	425	4.26	600	48.8	759	346	7.24	170	55.1	52.0
1400	1331	432	4.26	600	46.9	758	346	7.24	170	54.3	50.6
1400	1331	432	4.26	600	46.9	758	346	7.24	171	54.3	50.6

Np no load	Np	Tp	Dp	Ps	t_{in}	Nm	Tm	Dm	Pc	t_{out}	t_{avg}
1200	961	1116	4.26	1600	46.9	537	1505	7.24	161	54.3	50.6
1200	962	1116	4.26	1600	48.0	537	1505	7.24	160	54.3	51.2
1200	963	1109	4.26	1600	49.2	538	1505	7.24	160	55.1	52.1
1200	1004	979	4.26	1400	46.1	561	1274	7.24	163	53.9	50.0
1200	1003	979	4.26	1400	47.3	561	1274	7.24	163	54.3	50.8
1200	1003	979	4.26	1400	48.4	562	1274	7.24	163	55.1	51.8
1200	1044	842	4.26	1200	45.7	586	1044	7.24	164	53.9	49.8
1200	1040	850	4.26	1200	45.7	587	1051	7.24	165	53.1	49.4
1200	1041	850	4.26	1200	46.9	586	1051	7.24	164	53.9	50.4
1200	1075	713	4.26	1000	50.0	608	828	7.24	165	55.1	52.5
1200	1078	706	4.26	1000	46.5	608	814	7.24	166	54.3	50.4
1200	1077	713	4.26	1000	45.3	608	821	7.24	166	53.1	49.2
1200	1109	576	4.26	800	48.8	631	590	7.24	166	54.3	51.6
1200	1110	569	4.26	800	50.0	628	590	7.24	166	55.1	52.5
1200	1113	569	4.26	800	49.2	631	598	7.24	166	55.1	52.1
1200	1143	432	4.26	600	46.5	653	360	7.24	166	53.1	49.8
1200	1144	432	4.26	600	48.0	653	360	7.24	166	54.3	51.2
1200	1144	432	4.26	600	49.2	651	360	7.24	166	55.1	52.1
1000	883	691	4.26	1000	48.4	498	821	7.24	159	54.3	51.4
1000	885	684	4.26	1000	49.6	499	821	7.24	160	54.3	52.0
1000	883	684	4.26	1000	46.9	498	828	7.24	160	53.9	50.4
1000	907	554	4.26	800	47.3	514	590	7.24	161	53.1	50.2
1000	909	554	4.26	800	48.0	516	590	7.24	161	53.9	51.0
1000	906	547	4.26	800	49.2	514	590	7.24	161	53.9	51.6
1000	931	418	4.26	600	45.7	531	367	7.24	162	53.1	49.4
1000	929	425	4.26	600	44.9	528	367	7.24	162	52.0	48.4
1000	931	425	4.26	600	45.7	528	360	7.24	162	52.3	49.0

APPENDIX E

AVERAGED AND REDUCED DATA AT FULL DISPLACEMENT

Np no load	Np	Tp	Dp	Ps	Nm	Tm	Dm	Pc	ΔP	K/μ	L
2400	2132	1147	4.26	1600	1193	1447	7.24	183	1417	1.973	445.0
2400	2172	1020	4.26	1400	1219	1215	7.24	180	1220	2.200	427.2
2400	2201	878	4.26	1200	1239	977	7.24	180	1020	2.500	405.9
2400	2228	742	4.26	1000	1260	742	7.24	181	819	2.830	368.9
2400	2269	598	4.26	800	1287	504	7.24	181	619	3.533	348.1
2400	2309	461	4.26	600	1314	274	7.24	181	419	4.843	323.0
2200	1958	1147	4.26	1600	1096	1457	7.24	176	1424	1.792	406.0
2200	1991	1013	4.26	1400	1119	1226	7.24	178	1222	1.954	380.1
2200	2018	878	4.26	1200	1138	994	7.24	178	1022	2.198	357.6
2200	2052	742	4.26	1000	1161	761	7.24	177	823	2.564	335.9
2200	2078	598	4.26	800	1179	531	7.24	178	622	3.195	316.3
2200	2107	463	4.26	600	1199	302	7.24	179	421	4.404	295.1
2000	1714	1133	4.26	1600	960	1464	7.24	172	1428	1.545	351.2
2000	1755	1003	4.26	1400	987	1241	7.24	173	1227	1.692	330.4
2000	1795	871	4.26	1200	1012	1001	7.24	174	1026	1.959	319.8
2000	1846	734	4.26	1000	1045	763	7.24	175	825	2.271	298.2
2000	1873	598	4.26	800	1064	538	7.24	175	625	2.771	275.6
2000	1894	456	4.26	600	1080	310	7.24	176	424	3.693	249.2
1800	1484	1123	4.26	1600	830	1490	7.24	166	1434	1.370	312.6
1800	1528	991	4.26	1400	859	1255	7.24	168	1232	1.480	290.1
1800	1563	855	4.26	1200	881	1022	7.24	168	1032	1.704	279.9
1800	1617	720	4.26	1000	916	787	7.24	169	831	1.940	256.6
1800	1659	581	4.26	800	943	554	7.24	171	629	2.398	240.0
1800	1716	441	4.26	600	978	324	7.24	172	428	3.368	229.4
1600	1302	1118	4.26	1600	729	1498	7.24	163	1437	1.174	268.6
1600	1350	981	4.26	1400	757	1260	7.24	164	1236	1.374	270.3
1600	1382	845	4.26	1200	779	1022	7.24	165	1035	1.502	247.4
1600	1425	703	4.26	1000	804	785	7.24	168	832	1.885	249.5
1600	1451	569	4.26	800	824	557	7.24	170	630	2.107	211.2
1600	1493	430	4.26	600	850	324	7.24	169	431	3.006	206.2
1400	1160	1107	4.26	1600	649	1488	7.24	166	1434	1.064	242.8
1400	1201	979	4.26	1400	673	1260	7.24	167	1233	1.242	243.7
1400	1228	842	4.26	1200	691	1027	7.24	168	1032	1.391	228.4
1400	1268	706	4.26	1000	716	797	7.24	169	831	1.647	217.8
1400	1302	569	4.26	800	739	569	7.24	169	631	1.953	196.2
1400	1331	430	4.26	600	758	346	7.24	170	430	2.661	182.1
1200	962	1114	4.26	1600	537	1505	7.24	160	1440	0.917	210.2
1200	1003	979	4.26	1400	561	1274	7.24	163	1237	1.072	211.1
1200	1042	847	4.26	1200	586	1049	7.24	164	1036	1.190	196.3
1200	1077	711	4.26	1000	608	821	7.24	166	834	1.402	186.1
1200	1111	571	4.26	800	630	593	7.24	166	634	1.701	171.7
1200	1144	432	4.26	600	652	360	7.24	166	434	2.214	153.0
1000	884	686	4.26	1000	498	823	7.24	160	840	1.199	160.3
1000	907	552	4.26	800	515	590	7.24	161	639	1.330	135.2
1000	930	423	4.26	600	529	365	7.24	162	438	1.891	131.8

APPENDIX F

SPEED AND TORQUE DATA AT FULL DISPLACEMENT ADJUSTED FOR CONSTANT CHARGE PRESSURE

Δ P	Np	Tp	Nm	Tm
1430	2132	1158	1193	1460
1430	1958	1152	1096	1463
1430	1714	1135	960	1466
1430	1484	1120	830	1486
1430	1302	1113	729	1491
1430	1160	1104	649	1484
1430	962	1106	537	1495
1230	2172	1028	1219	1225
1230	1991	1020	1119	1234
1230	1755	1005	987	1244
1230	1528	989	859	1253
1230	1350	976	757	1254
1230	1201	977	673	1257
1230	1003	973	561	1267
1030	2201	887	1239	987
1030	2018	885	1138	1002
1030	1795	874	1012	1005
1030	1563	853	881	1020
1030	1382	841	779	1017
1030	1228	840	691	1025
1030	1042	842	586	1043
830	2228	752	1260	752
830	2052	748	1161	767
830	1846	738	1045	768
830	1617	719	916	786
830	1425	701	804	783
830	1268	705	716	796
830	1077	708	608	817
830	884	678	498	813
630	2269	609	1287	513
630	2078	606	1179	538
630	1873	603	1064	542
630	1659	582	943	555
630	1451	569	824	557
630	1302	568	739	568
630	1111	567	630	589
630	907	544	515	582
430	2309	473	1314	281
430	2107	473	1199	308
430	1894	462	1080	314
430	1716	443	978	326
430	1493	429	850	323
430	1331	430	758	346
430	1144	428	652	357
430	930	415	529	358

APPENDIX G

COMPARISON OF MODEL A AND MEASURED VALUES
AT FULL DISPLACEMENT

Np meas	Tp meas	HPp meas	Nm meas	Tm meas	Np calc	Tp calc	HPp calc	Np/Np calculated/measured	Tp/Tp calculated/measured	HPp/HPp calculated/measured	ΔNp calc - meas	ΔTp calc - meas	ΔHPp calc - meas
2132	1147	38.80	1193	1447	2142	1164	39.56	1.0047	1.0148	1.0196	+10	+17	+0.76
2172	1020	35.15	1219	1215	2170	1024	35.26	0.9991	1.0039	1.0030	- 2	+ 4	+0.11
2201	878	30.66	1239	972	2187	877	30.43	0.9936	0.9989	0.9925	-14	- 1	-0.23
2228	742	26.23	1260	742	2206	738	25.83	0.9901	0.9946	0.9848	-22	- 4	-0.40
2269	598	21.53	1287	504	2235	595	21.10	0.9850	0.9950	0.9801	-34	- 3	-0.43
2309	461	16.89	1314	274	2265	457	16.42	0.9809	0.9913	0.9724	-44	- 4	-0.47
1958	1147	35.63	1096	1457	1978	1157	36.31	1.0102	1.0087	1.0190	+20	+10	+0.68
1991	1013	32.00	1119	1226	2000	1018	32.30	1.0045	1.0049	1.0095	+ 9	+ 5	+0.30
2018	878	28.11	1138	994	2016	878	28.08	0.9990	1.0000	0.9990	- 2	0	-0.03
2052	742	24.16	1161	761	2039	737	23.84	0.9937	0.9933	0.9870	-13	- 5	-0.32
2078	598	19.72	1179	531	2053	598	19.48	0.9880	1.0000	0.9880	-25	0	-0.24
2107	463	15.48	1199	302	2071	459	15.08	0.9829	0.9914	0.9744	-36	- 4	-0.40
1714	1133	30.81	960	1464	1746	1144	31.69	1.0187	1.0097	1.0286	+32	+11	+0.88
1755	1003	27.93	987	1241	1777	1010	28.48	1.0125	1.0070	1.0196	+22	+ 7	+0.55
1795	871	24.81	1012	1001	1802	866	24.76	1.0039	0.9943	0.9981	+ 7	- 5	-0.05
1846	734	21.50	1045	763	1841	723	21.12	0.9973	0.9850	0.9823	- 5	-11	-0.38
1873	598	17.77	1064	538	1857	587	17.30	0.9915	0.9816	0.9732	-16	-11	-0.47
1894	456	13.70	1080	310	1868	449	13.31	0.9863	0.9846	0.9711	-26	- 7	-0.39
1484	1123	26.44	830	1490	1527	1143	27.69	1.0290	1.0178	1.0473	+43	+20	+1.25
1528	991	24.03	859	1255	1559	1002	24.79	1.0203	1.0111	1.0316	+31	+11	+0.76
1563	855	21.20	881	1022	1580	861	21.58	1.0109	1.0070	1.0180	+17	+ 6	+0.38
1617	720	18.47	916	787	1623	721	18.57	1.0037	1.0014	1.0051	+ 6	+ 1	+0.10
1659	581	15.29	943	554	1652	581	15.23	0.9958	1.0000	0.9958	- 7	0	-0.06
1716	441	12.01	978	324	1695	444	11.94	0.9878	1.0068	0.9945	-21	+ 3	-0.07

Np meas	Tp meas	HPp meas	Nm meas	Tm meas	Np calc	Tp calc	HPp calc	Np/Np	Tp/Tp	HPp/HPp	ΔNp	ΔTp	ΔHPp
								calculated/measured			calc - meas		
1302	1118	23.10	729	1498	1355	1135	24.40	1.0407	1.0152	1.0565	+53	+17	+1.30
1350	981	21.01	757	1260	1386	992	21.82	1.0267	1.0112	1.0382	+36	+11	+0.81
1382	845	18.53	779	1022	1406	848	18.92	1.0174	1.0036	1.0210	+24	+ 3	+0.39
1425	703	15.89	804	785	1432	706	16.04	1.0049	1.0043	1.0092	+ 7	+ 3	+0.15
1451	569	13.10	824	557	1450	568	13.07	0.9993	0.9982	0.9976	- 1	- 1	-0.03
1493	430	10.19	850	324	1477	428	10.03	0.9893	0.9953	0.9847	-16	- 2	-0.16
1160	1107	20.37	649	1488	1218	1118	21.61	1.0500	1.0099	1.0604	+58	+11	+1.24
1201	979	18.66	673	1260	1243	981	19.35	1.0350	1.0020	1.0371	+42	+ 2	+0.69
1228	842	16.41	691	1027	1256	840	16.74	1.0228	0.9976	1.0204	+28	- 2	+0.33
1268	706	14.20	716	797	1283	702	14.29	1.0118	0.9943	1.0061	+15	- 4	+0.09
1302	569	11.75	739	569	1305	564	11.68	1.0023	0.9912	0.9935	+ 3	- 5	-0.07
1331	430	9.08	758	346	1322	429	9.00	0.9932	0.9977	0.9909	- 9	- 1	-0.08
962	1114	17.00	537	1505	1028	1114	18.17	1.0686	1.0000	1.0686	+66	0	+1.17
1003	979	15.58	561	1274	1053	975	16.29	1.0499	0.9959	1.0456	+50	- 4	+0.71
1042	847	14.00	586	1049	1079	840	14.38	1.0355	0.9917	1.0270	+37	- 7	+0.38
1077	711	12.15	608	821	1100	702	12.25	1.0214	0.9873	1.0084	+23	- 9	+0.10
1111	571	10.07	630	593	1121	565	10.05	1.0090	0.9895	0.9984	+10	- 6	-0.02
1144	432	7.84	652	360	1142	424	7.68	0.9983	0.9815	0.9798	- 2	- 8	-0.16
884	686	9.62	498	823	913	689	9.98	1.0328	1.0044	1.0373	+29	+ 3	+0.36
907	552	7.94	515	590	925	548	8.04	1.0198	0.9928	1.0125	+18	- 4	+0.10
930	423	6.24	529	365	933	411	6.08	1.0032	0.9716	0.9748	+ 3	-12	-0.16

APPENDIX H

COMPARISON OF MODEL B AND MEASURED VALUES AT FULL DISPLACEMENT

Np meas	Tp meas	HPp meas	Nm meas	Tm meas	Np calc	Tp calc	HPp calc	Np/Np calculated/measured	Tp/Tp calculated/measured	HPp/HPp calculated/measured	ΔNp calc - meas	ΔTp calc - meas	ΔHPp calc - meas
2132	1147	38.80	1193	1447	2103	1155	38.54	0.9864	1.0070	0.9933	-29	+ 8	-0.26
2172	1020	35.15	1219	1215	2143	1019	34.65	0.9866	0.9990	0.9857	-29	- 1	-0.50
2201	878	30.66	1239	977	2173	878	30.27	0.9873	1.0000	0.9873	-28	0	-0.39
2228	742	26.23	1260	742	2205	740	25.89	0.9897	0.9973	0.9870	-23	- 2	-0.34
2269	598	21.53	1287	504	2247	600	21.39	0.9903	1.0033	0.9936	-22	+ 2	-0.14
2309	461	16.89	1314	274	2289	466	16.92	0.9913	1.0108	1.0021	-20	+ 5	+0.03
1958	1147	35.63	1096	1457	1938	1148	35.30	0.9898	1.0009	0.9906	-20	+ 1	-0.33
1991	1013	32.00	1119	1226	1973	1012	31.68	0.9910	0.9990	0.9900	-18	- 1	-0.32
2018	878	28.11	1138	994	2002	876	27.83	0.9921	0.9977	0.9898	-16	- 2	-0.28
2052	742	24.16	1161	761	2037	739	23.88	0.9927	0.9960	0.9887	-15	- 3	-0.28
2078	598	19.72	1179	531	2063	603	19.74	0.9928	1.0084	1.0011	-15	+ 5	+0.02
2107	463	15.48	1199	302	2093	468	15.54	0.9934	1.0108	1.0041	-14	+ 5	+0.06
1714	1133	30.81	960	1464	1707	1135	30.74	0.9959	1.0018	0.9977	- 7	+ 2	-0.07
1755	1003	27.93	987	1241	1749	1004	27.86	0.9966	1.0010	0.9976	- 6	+ 1	-0.07
1795	871	24.81	1012	1001	1787	864	24.50	0.9955	0.9920	0.9875	- 8	- 7	-0.31
1846	734	21.50	1045	763	1839	725	21.15	0.9962	0.9877	0.9840	- 7	- 9	-0.35
1873	598	17.77	1064	538	1868	592	17.55	0.9973	0.9900	0.9873	- 5	- 6	-0.22
1894	456	13.70	1080	310	1891	457	13.71	0.9984	1.0022	1.0006	- 3	+ 1	-0.01
1484	1123	26.44	830	1490	1486	1134	26.74	1.0013	1.0098	1.0112	+ 2	+11	+0.30
1528	991	24.03	859	1255	1532	996	24.21	1.0026	1.0050	1.0077	+ 4	+ 5	+0.18
1563	855	21.20	881	1022	1565	859	21.33	1.0013	1.0047	1.0060	+ 2	+ 4	+0.13
1617	720	18.47	916	787	1620	723	18.58	1.0019	1.0042	1.0060	+ 3	+ 3	+0.11
1659	581	15.29	943	554	1662	586	15.45	1.0018	1.0086	1.0104	+ 3	+ 5	+0.16
1716	441	12.01	978	324	1718	453	12.35	1.0012	1.0272	1.0284	+ 2	+12	+0.34

Np meas	Tp meas	HPp meas	Nm meas	Tm meas	Np calc	Tp calc	HPp calc	Np/Np calculated/measured	Tp/Tp calculated/measured	HPp/HPp calculated/measured	ΔNp calc - meas	ΔTp calc - meas	ΔHPp calc - meas
1302	1118	23.10	729	1498	1315	1126	23.49	1.0100	1.0072	1.0172	+13	+ 8	+0.39
1350	981	21.01	757	1260	1358	986	21.25	1.0059	1.0051	1.0111	+ 8	+ 5	+0.24
1382	845	18.53	779	1022	1391	846	18.67	1.0065	1.0012	1.0077	+ 9	+ 1	+0.14
1425	703	15.89	804	785	1430	707	16.04	1.0035	1.0057	1.0092	+ 5	+ 4	+0.15
1451	569	13.10	824	557	1460	573	13.27	1.0062	1.0070	1.0133	+ 9	+ 4	+0.17
1493	430	10.19	850	324	1500	436	10.38	1.0047	1.0140	1.0187	+ 7	+ 6	+0.19
1160	1107	20.37	649	1488	1178	1109	20.73	1.0155	1.0018	1.0174	+18	+ 2	+0.36
1201	979	18.66	673	1260	1215	975	18.80	1.0117	0.9959	1.0075	+14	- 4	+0.14
1228	842	16.41	691	1027	1242	838	16.51	1.0114	0.9952	1.0066	+14	- 4	+0.10
1268	706	14.20	716	797	1280	703	14.28	1.0095	0.9958	1.0052	+12	- 3	+0.08
1302	569	11.75	739	569	1316	569	11.88	1.0108	1.0000	1.0108	+14	0	+0.13
1331	430	9.08	758	346	1344	438	9.34	1.0098	1.0186	1.0286	+13	+ 8	+0.26
962	1114	17.00	537	1505	988	1105	17.32	1.0270	0.9919	1.0187	+26	- 9	+0.32
1003	979	15.58	561	1274	1025	969	15.76	1.0219	0.9898	1.0115	+22	-10	+0.18
1042	847	14.00	586	1049	1064	838	14.15	1.0211	0.9894	1.0103	+22	- 9	+0.15
1077	711	12.15	608	821	1097	703	12.24	1.0186	0.9887	1.0071	+20	- 8	+0.09
1111	571	10.07	630	593	1131	569	10.21	1.0180	0.9965	1.0144	+20	- 2	+0.14
1144	432	7.84	652	360	1164	432	7.98	1.0175	1.0000	1.0175	+20	0	+0.14
884	686	9.62	498	823	910	691	9.98	1.0294	1.0073	1.0369	+26	+ 5	+0.36
907	552	7.94	515	590	935	553	8.20	1.0309	1.0018	1.0327	+28	+ 1	+0.26
930	423	6.24	529	365	955	420	6.36	1.0269	0.9929	1.0196	+25	- 3	+0.12

APPENDIX I

RAW DATA AT APPROXIMATELY THREE-FOURTHS DISPLACEMENT

Np no load	Np	Tp	Dp	Ps	t_{in}	Nm	Tm	Dm	Pc	t_{out}	t_{avg}
2200	1968	1087	3.19	1990	47.7	1100	1390	5.44	176	56.6	52.1
2200	1972	1094	3.19	1980	48.8	1102	1375	5.40	175	57.0	52.9
2200	1969	1080	3.19	1980	46.5	1101	1368	5.37	175	57.0	51.8
2200	1973	1080	3.19	1990	48.0	1098	1368	5.37	175	57.0	52.5
2200	1976	1080	3.19	2000	47.7	1101	1368	5.37	176	56.6	52.1
2200	1976	1080	3.19	1980	46.9	1102	1375	5.37	175	56.3	51.6
2200	2023	907	3.19	1610	47.7	1143	1051	5.47	177	56.6	52.1
2200	2025	893	3.19	1630	47.3	1135	1037	5.37	177	56.3	51.8
2200	2020	907	3.19	1620	46.9	1142	1044	5.37	177	56.3	51.6
2200	2023	914	3.19	1610	47.3	1137	1044	5.37	177	56.6	52.0
2200	2019	907	3.19	1610	48.8	1135	1051	5.40	177	57.0	52.9
2200	2023	907	3.19	1600	48.8	1139	1051	5.44	177	57.0	52.9
2200	2071	677	3.19	1210	48.0	1176	691	5.40	178	56.3	52.1
2200	2067	684	3.19	1200	48.0	1186	698	5.40	179	56.6	52.3
2200	2071	691	3.19	1200	47.3	1181	706	5.40	179	56.3	51.8
2200	2069	691	3.19	1210	46.9	1169	691	5.40	179	56.3	51.6
2200	2068	684	3.19	1220	46.9	1181	691	5.40	179	56.3	51.6
2200	2065	698	3.19	1200	48.4	1176	698	5.40	178	56.3	52.3
2200	2115	490	3.19	820	47.3	1200	353	5.40	179	56.3	51.8
2200	2110	490	3.19	820	48.4	1194	360	5.40	179	56.3	52.3
2200	2116	497	3.19	800	48.4	1216	360	5.40	179	56.3	52.3
2200	2111	482	3.19	820	48.4	1213	374	5.40	179	56.3	52.3
2200	2112	475	3.19	830	47.7	1209	360	5.40	179	56.3	52.0
2200	2113	490	3.19	820	46.9	1215	367	5.44	179	56.3	51.6
1800	1489	1080	3.19	2000	48.8	824	1426	5.50	163	56.3	52.5
1800	1483	1073	3.19	1990	49.2	828	1411	5.47	163	56.3	52.7
1800	1490	1066	3.17	2000	48.4	827	1411	5.24	163	56.3	52.3
1800	1489	1066	3.19	2000	47.3	829	1411	5.37	164	55.9	51.6
1800	1489	1066	3.19	1990	46.5	832	1404	5.37	166	55.1	50.8
1800	1493	1073	3.19	1980	46.1	831	1397	5.56	165	55.1	50.6
1800	1582	871	3.17	1620	48.4	888	1066	5.53	168	56.3	52.3
1800	1577	878	3.19	1610	47.3	888	1080	5.50	169	55.9	51.6
1800	1586	878	3.19	1620	46.1	883	1073	5.50	169	55.1	50.6
1500	1578	878	3.19	1610	46.1	890	1080	5.44	168	55.1	50.6
1800	1585	878	3.19	1630	46.9	886	1066	5.50	169	55.1	51.0
1800	1580	886	3.19	1610	48.0	884	1080	5.53	168	54.3	51.2

Np no load	Np	Tp	Dp	Ps	t_{in}	Nm	Tm	Dm	Pc	t_{out}	t_{avg}
1800	1660	662	3.19	1210	46.5	946	727	5.37	171	55.1	50.8
1800	1653	670	3.19	1220	46.5	935	720	5.47	171	55.1	50.8
1800	1656	677	3.19	1210	47.3	944	727	5.47	171	55.1	51.2
1800	1661	662	3.19	1220	48.4	939	720	5.50	171	55.9	52.2
1800	1661	670	3.17	1230	49.2	935	720	5.50	170	56.6	52.9
1800	1652	677	3.19	1200	48.8	938	734	5.34	170	56.3	52.5
1800	1719	468	3.19	820	48.0	985	382	5.40	172	55.1	51.6
1800	1720	454	3.19	800	49.2	984	389	5.44	171	56.3	52.7
1800	1719	461	3.19	820	49.2	976	382	5.40	172	56.3	52.7
1800	1721	461	3.19	820	48.0	986	382	5.40	172	55.9	52.0
1800	1715	468	3.19	820	46.9	980	382	5.40	172	55.1	51.0
1800	1714	475	3.19	810	45.7	982	396	5.40	173	54.3	50.0
1400	1140	1066	3.17	2020	50.0	633	1433	5.31	160	55.1	52.5
1400	1145	1066	3.25	2010	49.2	636	1426	5.50	162	55.1	52.1
1400	1143	1066	3.17	2000	47.7	636	1418	5.47	161	55.1	51.4
1400	1145	1058	3.21	2000	46.5	639	1418	5.50	162	55.1	50.8
1400	1145	1058	3.26	2000	45.7	638	1411	5.31	163	53.9	49.8
1400	1146	1058	3.25	1980	45.3	640	1411	5.44	162	53.9	49.6
1400	1202	864	3.23	1610	48.8	676	1080	5.37	164	55.1	52.0
1400	1203	864	3.17	1610	49.6	677	1073	5.40	164	55.1	52.3
1400	1198	857	3.23	1610	49.6	678	1080	5.47	164	55.1	52.3
1400	1204	857	3.23	1610	48.4	677	1080	5.34	164	55.1	51.8
1400	1198	864	3.15	1610	47.3	678	1087	5.34	165	54.7	51.0
1400	1202	871	3.17	1610	46.1	679	1080	5.40	165	53.9	50.0
1400	1263	655	3.19	1210	47.3	720	734	5.40	167	53.9	50.6
1400	1265	655	3.19	1200	48.4	718	734	5.44	167	54.3	51.4
1400	1263	655	3.19	1210	48.8	719	734	5.37	167	55.1	52.0
1400	1268	655	3.19	1210	50.0	719	734	5.40	167	55.1	52.5
1400	1261	655	3.19	1210	50.0	718	734	5.40	167	55.1	52.5
1400	1258	655	3.19	1200	48.8	720	734	5.40	167	55.1	52.0
1400	1317	439	3.19	790	46.9	759	403	5.44	168	53.9	50.4
1400	1318	454	3.19	800	48.0	758	403	5.37	168	54.3	51.2
1400	1321	454	3.19	800	48.8	757	403	5.37	168	54.7	51.8
1400	1316	439	3.19	800	49.6	754	396	5.40	168	55.1	52.3
1400	1321	446	3.19	790	50.0	759	403	5.40	168	55.1	52.5
1400	1320	446	3.19	810	49.2	755	410	5.40	167	55.1	52.1

APPENDIX J

AVERAGED DATA AT APPROXIMATELY THREE-FOURTHS DISPLACEMENT

Np no load	Np	Tp	Dp	Ps	Nm	Tm	Dm	Pc	ΔP
2200	1972	1084	3.19	1987	1101	1374	5.39	175	1812
2200	2022	906	3.19	1613	1139	1046	5.40	177	1436
2200	2069	688	3.19	1207	1178	696	5.40	179	1028
2200	2113	487	3.19	818	1208	362	5.41	179	639
1800	1489	1071	3.19	1993	829	1410	5.42	164	1829
1800	1581	878	3.19	1617	887	1074	5.50	169	1448
1800	1657	670	3.19	1215	940	725	5.44	171	1044
1800	1718	465	3.19	815	982	386	5.41	172	643
1400	1144	1062	3.22	2002	637	1420	5.42	162	1840
1400	1201	863	3.20	1610	678	1080	5.39	164	1446
1400	1263	655	3.19	1207	719	734	5.40	167	1040
1400	1319	446	3.19	798	757	403	5.40	168	630

APPENDIX K

RAW DATA AT APPROXIMATELY ONE-HALF DISPLACEMENT

Np no load	Np	Tp	Dp	Ps	t_{in}	Nm	Tm	Dm	Pc	t_{out}	t_{avg}
2200	2031	778	2.12	2000	47.3	1092	871	3.70	178	55.1	51.2
2200	2029	778	2.12	2010	46.5	1095	878	3.73	177	55.1	50.8
2200	2034	770	2.12	2000	46.9	1094	878	3.70	177	55.1	51.0
2200	2036	778	2.12	2010	48.0	1093	878	3.57	176	55.9	52.0
2200	2031	778	2.12	2010	49.6	1101	871	3.70	177	56.6	53.1
2200	2035	770	2.12	2010	49.6	1104	871	3.63	176	57.0	53.3
2200	2064	641	2.12	1620	48.8	1131	655	3.60	177	55.9	52.3
2200	2071	634	2.12	1630	48.8	1131	648	3.60	177	56.6	52.7
2200	2066	641	2.12	1640	48.8	1135	655	3.66	178	56.6	52.7
2200	2063	648	2.12	1630	48.0	1133	648	3.63	177	56.3	52.1
2200	2062	641	2.12	1630	47.3	1144	655	3.60	178	55.9	51.6
2200	2066	655	2.12	1640	46.9	1132	648	3.63	177	55.9	51.4
2200	2100	504	2.14	1230	47.7	1190	425	3.60	179	55.9	51.8
2200	2096	518	2.14	1230	46.9	1173	418	3.60	178	55.9	51.4
2200	2097	511	2.14	1220	46.5	1175	418	3.60	179	55.1	50.8
2200	2097	518	2.14	1240	47.7	1171	418	3.63	179	55.9	51.8
2200	2100	511	2.12	1230	49.2	1184	425	3.60	178	56.3	52.7
2200	2096	511	2.12	1220	49.6	1165	418	3.63	178	57.0	53.3
2200	2128	360	2.12	810	48.0	1217	202	3.63	178	56.3	52.1
2200	2128	367	2.12	820	47.7	1221	202	3.60	178	54.3	51.0
2200	2126	374	2.14	810	47.3	1214	202	3.63	177	55.1	51.2
2200	2126	382	2.14	830	47.3	1188	202	3.60	178	55.1	51.2
2200	2127	374	2.12	850	48.0	1221	209	3.60	178	55.9	52.0
2200	2126	374	2.14	830	49.2	1202	209	3.60	178	56.3	52.7
1800	1647	756	2.12	1990	49.6	914	850	3.41	169	56.3	52.9
1800	1646	756	2.12	1990	48.8	916	850	3.70	168	56.3	52.6
1800	1645	756	2.12	1990	47.7	917	850	3.63	169	55.9	51.8
1800	1646	756	2.12	1990	46.9	918	850	3.41	169	55.1	51.0
1800	1643	756	2.12	2000	46.5	917	842	3.44	168	55.1	50.8
1800	1648	756	2.12	2000	46.9	918	850	3.41	169	55.1	51.0
1800	1685	626	2.12	1620	47.7	949	641	3.60	169	55.9	51.8
1800	1690	634	2.12	1620	46.9	958	641	3.47	169	55.1	51.0
1800	1688	619	2.12	1620	46.5	955	634	3.60	170	55.1	50.8
1800	1693	626	2.12	1620	47.3	950	648	3.44	169	55.1	51.2
1800	1690	634	2.12	1630	48.4	947	641	3.63	169	55.9	52.1
1800	1692	626	2.12	1610	49.6	956	641	3.47	169	56.3	52.9

Np no load	Np	Tp	Dp	Ps	t_{in}	Nm	Tm	Dm	Pc	t_{out}	t_{avg}
1800	1733	482	2.12	1230	46.9	998	425	3.50	172	55.1	51.0
1800	1734	490	2.12	1230	47.7	996	425	3.57	171	55.1	51.4
1800	1730	497	2.12	1210	49.2	985	418	3.54	171	56.3	52.7
1800	1731	482	2.12	1230	50.0	988	418	3.47	171	56.3	53.1
1800	1729	497	2.12	1220	48.8	996	432	3.47	170	56.3	52.5
1800	1731	490	2.12	1230	47.3	999	432	3.60	171	55.1	51.2
1800	1763	346	2.12	820	49.6	1021	194	3.50	171	56.3	52.9
1800	1762	353	2.12	820	48.8	1015	202	3.54	171	56.3	52.5
1800	1765	346	2.12	820	47.3	1034	209	3.50	171	55.1	51.2
1800	1759	353	2.14	810	46.9	1016	209	3.54	170	55.1	51.0
1800	1758	346	2.12	820	47.3	1033	209	3.50	170	55.1	51.2
1800	1760	353	2.14	800	48.0	1014	209	3.50	170	55.1	51.6
1400	1227	734	2.08	1990	46.9	671	871	3.50	162	54.3	50.6
1400	1226	727	2.05	1990	47.3	668	871	3.47	162	55.1	51.2
1400	1226	734	2.10	1980	48.0	669	864	3.50	162	55.1	51.6
1400	1223	727	2.10	1980	48.8	670	864	3.47	162	55.1	52.0
1400	1224	727	2.07	1980	49.2	669	864	3.50	162	55.9	52.5
1400	1227	727	2.07	1990	48.8	671	864	3.47	162	55.1	52.0
1400	1257	605	2.08	1610	46.9	696	655	3.50	165	53.9	50.4
1400	1258	605	2.10	1600	47.7	692	655	3.47	165	53.9	50.8
1400	1258	605	2.07	1610	48.4	695	655	3.50	164	55.1	51.8
1400	1255	598	2.07	1610	49.2	694	655	3.54	164	55.1	52.1
1400	1255	598	2.07	1600	49.6	692	648	3.47	164	55.1	52.3
1400	1254	598	2.08	1600	48.8	693	655	3.57	165	55.1	52.0
1400	1300	468	2.10	1210	47.3	722	432	3.54	166	53.9	50.6
1400	1302	468	2.08	1210	48.0	725	432	3.47	166	53.9	51.0
1400	1300	461	2.08	1210	48.8	723	432	3.54	166	55.1	52.0
1400	1301	461	2.07	1200	49.6	722	432	3.54	165	55.1	52.3
1400	1299	461	2.07	1200	50.0	721	432	3.54	166	55.1	52.5
1400	1304	468	2.08	1220	48.8	721	439	3.54	166	55.1	52.0
1400	1332	331	2.08	810	46.5	746	223	3.54	167	53.1	49.8
1400	1328	331	2.08	820	46.9	754	223	3.54	167	52.0	49.4
1400	1329	331	2.08	820	47.7	761	230	3.54	166	53.9	50.8
1400	1330	338	2.08	830	48.0	747	223	3.50	166	53.9	51.0
1400	1328	331	2.08	820	49.2	730	216	3.54	166	55.1	52.1
1400	1333	331	2.07	810	50.0	746	223	3.54	166	55.1	52.5

APPENDIX L

AVERAGED DATA AT APPROXIMATELY ONE-HALF DISPLACEMENT

Np no load	Np	Tp	Dp	Ps	Nm	Tm	Dm	Pc	Δ P
2200	2033	775	2.12	2007	1097	875	3.67	177	1830
2200	2065	643	2.12	1632	1134	652	3.62	177	1455
2200	2098	512	2.13	1228	1176	420	3.61	179	1049
2200	2127	372	2.13	825	1211	204	3.61	178	647
1800	1646	756	2.12	1993	917	849	3.50	169	1824
1800	1690	628	2.12	1620	953	641	3.54	169	1451
1800	1731	490	2.12	1225	994	425	3.53	171	1054
1800	1761	350	2.13	815	1022	205	3.51	171	644
1400	1226	728	2.08	1985	670	866	3.49	162	1823
1400	1256	602	2.08	1605	694	654	3.51	165	1440
1400	1301	465	2.08	1208	722	433	3.53	166	1042
1400	1330	332	2.08	818	747	223	3.53	166	652

APPENDIX M

COMPARISON OF MODEL B AND MEASURED VALUES
AT APPROXIMATELY THREE-FOURTHS DISPLACEMENT

Np meas	Tp meas	Dp	HPp meas	Nm meas	Tm meas	Dm	Np calc	Tp calc	HPp calc	Np/Np calculated/measured	Tp/Tp calculated/measured	HPp/HPp calculated/measured	ΔNp calc - meas	ΔTp calc - meas	ΔHPp calc - meas
1972	1084	3.19	33.92	1101	1374	5.39	1971	1112	34.78	0.9995	1.0258	1.0253	- 1	+28	+0.86
2022	906	3.19	29.07	1139	1046	5.40	2029	916	29.49	1.0035	1.0110	1.0145	+ 7	+10	+0.42
2069	688	3.19	22.59	1178	696	5.40	2084	708	23.41	1.0072	1.0291	1.0365	+15	+20	+0.82
2113	487	3.19	16.33	1208	362	5.41	2129	509	17.19	1.0076	1.0452	1.0531	+16	+22	+0.86
1489	1071	3.19	25.30	829	1410	5.42	1520	1094	26.38	1.0208	1.0215	1.0427	+31	+23	+1.08
1581	878	3.19	22.02	887	1074	5.50	1630	888	22.97	1.0310	1.0114	1.0427	+49	+10	+0.95
1657	670	3.19	17.61	940	725	5.44	1694	692	18.60	1.0223	1.0328	1.0559	+37	+22	+0.99
1718	465	3.19	12.68	982	386	5.41	1746	494	13.69	1.0163	1.0624	1.0797	+28	+29	+1.01
1144	1062	3.22	19.28	637	1420	5.42	1182	1083	20.31	1.0332	1.0198	1.0536	+38	+21	+1.03
1201	863	3.20	16.45	678	1080	5.39	1243	880	17.36	1.0350	1.0197	1.0554	+42	+17	+0.91
1263	655	3.19	13.13	719	734	5.40	1308	672	13.95	1.0356	1.0260	1.0625	+45	+17	+0.82
1319	446	3.19	9.33	757	403	5.40	1362	476	10.29	1.0326	1.0673	1.1021	+43	+30	+0.96

APPENDIX N

COMPARISON OF MODEL B AND MEASURED VALUES AT APPROXIMATELY ONE-HALF DISPLACEMENT

Np meas	Tp meas	Dp	HPp meas	Nm meas	Tm meas	Dm	Np calc	Tp calc	HPp calc	Np/Np calculated/measured	Tp/Tp calculated/measured	HPp/HPp calculated/measured	ΔNp calc - meas	ΔTp calc - meas	ΔHPp calc - meas
2033	775	2.12	25.00	1097	875	3.67	2066	806	26.42	1.0162	1.0400	1.0569	+33	+31	+1.42
2065	643	2.12	21.07	1134	652	3.62	2089	682	22.61	1.0116	1.0607	1.0730	+24	+39	+1.54
2098	512	2.13	17.04	1176	420	3.61	2130	547	18.49	1.0153	1.0684	1.0847	+32	+35	+1.45
2127	372	2.13	12.55	1211	204	3.61	2174	419	14.45	1.0221	1.1263	1.1512	+47	+47	+1.90
1646	756	2.12	19.74	917	849	3.50	1682	793	21.16	1.0219	1.0489	1.0719	+36	+37	+1.42
1690	628	2.12	16.84	953	641	3.54	1744	661	18.29	1.0320	1.0525	1.0862	+54	+33	+1.45
1731	490	2.12	13.46	994	425	3.53	1793	532	15.13	1.0358	1.0857	1.1246	+62	+42	+1.67
1761	350	2.13	9.78	1022	205	3.51	1806	399	11.43	1.0256	1.1400	1.1691	+45	+49	+1.65
1226	728	2.08	14.16	670	866	3.49	1296	763	15.69	1.0571	1.0481	1.1079	+70	+35	+1.53
1256	602	2.08	12.00	694	654	3.51	1327	632	13.31	1.0565	1.0498	1.1092	+71	+30	+1.31
1301	465	2.08	9.60	722	433	3.53	1365	497	10.76	1.0492	1.0688	1.1214	+64	+32	+1.16
1330	332	2.08	7.01	747	223	3.53	1392	370	8.17	1.0466	1.1145	1.1664	+62	+38	+1.16

APPENDIX O

COMPARISON OF MODEL C AND MEASURED VALUES
AT APPROXIMATELY THREE-FOURTHS DISPLACEMENT

Np meas	Tp meas	Dp	HPp meas	Nm meas	Tm meas	Dm	Np calc	Tp calc	HPp calc	Np/Np calculated/measured	Tp/Tp calculated/measured	HPp/HPp calculated/measured	ΔNp calc - meas	ΔTp calc - meas	ΔHPp calc - meas
1972	1084	3.19	33.92	1101	1374	5.39	1971	1093	34.18	0.9995	1.0083	1.0078	- 1	+ 9	+0.26
2022	906	3.19	29.07	1139	1046	5.40	2029	897	28.88	1.0035	0.9901	0.9935	+ 7	- 9	-0.19
2069	688	3.19	22.59	1178	696	5.40	2084	690	22.82	1.0072	1.0029	1.0102	+15	+ 2	+0.23
2113	487	3.19	16.33	1208	362	5.41	2128	491	16.58	1.0071	1.0082	1.0154	+15	+ 4	+0.25
1489	1071	3.19	25.30	829	1410	5.42	1520	1079	26.02	1.0208	1.0075	1.0284	+31	+ 8	+0.72
1581	878	3.19	22.02	887	1074	5.50	1630	873	22.58	1.0310	0.9943	1.0251	+49	- 5	+0.56
1657	670	3.19	17.61	940	725	5.44	1693	677	18.19	1.0217	1.0104	1.0324	+36	+ 7	+0.58
1718	465	3.19	12.68	982	386	5.41	1745	479	13.26	1.0157	1.0301	1.0463	+27	+14	+0.58
1144	1062	3.22	19.28	637	1420	5.42	1182	1071	20.09	1.0332	1.0085	1.0420	+38	+ 9	+0.81
1201	863	3.20	16.45	678	1080	5.39	1243	868	17.12	1.0350	1.0058	1.0410	+42	+ 5	+0.67
1263	655	3.19	13.13	719	734	5.40	1307	660	13.69	1.0348	1.0076	1.0427	+44	+ 5	+0.56
1319	446	3.19	9.33	757	403	5.40	1362	464	10.03	1.0326	1.0404	1.0743	+43	+18	+0.70

APPENDIX P

COMPARISON OF MODEL C AND MEASURED VALUES AT APPROXIMATELY ONE-HALF DISPLACEMENT

Np meas	Tp meas	Dp	HPp meas	Nm meas	Tm meas	Dm	Np calc	Tp calc	HPp calc	Np/Np calculated/measured	Tp/Tp calculated/measured	HPp/HPp calculated/measured	ΔNp calc - meas	ΔTp calc - meas	ΔHPp calc - meas
2033	775	2.12	25.00	1097	875	3.67	2065	772	25.29	1.0157	0.9961	1.0118	+32	- 3	+0.29
2065	643	2.12	21.07	1134	652	3.62	2088	648	21.47	1.0111	1.0078	1.0190	+23	+ 5	+0.40
2098	512	2.13	17.04	1176	420	3.61	2128	514	17.35	1.0143	1.0039	1.0183	+30	+ 2	+0.31
2127	372	2.13	12.55	1211	204	3.61	2173	385	13.27	1.0216	1.0349	1.0573	+46	+13	+0.72
1646	756	2.12	19.74	917	849	3.50	1681	764	20.38	1.0213	1.0106	1.0321	+35	+ 8	+0.64
1690	628	2.12	16.84	953	641	3.54	1743	632	17.48	1.0314	1.0064	1.0379	+53	+ 4	+0.64
1731	490	2.12	13.46	994	425	3.53	1792	503	14.30	1.0352	1.0265	1.0627	+61	+13	+0.84
1761	350	2.13	9.78	1022	205	3.51	1805	371	10.63	1.0250	1.0600	1.0865	+44	+21	+0.85
1226	728	2.08	14.16	670	866	3.49	1295	740	15.20	1.0563	1.0165	1.0737	+69	+12	+1.04
1256	602	2.08	12.00	694	654	3.51	1326	609	12.81	1.0557	1.0116	1.0680	+70	+ 7	+0.81
1301	465	2.08	9.60	722	433	3.53	1364	474	10.26	1.0484	1.0194	1.0687	+63	+ 9	+0.66
1330	332	2.08	7.01	747	223	3.53	1391	348	7.68	1.0459	1.0482	1.0963	+61	+16	+0.67

APPENDIX Q

COMPARISON OF SUNDSTRAND PUMP DATA AND MODEL C

ΔP	Np	HPmp Sund	HPcp Sund	HPp Sund	HPp calc	HPp/HPp calc / Sund	ΔHPp calc - Sund
3000	500	16.80	0.19	16.99	17.00	1.0006	+0.01
3000	750	25.55	0.33	25.88	25.54	0.9869	-0.34
3000	1000	34.30	0.48	34.78	34.12	0.9810	-0.66
3000	1250	43.05	0.63	43.68	42.72	0.9780	-0.96
3000	1500	51.80	0.78	52.58	51.35	0.9766	-1.23
3000	1750	60.55	0.96	61.51	60.02	0.9758	-1.49
3000	2000	69.30	1.13	70.43	68.71	0.9756	-1.72
3000	2250	78.05	1.31	79.36	77.43	0.9757	-1.93
3000	2500	86.80	1.49	88.29	86.18	0.9761	-2.11
3000	2750	95.55	1.70	97.25	94.96	0.9765	-2.29
5000	500	27.50	0.19	27.69	27.92	1.0083	+0.23
5000	750	41.70	0.33	42.03	41.93	0.9976	-0.10
5000	1000	55.90	0.48	56.38	55.96	0.9926	-0.42
5000	1250	70.10	0.63	70.73	70.03	0.9901	-0.70
5000	1500	84.30	0.78	85.08	84.12	0.9887	-0.96
5000	1750	98.50	0.96	99.46	98.25	0.9878	-1.21
5000	2000	112.70	1.13	113.83	112.40	0.9874	-1.43
5000	2250	126.90	1.31	128.21	126.58	0.9873	-1.63
5000	2500	141.10	1.49	142.59	140.79	0.9874	-1.80
5000	2750	155.30	1.70	157.00	155.03	0.9875	-1.97

APPENDIX R

COMPARISON OF SUNDSTRAND MOTOR DATA AND MODEL C

ΔP	Nm	Tm Sund	Tm calc	Tm/Tm calc/Sund	ΔTm calc - Sund
3000	250	3190	3339	1.0467	+149
3000	500	3260	3333	1.0224	+ 73
3000	750	3300	3328	1.0085	+ 28
3000	1000	3280	3322	1.0128	+ 42
3000	1250	3260	3316	1.0172	+ 56
3000	1500	3240	3310	1.0216	+ 70
3000	1750	3220	3305	1.0264	+ 85
3000	2000	3200	3299	1.0309	+ 99
3000	2250	3180	3293	1.0355	+113
5000	250	5410	5635	1.0416	+225
5000	500	5500	5629	1.0235	+129
5000	750	5520	5624	1.0188	+104
5000	1000	5510	5618	1.0196	+108
5000	1250	5500	5612	1.0204	+112
5000	1500	5490	5607	1.0213	+117
5000	1750	5480	5601	1.0221	+121
5000	2000	5460	5595	1.0247	+135
5000	2250	5440	5589	1.0274	+149

APPENDIX S

SUNDSTRAND EFFICIENCY DATA

ΔP	Np	ηvp	ηp	Nm	ηvm	ηm	ηv	η
3000	500	0.938	0.886	252	0.912	0.850	0.855	0.753
3000	750	0.949	0.900	395	0.943	0.888	0.895	0.799
3000	1000	0.954	0.906	535	0.953	0.903	0.909	0.818
3000	1250	0.957	0.907	674	0.958	0.908	0.917	0.824
3000	1500	0.958	0.907	813	0.962	0.911	0.922	0.826
3000	1750	0.959	0.906	954	0.966	0.913	0.926	0.827
3000	2000	0.959	0.904	1092	0.968	0.915	0.928	0.827
3000	2250	0.960	0.901	1233	0.970	0.915	0.931	0.824
3000	2500	0.961	0.896	1373	0.971	0.914	0.933	0.819
3000	2750	0.962	0.891	1513	0.972	0.912	0.935	0.813
5000	500	0.875	0.838	213	0.827	0.780	0.724	0.654
5000	750	0.897	0.860	347	0.877	0.832	0.787	0.716
5000	1000	0.909	0.872	483	0.903	0.861	0.821	0.751
5000	1250	0.916	0.878	616	0.914	0.874	0.837	0.767
5000	1500	0.919	0.882	749	0.923	0.883	0.848	0.779
5000	1750	0.921	0.883	882	0.930	0.891	0.857	0.787
5000	2000	0.922	0.883	1013	0.934	0.896	0.861	0.791
5000	2250	0.924	0.882	1147	0.938	0.899	0.867	0.793
5000	2500	0.925	0.881	1280	0.941	0.901	0.870	0.794
5000	2750	0.927	0.877	1414	0.943	0.902	0.874	0.791

APPENDIX T

MODEL C EFFICIENCY DATA

ΔP	Np	Tp	Nm	Tm	ηv	η
3000	500	2143	87	3343	0.296	0.271
3000	750	2147	235	3340	0.533	0.487
3000	1000	2150	382	3335	0.649	0.593
3000	1250	2154	529	3333	0.719	0.655
3000	1500	2158	676	3330	0.766	0.695
3000	1750	2161	823	3325	0.799	0.724
3000	2000	2165	970	3322	0.824	0.744
3000	2250	2169	1117	3319	0.844	0.760
3000	2500	2173	1264	3316	0.859	0.772
3000	2750	2176	1411	3312	0.872	0.781
5000	500	3520	11	5641	0.037	0.035
5000	750	3523	158	5636	0.358	0.337
5000	1000	3527	305	5634	0.518	0.487
5000	1250	3531	452	5631	0.615	0.577
5000	1500	3535	599	5628	0.679	0.636
5000	1750	3538	746	5623	0.724	0.678
5000	2000	3542	893	5620	0.759	0.708
5000	2250	3546	1040	5617	0.786	0.732
5000	2500	3549	1188	5613	0.808	0.752
5000	2750	3553	1335	5610	0.825	0.767

APPENDIX U

COMPARISON OF SUNDSTRAND EFFICIENCY DATA
AND MODEL C

ΔP	Np	ηv Sund	ηt Sund	η Sund	ηv calc	ηt calc	η calc	ηv/ηv Sundstrand/calculated	ηt/ηt Sundstrand/calculated	η/η Sundstrand/calculated	Δηv Sundstrand - calculated	Δηt Sundstrand - calculated	Δη Sundstrand - calculated
3000	500	0.855	0.881	0.753	0.296	0.916	0.271	0.346	1.040	0.360	-0.559	+0.035	-0.482
3000	750	0.895	0.893	0.799	0.533	0.914	0.487	0.596	1.024	0.610	-0.362	+0.021	-0.312
3000	1000	0.909	0.900	0.818	0.649	0.914	0.593	0.714	1.016	0.725	-0.260	+0.014	-0.225
3000	1250	0.917	0.899	0.824	0.719	0.911	0.655	0.784	1.013	0.795	-0.198	+0.012	-0.169
3000	1500	0.922	0.896	0.826	0.766	0.907	0.695	0.831	1.012	0.841	-0.156	+0.011	-0.131
3000	1750	0.926	0.893	0.827	0.799	0.906	0.724	0.863	1.015	0.875	-0.127	+0.013	-0.103
3000	2000	0.928	0.891	0.827	0.824	0.903	0.744	0.888	1.013	0.900	-0.104	+0.012	-0.083
3000	2250	0.931	0.885	0.824	0.844	0.900	0.760	0.907	1.017	0.922	-0.087	+0.015	-0.064
3000	2500	0.933	0.878	0.819	0.859	0.899	0.772	0.921	1.024	0.943	-0.074	+0.021	-0.047
3000	2750	0.935	0.870	0.813	0.872	0.896	0.781	0.933	1.030	0.961	-0.063	+0.026	-0.032
5000	500	0.724	0.903	0.654	0.037	0.946	0.035	0.051	1.048	0.054	-0.687	+0.043	-0.619
5000	750	0.787	0.910	0.716	0.358	0.941	0.337	0.455	1.034	0.471	-0.429	+0.031	-0.379
5000	1000	0.821	0.915	0.751	0.518	0.940	0.487	0.631	1.027	0.648	-0.303	+0.025	-0.264
5000	1250	0.837	0.916	0.767	0.615	0.938	0.577	0.735	1.024	0.752	-0.222	+0.022	-0.190
5000	1500	0.848	0.919	0.779	0.679	0.937	0.636	0.801	1.020	0.816	-0.169	+0.018	-0.143
5000	1750	0.857	0.918	0.787	0.724	0.936	0.678	0.845	1.020	0.861	-0.133	+0.018	-0.109
5000	2000	0.861	0.919	0.791	0.759	0.933	0.708	0.882	1.015	0.895	-0.102	+0.014	-0.083
5000	2250	0.867	0.915	0.793	0.786	0.931	0.732	0.907	1.017	0.923	-0.081	+0.016	-0.061
5000	2500	0.870	0.913	0.794	0.808	0.931	0.752	0.929	1.020	0.947	-0.062	+0.018	-0.042
5000	2750	0.874	0.905	0.791	0.825	0.930	0.767	0.944	1.028	0.970	-0.049	+0.025	-0.024

APPENDIX V

COMPARISON OF SUNDSTRAND PUMP DATA AND MODEL C WITHOUT VISCOSITY ALLOWANCE

ΔP	Np	HPmp Sund	HPcp Sund	HPp Sund	HPp calc	HPp/HPp calc / Sund	ΔHPp calc - Sund
3000	500	16.80	0.19	16.99	17.14	1.0088	+0.15
3000	750	25.55	0.33	25.88	25.85	0.9988	-0.03
3000	1000	34.30	0.48	34.78	34.66	0.9965	-0.12
3000	1250	43.05	0.63	43.68	43.57	0.9975	-0.11
3000	1500	51.80	0.78	52.58	52.57	0.9998	-0.01
3000	1750	60.55	0.96	61.51	61.68	1.0028	+0.17
3000	2000	69.30	1.13	70.43	70.88	1.0064	+0.45
3000	2250	78.05	1.31	79.36	80.17	1.0102	+0.81
3000	2500	86.80	1.49	88.29	89.57	1.0145	+1.28
3000	2750	95.55	1.70	97.25	99.06	1.0186	+1.81
5000	500	27.50	0.19	27.69	28.06	1.0134	+0.37
5000	750	41.70	0.33	42.03	42.23	1.0048	+0.20
5000	1000	55.90	0.48	56.38	56.51	1.0023	+0.13
5000	1250	70.10	0.63	70.73	70.88	1.0021	+0.15
5000	1500	84.30	0.78	85.08	85.34	1.0031	+0.26
5000	1750	98.50	0.96	99.46	99.91	1.0045	+0.45
5000	2000	112.70	1.13	113.83	114.57	1.0065	+0.74
5000	2250	126.90	1.31	128.21	129.33	1.0087	+1.12
5000	2500	141.10	1.49	142.59	144.18	1.0112	+1.59
5000	2750	155.30	1.70	157.00	159.13	1.0136	+2.13

APPENDIX W

COMPARISON OF SUNDSTRAND MOTOR DATA AND MODEL C WITHOUT VISCOSITY ALLOWANCE

ΔP	Nm	Tm Sund	Tm calc	Tm/Tm calc/Sund	ΔTm calc - Sund
3000	250	3190	3326	1.0426	+136
3000	500	3260	3307	1.0144	+ 47
3000	750	3300	3288	0.9964	- 12
3000	1000	3280	3269	0.9966	- 11
3000	1250	3260	3250	0.9969	- 10
3000	1500	3240	3232	0.9975	- 8
3000	1750	3220	3213	0.9978	- 7
3000	2000	3200	3194	0.9981	- 6
3000	2250	3180	3175	0.9984	- 5
5000	250	5410	5622	1.0392	+212
5000	500	5500	5603	1.0187	+103
5000	750	5520	5584	1.0116	+ 64
5000	1000	5510	5565	1.0100	+ 55
5000	1250	5500	5546	1.0084	+ 46
5000	1500	5490	5528	1.0069	+ 38
5000	1750	5480	5509	1.0053	+ 29
5000	2000	5460	5490	1.0018	+ 30
5000	2250	5440	5471	1.0057	+ 31

APPENDIX X

MODEL C WITHOUT VISCOSITY ALLOWANCE
EFFICIENCY DATA

ΔP	Np	Tp	Nm	Tm	ηv	η
3000	500	2160	232	3327	0.789	0.715
3000	750	2172	379	3316	0.859	0.771
3000	1000	2185	526	3306	0.894	0.796
3000	1250	2197	673	3294	0.915	0.807
3000	1500	2209	820	3283	0.929	0.812
3000	1750	2221	967	3271	0.939	0.814
3000	2000	2234	1114	3261	0.947	0.813
3000	2250	2246	1261	3250	0.952	0.811
3000	2500	2258	1408	3238	0.957	0.808
3000	2750	2270	1555	3227	0.961	0.804
5000	500	3537	208	5625	0.707	0.662
5000	750	3549	355	5614	0.804	0.749
5000	1000	3561	503	5602	0.855	0.791
5000	1250	3574	650	5593	0.884	0.814
5000	1500	3586	797	5581	0.903	0.827
5000	1750	3598	944	5569	0.917	0.835
5000	2000	3610	1091	5558	0.927	0.840
5000	2250	3623	1238	5548	0.935	0.843
5000	2500	3635	1385	5537	0.942	0.844
5000	2750	3647	1532	5525	0.947	0.844

APPENDIX Y

COMPARISON OF SUNDSTRAND EFFICIENCY DATA AND MODEL C WITHOUT VISCOSITY ALLOWANCE

ΔP	Np	ηv Sund	ηt Sund	η Sund	ηv calc	ηt calc	η calc	ηv/ηv Sundstrand/calculated	ηt/ηt Sundstrand/calculated	η/η Sundstrand/calculated	Δηv Sundstrand - calculated	Δηt Sundstrand - calculated	Δη Sundstrand - calculated
3000	500	0.855	0.881	0.753	0.789	0.906	0.715	0.923	1.028	0.950	-0.066	+0.025	-0.038
3000	750	0.895	0.893	0.799	0.859	0.898	0.771	0.960	1.006	0.965	-0.036	+0.005	-0.028
3000	1000	0.909	0.900	0.818	0.894	0.890	0.796	0.983	0.989	0.973	-0.015	-0.010	-0.022
3000	1250	0.917	0.899	0.824	0.915	0.882	0.807	0.998	0.981	0.979	-0.002	-0.017	-0.017
3000	1500	0.922	0.896	0.826	0.929	0.874	0.812	1.008	0.975	0.983	+0.007	-0.022	-0.014
3000	1750	0.926	0.893	0.827	0.939	0.867	0.814	1.014	0.971	0.984	+0.013	-0.026	-0.013
3000	2000	0.928	0.891	0.827	0.947	0.859	0.813	1.020	0.964	0.983	+0.019	-0.032	-0.014
3000	2250	0.931	0.885	0.824	0.952	0.852	0.811	1.023	0.963	0.984	+0.021	-0.033	-0.013
3000	2500	0.933	0.878	0.819	0.957	0.844	0.808	1.026	0.961	0.987	+0.024	-0.034	-0.011
3000	2750	0.935	0.870	0.813	0.961	0.837	0.804	1.028	0.962	0.989	+0.026	-0.033	-0.009
5000	500	0.724	0.903	0.654	0.707	0.936	0.662	0.977	1.037	1.012	-0.017	+0.033	+0.008
5000	750	0.787	0.910	0.716	0.804	0.932	0.749	1.022	1.024	1.046	+0.017	+0.022	+0.033
5000	1000	0.821	0.915	0.751	0.855	0.925	0.791	1.041	1.011	1.053	+0.034	+0.010	+0.040
5000	1250	0.837	0.916	0.767	0.884	0.921	0.814	1.056	1.005	1.061	+0.047	+0.005	+0.047
5000	1500	0.848	0.919	0.779	0.903	0.916	0.827	1.065	0.997	1.062	+0.055	-0.003	+0.048
5000	1750	0.857	0.918	0.787	0.917	0.911	0.835	1.070	0.992	1.061	+0.060	-0.007	+0.048
5000	2000	0.861	0.919	0.791	0.927	0.906	0.840	1.077	0.986	1.062	+0.066	-0.013	+0.049
5000	2250	0.867	0.915	0.793	0.935	0.902	0.843	1.078	0.986	1.063	+0.068	-0.013	+0.050
5000	2500	0.870	0.913	0.794	0.942	0.896	0.844	1.083	0.981	1.063	+0.072	-0.017	+0.050
5000	2750	0.874	0.905	0.791	0.947	0.891	0.844	1.084	0.985	1.067	+0.073	-0.014	+0.053

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VITA

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DETERMINATION OF A COEFFICIENT MODEL FOR A HYDROSTATIC TRANSMISSION

by

DAVID ANTHONY PACEY

B. S., Kansas State University, 1974

AN ABSTRACT OF A THESIS

submitted in partial fulfillment of the

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ABSTRACT

The application of automatic controls requires an understanding of the controlled process. Previous research through computer analysis had shown that cost of operation of a vehicle equipped with a hydrostatic transmission could be minimized with the use of automatic controls. The objective of this thesis was to determine and evaluate a model for a hydrostatic transmission to be used for determining the requirements of the automatic controller. Wilson's Model was chosen for initial evaluation. It is a coefficient model based on a simplified analytic development with experimentally determined coefficients.

A hydrostatic transmission with full instrumentation on a laboratory test stand provided the experimental test set-up. Speed, torque, and pressure data were taken at full displacement with constant oil temperature to determine the coefficients of the basic model.

The basic model, Model A, was evaluated at full displacement by comparing pump speed and torque valves calculated with the model to actual measured data. The model calculated speed 9.0 rpm high on the average with a standard deviation of 26.2 rpm. Torque was calculated 0.6 in.lb high on the average with a standard deviation of 7.6 in.lb.

Modifications were made to the flow equations of the basic model to provide better speed predictions. A change in the method of determination of the coefficients was also made to provide better torque predictions. Evaluation of this modal, Model B, at full displacement showed speed and torque predictions to be much improved as especially evident in the lower values of standard deviation. Speed was calculated 1.7 rpm high on the

average with a standard deviation of 16.7 rpm. Torque was calculated 0.7 in.lb high on the average with a standard deviation of 5.4 in.lb.

Model B was evaluated at partial displacements of the transmission by comparison to actual data. This evaluation revealed that torque losses needed to be represented as a function of transmission displacement. The model was further modified to Model C to make the viscous drag and dry friction torque losses functions of displacement. This change did not alter the model at full displacement from Model B. Evaluation of Model C showed much improved partial displacement calculations when compared to Model B. At one-half displacement, pump speed was calculated 48.9 rpm high on the average with a standard deviation of 16.2 rpm. Pump torque was calculated 8.9 in.lb high with a standard deviation of 6.6 in.lb.

Model C was then compared to the manufacturer's performance data at full displacement which were recorded with much less viscous oil. The model did have viscosity included in the viscous drag and leakage terms and should have accounted for the viscosity change; however, the only way that the model would give a good comparison was to use the viscosity value used in this research and not the manufacturer's test viscosity.

It was concluded that Model C provided a good transmission model at full and partial displacements but only if used with the same viscosity oil as used in this research. Further research and possible model modifications will be necessary to account for changing oil viscosity.