This is to certify that the

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MODELING AND PERFORMANCE OF A HYDRAULIC ACTUATOR SYSTEM

presented by

BASIL JACOB JOSEPH

has been accepted towards fulfillment of the requirements for

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MODELING AND PERFORMANCE OF A HYDRAULIC ACTUATOR SYSTEM

By

Basil Jacob Joseph

A THESIS

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ABSTRACT

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By

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The design engineer of today is invariably faced with the challenges of speed, accuracy and economy in his work. Not only does he or she have to generate the best design, but it should be done within the least amount of time and with the least expense. The science of representing components and systems by expressing their physics in mathematical terms is called mathematical modeling. Such models can be built with varying complexity depending on which aspect of the design the engineer wishes to study. Mathematical modeling is fast becoming an indispensable ally in the design field, especially with the advent of powerful personal computers and relatively inexpensive work stations.

The focus of this thesis is a Hydraulic Actuator Subsystem. The design of the larger system that includes the Hydraulic Actuator Subsystem is part of an ongoing design project. Structured modeling techniques were used to develop a mathematical model of the subsystem. Once the model was developed it was validated by comparing its behavior with known hardware performance. This validated model was a powerful tool in testing the design and improving the design.

The system was modeled using bond graphs and the simulations were conducted using the software package ENPORT. The effects of entrained air in the fluid, various operating temperatures, and material properties of key components were investigated. Simulations were run under various conditions and the system performance was evaluated.

Dedication

To my dearest mother and father: I am the arrow sent forth from their bow.

The powerful bow will bend and flex to give an arrow the gift of flight.

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My colleagues in the Computational Design Laboratory, especially Joe DeRose and Michael Hales have been a great source of support and encouragement.

Finally special thanks to my dear brother who always kept me going, especially when the going got tough.

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NOMENCLATURE

A	-	Area
e	-	Eccentricity
K	-	Spring Stiffness
P	-	Pressure
R_x	-	Hydraulic Resistance
V	-	Volume
Xs	-	Spool Displacement
Xp	-	Actuator Piston Movement
β	-	Bulk Modulus
γ	-	Ratio of Specific Heats
μ	-	Kinematic Visosity
ρ	-	Density

ABBREVIATIONS

SSV	-	Solenoid-Spool Valve
HS	-	Hydraulic Subsystem

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Chapter 1

INTRODUCTION

1.1 Problem Definition

1.1.1 The importance of Modeling in Design

For a long time design engineers have used physical models and mock-ups to help them while designing a new device. Thus we had scaled physical models of huge pumps, buildings, airplanes and so on. Such models are helpful in visualizing the final product and in investigating the behavior of the device under different conditions. Frequently an engineer was also required to improve the performance of an existing design. He or she had to understand the current design precisely and then suggest changes to be made. To verify the innovations, a sample component of the existing design (or a scaled model) would be modified to incorporate the changes and then tested. This was true, for example, in the case of automobile engines and other expensive systems. There was little or no room for oversight, especially if considerable machining was needed, as this would prove costly in terms of both time and money.

Engineers have long been using the physics of systems, expressed mathematically, to analyze them under extreme conditions. For example, stress analysis would be used to compute the maximum allowable load on a bridge or any such load supporting member, the maximum compression viable in a reciprocating gasoline engine cylinder before the flash point of the fuel is reached, the maximum pressure a gas cylinder can contain, the maxim

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maximum current a conductor can carry, the maximum number of revolutions that an engine can sustain, and so on. The mathematical principles were always used to predict the outer limits of safe operation. Yet when complex engineering systems were built there were often surprises in the first few trials - sometimes accompanied by extreme consequences. These might have been avoided if the systems engineer would have analyzed the behavior of each and every component during the entire operation of the system. For even slightly complicated systems, this would require considerable amounts of time and effort in manual computing - till the advent of the modern computer.

The computer could do complex calculations not only faster but even more accurately than the average engineer. And it could do them endlessly without "inadvertent" (human) errors. The engineer could program all the mathematical formulae into a computer and punch in different values for different variables and the computer would return the state of the system at each instant in time. This concept can then be taken a step further to study the whole system during the entire period of operation - at every instant in time. One only had to instruct the computer as to how different parameters changed in time (if at all they did). A computer model obviates the necessity of constructing hardware experiments that consumed time and effort. An accurate model that captures all the relevant physics can be used to identify the dominant factors so that designers can concentrate on those parts of the system. Multiple simulations of the model can provide answers to a whole range of "what if?" questions which would otherwise require costly and sometimes dangerous hardware experiments. Powerful personal computers have now made it possible for any design engineer to use modeling techniques in his d

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1.1.2 Structured Modeling of Systems

"Models of systems are simplified, abstracted constructs used to predict their behavior" [1]. Even while engineers constructed scaled physical models, they did not incorporate every detail - only the relevant ones were reproduced. This is a characteristic feature of all modeling - physical or mathematical. One could incorporate a myriad of mathematical relations that pertain to a large system and construct a computational mammoth. The computations can then sometimes become nearly impossible - even by computers, or if at all possible they will only generate a great deal of unnecessary information together with the relevant. For example the calculation of frictional heat produced when a piston moves inside a cylinder once in five minutes may be totally irrelevant from a particular systems viewpoint, even though such a formula can be programmed into the model. Albeit, over simplification of a system should be avoided, for that may fail to capture important physical effects. So there is some degree of skill involved in breaking down a complex system into its component mathematical relations. A competent system designer needs a procedure for constructing different models (if required) of a large system that can all together predict the complete behavior of the system under study.

Many approaches have been developed over the years for the effective modeling of systems. The Bond Graph theory [1] is particularly useful for systems spanning multiple energy domains. The bonds represent the power transfer between various elemen

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elements in the system and if compatible units are used, power can be equated across different energy domains. The nature of the various parts of the system are captured by any one of a small set of ideal elements that can be used across the board for all energy types. For example a mechanical spring, an electric capacitance and a hydraulic compliance are all energy storage elements. In bond graph theory, all of them are represented by the same ideal element - the capacitor (or **C** element). Thus it becomes possible to perceive the overall structure of a large and complex system model. This understanding will be invaluable in studying the system behavior. The software package ENPORT [2] allows us to build bond graph models for nonlinear systems and simulate their behavior.

1.1.3 The System under Study

In this thesis we apply structured modeling techniques to the evolving design of a hydraulic subsystem. This particular subsystem is part of a larger system which itself is being designed at the same time. Even though we were not involved in the modeling of the larger system, good communication with groups designing the other subsystems was vital to the success of the overall project. Limitations, changes and new possibilities within each subsystem may directly or indirectly affect the design (and hence the modeling) of our hydraulic subsystem.

Purpose of the System

The hydraulic subsystem has two main functions to perform as listed below. The reader

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reader should also read the next section (*Overview of the Hydraulic System*) to fully comprehend the terms used here:

1. Cause a latch pin (in the actuator) to engage or disengage subject to a command signal.

2. Maintain the oil pressure in the external load circuit above a minimum mark at all times.

Overview of the Hydraulic System

The hydraulic subsystem (HS) consists of a pump which supplies high pressure oil to a Solenoid-Spool Valve (SSV) which in turn controls the oil flow to an external load circuit. The SSV consists of a solenoid valve and a spool valve housed in one unit. The solenoid controls the position of the spool inside the spool valve, which in turn changes some port openings in the spool valve chamber. These ports control the inflow of fluid from the pump (into the SSV) and out into the external load circuit. The external load circuit consists of a buffer volume, an actuator and a leakage demand. The actuator and the leakage are fed from the buffer volume. To drain out any excess oil in the subsystem, the SSV has a port that communicates with a sump. In all the discussions that follow in this thesis, the term system refers to the Hydraulic Subsystem, unless otherwise noted. The complete system schematic is shown in Figure 1.1. In the figure **VC** is an electrical signal line. All other lines between the various components are hydraulic.

The SSV operates in two distinct modes which are dictated by the electrical signal input (

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input (**VC**). A high voltage signal makes the solenoid valve change the spool position to allow maximum inflow from the pump (through **SPLY**) and out into the buffer (through **S15**). This leads to a high pressure in the buffer which pushes a piston inside the actuator causing the actuator pin to disengage. A low voltage signal makes the solenoid valve change the spool position to let the least amount of flow into the buffer, thus dropping the pressure. A low pressure in the buffer will cause the actuator pin to move to the other position (engage). By virtue of the solenoid-spool valve design, this low pressure in the load circuit is not allowed below a certain minimum mark that is needed to supply the leakage demand that is also part of the external load. Slight increases in this leakage

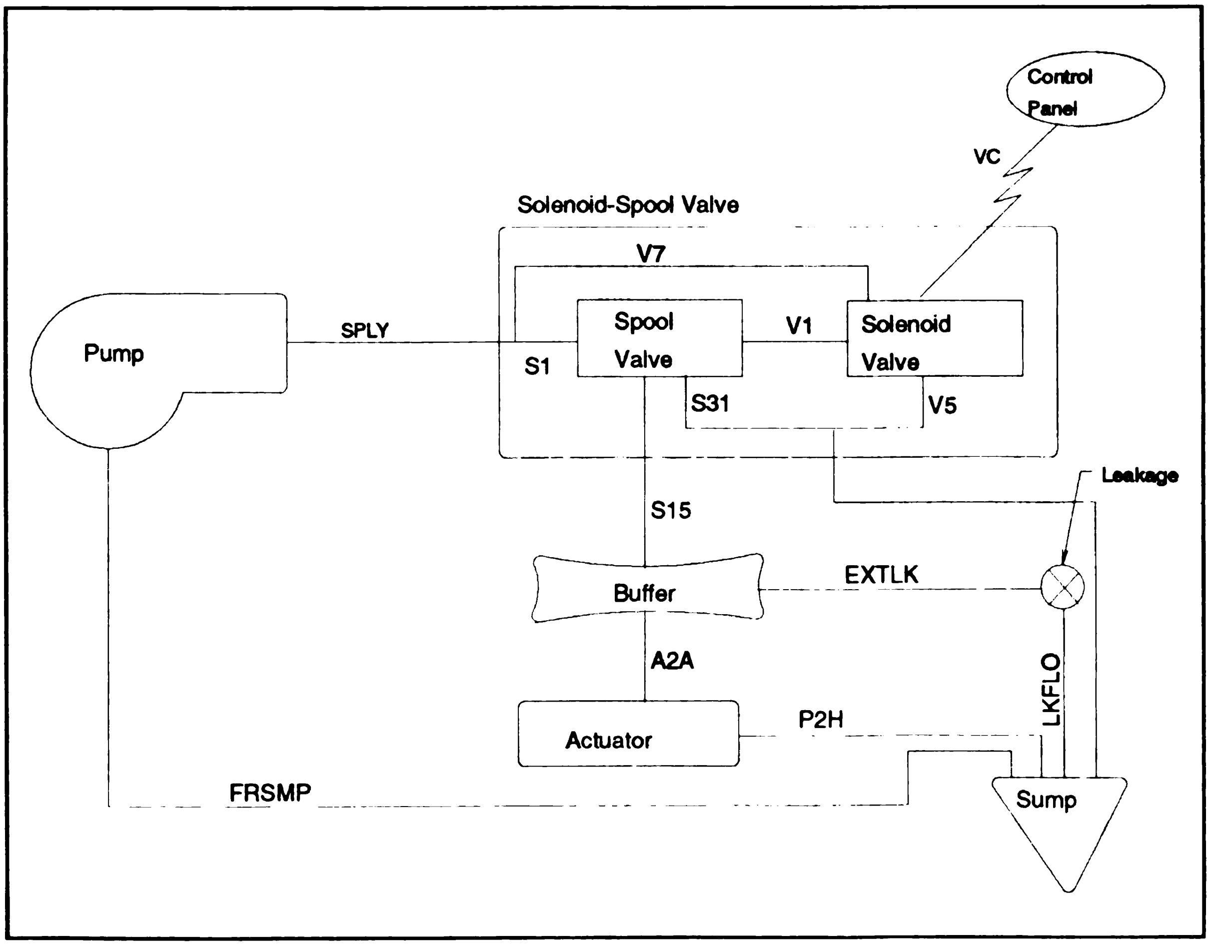

Figure 1.1 Detailed Schematic of Hydraulic Subsystem

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demand will not affect the system low pressure regulation mark. The regulation by the solenoid-spool valve is further explained in Chapter 3. The detailed physical dynamics inside the HS are dealt with in Chapter 3.

To summarize, the two states of operation for the HS are:

High Pressure State: When the spool valve configuration results in a high pressure in the external load circuit. This is the pump supply pressure. The actuator pin is then in the disengaged mode.

Low Pressure State: When the spool valve configuration results in a low pressure in the load circuit. The actuator pin is then in engaged mode. In this state any small variation in the leakage demand is met by regulating action by the spool valve. Hence this is also called regulation mode.

A simple description of the major

Pump

An ideal pump would be a source of high pressure oil capable of providing any amount of flow at the same pressure. But in reality fluctuations in flow demand can cause the output pressure from the pump to vary. The system is modeled with such a realistic pump

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pump. In Figure 1.1 we show the pump drawing oil from the sump (**FRSMP**) and supplying it at a higher pressure to the SSV through the line marked **SPLY**.

Solenoid-Spool Valve

The spool valve and the solenoid valve are two virtually independent units inside a single housing. Oil from the pump flows into both these valves. The solenoid valve uses oil supplied by the pump (through **V7**) to perform its controlling action on the spool valve. The solenoid valve and the spool valve are both described in detail in Chapter 3 entitled *Description of the Model.* Depending upon the voltage signal received through **VC,** the solenoid either charges up or discharges. This opens or closes a valve inside the solenoid valve which controls the flow of oil (through **V1**) into one side of the spool valve chamber. The pressure thus built up on one side of the spool controls the position of the spool inside its chamber. The position of the spool determines the spool valve's port openings to the pump, the actuator and the drain - thus controlling the inflow (through **SPLY**) and outflow through **S15** and **S31**. When the solenoid valve closes the flow through **V1** the oil is drained out of it through **V5**.

The Buffer Volume

The buffer is simply a large volume with an inlet port and one or more outlet ports. Oil from the SSV flows in through the inlet (**S15**) and flows out through the outlet port to the actuator (**A2A**).

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The Actuator

The actuator consists of a piston in a cylinder. Oil from the buffer (line **A2A**) flows into one side of the piston and pushes it against a spring. The piston has a pin projecting out of it and which is long enough to protrude outside the actuator body; and the amount of protrusion outside the body depends upon the position of the piston inside the cylinder. Oil that flows past the piston is drained out into the sump through line **P2H**. The actuator is more fully described in Chapter 3.

Leakage

A typical HS such as this provides the oil for forced lubrication to moving parts. One of the duties of the SSV is to maintain the minimum pressure needed for this purpose. Such a lubrication demand is modeled here as a simple orifice that is fed from the buffer (**EXTLK**) and which drains into the sump (**LKFLO**). The area of the orifice can be varied to emulate a higher flow demand.

Sump

In a typical closed system such as the HS, the sump will be a reservoir (usually at atmospheric pressure) of oil that may be shared by other subsystems in the larger system. The pump will draw oil from this (**FRSMP**) and all excess oil in the subsystem drains out into this sump (**S31, V5, LKFLO, P2H**). Throughout our modeling we have assumed that the sump is at atmospheric pressure.

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Performance Specifications

The two equilibrium states of the system have been described earlier under *Overview of the System*. The system needs to change (and stabilize) from one state to the other in a relatively short time for the satisfactory performance of the Hydraulic Actuator Subsystem within the larger system. The system is expected to perform a set of primary functions after which a set of secondary performance criteria also need to be satisfied.

Primary Specifications

1. Complete engagement of the actuator pin should be achieved within 27 milliseconds.

2. Complete disengagement of the actuator pin should be achieved within 27 milliseconds.

3. The regulation pressure in the disengaged mode should be above 22.034 N/cm^2 absolute (17 psi gage).

Secondary Specifications

1. Meet all the primary specifications when the operating conditions vary :

   a. Fluid temperature varies from 150 °F to 250 °F

   b. Percentage of air in the fluid varies from 3.5% to 7%

2. Meet all the primary specifications when manufacturing tolerances vary on:

   a. Geometric dimensions

   b. Spring stiffness

   c. Surface finishes

3. Consideration of possible failure:

   Achieve a safe mode of operation if the oil supply were to be interrupted. In this case the pin should attain engagement.

An acceptable computer model should be able to perform the above functions as well. The system performance in the model is studied by monitoring three key variables:

1. The position of the spool inside the spool valve.

2. The position of the pin inside the actuator.

3. The pressure in the external load circuit.

1.2 Research Objectives

The principal objective of this research was to develop a reliable computer model for the Hydraulic Actuator System using structured modeling techniques and then to use the model to aid in the ongoing design process. Towards this end we had to accomplish the following four steps:

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Study the Complete System: The contribution of every component to the overall system behavior needed to be grasped completely. The more important and the less important properties of components from a systems viewpoint needed to be distinguished. The crucial effects that require detailed modeling had to be identified as opposed to those that called for simpler treatment. The expected system performance also needed to be understood.

Develop a Model: Once the nature of the different parts of the system were understood and the various physical effects relevant to the system's performance were identified, structured modeling techniques had to be applied to develop a system model. We chose bond graphs as our modeling tool and used the software package ENPORT to generate the model of the system and simulate its behavior on the computer.

Validate the Model: Once the model had been built on the computer, then it needed to be tested and validated. Validation entailed simulating the model under known conditions and recording its performance. The performance of the model was then compared to available test results of hardware experiments. The validated model is chosen as the nominal design.

Parametric Studies: The nominal design was used to run various parametric studies to ensure that the model performed its primary and secondary functions. The effects of operating conditions like temperature and air fraction in the hydraulic fluid were investigated. Some system design parameters were changed slightly to see how the model behaved. These model parametric studies were used to improve the design and perfo

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performance of the subsystem.

1.3 Organization of the Thesis

The thesis is organized into five chapters and a set of appendices. The current chapter contains the motivation for this research, the introduction to the problem, the research objectives and the outline of the thesis. Chapter 2 records the evolution of the model from one that had a very basic representation of the various component parts to one with the quite detailed modeling of the dominant effects. Chapter 3 describes in detail the various parts and their physical effects that were considered important from a system point of view. Chapter 4 discusses some comparative results of parametric studies conducted with the fully evolved model. Chapter 5 draws a set of conclusions from the whole modeling effort. Appendix A contains some important equations, mathematical derivations, and a list of key (named) parameters used by the system model. Named parameters are symbolic constants used in various equations. Appendix B contains all the figures pertaining to the model bond graph and the results of the comparative studies discussed in chapter 4. Appendix C lists the ENPORT model file for the fully evolved model. Appendix D separately defines the various nodes in the model bond graph. Appendix E lists the user defined subroutines used by the model. These subroutines provide function definitions to pertinent nodes that cannot be adequately described by the ENPORT software library functions.

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Chapter 2

A SET OF HYDRAULIC MODELS

2.1 Model Evolution

Successful mathematical modeling requires a great deal of skill besides a knowledge of the physical and mathematical principles. An experienced modeler will have a good understanding of the various energy domains he or she deals with. He or she will be able to quickly identify the more important physical effects that need to be captured in the model of any system. In this research, work besides developing an accurate model, we were also seeking an insight and some experience in structural modeling. As implied in Section 1.1.2, a simpler model with less computations is preferable to a more complex model - if both of them can predict the system's behavior with reasonable accuracy. Our goal was to develop a model that has the fewest number of elements with the simplest possible mathematics and yet which can predict system behavior with a satisfactory degree of accuracy.

The hydraulic system described in chapter 1 was modeled in progressive stages starting from a very basic model. Detailed and complete design data was not available to us as the hardware itself was being designed. So we started our efforts with models where we tried to emulate the qualitative behavior of the key components. This was very useful as a preliminary step as it helped us build a "skeleton" for the system model. As we gained a better understanding of the system more physical effects were added to the model. After arriving at a model that truthfully portrayed the qualitative behavior, we incorporated actual hardware design details into the model. When this model could not predict actual hardware behavior satisfactorily, we were faced with two modeling issues:

1. Should we add more physical effects to the model in order to improve its accuracy? This included questions such as whether we should consider the flow forces on the spool when the oil flows through the spool valve ports and whether we should consider the inertial effects of the fluid in the lines and the buffer volume.

2. Should we use better parameters and more complex mathematical expressions for the physical effects already modeled? This included questions such as whether we should model the hydraulic compliances in the chambers such that they vary with pressure and whether we should compute a more accurate value for the coefficient of discharge (**Cd**) at the various orifices.

These are issues that any modeler has to contend with and they require both experience and skill to resolve efficiently. A major benefit from this research work was such an experience. This chapter briefly documents our efforts during the evolution of the model.

2.2 The Two Modes of Operation

Before the progression of models is described, some conventions need to be established. As briefly described in Section 1.1.3 under "Detailed Operation of the System" the system being modeled has two distinct steady states of operation. These states are described in detail with reference to Figures 2.1 and 2.2 which show the nomenclature of the solenoid-spool valve and the actuator. In Figure 2.1 **Xs** denotes the

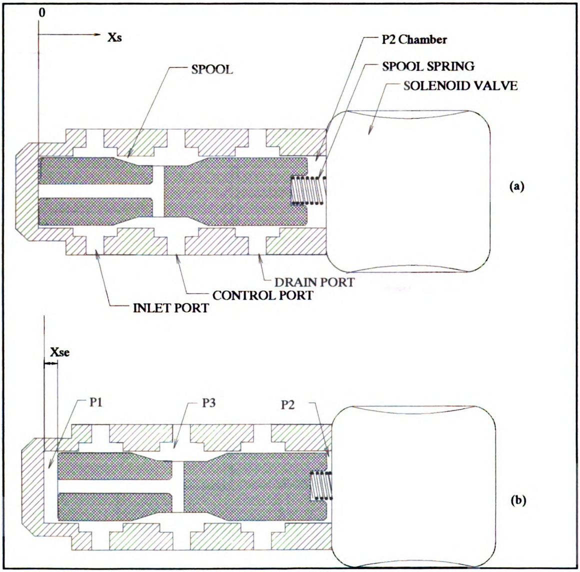

Figure 2.1 Spool Valve steady States

spool movement and in Figure 2.2 **Xp** denotes the pin movement. When **Xs** is zero as shown in Figure 2.1 (a), the inlet port is wide open leading to a high control port pressure and consequently the external load circuit is in a high pressure state. The actuator configuration in this state is shown in Figure 2.2 (b) where **Xp** equals **Xpd.** When the spool valve is in regulation mode, the spool is at or around **Xse** as shown in Figure 2.1 (b). This sets a low control port pressure and hence a low pressure state in the external

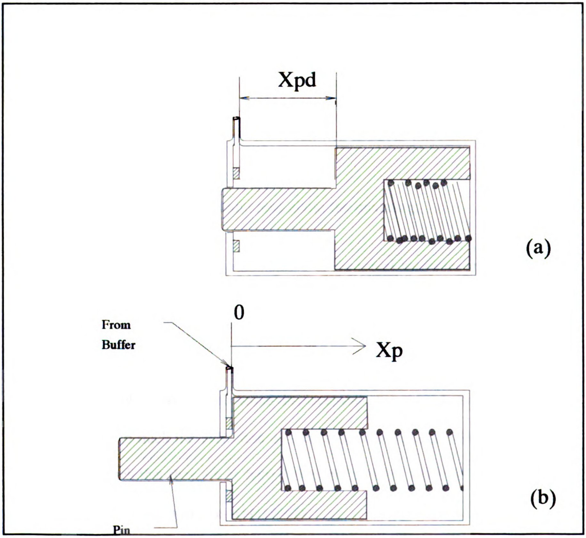

Figure 2.2 Actuator Steady States.

load circuit. Then the pin is in engaged mode (**Xp** now equals 0) as shown in Figure 2.2 (b). The high pressure state of the system is also referred to as the ***Pin Disengaged (or Retracted) Mode***; and the low pressure state of the system is also called the ***Pin Engaged Mode.*** These states have been summarized in Table 2.1.

System State	P2 Pressure	Spool Position (Xs)	Control Pressure	Pin Position (Xp)
High Pressure	High	Xs = 0	High	Disengaged Xp = Xpd
Low Pressure	Low	Xs = Xse	Low	Engaged Xp = 0

Table 2.1 Steady States

Some points the reader should note about the modeling:

1. The spool and actuator piston spring in the actual hardware are installed such that they exert a preload force on the spool and piston even when they are at their 'zero' positions.

2. Instead of measuring the actual displacement of the spool and actuator piston, we chose to track the deflection of their respective springs. These springs were defined such that they are at 'zero deflection' position when the spool and piston are at their 'zero' positions respectively.

3. In order to track the control pressure (which is also the pressure in the external

load circuit), we chose to track the pressure at the control port.

4. P1, P2 and P3 are pressures that exist in the respective chambers shown in Figure 2.1.

2.3 Model #1: The Initial Model

A very basic model was constructed which had all the representative elements of the system (as envisioned at the time). This model concentrated primarily on the spool valve and we wanted to capture its structure and qualitative behavior. The elements, such as springs, masses, and resistances, did not have the exact nature as those in the real system. They were assumed to be very simple, linear and completely independent of each others' behavior. None of the parameters were actual although values used were comparable to each other in magnitude. For example, the hydraulic resistances ($\mathbf{R}_x$) at the port openings were assumed to have either one of two fixed values at either steady state; and these numbers were computed manually, even though these resistances actually depend upon the position of the spool. The model is shown in Figure 2.3 below.

Some points to note about the model:

The fluid was assumed to have no entrained air and the hydraulic chambers were assumed to behave like simple springs.

The hydraulic chamber formed by the right side of the spool and the right chamber walls was not modeled.

The end walls of the chambers were not modeled - so the spool and actuator piston were never restricted in their range of movement.

The same pressure as in the control chamber (P3) was assumed to exist on the left face of the spool.

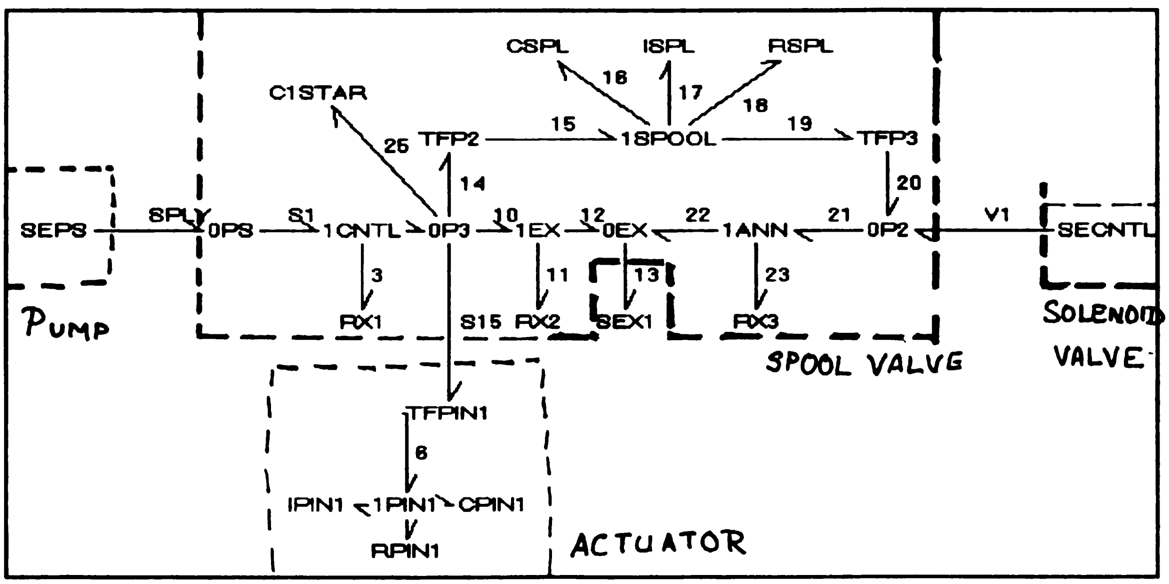

Figure 2.3 Model # 1: Initial Model

The pump was assumed to be a pressure source (**SEPS**) and have unlimited flow capability.

The solenoid valve was not modeled and a separate pressure source (**SECNTL**) was included to *set* the pressure on the right side of the spool - just as the

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The buffer volume was not modeled.

The model was exercised in the following manner. The spool was set at zero displacement (at left wall). The inlet pressure (SEPS) was set to a high value and the solenoid valve pressure port (SECNTL) was set to a very low value. With these initial conditions the simulation was started. The low pressure on the right side and high pressure on the left side of the spool caused it to move to the right.

Now the initial conditions were changed : the pressures on either side of the spool were equalized and the spool was placed in the final position attained by it at the end of the previous simulation. The spool moved towards the left wall because of the preload force in the spool spring. In both of the above cases, the piston displacement in the actuator was not tracked as the hydraulic resistances were not being varied when the spool moved and so the pressure profile seen by the piston would not be representative of the actual behavior.

This model was developed as a preliminary to one that had more complex (but real) element behavior. The purpose was to establish the model's qualitative behavior - specifically the spool's behavior. As noted before, the spool displacement is tracked by the spool spring (**CSPL**) deflection. The response of the model was found to generally agree with our expectations of the spool valve's behavior. Although, maybe due to errors in parameters used or relative scaling the behavior was not very pronounced. The reader is reminded that for lack of actual design data, all our parameters were "intelligent guesses".

2.4 Model #2: A qualitative model with more details

Upon confirming that the general behavior of the spool was as expected, the next step was to model the relation between the spool position and the hydraulic resistances at the spool valve ports. Thus the model shown in Figure 2.4 was developed. It is the same model as in Figure 2.3, except that some of the element definitions were changed and some more elements were added. These changes are summarized below:

The value for the hydraulic resistance (**R_x**) was re-computed each time the spool position changed. The spool positions and the resistances were assumed to have a linear relationship with a non-zero minimum value.

The chamber walls were added. These were modeled as extremely stiff springs (**CWALL** and **CSTP**) on either side of the spool and piston.

Again none of the elements used actual parameters - only ones with comparable magnitudes. This model was also exercised in both modes as described earlier. The control pressure (effort on **S15**) seen by the actuator was also tracked as was the piston movement (deflection of **CPIN1**) in the actuator. The behavior of the model was found to be even more realistic than Model #1. These results are included in Figure B2-1 to Figure B2-6 in Appendix B. It should be noted that none of the values have exact

physical significance; only the general trends were of interest.

Figure B2-1 to B2-3 show the spool, control pressure and pin behavior in the disengagement mode. In this mode the spool is initially in the regulation position (**Xse** in Figure 2.1 (b)) the pin is fully engaged (**Xp** = 0). The pressures on the two sides of

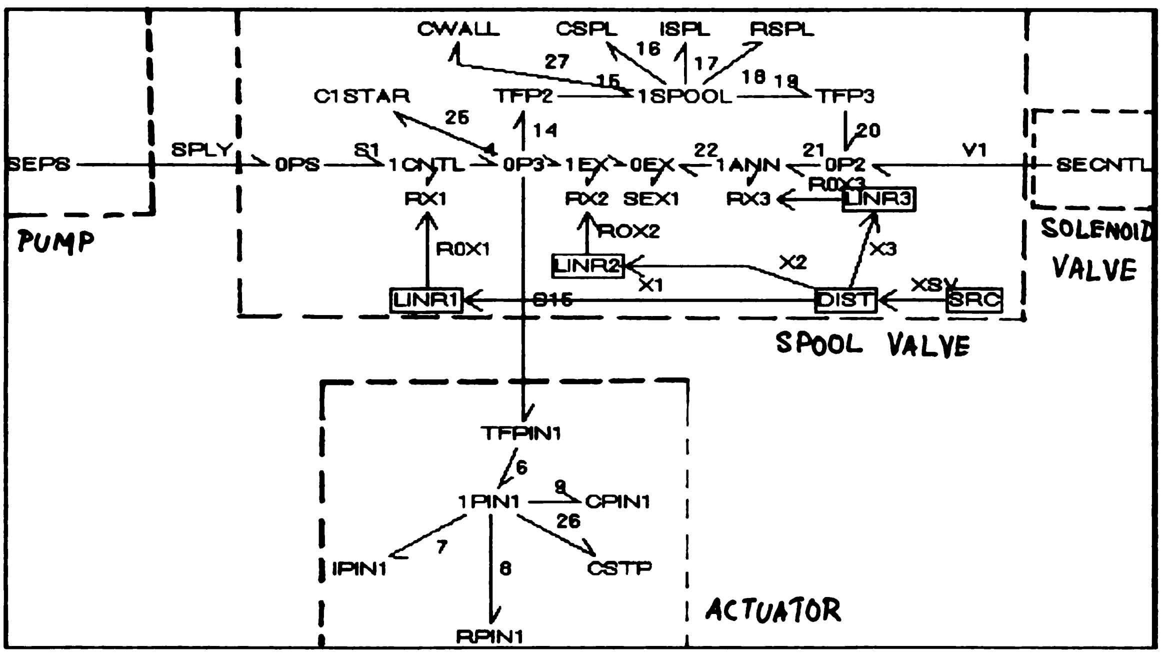

Figure 2.4 Model # 2: Qualitative model with more details.

the spool are then equated and this causes the spool to move towards 'zero' (pushed by its spring force) as seen in Figure B2-1, and the spool valve port openings to change. The $\mathbf{R}_{x1}$ resistance opens and the control pressure rises as seen in Figure B2-2. This rise in control port pressure pushes the piston in the actuator towards **Xpd** as seen in Figure B2-3.

Figure B2-4 to B2-6 show the spool, control pressure and pin behavior in the eng

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engagement mode. In this mode the spool is initially at **Xs = 0;** the pin is fully disengaged (**Xp = Xpd**). The pressure in the P2 chamber of the spool valve is then lowered and this causes the spool to move towards **Xse** - pushed by the pressure force in the P1 chamber, as seen in Figure B2-4, and the spool valve port openings change. The inlet port almost closes ($\mathbf{R_{r1}}$ increases steeply) and the control pressure falls as seen in Figure B2-5. This fall in control port pressure allows the piston in the actuator to move towards the 'zero' position as seen in Figure B2-6.

2.5 Model # 3: Model with realistic design parameters

In the previous section, we developed a model that had all the qualitative behavior of the three major components of the system. We could now incorporate actual design values for parameters and change the mathematical expressions for the element behaviors to follow the real system more closely. We introduced the nonlinear nature of some key elements. The parameters were taken from existing hardware and the following changes were made to the previous model.

The sliding resistance between the spool and the inner diameter of the chamber (**RSPL**) was modeled as a viscous friction. The equation used for this computation is included in Equation A.1 in Appendix A.

The hydraulic resistances of the ports were changed to be either annular or orifice in nature depending on the spool position. These are included as Equation A.2 and Equation A.3 in Appendix A.

Actual values were used for the bulk modulus, the density and the viscosity of the oil. Actual values were also used for the mass of the spool and piston, all geometric dimensions, spring stiffness and preloads. These values with their units are listed as Table A.1 and Table A.2 in Appendix A under Named Parameters and they are also included in Appendix D.

When incorporating actual design values, it was noticed that when the spool or piston struck the chamber walls they tended to bounce back a few times. This was on account of the walls being modeled as very stiff springs. In order to compensate for this effect, a damping (**RWALL** and **RSTP**) was introduced when the spool or piston impacted into the walls.

The hydraulic compliance of the fluid in the chamber on the left side of the spool (**C1STAR**) was modeled as that of a chamber with changing volume. The theory is described for Equation A.4 in Appendix A

A resistance ($\mathbf{R}_{x4}$) between the supply port and the left side of the spool was identified and assumed to act in parallel with the already existing $\mathbf{R}_{x1}$.

The model is shown in Figure 2.5.

This model was exercised like the earlier ones, with similar initial conditions. The results of these simulations are included as Figure B2-7 to Figure B2-10 in Appendix B. The most important observation about this model was that the fluid in the hydraulic

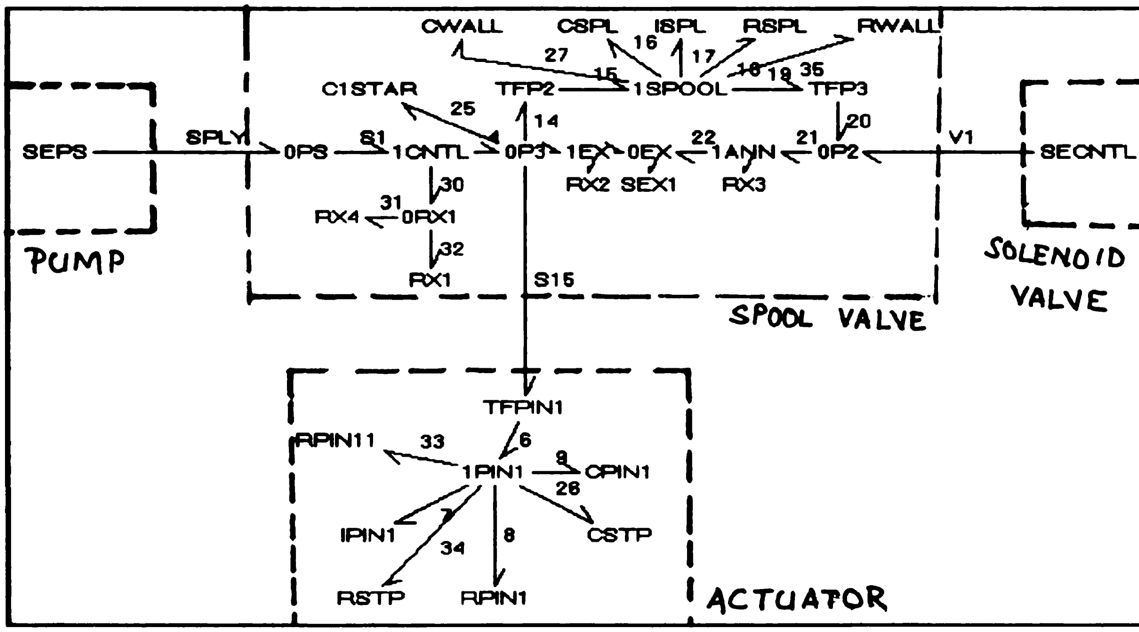

Figure 2.5 Model # 3 : Model w/ Actual parameters

chambers on either side of the spool and piston was too stiff which prevented it from quickly expanding to fill the volume created when the spool or piston moved. This effect was not seen in earlier models because in those cases the chamber volume was assumed to be constant, which in effect translated to a constant compliance fluid spring. In this model since the volume of the chamber is recomputed continuously, the fluid spring compliance changed continuously. Thus the pressure computations in the chambers sometimes yielded impossibly large numbers; here the fluid can be perceived as "tearing up".

We also notice that the "bouncing" when the spool or piston strikes the wall was not entirely eliminated. It was later realized that a greater damping coupled with higher precision while computing eliminated this problem.

2.6 Model # 4 : Model With Solenoid Characteristics and Air in Fluid

Since the above model's predictions were different from the hardware performance, especially with regards to the fluid's behavior, the modeling assumptions were re-evaluated and another model was built with some major modifications. The macro level model graph is shown in Figure 2.6. The individual unit bond graphs are included in Appendix B (Figure B1-1 to Figure B1-5). The major bonds connecting these components are shown and labeled in the macro graph. There is one exception to be noted. The pump are shown and labeled in the macro graph. There is one exception to be noted. The pump model as shown in Figure B1-1 is not used for this model. Here we used a simple

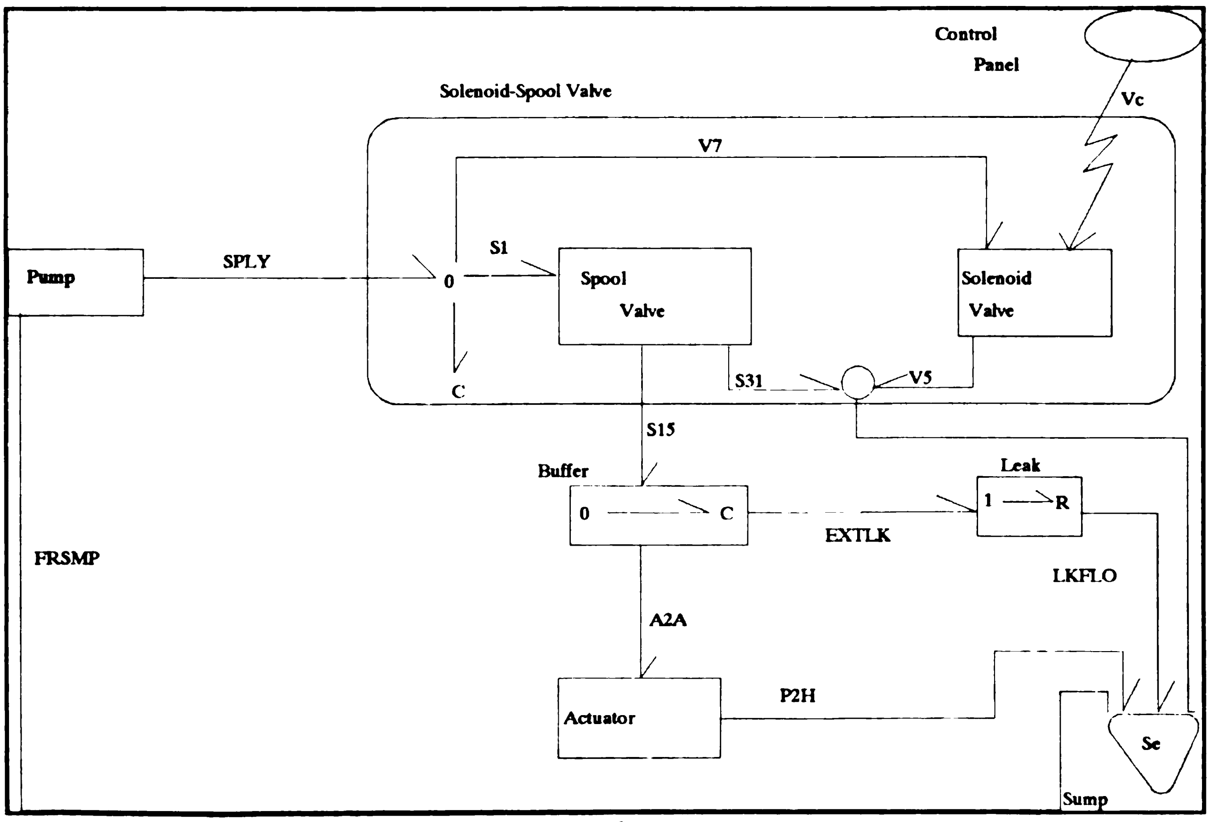

Figure 2.6 Model # 4: Macro Bond Graph

constant source of pressure (**SEPS**) to represent the pump. The drain shown in the macro graph is just a source of effort set to atmospheric pressure. It should be noted that in the actual hardware, the solenoid valve and the spool valve both drain into a common line which then drains into the sump - as shown in Figure 1.1 and 2.6. For clarity of the model, we show them as draining separately into the sump as shown in Figures B1-2 and B1-3. The buffer is a zero junction with a large volume hydraulic compliance. The line **FRSMP** is shown dashed because it is never modeled. This line represents the supply of oil from the sump into the pump. Since the pump in our model is a simple source of effort which can be set to any pressure, we need not have a line of supply from the sump in our model.

In any hydraulic system it is impossible to avoid the entrapment of air in the working fluid - either dissolved or as bubbles. The fluid in this system was assumed to have 3.5% air (by volume) present as bubbles. This would dramatically increase the compliance of the fluid as is discussed in Appendix B (Hydraulic Compliance with air - Equation A.5 in Appendix A). This theory was applied to the definitions of the hydraulic compliances on either side of the spool (**C1** and **C2**) in Figure B1-2 and in the actuator (**CARM2**) in Figure B1-4.

The chamber formed between the left face of the spool and the left wall was identified as a separate pressure region (**0P1**) with a compliance (**0C1**). This chamber is referred to as the **P1** chamber.

\# A resistance to flow due to the pressure equalizing passage was included (**R_{PQPG}**) - between the P1 chamber and the inlet port.

\# When the spool is at **0** and touching the wall, the complete area of the spool cannot be acted upon by the pressure in the P1 region. There is an "X" groove cut into this face of the spool so that the pressure has some surface area to work on. This detail was added to the model. More details are discussed in the chapter describing the physics (Chapter 3).

\# The solenoid part dynamics were modeled partially (Figure B1-3). Since the design details of the solenoid valve were not available, only the pressure-flow characteristics together with the triggering mechanism were modeled to represent the solenoid. See Chapter 3 for further details.

\# The large buffer volume between the SSV and the actuator was included in the model. This buffer will dampen any sudden spikes in the pressure profile and would also serve as a convenient take-off point for any more actuators.

\# A large leakage into the atmosphere was added to the output to see what effect it had on the performance of the system, especially in the low pressure regulation mode.

This model seemed accurate and the simulation results are included in Figures B2-11 to B2-12 in Appendix B. Yet upon examining the fluid flow profiles especially at the inlet to the SSV, some extremely large flow numbers were seen. The actual pump used in the hardware was incapable of these flows. These numbers were seen in the model because the pump was modeled as a source of pressure capable of providing almost infinite flows. The oscillations in pressure in the engagement mode are due to the large leakage introduced in the buffer circuit. This leakage flow demand during the low pressure mode causes the spool to drift towards **0** allowing more flow via $\mathbf{R}_{x1}$, which may prove to be too much inflow - thus we can see the spool *"hunt"* for an equilibrium position. The hardware was found to ave the same behavior.

2.7 Model # 5 : Model with Limited Flow Pump Characteristic

Realizing that a real pump needed to be modeled for a true representation of the system, some more changes were made to the model:

The physical dimensions of the pump were not available, and moreover a model for the pump was beyond the scope of this project. So as in the case of the solenoid valve, a pressure flow curve was obtained for the actual pump used with the hardware and was included in the model. Again the line from the sump (FRSMP) was not modeled because we are not modeling the whole pump; instead we use a source of flow in conjunction with a resistance to emulate the pump's pressure-flow characteristics. Refer Figure B1-1.

The macro model is exactly as shown in Figure 2.6. The individual units are expanded in the Figure B1-1 to Figure B1-5 in Appendix B. The results of the simulations of this model are shown in Figures B2-13 in Appendix B. Now the model could not produce effective disengagement of the pin. During the disengagement of the pin, it was seen that too much time was taken up in building up the pressure in the piston chamber. The same behavior was seen in the actual hardware experiments. This led to the conclusion that the pump was too weak and required a lot of flow to build up enough pressure to disengage the piston completely. The large leakage was also felt to contribute to system failure. We also felt that we should consider the effects of the existing chamber pressure when computing the hydraulic compliance at each time step.

2.8 Model # 6: The Most Complete Model

In all the previous models, we assumed that the model performance lacked accuracy because we did not model all the significant physical effects. But now, faced with the issues described in Section 2.2, we conclude that maybe we need to redefine the internal physics of some of the elements already modeled. We recognized that the hydraulic compliance is a major factor in the system performance. The assumptions made in modeling the hydraulic compliance were considered again. The air in the chamber dramatically reduced the effective bulk modulus of the hydraulic fluid in the chamber. But the bulk modulus of this air was also constantly changing with both the pressure in the chamber and the volume of the chamber. The effect of the existing chamber pressure on the bulk modulus and volume of air were now included in the calculations. The theory is discussed in detail in chapter 3, Section 3.2.3.2 and Appendix A (Equation A.14). The system model is exactly as shown in Figure 2.6 except that function blocks were created to compute the instantaneous values of β_{air} and V_{air} as the pressures in the chambers changed. These re-computed values were used in the calculation of the final pressure in the chamber. The function blocks are shown in Figure B1-6 in Appendix B.

This is the "fully evolved" model capable of predicting projected hardware performance. Actual hardware reflecting this model was not built for an accurate comparison, but it was felt that such hardware could be built as the next step. The main performance measurement was the time taken by the model to achieve complete engagement or disengagement of the piston pin after the command to switch modes had been issued. The performance of this model is given in Figures B2-14 to B2-16 in Appendix B.

In Figure B2-14 we see that the pin has no trouble disengaging within the time studied (50 milliseconds). Yet we notice that the piston movement and the pressure build-up seem slower. The supply pump characteristic was then changed to simulate a more powerful pump. The system performance in Figure B2-15 shows how the disengagement process is much quicker now.

Figure B2-16 shows the system performance after the large leakage in the buffer circuit had been reduced to a much smaller value. We see that the spool does not "hunt" for an equilibrium any more in the low pressure regulation mode. The switching time of this model was found to fall within the bounds of the system's primary and secondary specifications mentioned in Section 1.1.3. This model was then chosen as the nominal de

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design on which parametric studies would be carried out.

All the physics of this model's major components viz: the Pump, the Solenoid-Spool Valve, the Buffer and the Actuator are fully described in Chapter 3. The various nodes and their specific subroutine definitions are detailed in Appendix D and E. Adopting this version as the nominal design, some parametric studies were done on the system and these together with their results are discussed in Chapter 4 - *Results and Discussions*.

Chapter 3

DESCRIPTION OF COMPONENTS AND THEIR PHYSICS

3.1 Introduction

This chapter describes in detail the five major components in the system, viz; Spool valve, Solenoid Valve, Pump, Buffer and Actuator. The geometric dimensions are included and the various physical effects assumed to exist in the components are also explained.

3.2. Spool Valve

As mentioned earlier, the Solenoid-Spool Valve consists of the spool valve and the solenoid valve housed in one unit. The spool valve not only controls the oil flow to move the actuator piston, it also regulates the minimum pressure of flow in the external load circuit. This minimum pressure value is decided by a combination of the supply pump capability and the spool valve design. This will be elaborated later in this section. The physical effects inside the spool valve are discussed here and the way they have been modeled are described. Even though there may be numerous effects involved only the dominant ones that are relevant to capture the dynamic behavior have been modeled.

3.2.1 The Geometry

Before we describe the dynamics of the spool valve, we need to understand its geometry. A simple cross-section view of the spool valve is shown in Figure 3.1.

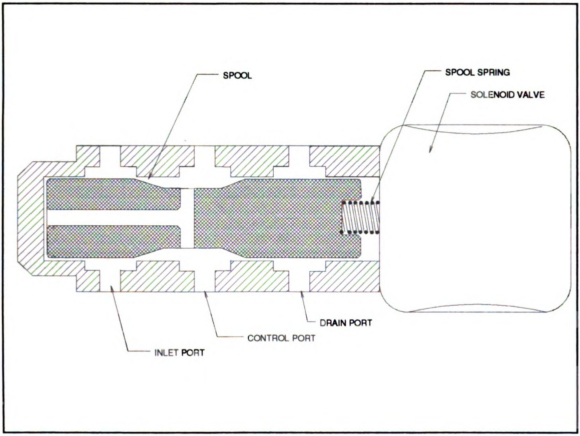

Figure 3.1 Spool Valve Cross-Section

As we can see, the spool valve consists of only one moving part - the spool, which is essentially two equal diameter cylinders connected end-to-end by a smaller diameter cylinder. The spool is within a chamber that is cylindrical. On one side, between the wall and the spool is a spring, which seats into a small cavity on the spool. When the spool chamber is filled with fluid, we will assume that the spool floats in the middle of the chamber with a small clearance all around. By virtue of its shape, the spool divides the chamber into three different regions as shown in Figure 3.2 below. The pressure in these regions are referred to as P_1, P_2 and P_3 .

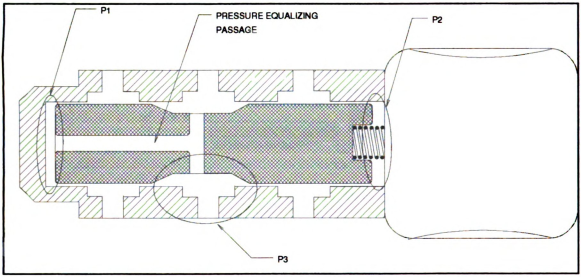

Figure 3.2 The Three Pressure Regions in the Spool Valve

The spool valve has three hydraulic ports to communicate with the rest of the system (refer Figure 3.1). The inlet port is where the high pressure supply (e.g. from a pump) comes in, the control port shown in the middle is where the controlled output flow from the spool valve comes out. The drain port is to drain the valve chamber when required. In the cross-section figures of the spool valve there is a passage shown through the spool body that connects the P_1 chamber and P_3 chamber. This passage is referred to as the pressure equalizing passage, since it equalizes the pressure between those two chambers. As shown in Figure 3.3 it has two interconnected bores across the smaller diameter section (although only one of these can be shown in a cross-section view) and one along the larger diameter section on the left side. The "**X**" groove (1 mm wide) on the face of the spool is designed so that when the spool touches the wall at its 'zero' position, there is still a small area on which fluid pressure in the P1 chamber can act.

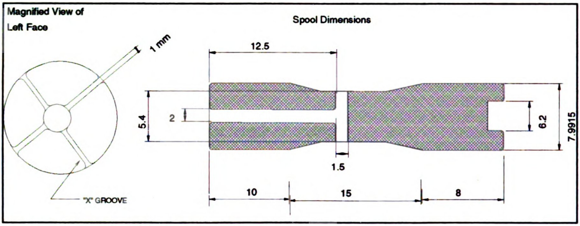

Figure 3.3 The Spool Dimensions

3.2.2 General Physics

If we assume that the spring on the side of the spool is not present, then the spool becomes a body free to move as per the dictations of the three forces generated by the pressures P_1, P_2 and P_3. But P_3 acts equally on all sides and cancels itself out. Hence the position of the spool is dependent only on the forces due to P_1 and P_2. The effective areas A1 and A2 of either face of the spool are equal. The spring on the P2 side of the spool has its maximum installed length lesser than the free length, and hence is always compressed, irrespective of where the spool is in its chamber. So for an equilibrium of forces on the spool,

$$\mathbf{P_1 * A_1 = P_2 * A_2 + F_\theta + K * Xs}$$

where **Xs** is the displacement of the spool as measured from the 'zero' position of the chamber (refer Figure 2.1). $\mathbf{F_\theta}$ is the preload force on the spool spring (by virtue of the shorter installed length) when the spool is touching the wall at **0**.

$\mathbf{F_\theta = K * (l_o - l_i)}$ l_o - free length of the spring

l_i - installed length of spring

K is the stiffness of the spring.

So the values of P_1 & P_2 determine the position of the spool in its chamber. Here we ignored the flow forces generated by fluid flowing through narrow passages into and out of the three chambers. The pressure in the P_2 chamber is controlled by the solenoid valve which is affixed on one side of the spool valve (as shown in Figure 3.1). The operation of the solenoid valve will be discussed later.

Spool at "Zero" Position

Let us assume that the spool is at 'zero' position and in contact with the wall. This configuration exists when P_1 and P_2 are equal. Then the preload force of the spool spring will push the spool to the wall. This spool valve configuration is shown in Figure 3.4.

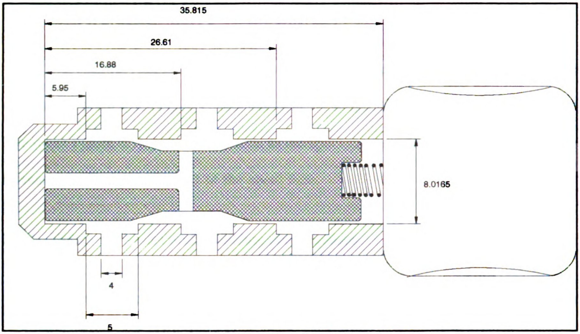

Figure 3.4 Spool shown at "Zero" with Chamber Dimensions

We know that P_1 equals P_3 due to the pressure equalizing passage when the spool is at **0**. This in turn is the supply pressure coming in through the inlet port. P_1 cannot act on all of A1 since the spool is assumed to be touching the wall. But there is the "X" groove cut into that face of the spool and so the size of the P1 chamber is only as big as the "X" groove. The force in P1 chamber of the of the spool is

$$\mathbf{F_{left} = P_1 * (\text{ Area of the "X"})}$$

The force on the other side (P2 chamber) of the spool is

$$\mathbf{F_{right} = P_2 * A_2 + F_0}$$

Spool moving away from "zero"

Now if we were to maintain $\mathbf{P}_1$ at the same high pressure and reduce $\mathbf{P}_2$, there will come a point when $\mathbf{F}_{left}$ is greater than $\mathbf{F}_{right}$. The spool will then start moving toward **Xse** (refer Figure 2.1). Note that as soon as the spool moves away from the wall, the area increases to the full area (A1) of the spool face.

3.2.3 Detailed Physics and Modeling Assumptions

A general picture of the spool valve operation was outlined above. This section attempts to look at the details of how the various configurations of the spool valve are achieved and the assumptions involved while modeling the spool valve dynamics.

3.2.3.1 Hydraulic Resistances

From the geometry of the spool valve (shown in Figure 3.4), we can deduce that the opening between the inlet port and the P3 chamber is the largest when the spool is at its 'zero' position. It follows that the incoming flow will be greatest in this configuration. And at the other end of the $\mathbf{P}_3$ chamber, there will be a minuscule flow out into the drain. For ease of discussion we will name the hydraulic resistances that play a role in the flow of fluid in and out of the spool valve:

$\mathbf{R}_{x1}$: Hydraulic Resistance to flow between inlet port and $\mathbf{P}_3$ chamber

$\mathbf{R}_{x2}$: Hydraulic Resistance to flow between $\mathbf{P}_3$ chamber and Drain

$\mathbf{R_{x3}}$: Hydraulic Resistance to flow between Drain and $\mathbf{P_2}$ chamber

$\mathbf{R_{x4}}$: Hydraulic Resistance to flow between inlet port and $\mathbf{P_1}$ chamber

Figure 3.5 shows these resistances. From the spool valve geometry shown in Figure 3.4, we see that the spool can move a maximum of only about 2.8 mm. It follows that $\mathbf{R_{x3}}$ and $\mathbf{R_{x4}}$ will always be annular resistances in their respective flow paths. In the configuration shown in Figure 3.4, $\mathbf{R_{x1}}$ is the resistance offered by an orifice and $\mathbf{R_{x2}}$ is an annular resistance. The resistances are calculated in the following manner referencing Figure 3.6.

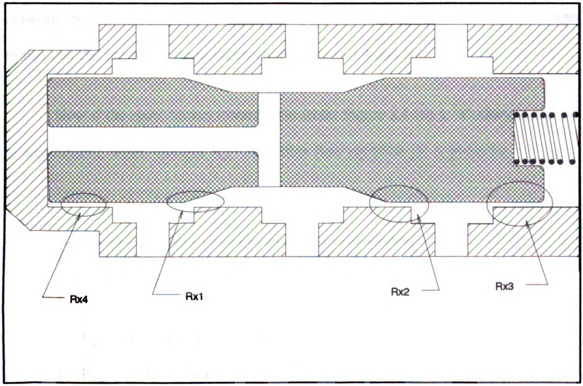

Figure 3.5 Hydraulic Resistances Identified

R_{x1}

The orifice area of **R_{x1}** can be computed from the magnified view shown in the bottom of Figure 3.6.

$$\begin{array}{l} \text{If } c = \sqrt{a^2+b^2} \\ \text{Then we have:} \\ \text{Area of Orifice, } A_o = \pi * \text{Diameter of the chamber} * c \end{array} \quad \text{...Eq. 3.1}$$

Where "a" and "b" are as shown in Figure 3.6. Note that "b" is the clearance between spool and chamber. It was calculated as the difference between the spool's larger radius and the chamber's inner radius (Refer Figure 3.3 and 3.4).

Now if the spool moves towards **Xse** (refer Figure 2.1 (b)), "a" changes and "c" is recalculated, which changes A_o. The orifice flow equation [3] is given by

$$Flow,\ Q = C_d * Area * \sqrt{2\frac{(P_{inlet} - P_3)}{\rho}} \quad \text{...Eq. 3.2}$$

where
C_d : Coefficient of Discharge
Area : from Eq. 3.1
$P_{inlet} - P_3$: the pressure drop across the Orifice
ρ : Density of Fluid

R_{x2}

From the geometry shown in Figure 3.6, we see that $\mathbf{R_{x2}}$ is the resistance offered by an annular passage of length **L**. This length of the annular tube decreases as the spool moves towards **Xse**. The laminar flow [3] through this tube is given by Equation 3.3.

$$\boxed{\text{Flow, } Q = \frac{\pi r c^3}{6\mu L}\left[1+\frac{3}{2}\left(\frac{e}{c}\right)^2\right](P_3 - P_{DRAIN})} \quad \text{...Eq. 3.3}$$

where

$\mathbf{P_3}$ - $\mathbf{P_{DRAIN}}$: the pressure drop in the direction of flow

L : as shown in Figure 3.6

e : The eccentricity between the centers of spool and chamber

c : The clearance between spool and chamber

μ : The Fluid Kinematic Viscosity

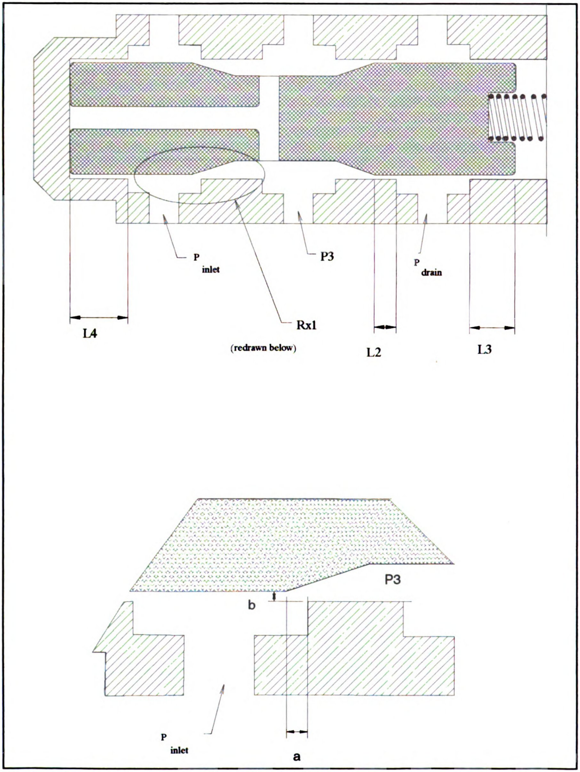

Figure 3.6 Dimensions for Hydraulic Resistances

As mentioned in Section 3.1.1, we assumed that the spool floats in the middle of the chamber and so the eccentricity is zero. The flow equation then became:

$$\boxed{Flow,\ Q = \frac{\pi r c^3}{6 \mu L}\ (P_3 - P_{DRAIN})} \quad ...\text{Eq. } 3.4$$

R_{l3} and **R_{l4}**

The flows through these resistances are always annular in nature and were computed in the same manner as in Equation 3.4. The Figure 3.6 depicts the lengths of the passages in these cases. It is obvious that as the spool moves towards **Xse,** L3 increases and L4 decreases.

Hydraulic Resistances - Spool off the "zero" position

When the pressure $\mathbf{P_2}$ is dropped very low, the spool is forced to move towards **Xse**. This occurs when the pressure force acting on the "X" on the left face of the spool is large enough to overcome the spring preload and low pressure combination on the right. Figure 3.7 shows the configuration in the spool valve when the spool has just started moving away from the 'zero' position.

Looking at the various flow paths identified in Figure 3.5, we see the following trends:

R_{x1} : Still remains an orifice flow, but the dimension 'a' has decreased - resulting in an increased resistance to flow from the inlet port to the **P_3** chamber.

R_{x2} : Still remains an annular passage flow; although the dimension 'L' is now reduced resulting in a slight lowering of resistance to flow from the **P_3** chamber to the drain port.

R_{x3} : With reference to Figures 3.6 and 3.7, the dimension 'L3' has increased, resulting in an increased **R_{x3}** resistance.

R_{x4} : With reference to Figures 3.6 and 3.7, the dimension 'L4' has decreased, resulting in a decreased **R_{x4}** resistance.

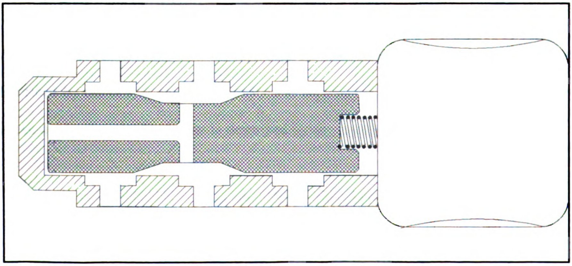

Figure 3.7 Spool off the "zero" position

Figure 3.8 shows two configurations of $\mathbf{R_{x1}}$ in the spool valve at instants following the one depicted in Figure 3.7. We see that $\mathbf{R_{x1}}$ first reaches a thresh-hold point where the dimension 'a' is zero. The flow is still an orifice flow. The continued movement of the spool towards **Xse** will change the nature of $\mathbf{R_{x1}}$. It then turns into an annular passage resistance that keeps increasing as the spool continues to move in that direction. The flow through this resistance is then given by the annular flow equation described in Equation 3.4 - except that the pressure difference is now measured between the inlet and the $\mathbf{P_3}$ chamber; and the length of the passage is **L1** as shown in Figure 3.8.

A similar yet opposite flow transformation takes place in the case of $\mathbf{R_{x2}}$. It starts out being an annular passage (when the spool is at the 'zero' position) whose length keeps decreasing till it reaches a thresh-hold point and then the annular flow equation ceases to apply when the flow path becomes an orifice. The correct mathematical description of these two flow transformations was a very important factor while developing the model for the spool valve.

Let us consider the flow through $\mathbf{R_{x1}}$. As described earlier, the initial flow was described by the orifice equation described in Equation 3.2. After the spool crosses the thresh-hold point, the final flow is described by the annular passage equation:

$$Flow,\ Q = \frac{\pi r c^3}{6 \mu L} (P_{inlet} - P_3)$$

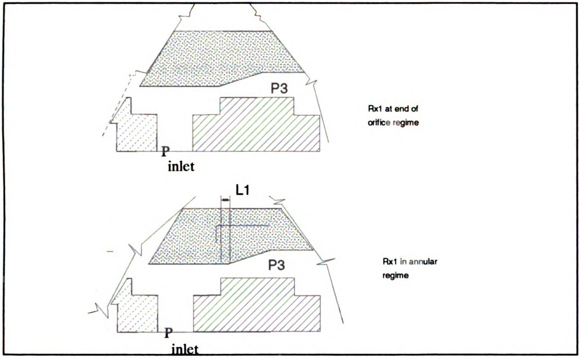

Figure 3.8 $\mathbf{R}_{x1}$ in Transition

We see that the length of the passage appears in the denominator of the annular flow equation. Just after the cross-over, in the initial stages of the annular flow regime, when the length of passage is very close to zero, this equation is prone to produce some very large flow numbers (or the equation "blows up") which are not indicative of the actual situation. This is because division by the length of passage might get very close to division by zero. Thus it became necessary to define a transition region, between the two flow regimes, that eliminated the huge numbers in the calculations and at the same time could effectively "patch up" the flow curves produced by both equations - orifice and annular. The computations in this transition region were neither that of an orifice nor of an annular flow.

We decided on a length for the transition region making sure that outside this region, the annular flow equation did not "blow up". Then we assumed that for one half of this region a 'constant area orifice equation' would apply and for the other half, a weighted average of orifice and annular equations would apply. The weightage of each equation will depend on the position of the spool within the transition region. The constant area orifice equation would apply in the half closer to the orifice flow regime and the weighted average would apply in the half closer to the annular flow regime. The definition of one half of the transition region as a 'constant area orifice' was necessary because using a weighted average in that half did not eliminate the 'division by zero error'. Using $\mathbf{R}_{x1}$ as an example, the computations in the transition region are described below in detail.

From the geometry of the spool valve chamber shown in Figure 3.4, it is evident that as the spool moves towards **Xse**, $\mathbf{R}_{x1}$ ceased to be an orifice type resistance after a spool displacement of 0.095cm. So the transition flow region for $\mathbf{R}_{x1}$ begins after this point. The transition length was chosen as 0.0015cm. So for the first half (note that this is the half closer to the orifice flow regime)of this transition length ie. 0.00075cm, a constant area orifice flow was assumed to exist. And the area of this orifice was the last computed area by Equation 3.1 just before $\mathbf{R}_{x1}$ entered the transition region. After the spool had traversed the 0.00075cm, the flow through $\mathbf{R}_{x1}$ was calculated as a weighted average of both orifice and annular flows as shown below:

$$\boxed{Flow = \left[1 - \frac{x}{L}\right] Q_{orifice} + \frac{x}{L} Q_{annular}} \quad \text{...Eq. 3.5}$$

where **x** is the spool displacement past the 0.00075cm mark; **L** is 0.00075cm for $\mathbf{R}_{x1}$

$\mathbf{Q}_{orifice}$ is the same flow number as calculated in the first half of the transition region.

$\mathbf{Q}_{annular}$ is calculated as in Equation 3.4; but the length of passage used in this equation was measured from the beginning of the transition region, ie. past 0.095cm of spool travel.

Once the spool crossed over this transition region, the flow was calculated using a regular annular flow equation as in Equation 3.4. When the spool moves back from **Xse** to **0,** the same set of computations are done in reverse order. These computations are done in ENPORT [2] by the sub-routine ZZSU69 (refer APPENDIX E). In the case of $\mathbf{R}_{x2}$, the same techniques are applied in order to prevent the computations from 'blowing up'. These computations are carried out in ENPORT by the sub-routine ZZSU70.

3.2.3.2 Hydraulic Compliances

The hydraulic compliance of a fluid is its ability to be compressed under pressure. It is quantified by the compressibility or the bulk modulus of the fluid - one being the reciprocal of the other. Bulk modulus denoted as β is defined as change in pressure divided by the fractional change in volume. As described by Merritt [3], an isothermal as well as adiabatic bulk modulus can be defined for a fluid. It can be shown that the adiabatic bulk modulus is the product of the isothermal bulk modulus and the ratio of specific heats. In most hydraulic design applications we use the adiabatic expression for bulk modulus, especially when the bulk modulus of air is to be calculated. Bulk modulus is the most important fluid property in determining the dynamic performance of a hydraulic system because it relates to the "stiffness" of the fluid and hence directly alters the "response time" in a hydraulic circuit. It is always a positive number. Bulk modulus is significantly altered by the slightest amount of air entrained in the fluid. Merritt and others have developed expressions for the effective bulk modulus of a fluid-air mixture inside a chamber as

$$\frac{1}{\beta_{eff}} = \frac{V_{air}}{V_{Total}}\left(\frac{1}{\beta_{air}}\right) + \frac{V_{oil}}{V_{Total}}\left(\frac{1}{\beta_{oil}}\right)$$

and ...Eq. 3.6

$$\beta_{eff} = V_{Total}\left[\frac{\beta_{air}\ \beta_{oil}}{\beta_{air}V_{oil} + \beta_{oil}V_{air}}\right]$$

where we ignore the effects of container expansion. The effect that entrained air has on the fluid bulk modulus is dependent not only on the volume of the chamber, but also on the pressure inside the chamber as we will see shortly.

Spool at 'Zero' Position Revisited

When oil under pressure flows into a chamber it gets compressed. If there is any air entrained, the mixture gets compressed to a greater degree. We have seen that when the spool is at **0**, a tiny chamber exists between the face of the spool and the wall of the chamber. This is the volume of the "**X**" groove. Oil forced into this chamber gets compressed due to its own compressibility and also due to the compressibility of the air entrained (if any) in the oil. The pressure in the chamber at any given time is the pressure of this compressed oil and air mixture. In the case of the spool valve, the inflow of oil raises the pressure in the chamber and after attaining a certain pressure within the chamber, the spool is pushed outward from the wall. This causes the volume of the chamber to increase, leading to a drop in the pressure. This will in turn allow more oil to flow into the chamber till the pressure builds up enough to move the spool again, and the whole process gets repeated. Ofcourse the activities inside the chamber do not repeat themselves in the same order; it is a dynamically changing situation. At the same time the mass of oil capable of flowing into the chamber is continually changing due to the changes in the hydraulic resistances caused by the spool movement.

These changing pressures and volumes affect the hydraulic compliance of the fluid inside the two chambers formed by either face of the spool and the respective chamber walls. An expression that relates the effective bulk modulus of a fluid-air mixture in a chamber when both the volume and the pressure are changing is developed in Appendix A (Equation A.13). These effects have been modeled by the ports **C1** and **C2** in the system bond graph (Figure B1-2). These ports are only sources of efforts whose value is assigned to them after a complex set of calculations have been carried out by the function blocks shown in Figure B1-6 of Appendix B.

$$\frac{\Delta P}{\Delta V_T} = -\frac{\beta_{eff}}{V_T}$$

or

$$\frac{dP}{dt} * \frac{dt}{dV_T} = -\frac{\beta_{eff}}{V_T}$$

or

$$\frac{dP}{dt} = -\frac{\beta_{eff}}{V_T} * \frac{dV_T}{dt}$$

and

$$\frac{dP}{dt} = -\frac{\beta_{eff}}{V_T} * Flow$$

The Equation A.13 shown in Appendix A together with the existing chamber pressure and the flow rate into the chamber is used by the block **DPC1** to obtain the pressure differential in that time step- as shown above; this differential is then integrated by the block **INTC1** to obtain the final pressure at that time step.

3.2.3.3 The End Walls of the Chamber

The two end walls of the spool chamber are modeled as very stiff springs with heavy one-way damping. The damping is active only when the spool strikes the wall and tries to "move into" it. The nodes that model these effects are **RWALL1** and **CWALL1**.

We have used only one resistance element and one spring element to model both walls together. They are both defined in such a way that they are inactive within a certain range of spool movement (which is the chamber length). If the spool attempts to cross over this range on either side, then these spring and damper properties take effect.

3.2.3.4 Viscous Friction on the sides

When the spool slides in its chamber filled with fluid, the fluid gets sheared. This fluid shearing causes viscous friction between the side walls and the spool. We assumed that only the larger diameter sections of the spool experienced significant viscous friction. The node **RSPL** models this effect. The equation used is included in Appendix A.

3.2.3.5 Pressure Equalizing Passage

This passage as described earlier has three interconnected bores. The passage offers a combined resistance and it is calculated as follows. Four coplanar short cylindrical passages join at a common point, from where a longer passage begins in a direction perpendicular to the other four. So the resistances of the four short passages act in parallel, and this combined resistance acts in series with the long passage. The corner resistance is also considered, where the fluid coming in from the four pipes has to "turn" a corner and flow into the longer pipe or vice versa. The corner resistance is assumed to be a multiple of the minimum resistance. The node $\mathbf{R_{PQPG}}$ models this resistance

3.2.3.6 Regulating Action of the Spool

In the regulation mode, the pressure force (due to fluid flowing in from the solenoid valve) on the P2 chamber side of the spool is almost non-existent. The spool is pushed towards **Xse** by the pressure force in the **P1** chamber, which is also the pressure in the control chamber (**P3**) - due to the pressure equalizing passage. At a certain spool position, the force pushing the spool towards **Xse** gets balanced by the spring force (which includes preload) acting on the other side of the spool. Now when there is an increased flow demand from the actuator circuit (for e.g. caused by a greater leakage), the pressure in the control chamber drops leading to a drop in pressure in the **P1** chamber. This upsets the balance of forces on either side of the spool and the spring forces now dominate. The spool will be pushed towards the **0** position. This in turn opens up the $\mathbf{R_{x1}}$ path and allows more inflow from the pump, building up pressure in the control chamber. When the pressure force in the P1 chamber of the spool rises high enough it prevents the spool from being pushed any farther by the spring forces; the spool has then found its new regulating position. This is how the spool valve meets any reasonable demands of flow and always maintains a minimum low pressure.

3.3 Solenoid Valve

The solenoid valve is not modeled with all its dynamics. Only the hydraulic resistances of its ports are varied according to the manufacturer's data. This is simulated as a rate of change of orifice area with time. The solenoid valve shares the oil supply from the pump (with the spool valve) to control the spool position. When the solenoid in the valve is charged up by a high voltage, it attracts an armature from a default position. The armature is coupled to a ball which controls the port openings to the spool valve chamber and the drain. See Figure 3.11.

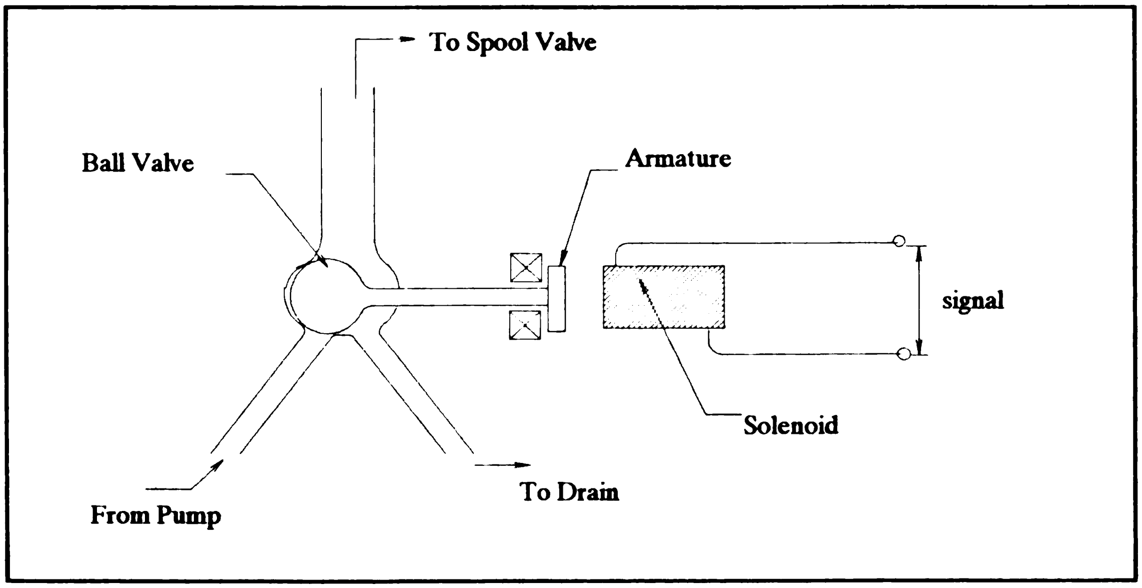

Figure 3.9 Solenoid Valve - in principle

No details of the solenoid valve geometry are known - except the time taken for the solenoid to charge or discharge. The manufacturer also provided the maximum flow through either port for a given pressure difference. So from the Orifice Flow Equation:

$$Flow,\ Q = C_d * Area * \sqrt{2\frac{(P_1 - P_2)}{\rho}}$$

where
C_d : Coefficient of Discharge
Area : of orifice
P_1-P_2: the pressure drop across the Orifice
ρ : Density of Fluid

which we can re-write as

$$Q = C_d * Area * \sqrt{\frac{2}{\rho}} * \sqrt{P_1 - P_2}$$

knowing Q, P_1-P_2, and ρ and assuming Area is 1 unit, we calculate a value for $C_d * Area * \sqrt{\frac{2}{\rho}}$ Using this value as **CNOT** and assuming that Area changes from 0 to 1 within the time taken to charge or discharge the solenoid, we can compute the flow through the ports at all times. The solenoid is known to take 6 milliseconds to charge up and 3 milliseconds to discharge. The area is assumed to change between 0 and 1 during this time in an exponential manner. A transfer function is used to model these openings to the two ports - one to the spool valve and the other to the drain. When one port opens, the other closes within the same span of time. It is assumed that during charge-up of the solenoid, the port to the spool chamber opens and the drain port closes. In the model, **RSE** and **RSC** are assumed to be orifice resistances (as described above) with their areas changing exponentially.

3.4 Buffer Volume

The buffer volume is just a large chamber of constant volume. It can be considered as a plenum for supply to more than one actuator and also as an absorber for any pressure spikes. The fluid inside this chamber acts like a huge compliance.

3.5 Pump

The pump is not modeled in its entirety. The combination of **SFPMP** and **RPMP** together emulate the pressure-flow curve of the actual pump. **CINLT** can be considered as the hydraulic compliance of the line between the pump and the **SSV.**

3.6 Actuator

The actuator shown in Figure 3.12 has more or less the same mechanical elements as the spool valve. The piston slides in the cylinder and the pin slides in the hole on the body. The sliding friction of these elements is modeled by **RFRN2** and **RFRE2** respectively. Their equations are exactly as those for **RSPL**. The end walls are modeled by a combination of **CPIN2** and **RPIN2. CPIN2** is defined to have two different properties in two ranges of operation - one as the pin spring and the other as the end wall. When the piston moves within its allowed range (i.e. within the two walls) it acts as a simple retainer spring, with a certain stiffness and preload. But once the piston strikes either wall, then the spring stiffness changes to a very high number to imitate a metal wall.

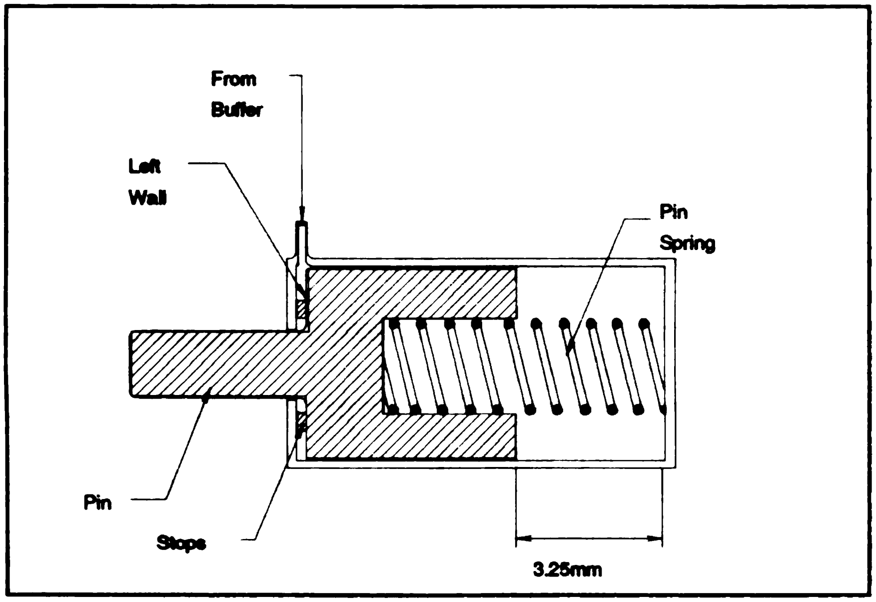

Figure 3.10 The Actuator

Atmospheric pressure exists on the right side of the piston. The small stops seen between the piston and the left cylinder wall are stops which help to serve the same purpose as the "X" groove on the spool - to provide an area for the pressure force to act on when the piston is at "zero" (refer Figure 2.2). As in the case of the spool spring, the piston spring has a preload force keeping the piston against the **0** position unless and until the pressure force exceeds this spring force.

Chapter 4

RESULTS AND DISCUSSIONS

As mentioned earlier, the actual design of the system was also being carried out in parallel with the model development. Hardware experiments were set up only for the design modeled in Section 2.7. As we already saw in the model performance, this design was not satisfactory, mostly because the pump was not powerful enough to build up the required disengagement pressure. The design team then decided to reduce the leakage and improve the pump performance. The pump curve used in Section 2.8 reflects this new pump and leakage. The model described in Section 2.8 was then chosen as the nominal design because its performance was close to the actual hardware's projected performance with the new pump and leakage. The model file (for ENPORT) is listed in Appendix C and the individual node descriptions and subroutine definitions are in Appendices D and E. This chapter describes some parametric studies conducted on this nominal design. The studies were done to ensure that the system met the primary and secondary performance specifications. To have complete faith in the model, it is important to build the actual hardware and duplicate its performance in the model. The studies discussed here help in establishing the methods and reasoning involved.

The system response to different conditions is studied by monitoring mainly the control pressure **P3**, the pin movement and the spool movement. As and when required, other variables are compared. A key of the various parameters that have been varied is given in Table 4.1 and a discussion of the studies and their results follow. The plots for the various results are given in Appendix B. Some of these plots are shown for a much longer time than is necessary to observe the system behavior because there are other plots that did require such a long time to observe all the trends.

Study Serial #	Parameter	Nominal Value	New Value
1	Air Fraction	3.5% by Volume	7% by Volume
2	Leakage Load	0.05 cm^2 orifice	0.5 cm^2 orifice
3	Viscosity	1.092E-06 N-s/ cm^2	2.37E-06 N-s/ cm^2
4	Spool Spring Stiffness(KSPOOL)	18 N/cm	27 N/cm
5	Oil Bulk Modulus	1.72E+05 N/cm^2	5.8E+05 N/cm^2

Table 4.1 Key for Parametric Study

4.1 Air Fraction Study

As discussed in earlier chapters, the presence of air in the working fluid has a marked effect on the system performance. In the nominal design we assume that 3.5% air(by volume) is present as bubbles(i.e. undissolved) in the oil. It is not possible to keep this percentage of air a constant, more often than not it tends to increase. So we study the effect of 7%(by volume) air in the oil. This would make the oil softer than the nominal. As far as system performance we can expect a slight increase in the disengagement time of the piston pin. The softer fluid will take more time to build enough pressure in the chamber to offset the preload force in the spring. We will also see that the spool tends to oscillate with a larger amplitude while "hunting" to find the regulating pressure in the engagement mode - because the fluid has become more compliant. These variables for the nominal design and the parametric study have been plotted in Appendix B for comparison.

Looking at the comparative plots, we realize that the model behaved as expected. During the pin engagement, we do see the greater amplitude in the spool movement and the pressure oscillations in the control chamber - Figures B2-1 and B2-2 in Appendix B. After all that we see the pressure being regulated to nearly the same value - Figure B2-2 in Appendix B. But the pin disengagement (Figure B2-3 in Appendix B) is not affected because the small size of the chamber when the piston is hard left allows the pressure to be built up rapidly; moreover the softer fluid flows faster to fill that chamber. But once the pin starts moving, we see that the pressure in the system climbs much slower than in the Nominal Design - see Figure B2-4 in Appendix B.

4.2 Leakage Load Variation

As mentioned in Chapter 3, the spool valve settles to a constant low pressure in the regulation mode. One of the purposes of the spool valve is to always guarantee this minimum regulation pressure in the actuator circuit. The leakage added to the buffer volume is meant to simulate a constant flow draining. So even if the leakage orifice area were to be increased from the nominal, the spool valve should regulate the flow into the actuator circuit to maintain the same minimum pressure as the nominal design does. The control chamber pressure and the pin movement in either mode are compared below for both the nominal design and the higher leakage model.

In the case of the higher leakage model, it can be seen that the pressure regulates to about the same level as in the nominal design during the regulation mode(engagement mode) - see Figure B2-5 in Appendix B. During the disengagement mode we see that due to the higher drainage from the actuator circuit, it takes more time for the control pressure to build up to the maximum and the pin thus takes slightly longer to disengage fully - see Figures B2-6 and B2-7 in Appendix B respectively.

4.3 Viscosity Variation Study

The viscosity of the working fluid affects the viscous friction when the spool or the piston slides in the chamber. It also affects the flow rate through the annular passages. High viscosity conditions will exist when the system operates at lower temperatures. When operating in such conditions, the nominal design tends to be a little sluggish as will all hydraulic systems.

Given in Appendix B are the comparative plots for the nominal design and the lower temperature simulation. It is seen during the engagement mode, that the oscillations of the spool movement and control pressure are very subdued before the spool valve finds the regulation pressure - see Figures B2-8 and B2-9. During disengagement, the control pressure takes longer to build up to the maximum value. the pin takes slightly longer to complete disengagement - see Figure B2-10 in Appendix B.

4.4 Spool Spring Variation

The three previous studies can be classified as robustness studies; the system may be called upon to operate under those conditions sometimes and it is important that the system not fail. A useful computer model should also be able to help in the modifications of an existing design; changing geometry or material properties of components in the model should yield results that faithfully replicate the hardware performance if these same properties were changed physically. It has already been mentioned in Chapter 3 that the regulating pressure achieved by the spool valve is decided by a combination of the supply pump capacity, the spool spring characteristic and the geometry of the spool valve ports(size and position). By choosing a stiffer spool spring, we should be able to raise this regulated pressure mark. We chose a spring that was 1.5 times as stiff as the nominal design but has the same free length. The comparative system response is shown in Figures B2-11 and B2-12 in Appendix B. We see that in the engagement mode, the regulation pressure has been raised. As can be inferred from section 3.2.3.6, a stiffer spring will push the spool towards **0** even more than in the nominal design. This opens up the $\mathbf{R}_{z1}$ path even more and lets more oil to flow in through the inlet port and thus raising the pressure. During the disengagement, the quicker movement of the spool to the left builds up the control pressure faster and the pin disengages faster than the nominal - see Figures B2-13 in Appendix B.

Chapter 5

CONCLUSIONS

5.1 Summary

In Section 1.2 there were four broad steps that were to be completed to achieve the principal objective of this research. Below we restate the steps and summarize our accomplishments.

Study the Complete System: The system was studied in detail and all the physical effects that needed to be modeled to capture the relevant behavior to sufficient accuracy were identified. The individual components and their important applicable physics were treated in detail in Chapter 3.

Develop a Model: Chapter 2 records the evolution of the initial model into the final model. The several iterations in this modeling process are of interest from a modeling education perspective. In the context of learning about a hydraulic control system one can also gain insight into the process of structured modeling. Some very important modeling issues were:

- The inclusion of air in the fluid,
- The effect of chamber pressure on the hydraulic compliance,

- The pump characteristics - Flow versus Pressure curve

- The effective definition of the hydraulic resistance of the ports,

- The leakage in the load circuit and the resistance of the pressure equalizing passage.

Validate the Model: During the period when we were developing our computer models for an evolving system design, there were no reliable detailed results of systematic hardware experiments available to us. It was agreed by the engineering group that the model performed in a satisfactory manner. The most critical performance characteristic was the time (s) taken to switch from engagement to disengagement (and reverse), once the command to switch modes was issued. Both switching times were found to occur within the time frame of 27 milliseconds. The regulation pressure in the model was about 20 N/cm^2 absolute.

Parametric Studies: The system model was used for performing some parametric studies as discussed in Chapter 4, based on the understanding gained about the model as reported in the second and third chapters. These parametric studies produced results that were judged reasonable by the engineering group. Once the model can be verified in some detail by comparison with reliable hardware test results, it will be a powerful tool for improving the design of the system. Both parametric studies and design innovations can be performed on the model with great confidence.

Since all the steps were completed satisfactorily within a reasonable time period, we conclude that the research objectives were met.

5.2 Topics for Further Research

Pump

The pump was not modeled to include any internal dynamics in this work. It is possible that the pump dynamics may play a role of some importance in the system performance. Modeling the pump more completely and incorporating that in the system should be the next step to pursue.

Solenoid

We must consider including the solenoid dynamics of the SSV in the model. In our study it was only modeled as a pair of controlled resistances to flow.

System Leakages

The various individual leakages back to drain can be modeled in detail. A more thorough study of the leakages could be conducted. The leakages were all lumped together in this work. The total leakage is an important parameter when sizing the pump.

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2. ENPORT/pc *Professional User's Manual.* Rosencode Associates, Inc. May 1994.

3. Merritt H. E. *Hydraulic Control Systems.* John Wiley & Sons, Inc. : New York, Inc. New York, 1967.

Note:

A considerable amount of engineering information about the device being designed was provided by FORD Motor Co. in informal technical reports, not cited herein.

APPENDIX A

EQUATIONS, DERIVATIONS AND NAMED PARAMETERS

Equation for Viscous Sliding Friction:

The spool can be considered as a flat plate that is rolled up. So we can use the viscous friction equation for two plates sliding over each other[3]. The drag effects due to the pressure differences on either side are neglected. The friction force is given as:

$$F = \frac{\mu . U . L . w}{h}$$

where
μ : Kinematic Viscosity
U : Velocity of moving plate
L: Length of moving Plate
w : Width of moving Plate
h : Distance between Plates

...Equation A.1

Orifice Flow Equation :

This equation [3] is to compute the turbulent liquid flow rate through an orifice. We need to know the area of the orifice, the Coefficient of Discharge (which we assume for the system), the pressure difference between either side of the orifice and the density of the liquid.

$$\boxed{Flow,\ Q = C_d * Area * \sqrt{2\frac{(P_1 - P_2)}{\rho}}}$$ ...Equation A.2

Where :

Cd : Coefficient of Discharge

Area : Area of Orifice

P1 - P2 : Pressure drop across Orifice

ρ : Density of fluid

Annular Flow Equation

Again from the same reference as above, this equation computes the rate of flow through an annular passage.

$$\boxed{Flow,\ Q = \frac{\pi r c^3}{6\mu L}\left[1+\frac{3}{2}\left(\frac{e}{c}\right)^2\right](P_1-P_2)}$$ ...Equation A.3

where

P_1 - P_2 : the pressure drop in the direction of flow.

L : Length of the passage

e : The eccentricity between the centers of the two cylindrical bodies; it is zero if they are concentric

c : The clearance between the outer cylinder and the inner one

μ : The Fluid Kinematic Viscosity

Pressure Calculation in a Hydraulic Chamber with Changing Volume:

We need an equation to compute the pressure at each time step in a chamber where a compressible fluid is flowing in and the volume is changing. We know from books on hydraulic power [3] that for a fluid compressed inside a chamber:

$$\frac{dP}{dV} = -\frac{\beta}{V}$$

where the negative sign can be omitted when the volume is increasing. Here,

P : pressure in the chamber

β : the bulk modulus of the fluid

V : the total volume in the chamber

Now dP = P - P_0 ; where P_0 is the initial pressure and P is the final pressure, and if we assume gage pressures, then

$$P = \frac{\beta}{V} * dV \qquad \text{...(A)}$$

In the case of the spool valve chambers, we have a changing total volume as the spool moves. This is computed as :

$$V = V_0 + A_{spool} * X_{spool}$$

where

V_0 is the initial chamber volume (when $X_{spool} = 0$)

A_{spool} is the area of the spool face

X_{spool} is the displacement of the spool from its zero position.

By defining the chamber as a C element [1], we have

Effort = Stiffness * displacement ... (B) where displacement is the time integral of Flow.

Drawing a parallel between (A) and (B); the pressure at each time step is given by:

$$P = \frac{\beta}{V_0 + A_{spool} * X_{spool}} + \int(\textit{Flow into the chamber for that time step})$$

where the second term on the right is the change in fluid Volume for that time step. Thus the relation we are looking for is:

$$\boxed{P = \frac{\beta}{V_0 + A_{spool} * X_{spool}} + \textit{change in volume}} \quad \text{...Equation A.4}$$

The Effect of Air Entrainment on the Bulk Modulus of the fluid in a Chamber

When there is undissolved air trapped in the fluid, the effective bulk modulus is calculated [3] as follows:

$$\frac{1}{\beta_{eff}} = \frac{1}{\beta_{air}} + \frac{1}{\beta_{oil}}$$

where we ignore the container. The bulk modulus of air may be calculated [3] as :

$$\beta_{air} = \text{Ratio of specific heats} * \text{Pressure}$$

The supply pressure from the pump is used for this calculation. We assume β_{air} is constant at all chamber pressures. Thus we arrive at

$$\boxed{P = \frac{\beta_{eff}}{V_0 + A_{spool} * X_{spool}} + change\ in\ volume} \text{ ...Equation A.5}$$

Since β_{air} is much smaller than β_{oil} , it dominates the calculation leading to a very compliant fluid.

An Expression for Bulk Modulus of Oil-Air Mixture in a Chamber when Pressure and Volume are Changing

Let

x be the volume fraction of air in the oil at **STP**

$\mathbf{V_{Total}}$ be the Total Volume of chamber($\mathbf{V_{Total} = V_{oil} + V_{air}}$)

$\Delta \mathbf{V_{Total}}$ be the change in Total Volume of the oil

P be the pressure in the chamber

β_{oil} be the bulk modulus of the oil with no air entrained

β_{eff} be the effective bulk modulus of oil with air entrained

We know [3]

$$\frac{dP}{dV} = -\frac{\beta}{V}$$

when we substitute the expression for β_{eff} [3], and re-write in discrete form we have

$$\frac{\Delta P}{\Delta V_{Total}} = -\frac{\beta_{eff}}{V_{Total}} = -\frac{\beta_{air}\ \beta_{oil}}{\beta_{air} V_{oil} + \beta_{oil} V_{air}} \qquad \text{....Equation A.6}$$

where V_{oil} and V_{air} are the respective volumes under current chamber conditions.

Now V_{air} can be calculated from the initial volume fraction of air in oil at **STP** with the equation for isentropic compression

$$P_1\ V_1^{\,n} = P_2\ V_2^{\,n} \quad \text{...Equation A.7}$$

where states (1) and (2) refer to **STP** and the present chamber conditions respectively; P_1 in Equation A.7 $P_{atmosphere}$. Then

$$V_2 = V_1\left[\frac{P_1}{P_2}\right]^{1/n}$$

which can be re-written as ...Equation A.8

$$V_{air} = V_{air@\,STP}\left[\frac{P_{atmosphere}}{P}\right]^{1/n}$$

P being the current Chamber Pressure

Recalling that **x** is the volume fraction of air in oil at **STP**, we have

$$V_{air\ @\ STP} = x\ V_{Total} \qquad \text{...Equation A.9}$$

which is the volume the entrained air would occupy at **STP**; Then

$$V_2 = V_{air} = x\, V_{Total}\left[\frac{P_{atmosphere}}{P}\right]^{\frac{1}{n}} \qquad \text{...Equation A.10}$$

Also since $\mathbf{V_T = V_{oil} + V_{air}}$, we have

$$V_{oil} = V_{Total}\left[1 - x\left(\frac{P_{atm}}{P}\right)^{\frac{1}{n}}\right] \qquad \text{...Equation A.11}$$

and knowing that for isentropic compression of air, the bulk modulus [3] is given by

$$\beta_{air} = P * \gamma_{air}$$

where

P is the current chamber pressure

γ_{air} is the ratio of specific heats

...Equation A.12

where we will assume that γ_{air} = *1.4 ;*

From Equations A.6, A.10, A.11 and A.12 we have

$$\frac{\Delta P}{\Delta V_{Total}} = -\frac{\gamma_{air}\, P\, \beta_{oil}}{\beta_{oil}\, x\, V_{Total}\left(\frac{P_{atm}}{P}\right)^{1/n} + \gamma_{air}\, P\, V_{Total}\left[1 - x\left(\frac{P_{atm}}{P}\right)^{1/n}\right]} \qquad \text{...Equation A.13}$$

re-arranging terms and simplifying, we arrive at

$$\frac{\Delta P}{\Delta V_T} = - \frac{\beta_{eff}}{V_T}$$

where

...Equation A.14

$$\beta_{eff} = \frac{\beta_{oil}}{\left[1 - x\left(\frac{P_{atm}}{P}\right)^{\frac{1}{n}}\right]} \left[\frac{1}{1 + \frac{\beta_{oil}\, x\, (P_{atm})^{\frac{1}{n}}\, P^{-\left(\frac{n+1}{n}\right)}}{\gamma_{air}\left[1 - x\left(\frac{P_{atm}}{P}\right)^{\frac{1}{n}}\right]}}\right]$$

Parameter	Value	Units	Description
A	1	cm	Refer to figure of Spool Valve Geometry (Figure 10-24)
AIRFRA	3.5	%	AIR FRAction in oil
B	1.5	cm	Refer to figure of Spool Valve Geometry (Figure 10-24)
BRK1	0.05	sec	Length of command pulse that controls engagement and disengagement. Developed mainly for simulation purposes: chosen as 50 ms in this version
C	0.8	cm	Refer to figure of Spool Valve Geometry (Figure 10-24)
CD	0.8		Coefficient of Discharge for all orifices
CNOT	17.0316		Const. Multiplier for orifice flow in Solenoid Valve
CORNER	15		Tuning factor for corner resistance in RPQPG
CREL	0.5		Relative Eccentricity Factor - for annular flow calculations
D	0.5	cm	Refer to figure of Spool Valve Geometry (Figure 10-24)
d1	0.2	cm	Refer to figure of Spool Valve Geometry (Figure 10-24)
d2	0.15	cm	Refer to figure of Spool Valve Geometry (Figure 10-24)
DAMPRT	150	N-s/cm	The damping coefficient for the pin chamber walls
DCHMBR	0.80165	cm	Refer to figure of Spool Valve Geometry (Figure 10-24)
DPIN	0.605	cm	Diameter of the Pin face
DRAFED	4.00E-01	cm	Diameter of feed hole for oil into the DRA
DSMALL	0.54	cm	Refer to figure of Spool Valve Geometry (Figure 10-24)
DSPOOL	0.79915	cm	Refer to figure of Spool Valve Geometry (Figure 10-24)
E	0.2	cm	Refer to figure of Spool Valve Geometry (Figure 10-24)
EMOD	1.72E+05	N/cm^2	Bulk Modulus of Oil (10W30)
F	0.62	cm	Refer to figure of Spool Valve Geometry (Figure 10-24)
FLSPSPR	1.129	cm	Free length of the spool spring
FLUXBILD	0.003	sec	Time taken for flux build-up in Solenoid Valve Coil
FLUXDISCH	0.003	sec	Time taken for flux discharge from Solenoid Valve Coil
G	0.845	cm	Refer to figure of Spool Valve Geometry (Figure 10-24)
GAMMA	1.4		Ratio of Specific Heats
H	1.093	cm	Refer to figure of Spool Valve Geometry (Figure 10-24)
I	0.973	cm	Refer to figure of Spool Valve Geometry (Figure 10-24)
ILSPSPR	0.96278	cm	Installed length of Spool Spring
KSPOOL	18	N/cm	Stiffness of Spool Spring (from COLETECH)
KSPRING	4	N/cm	Stiffness of Pin Spring
KWALL	1.00E+06	N/cm	Stiffness of the wall in the Spool Chamber
KWALL2	1.00E+06	N/cm	Stiffness of the wall in Pin chamber
LCHMBR	3.5815	cm	Refer to figure of Spool Valve Geometry (Figure 10-24)
LPIN	0.775	cm	Length of Pin: non-engagement section
LPINCHMBR	1.1	cm	Length of Pin chamber: non-engagement section
LSPOOL	3.3	cm	Refer to figure of Spool Valve Geometry (Figure 10-24)
MATLDNSTY	8.00E-05	N-s^2/cm^4	Density of Spool Material (SS 303)
NDRAFD	5.00E-01	cm	Diameter of feed hole into NDRA
PATM	10.14	N/cm^2	Atmospheric Pressure
PSUPLY	41.162	N/cm^2	Supply Pressure from pump
RHO	8.50E-06	N-s^2/cm	Density of Oil
UNSEATPRS	25	psig	The pressure at which the pin is designed to start movement from end.
VISCOS	1.09E-06	N-s/cm^2	Viscosity of oil @ 200 F
VOLSPL	1.1372	cm^3	Volume of Spool Material- refer spool figure
WALDMP	150	N-s/cm	Damping coefficient of the wall

NOTE: Some of the above are used as Named Parameters in the ENPORT model

Table A.1: Spread Sheet of Named Parameters

Parameter	Value	Units	Description
ASPOOL	5.02E-01	cm^2	Pi * (DSPOOL^2)/4: The area of the complete spool face
BILDUP	0.053	sec	BRK1 + FLUXBILDUP where 0.003 sec is the time required for flux build-up
BILDUP2	0.103	sec	BRK2 + FLUXDISCH where 0.003 sec is the time required for flux discharge
BRK2	0.1	sec	2*BRK1 the 2nd breakpoint for the command pulse train
BRK3	0.15	sec	3*BRK1 the 3rd break point for command pulsetrain
FPRELD	4.95517689	N	Preload on Pin Spring - the equivalent force of unseat pressure in Basic Parameter table
HSPL2	0.00125	cm	DCHMBR - DSPOOL: clearance between spool and chamber @ Rx2 end
HSPOOL	0.00125	cm	DCHMBR - DSPOOL: clearance between spool and chamber @ Rx1 end
PAREA	0.2874754	cm^2	Pi*DPIN^2/4: The area of the pin face - non-engagement section
PINMAX	3.25E-01	cm^2	LPINCHMBR- LPIN: The maximum distance that the pin can travel between walls
R1OVLP	0.095	cm	Refer Figure 10-24:(G+D/2)-A: Rx1 enters transition phase when spool moves this distance from left wall
R2OVLP	0.161	cm	Refer Figure 10-24 :(G+H+I-D/2)-(A+B): Rx2 enters transition phase when spool moves this distance from left wall
SPLMXX	0.2815	cm	LCHMBR-LSPOOL: Maximum ditance the spool can travel between the walls
SPRELO	2.99196	N	Preload on the Spool Spring
VOLCH1	0.033696	cm^3	The volume of the chamber on the left side when the spool is hard left: this is the vol of the "X"
VOLCH2	0.202463	cm^3	The volume on the right side of when the spool is hard left; also refer to Figure 10-24.
VSHFT	17.278	cm^3	The volume inside the rocker shaft: given by FORD
WIDSPL	2.5106038	cm	Pi * DSPOOL: Circumference of the spool's maximum dia.

Table A.2: Spread Sheet of Named Parameters (...continued)

APPENDIX B

SYSTEM BOND GRAPHS AND SIMULATION PLOTS

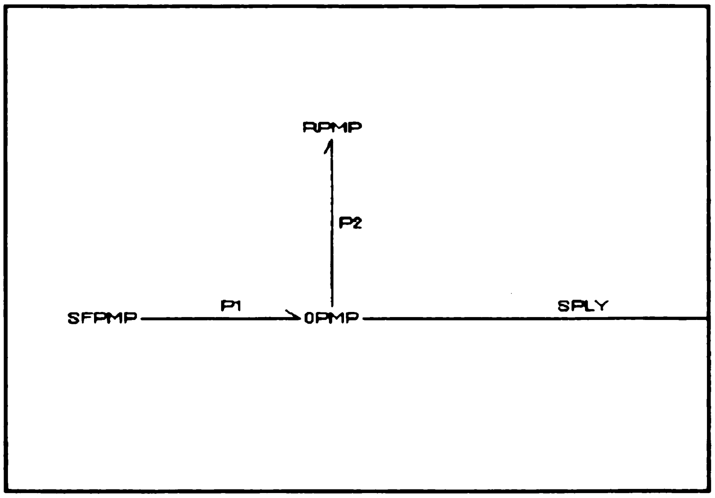

Figure B1-1: Bond Graph Model for the Flow Limited Pump

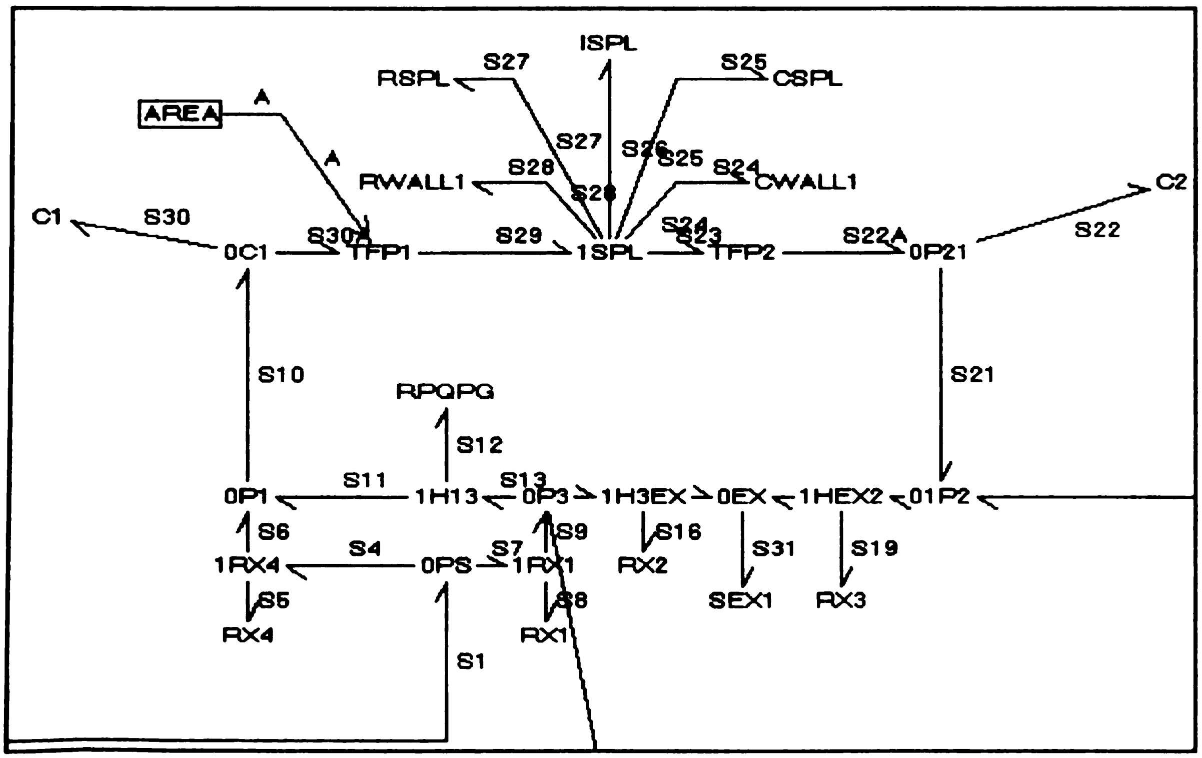

Figure B1-2: Bond Graph Representation of the Spool Valve

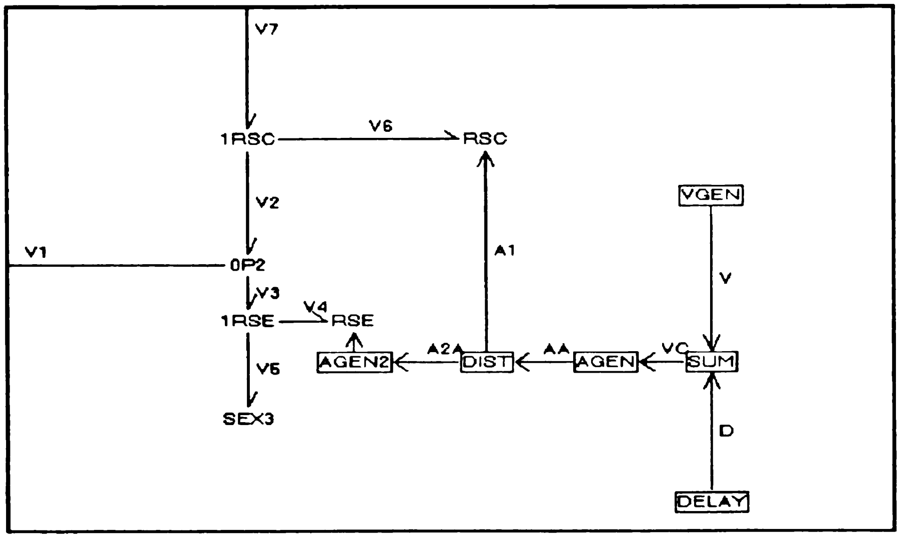

Figure B1-3: Bond Graph Representation of the Solenoid Valve

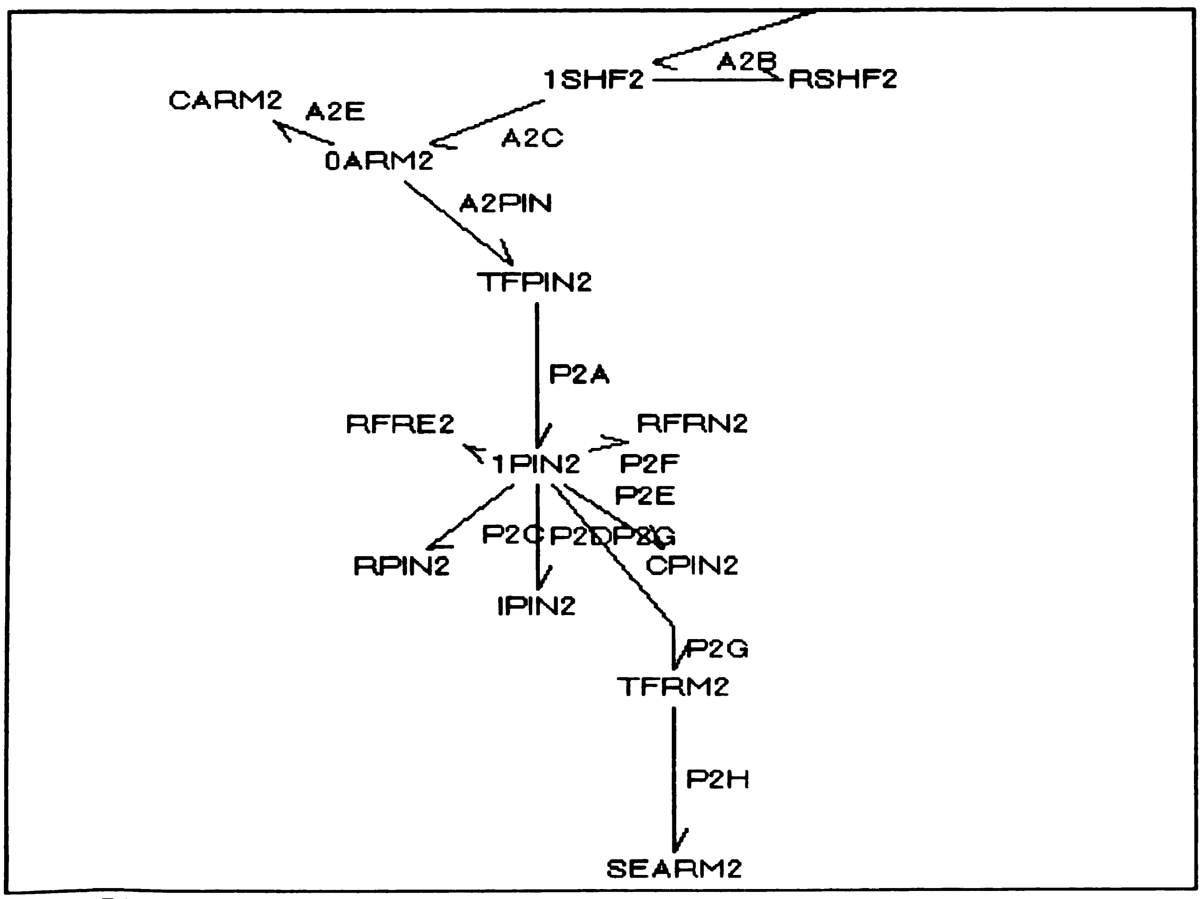

Figure B1-4: Bond Graph Representation of the Actuator

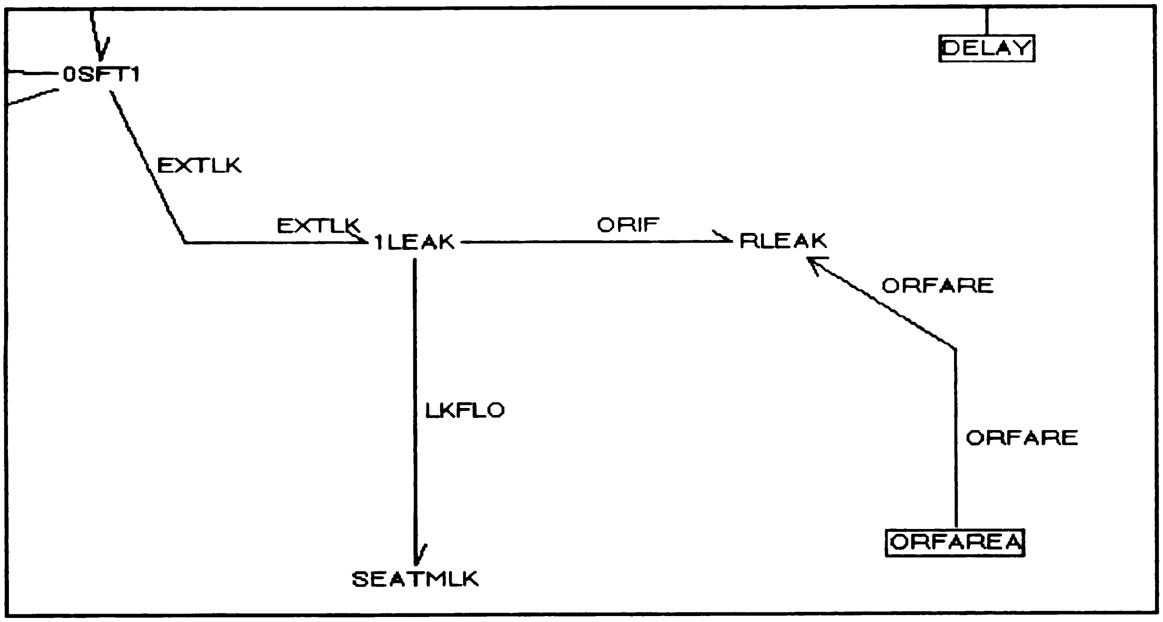

Figure B1-5: Bond Graph Representation of the Leakage

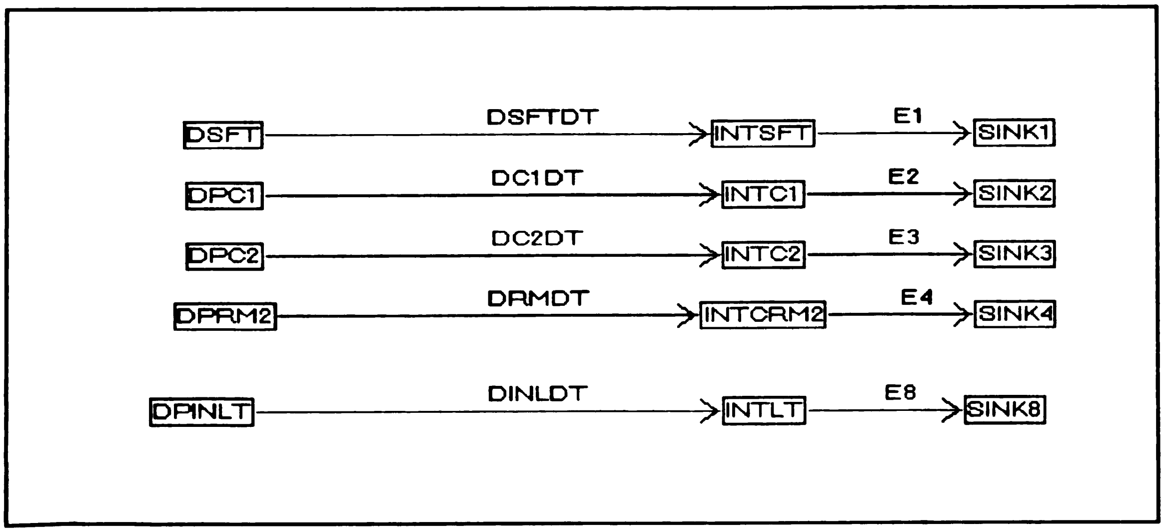

Figure B1-6: Bond Graph of the Function Blocks

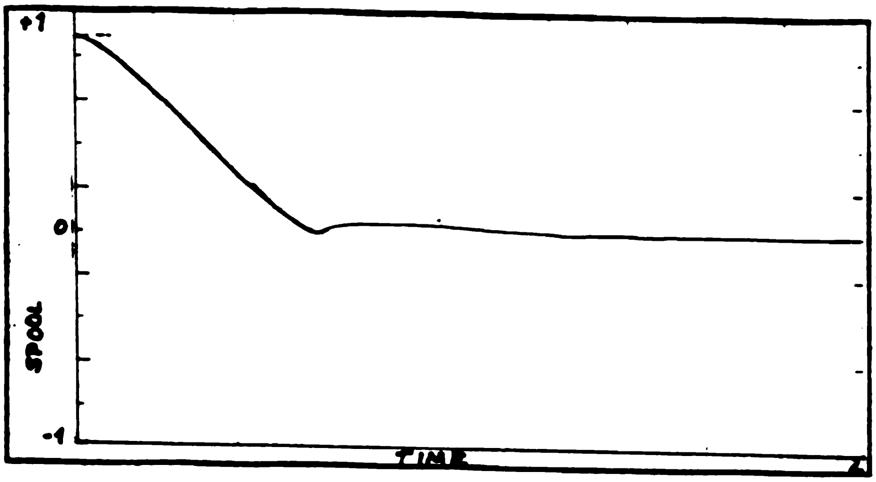

Figure B2-1: Spool Movement in Disengagement Mode-For Model described in Section 2.4

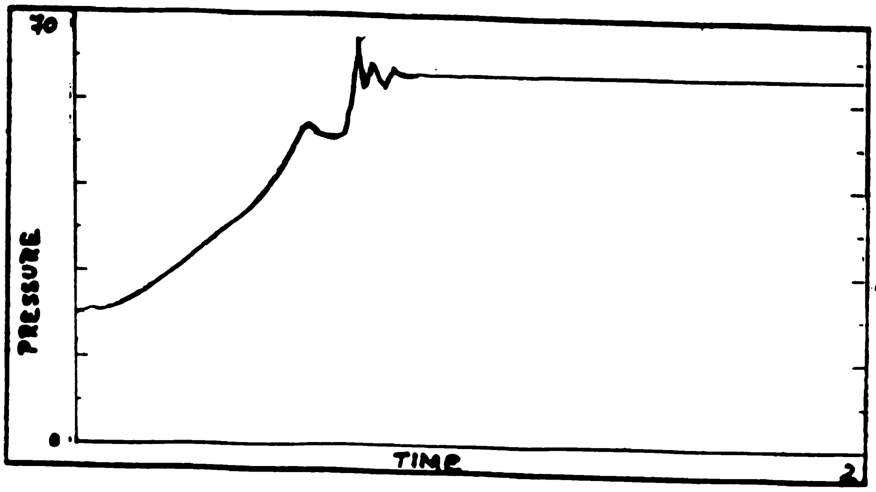

Figure B2-2: Pressure Profile in Disengagement Mode- For Model described in Section 2.4

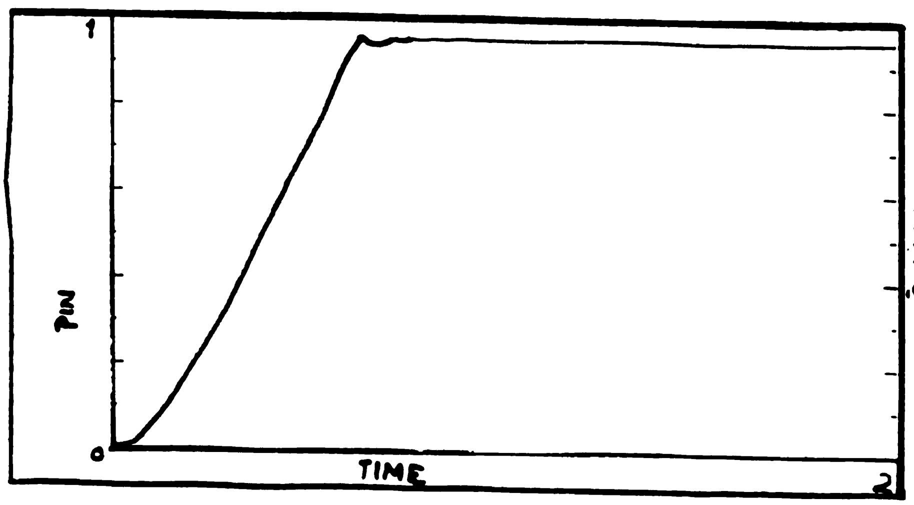

Figure B2-3: Pin Movement in Disengagement Mode- For Model described in Section 2.4

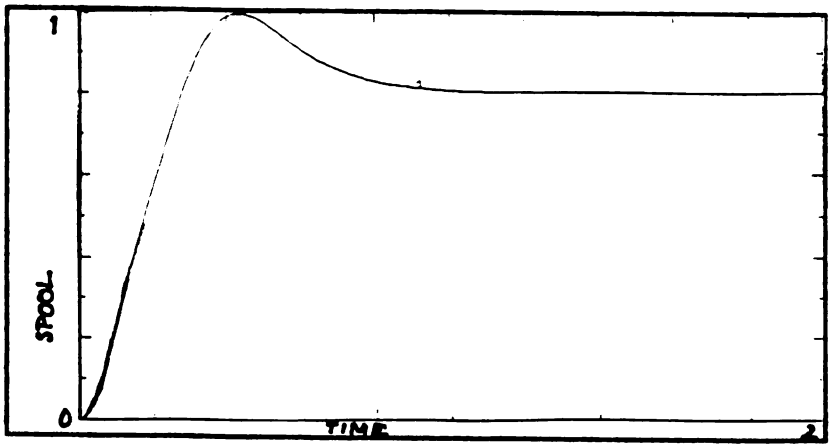

Figure B2-4: Spool Movement in Engagement Mode-For Model described in Section 2.4

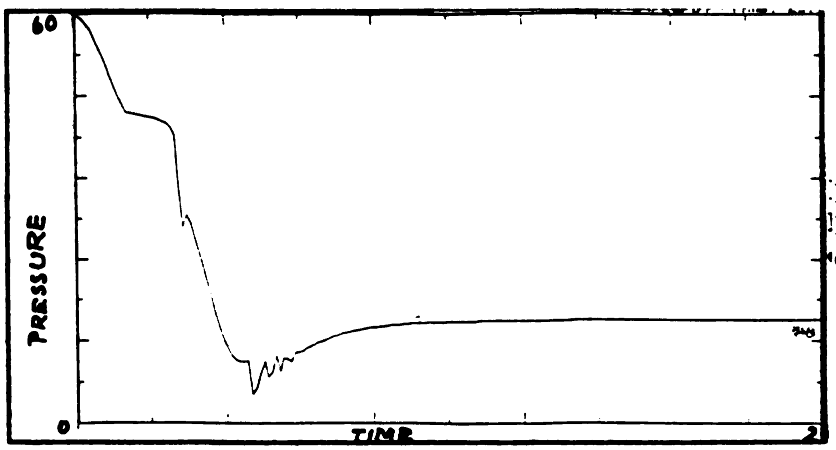

Figure B2-5: Pressure Profile in Engagement Mode- For Model described in Section 2.4

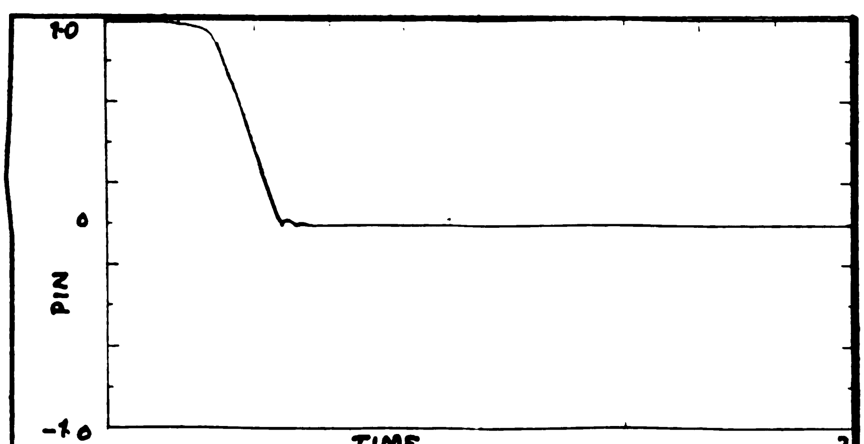

Figure B2-6: Pin Movement in Engagement Mode- For Model described in Section 2.4

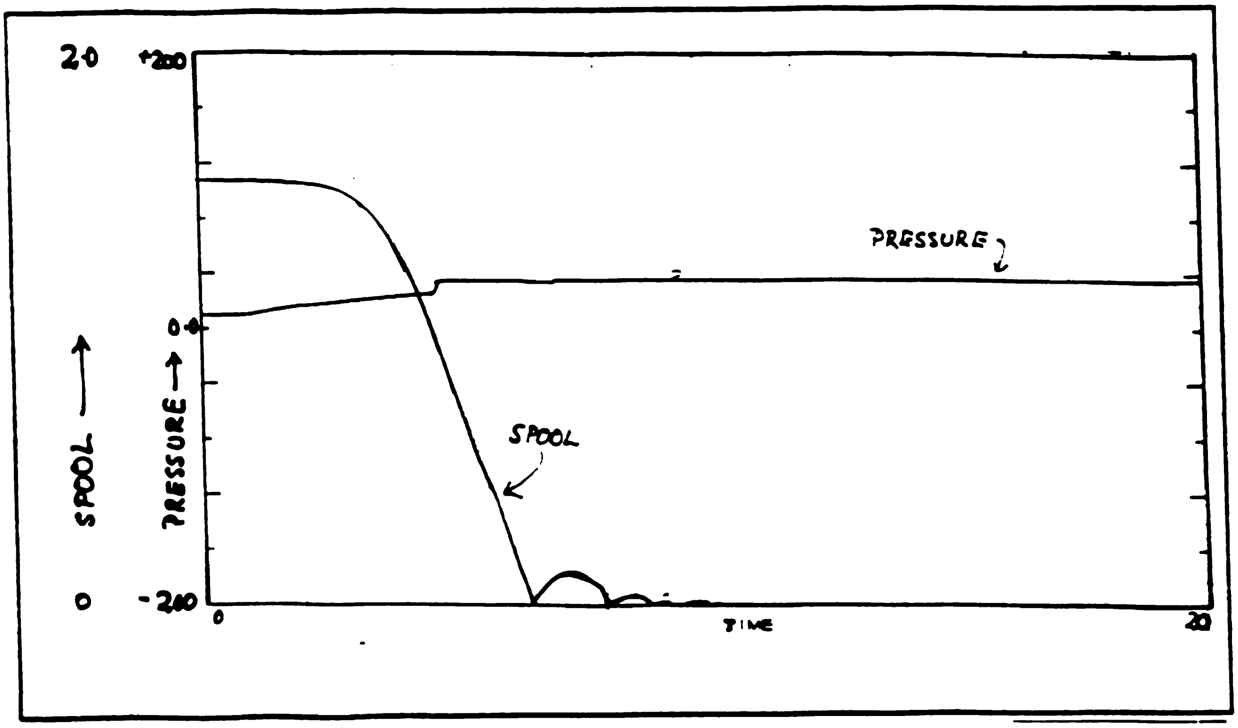

Figure B2-7: Spool Movement and Pressure Profile in Disengagement Mode-For Model described in section 2.5

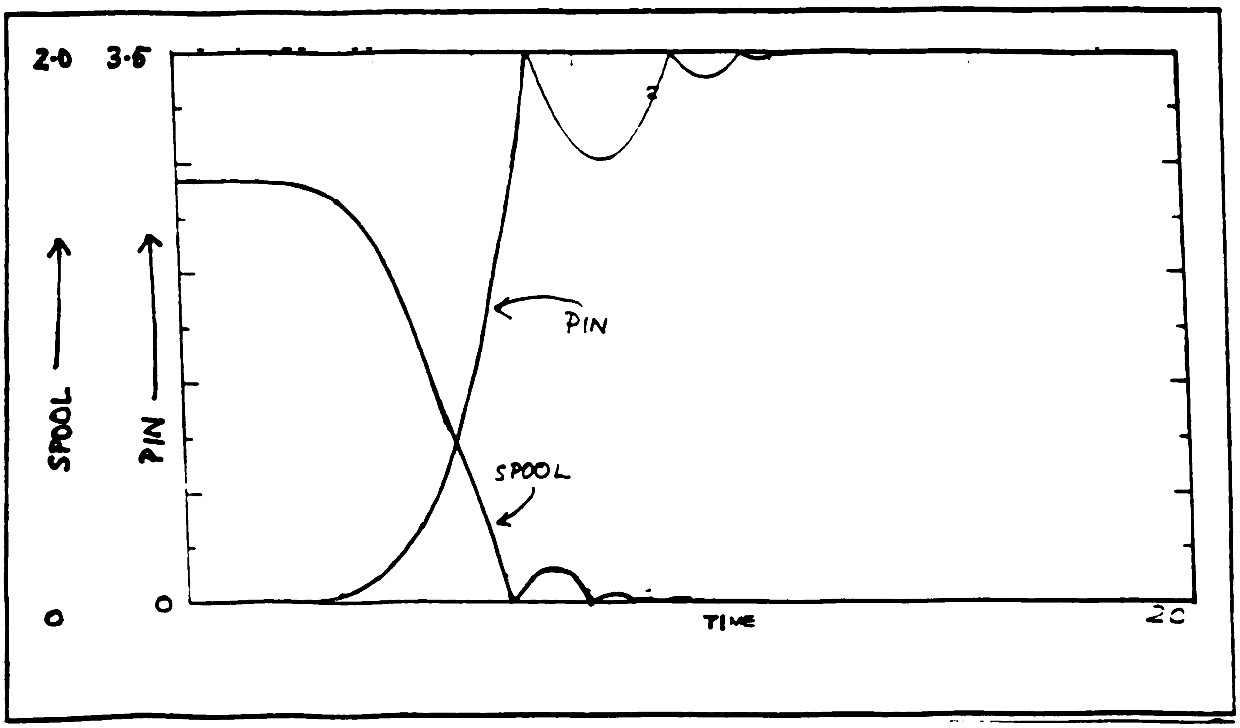

Figure B2-8: Spool and Pin Movement in Disengagement Mode- For Model described in Section 2.5

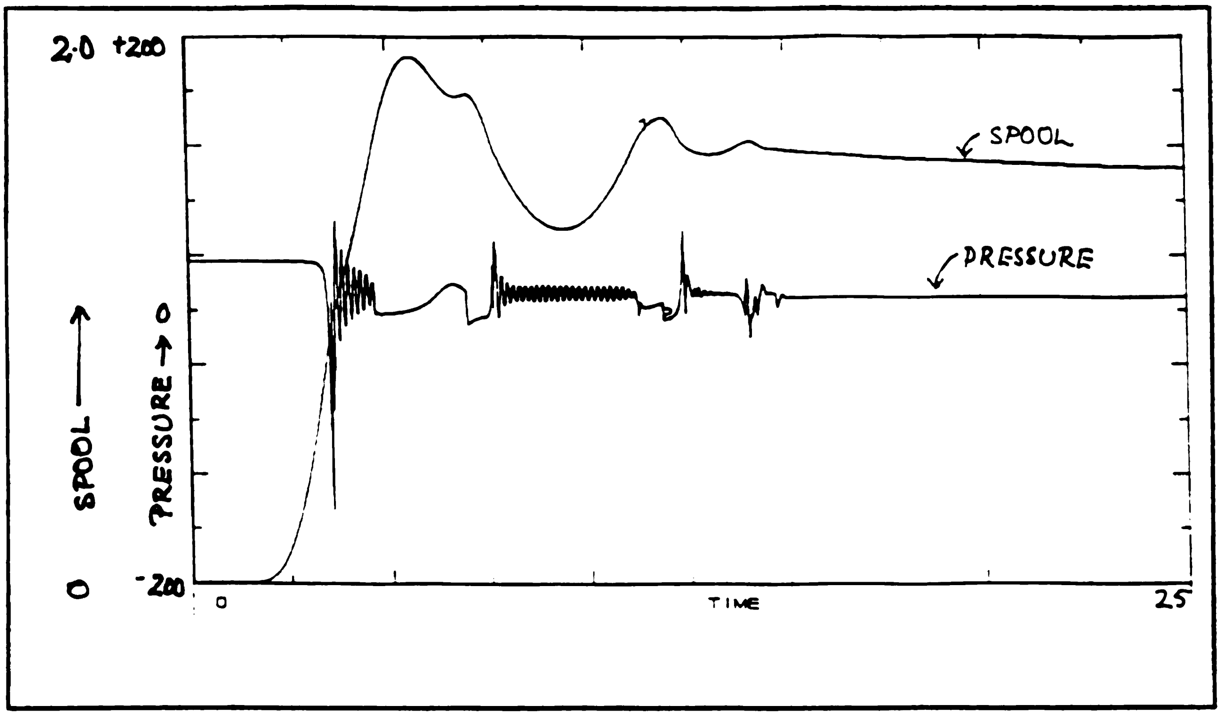

Figure B2-9: Spool Movement and Pressure Profile in Engagement Mode-For Model described in section 2.5

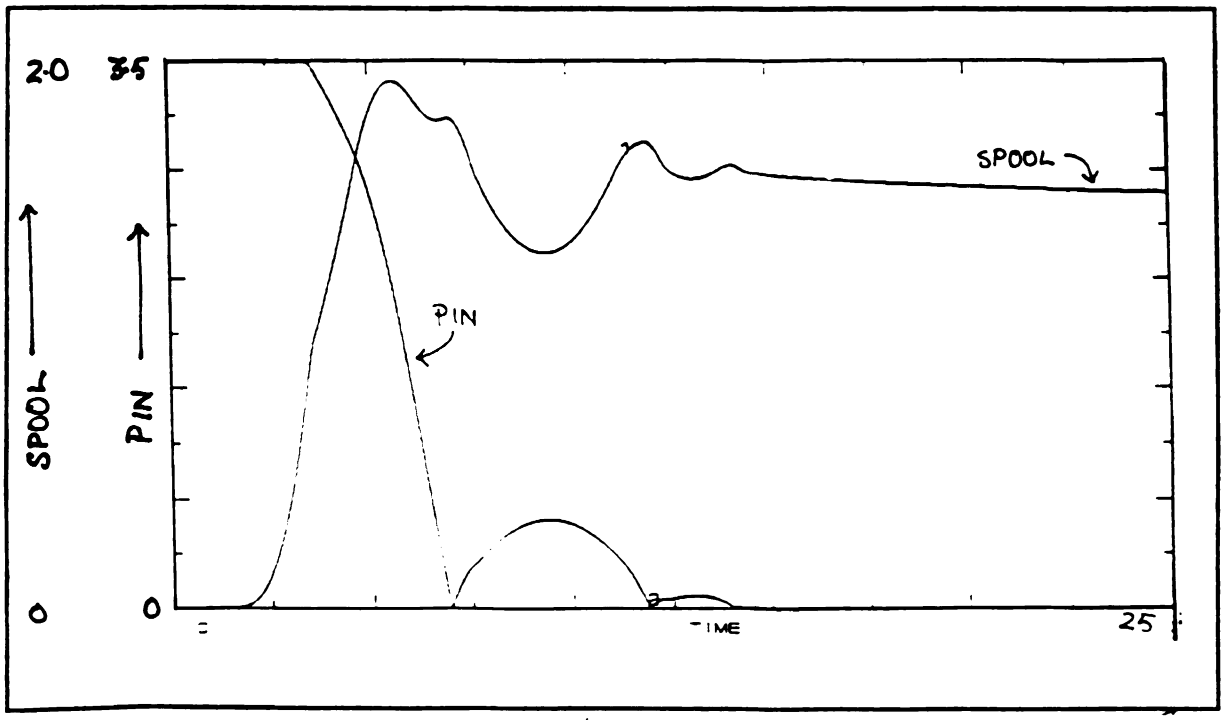

Figure B2-10: Spool and Pin Movement in Engagement Mode- For Model described in Section 2.5

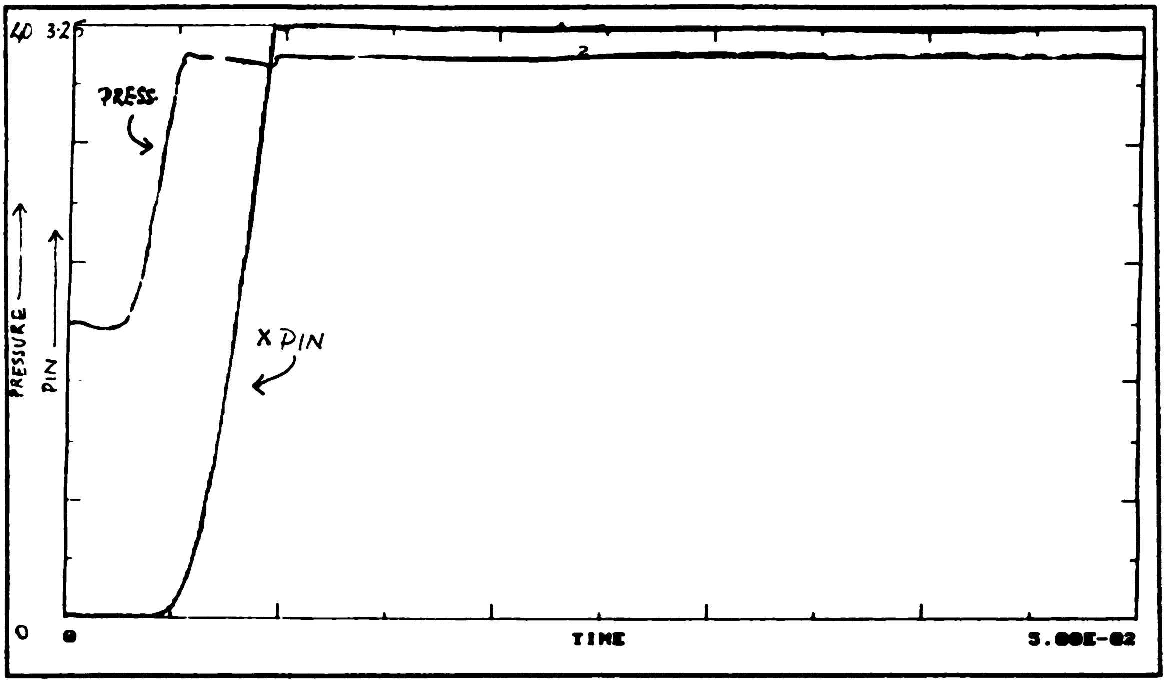

Figure B2-11: Pin Movement and Pressure Profile in Disengagement Mode-For Model described in section 2.6

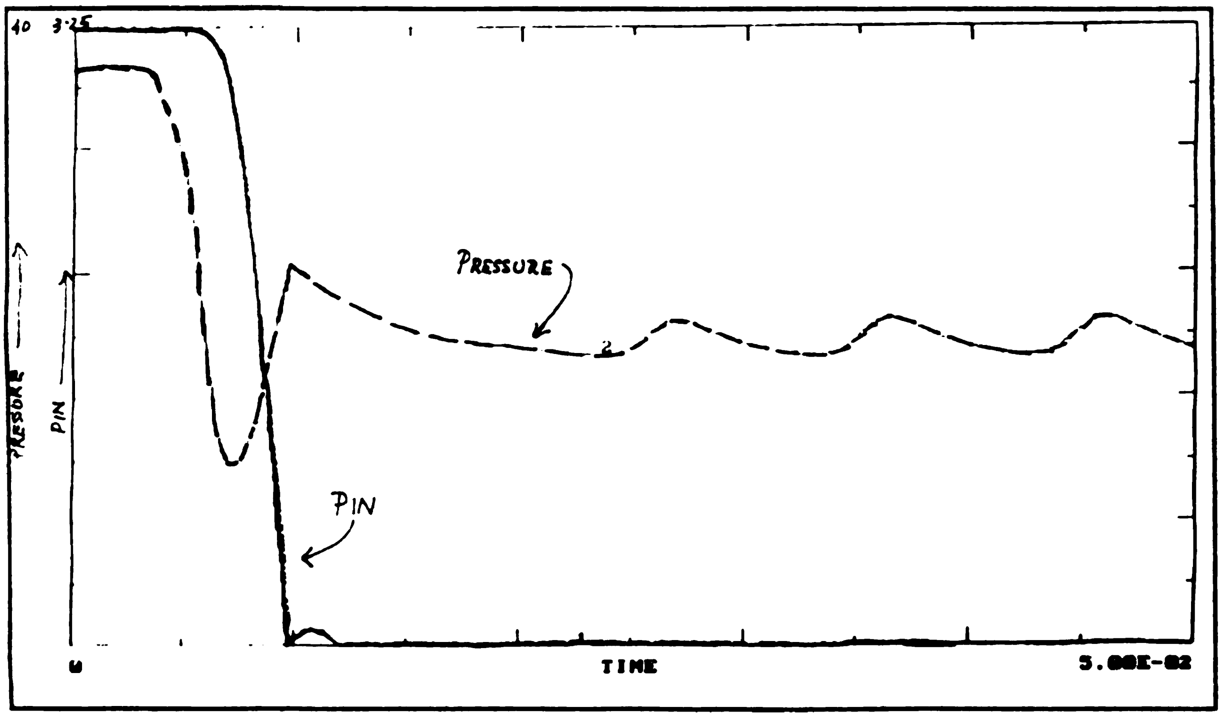

Figure B2-12: Pin Movement and Pressure Profile in Engagement Mode- For Model described in Section 2.6

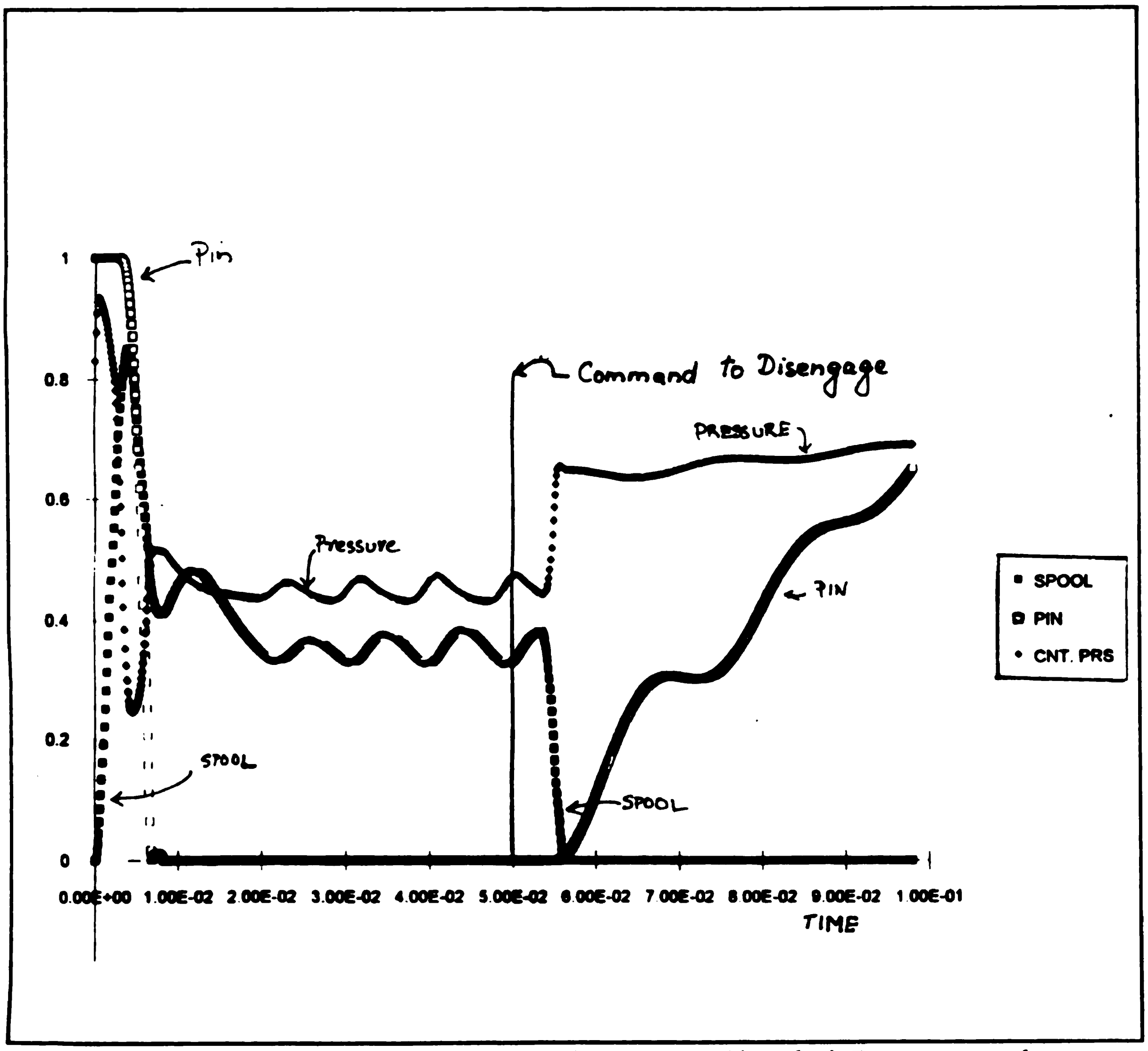

Figure B2-13: Spool Movement, Pin Movement and Pressure Profile in both Engagement and Disengagement Modes - for the Model described in Section 2.7.

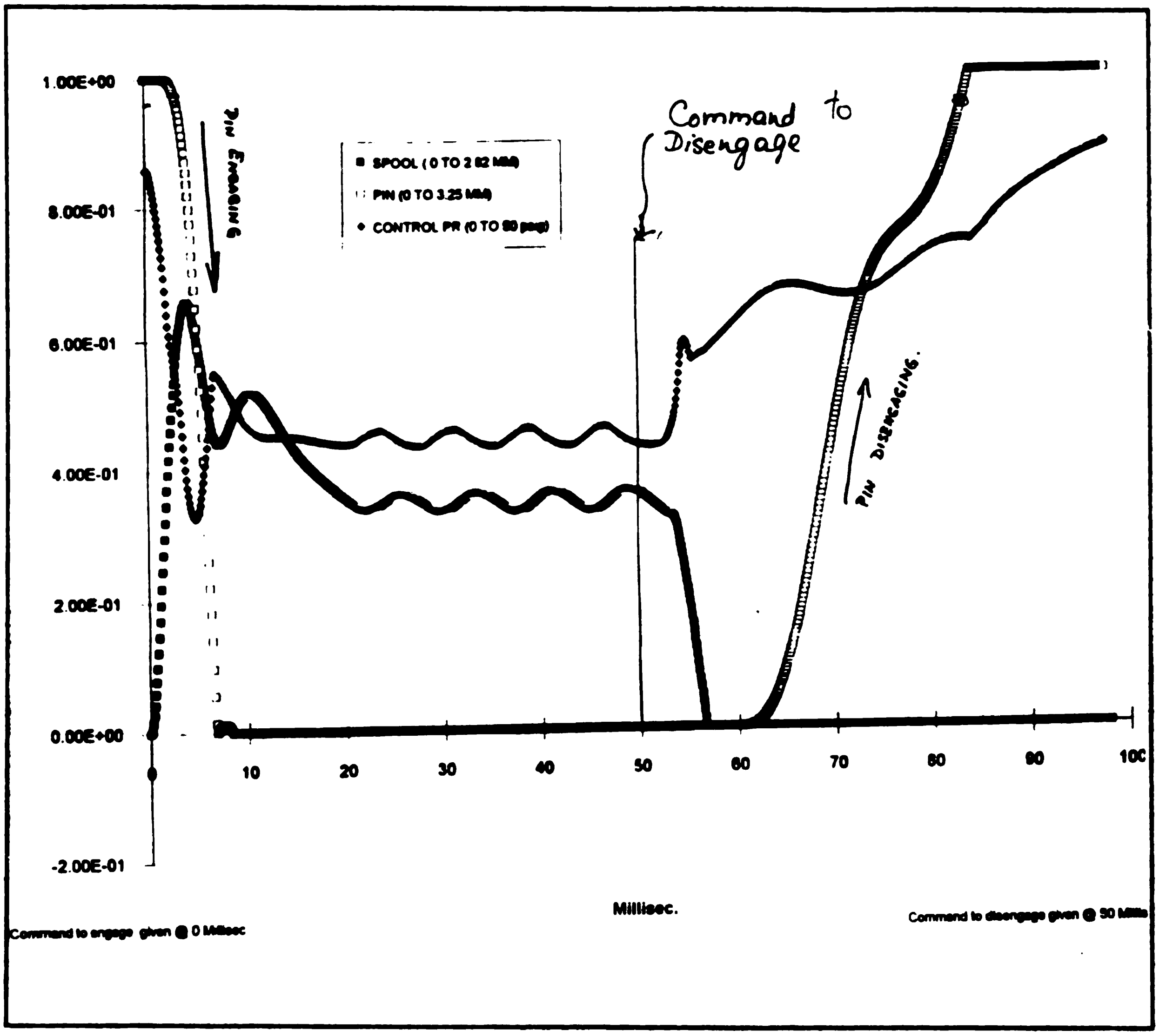

Figure B2-14: Spool Movement, Pin Movement and Pressure Profile in both Engagement and Disengagement Modes - for the the Complete Model described in Section 2.8. These results pertain to a low power pump.

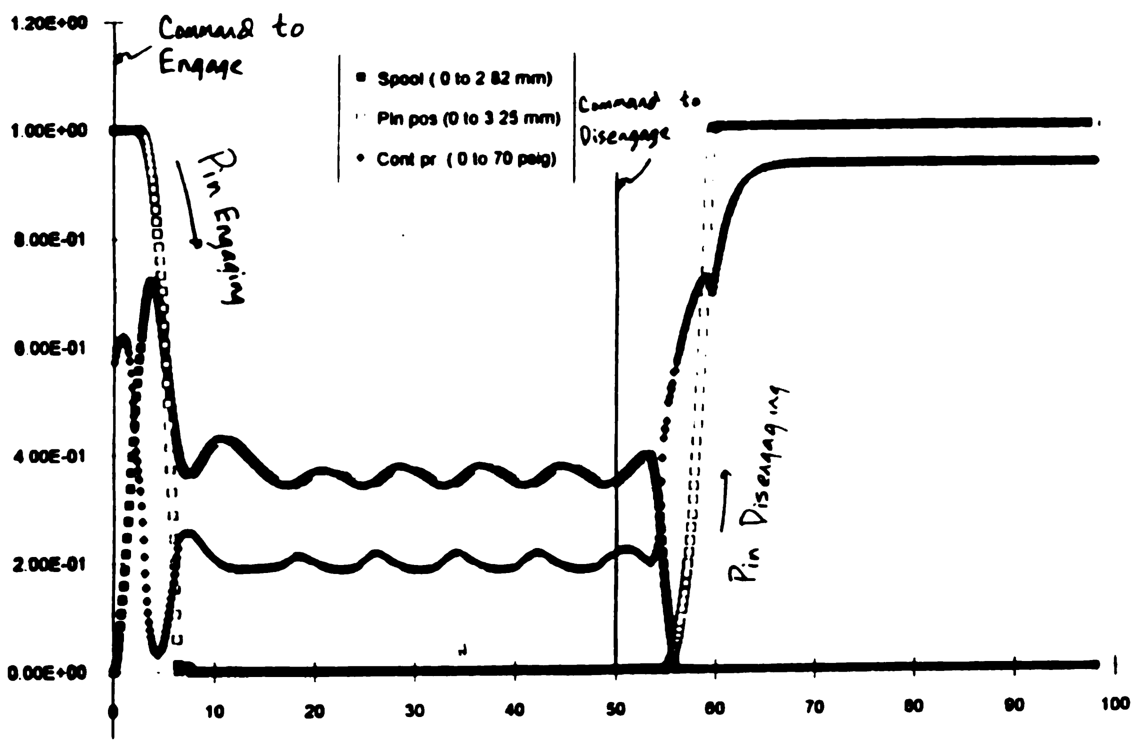

Figure B2-15: Spool Movement, Pin Movement and Pressure Profile in both Engagement and Disengagement Modes - for the Complete Model described in Section 2.8. These results pertain to a more powerful pump in the circuit.

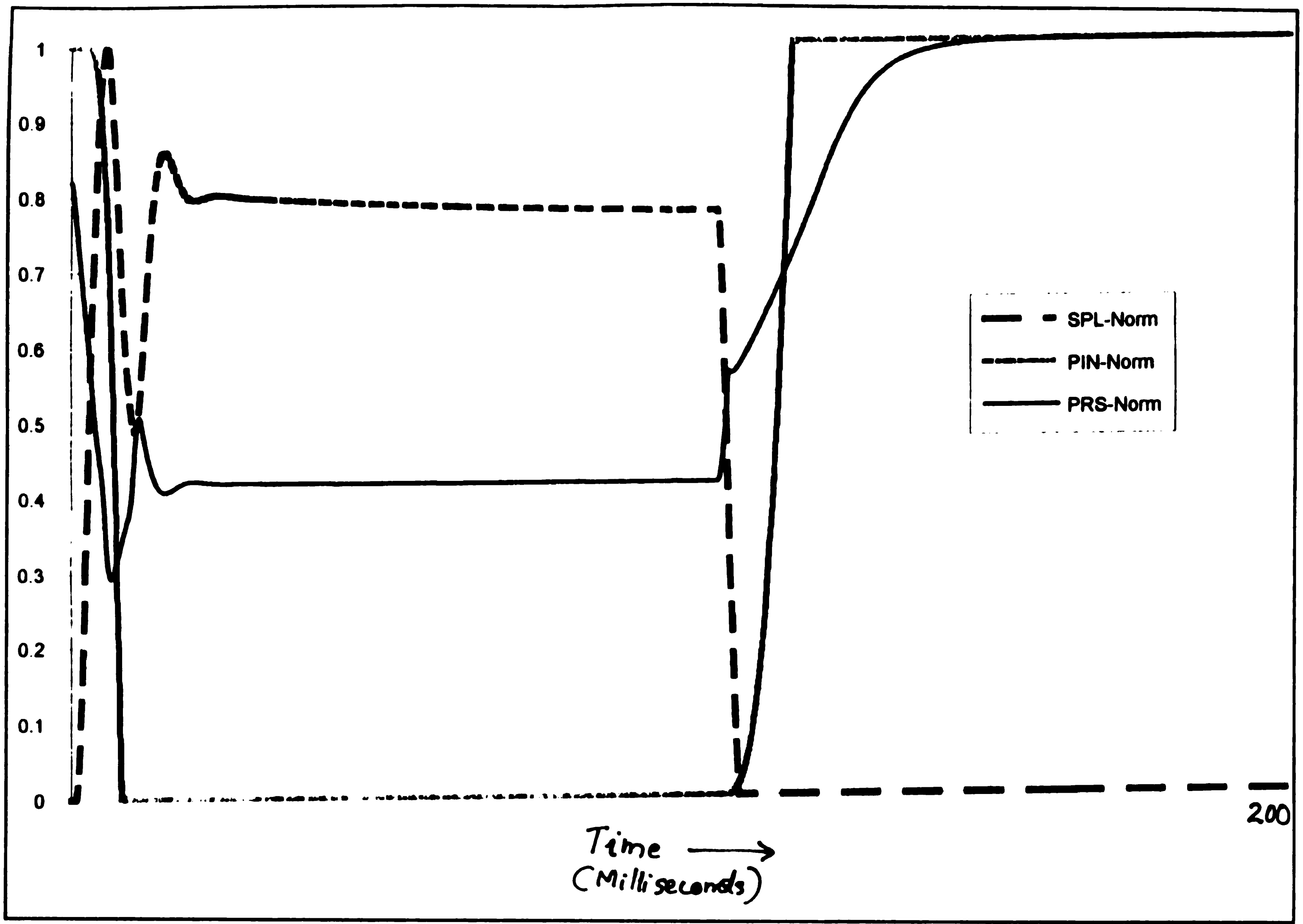

Figure B2-16: Spool Movement, Pin Movement and Pressure Profile in both Engagement and Disengagement Modes - for the Complete Model described in Section 2.8. The leakage from the actuator circuit has been reduced.

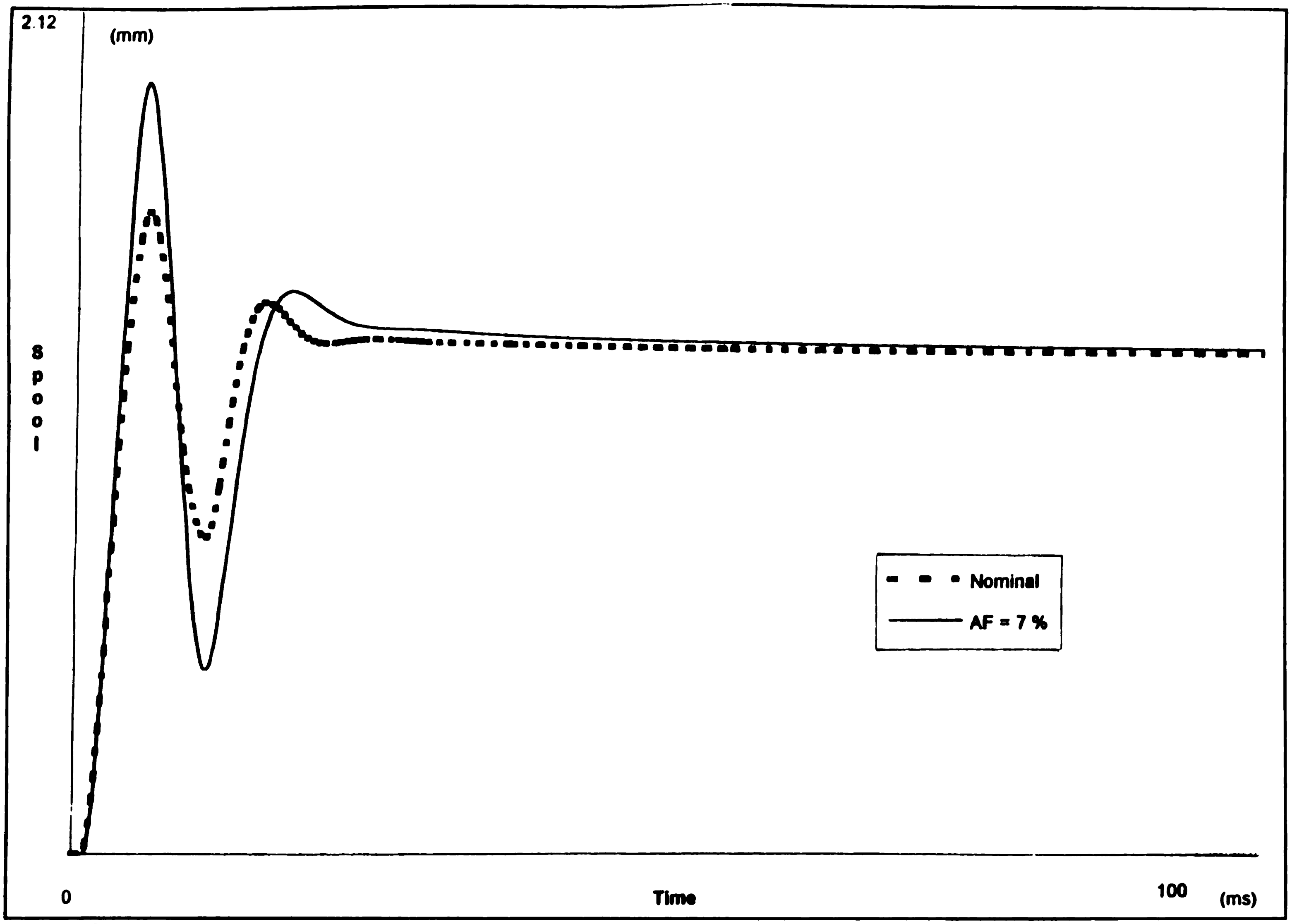

Figure B3-1: Spool Movement in Engagement Mode - for the Model described in Section 4.1. The air fraction in the fluid has been doubled from the Nominal value.

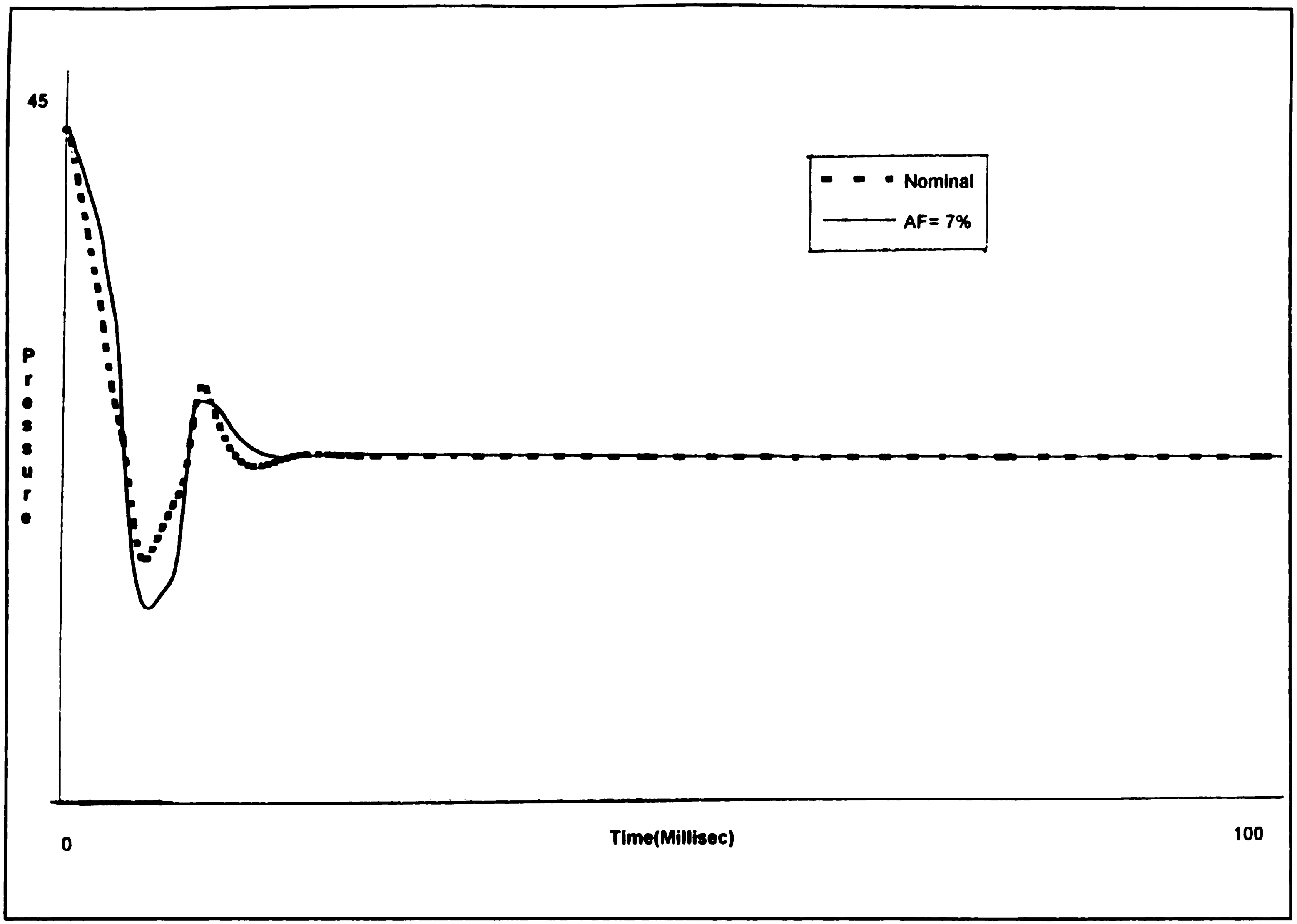

Figure B3-2: Pressure Profile in Engagement Mode - for the Model described in Section 4.1. The air fraction in the fluid has been doubled from the Nominal value

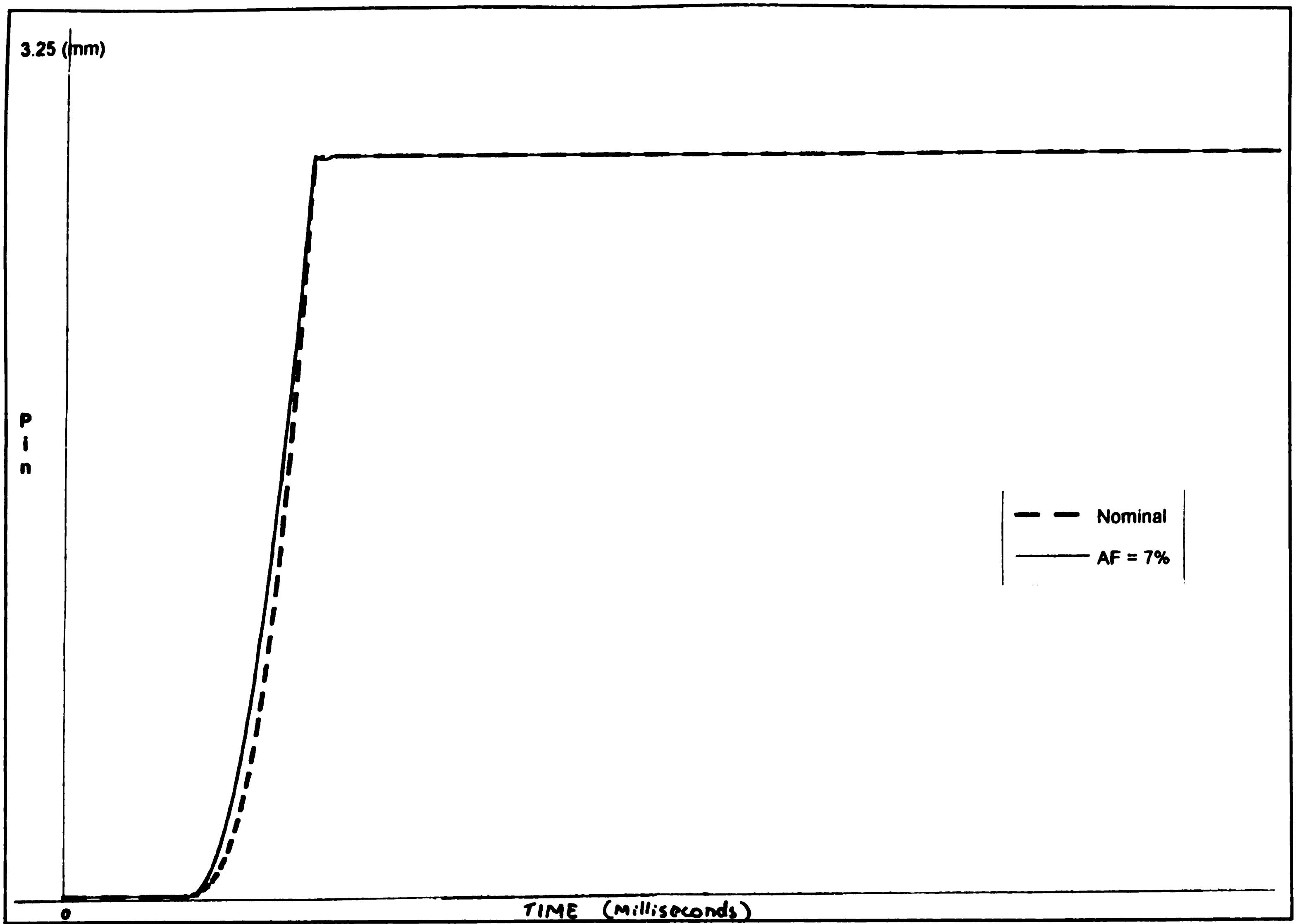

Figure B3-3: Pin Movement in Disengagement Mode - for the Model described in Section 4.1. The air fraction in the fluid has been doubled from the Nominal value

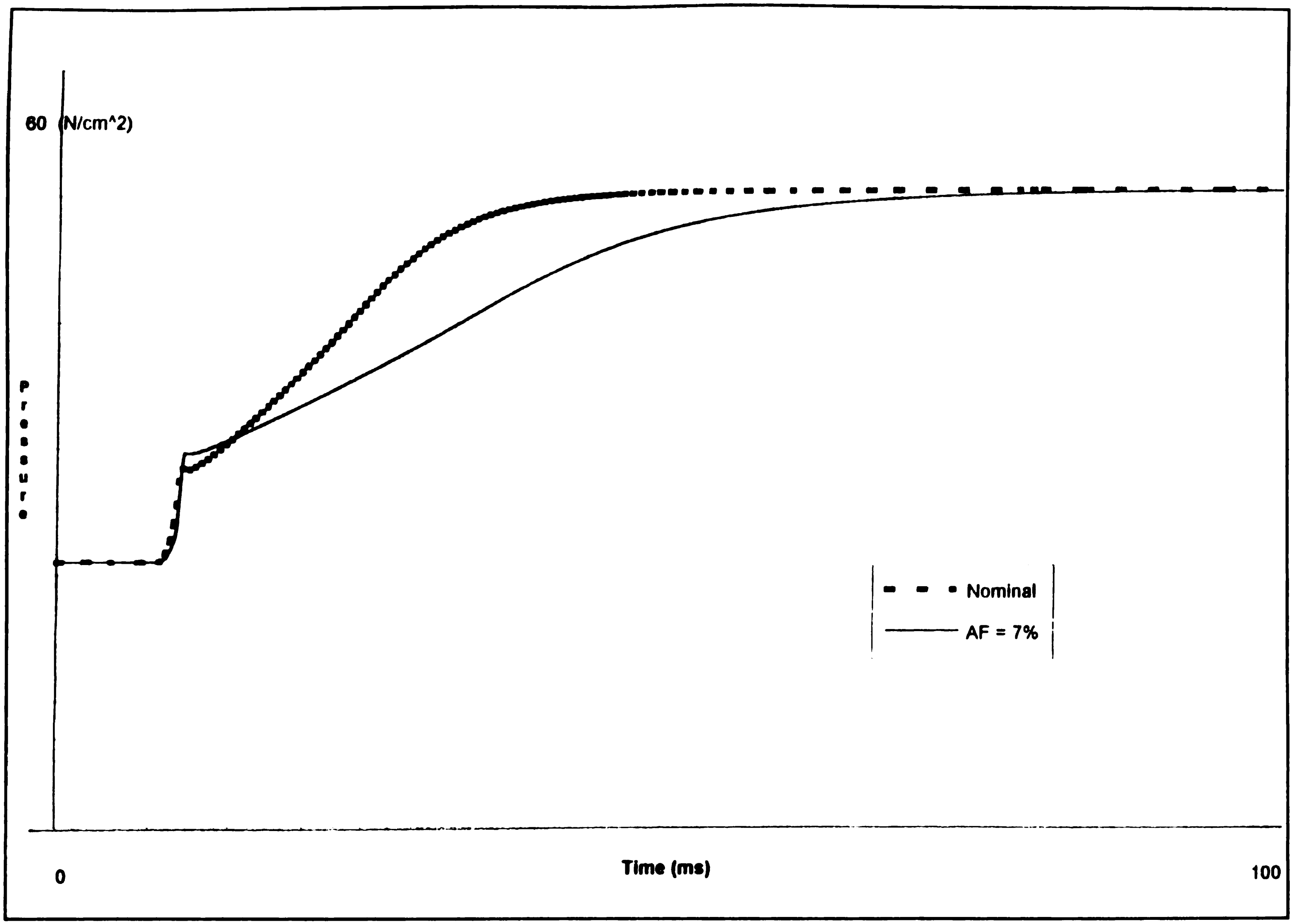

Figure B3-4: Pressure Profile in Disengagement Mode - for the Model described in Section 4.1. The air fraction in the fkuid has been doubled from the Nominal value

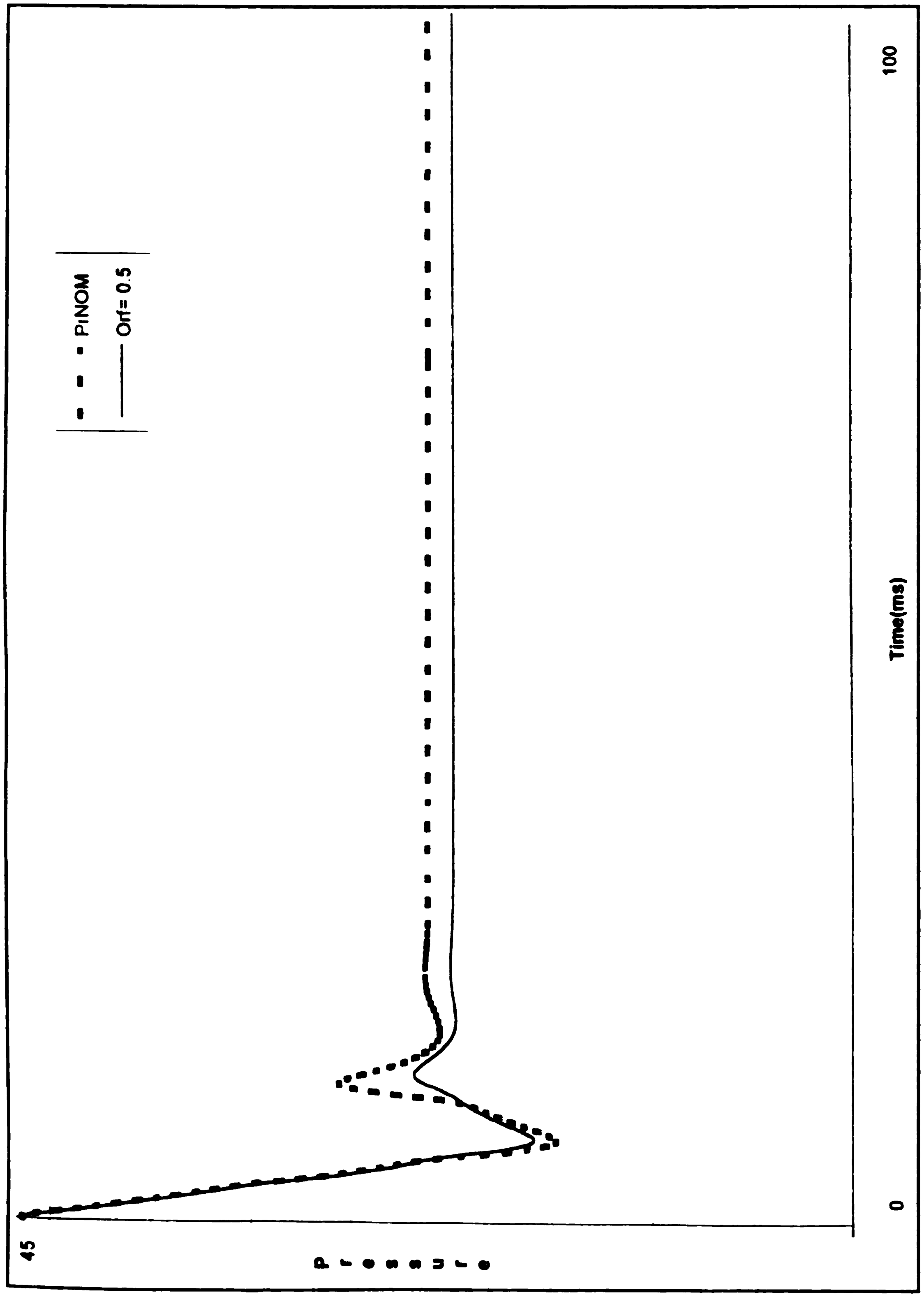

Figure B3-5: Pressure Profile in Engagement Mode - for the Model described in Section 4.2. The Leakage is ten times the Nominal value

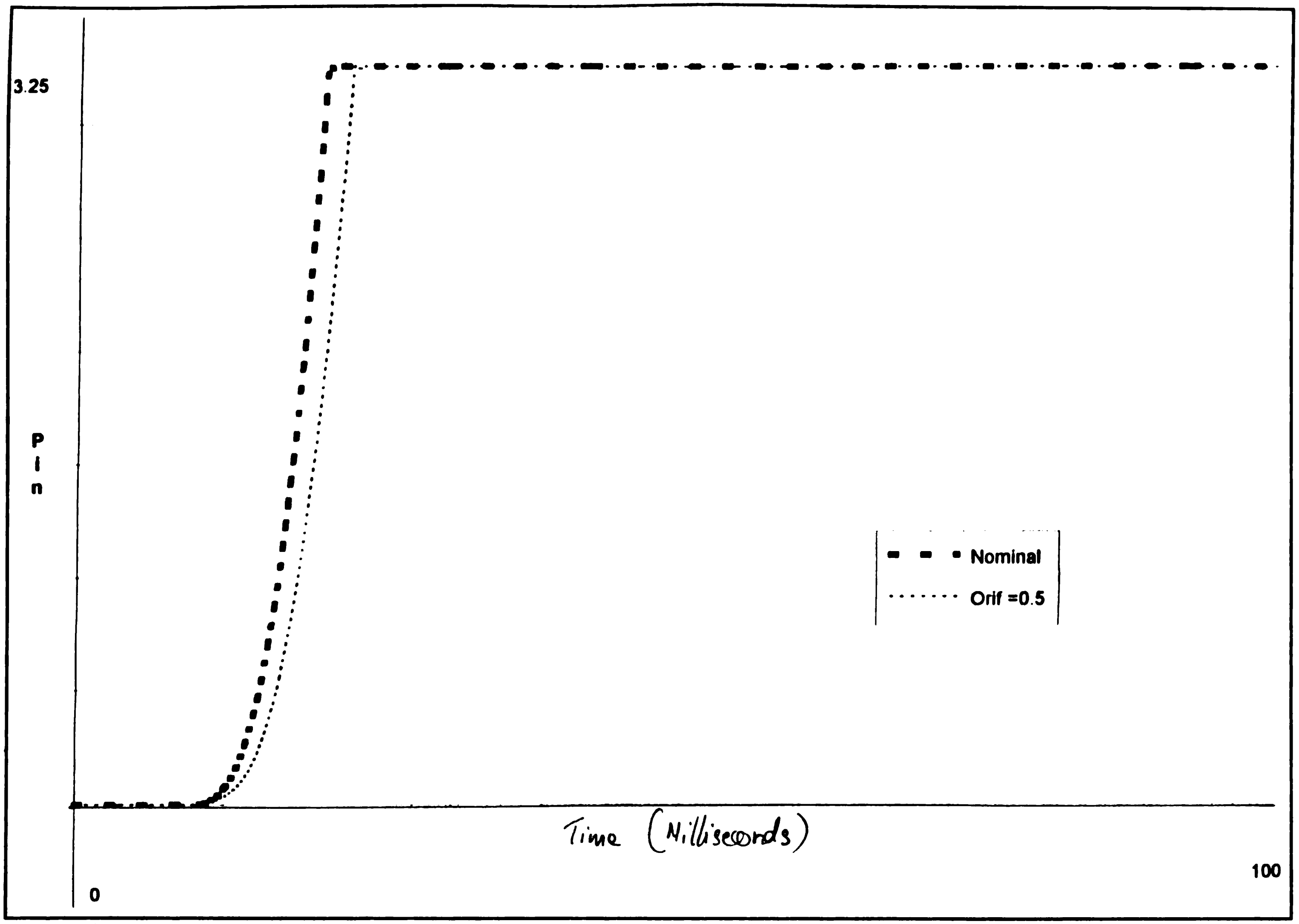

Figure B3-6: Pin Movement in Disengagement Mode - for the Model described in Section 4.2. The Leakage is ten times the Nominal value

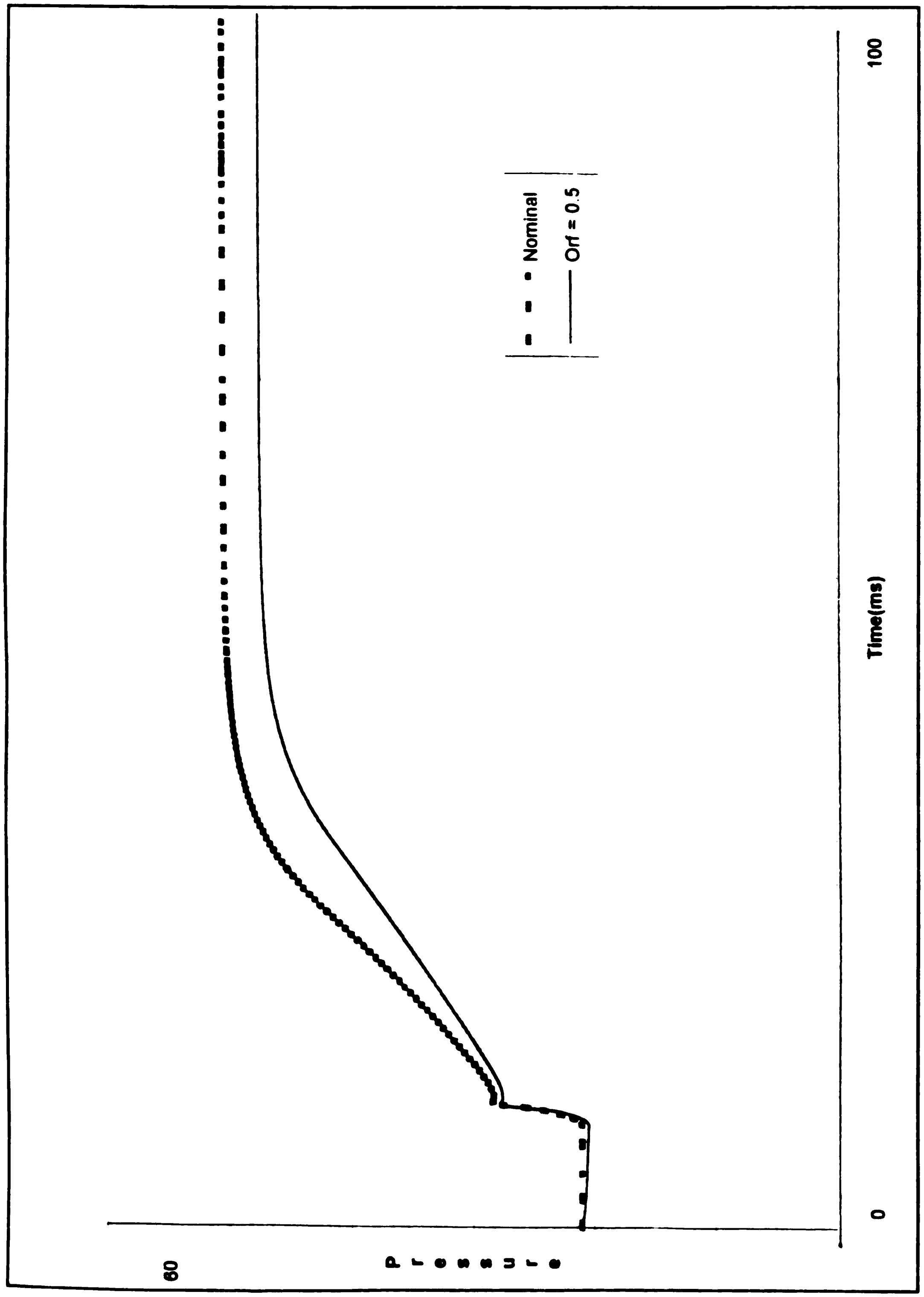

Figure B3-7: Pressure Profile in Disengagement Mode - for the Model described in Section 4.2. The Leakage is ten times the Nominal value

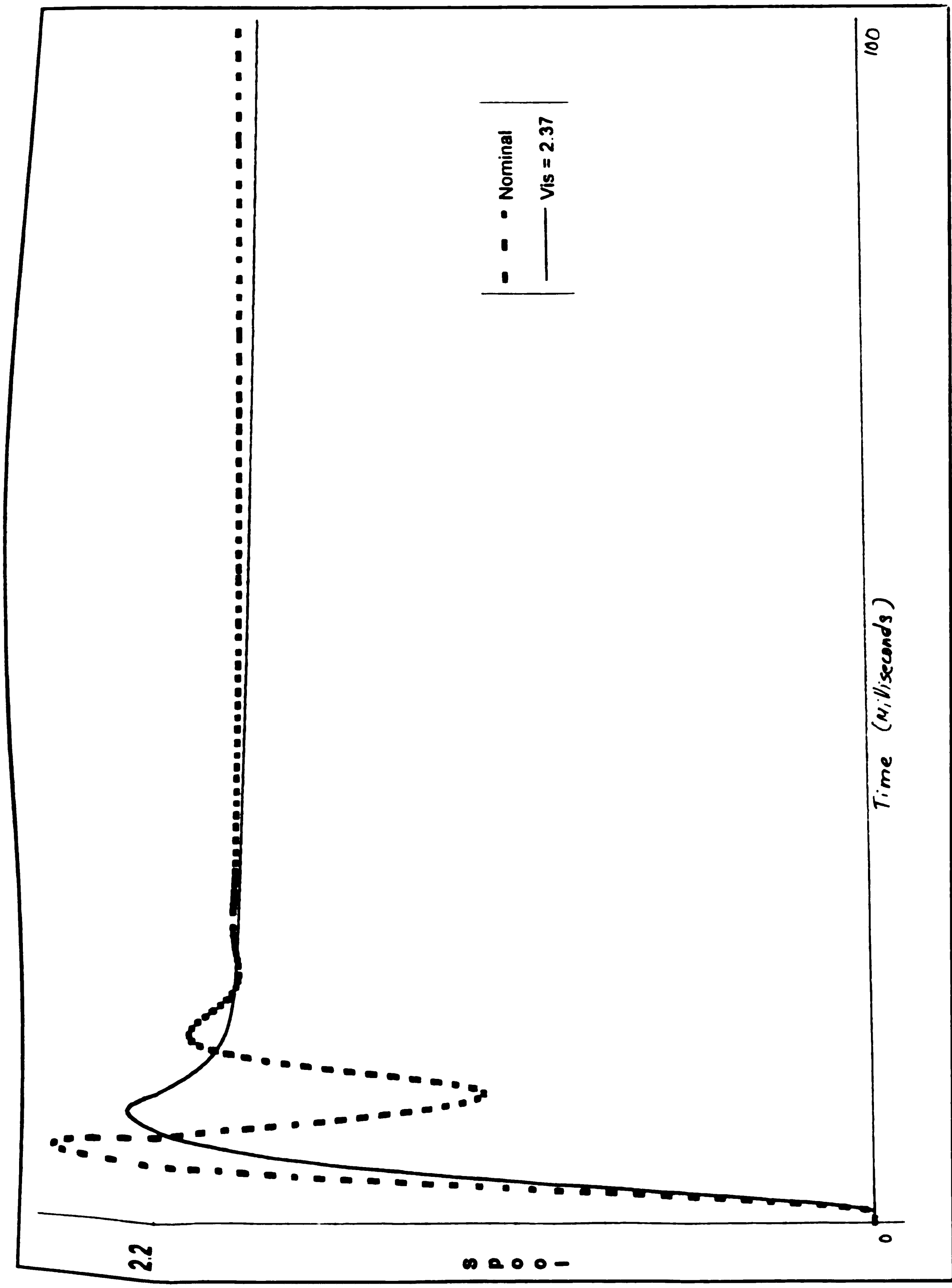

Figure B3-8: Spool Movement in Engagement Mode - for the Model described in Section 4.3. The Temperature is 50 degrees below the Nominal value

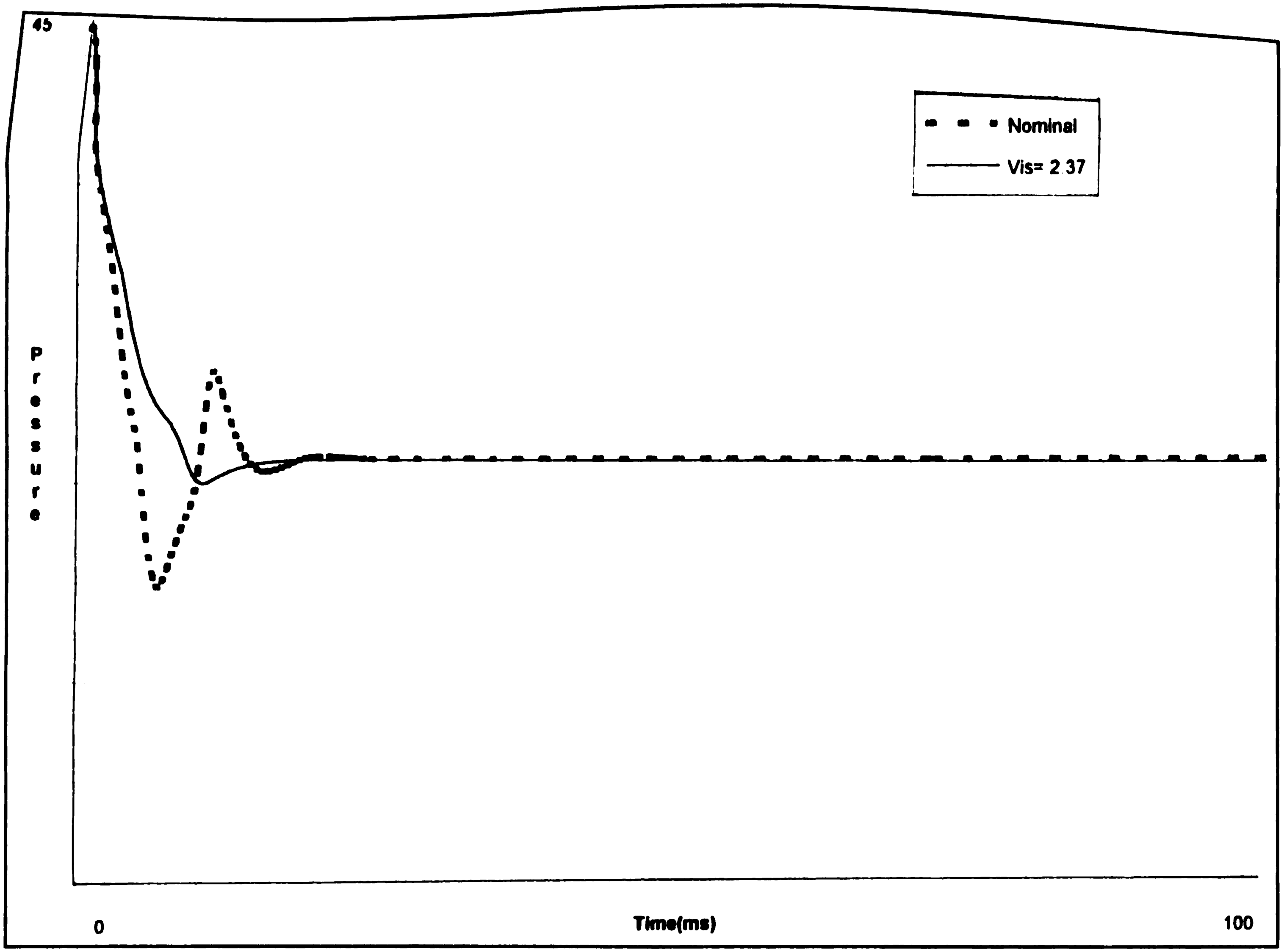

Figure B3-9: Pressure Profile in Engagement Mode - for the Model described in Section 4.3. The Temperature is 50 degrees below the Nominal value

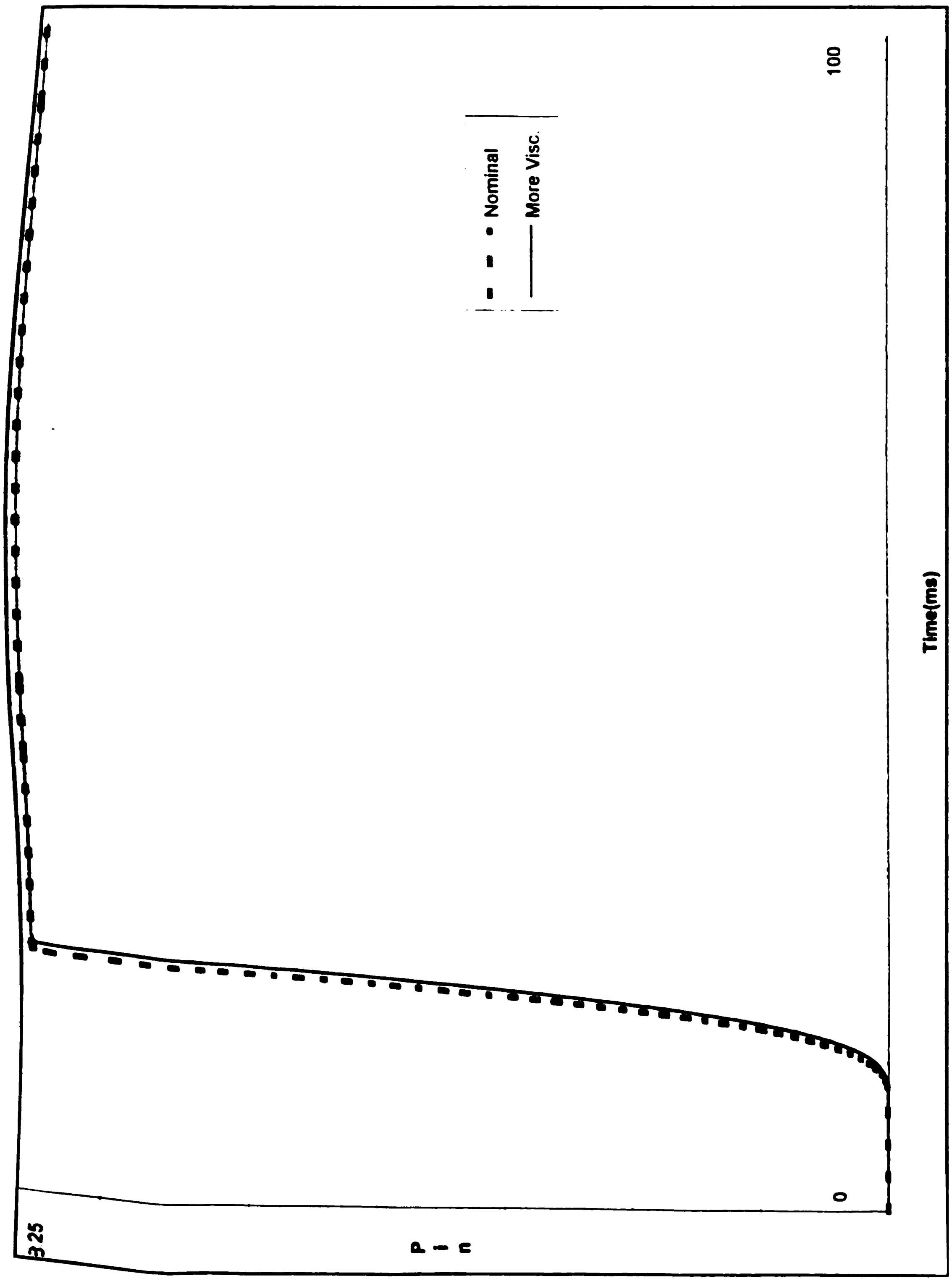

Figure B3-10: Pin Movement in Disengagement Mode - for the Model described in Section 4.3. The Temperature is 50 degrees below the Nominal value

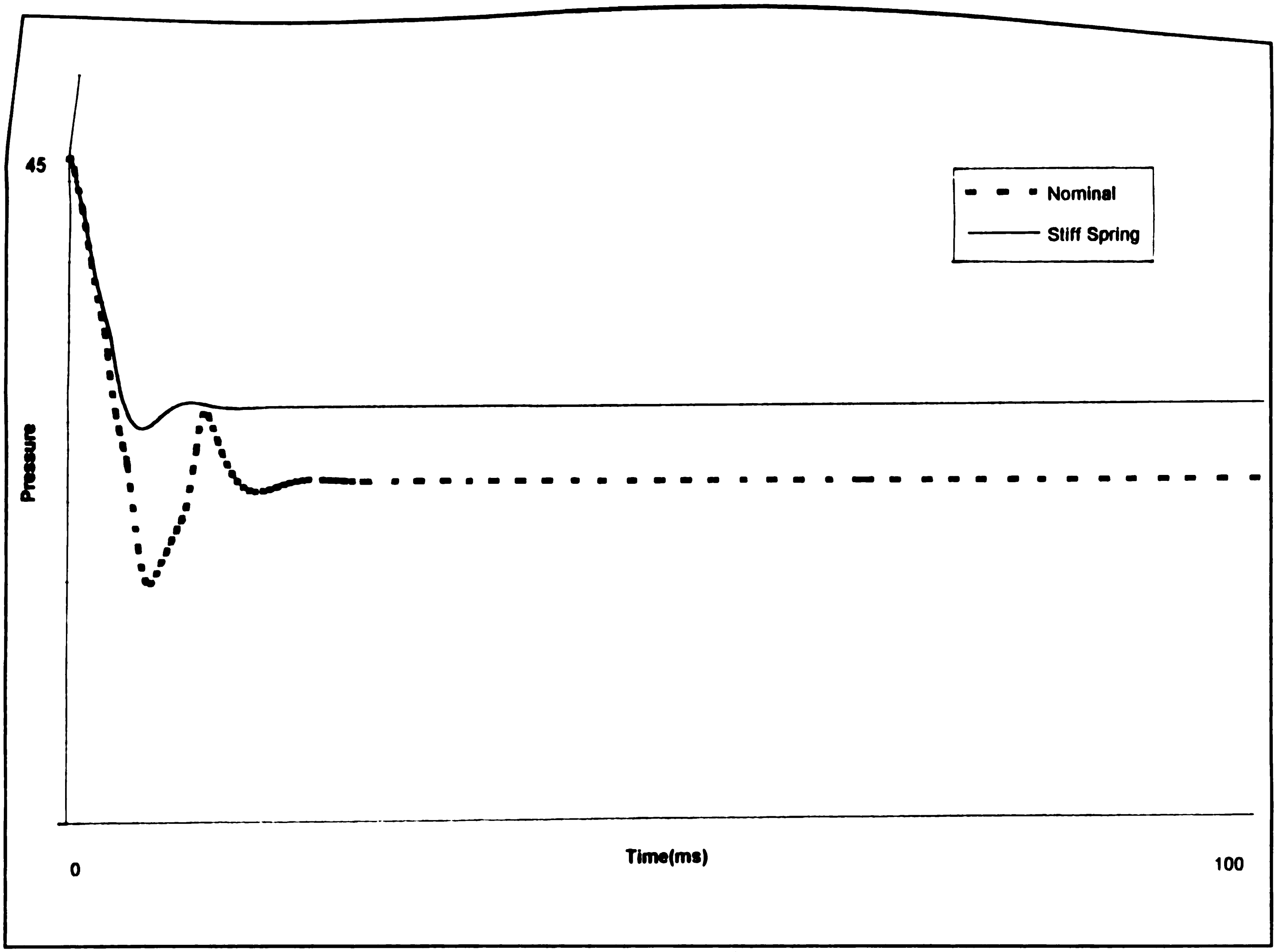

Figure B3-11: Pressure Profile in Engagement Mode - for the Model described in Section 4.4. The Spool Spring is twice as stiff as the Nominal value

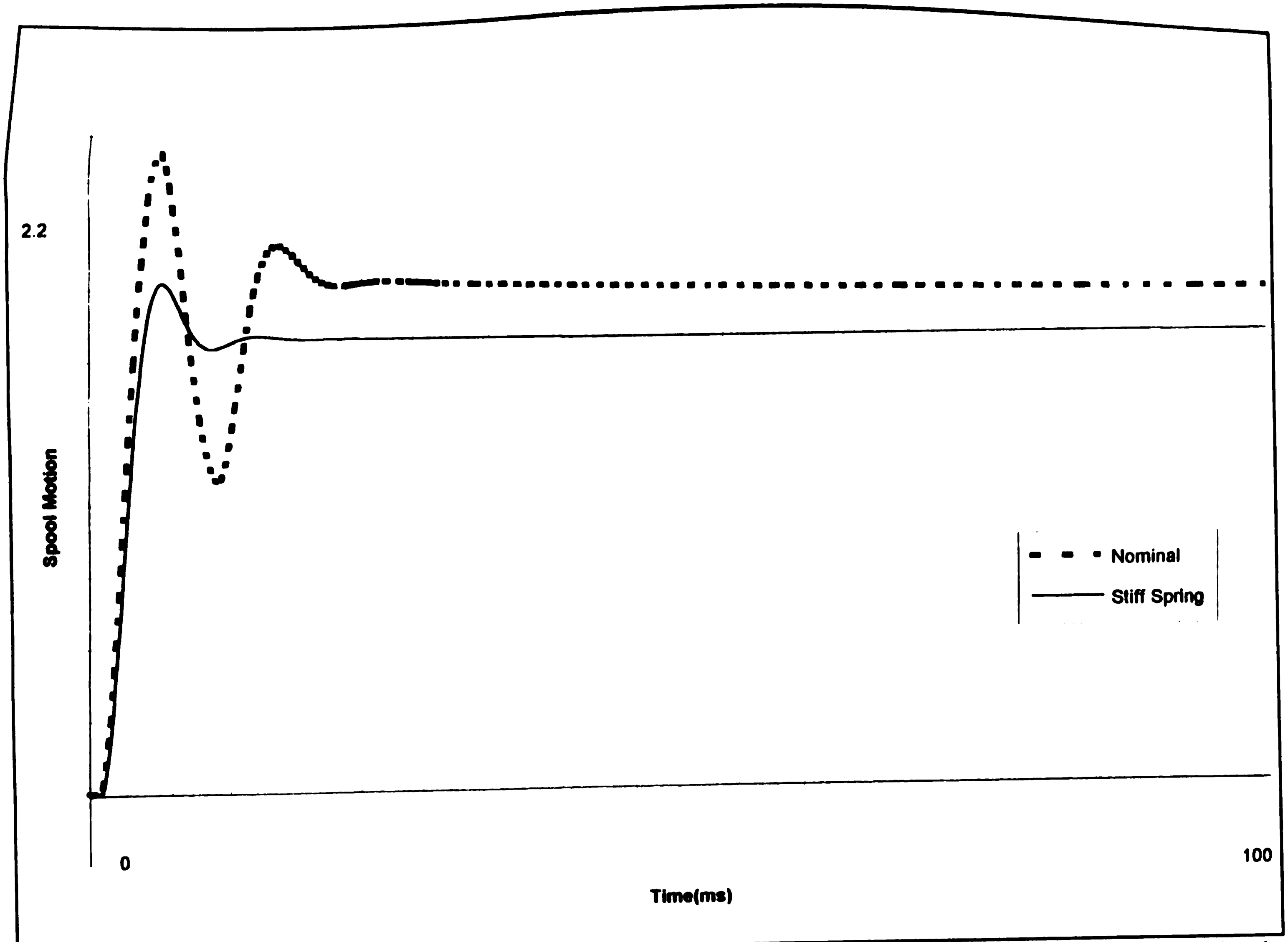

Figure B3-12: Spool Movement in Engagement Mode - for the Model described in Section 4.4. The Spool Spring is twice as stiff as the Nominal value

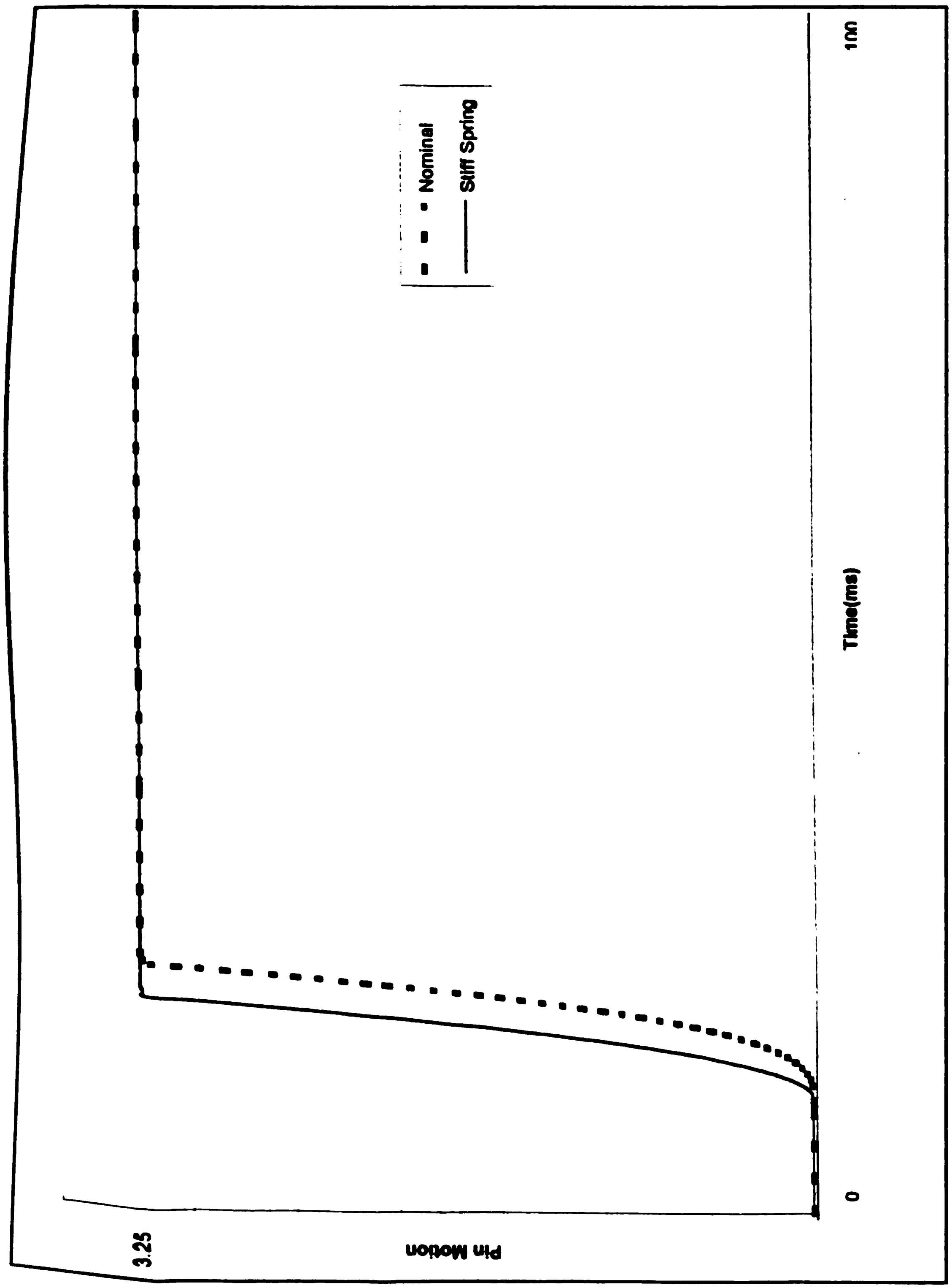

Figure B3-13: Pin Movement in Disengagement Mode - for the Model described in Section 4.4. The Spool Spring is twice as stiff as the Nominal value

APPENDIX C

ENPORT MODEL FILE FOR NOMINAL DESIGN

```
HEADING

 FILE   MODEL                         02:05:09  02/24/95  ENPORT/PC 5.2
   NOMDES_E.ENP                         Model_name: NOMDES_E

 TITLE
   The VDE with only the 1 DRA latching pin and the flow limited pump.

DESCRIPTION
   This model  has the flow limited pump. The solenoid valve feeds oil
   only to the 1 latching pin and none of the leakages associated with the
   pins are considered. The model is created only to generate results for
   the thesis document. The results may not be accurate from a FORD point
   of view.
   This is the pin engagement mode.
   I have added a leakage to the shaft to simulate the varying flow demand.
   This is the nominal Design: Flow limited pump, Low Leak, AF 3.5%, Beta
   varies with Pressure.

SYSTEM GRAPH DESCRIPTION

  NODE        TYPE    XLOC     YLOC    ACT   MACRO

    01P2      M0GV    900.     100.     T
    0EX       M0GV    300.     100.     T
    1H3EX     M1GV      0.     100.     T
    1HEX2     M1GV    600.     100.     T
    RX2       MRGV      0.    -100.     T
    RX3       MRGV    600.    -200.     T
    SEX1      MEGV    300.    -200.     T
    1RX1      M1GV   -300.    -100.     T
    0P3       M0GV   -300.     100.     T
    RX1       MRGV   -300.    -300.     T
    0PS       M0GV   -600.    -100.     T
    0P1       M0GV  -1200.     100.     T
    1RX4      M1GV  -1200.    -100.     T
    1H13      M1GV   -600.     100.     T
    RPQPG     MRGV   -600.     400.     T
    TFP1      MTGV   -800.     800.     T
    TFP2      MTGV    300.     800.     T
    0SFT1     M0GV    100.   -1800.     T
    0C1       M0GV  -1200.     800.     T
    1SPL      M1GV   -100.     800.     T
    RSPL      MRGV   -700.    1300.     T
    RWALL1    MRGV   -700.    1000.     T
```

CSPL	MCGV	500.	1300.	T
CWALL1	MCGV	500.	1000.	T
ISPL	MIGV	-100.	1400.	T
1SHF2	M1GV	-3300.	-2800.	T
RSHF2	MRGV	-2000.	-2800.	T
OP21	MOGV	900.	800.	T
OP2	MOGV	4300.	100.	T
1RSE	M1GV	4300.	-300.	T
RSE	MRGV	5100.	-300.	T
1RSC	M1GV	4300.	1000.	T
SEX3	MEGV	4300.	-1000.	T
RSC	MRGV	6100.	1000.	T
AREA	B+GV	-1400.	1200.	T
OARM2	MOGV	-4400.	-3200.	T
TFPIN2	MTGV	-3600.	-3800.	T
1PIN2	M1GV	-3600.	-4700.	T
RFRE2	MRGV	-4300.	-4500.	T
RFRN2	MRGV	-2800.	-4500.	T
CPIN2	MCGV	-2800.	-5200.	T
RPIN2	MRGV	-4300.	-5200.	T
IPIN2	MIGV	-3600.	-5400.	T
TFRM2	MTGV	-2900.	-5800.	T
SEARM2	MEGV	-2900.	-6700.	T
RX4	MRGV	-1200.	-300.	T
OINLT	MOGV	-8000.	2500.	T
SUM	BSGV	7800.	-600.	T
VGEN	B+GV	7800.	600.	T
DELAY	B+GV	7800.	-1600.	T
AGEN	BXGV	7000.	-600.	T
AGEN2	BAGV	5100.	-600.	T
DIST	BDGV	6100.	-600.	T
CSFT1	MEGV	-7600.	-1500.	T
C1	MEGV	-1800.	900.	T
C2	MEGV	1600.	1000.	T
CARM2	MEGV	-5200.	-2900.	T
INTSFT	BQGV	-12900.	-8200.	T
INTC1	BQGV	-12900.	-8700.	T
INTC2	BQGV	-12900.	-9200.	T
INTCRM2	BQGV	-12900.	-9700.	T
SINK1	B-GV	-10700.	-8200.	T
SINK2	B-GV	-10700.	-8700.	T
SINK3	B-GV	-10700.	-9200.	T
SINK4	B-GV	-10700.	-9700.	T
DSFT	B+GV	-17600.	-8200.	T
DPC1	B+GV	-17600.	-8700.	T
DPC2	B+GV	-17600.	-9200.	T
DPRM2	B+GV	-17600.	-9700.	T
SFPMP	MFGV	-18100.	2500.	T
OPMP	MOGV	-14700.	2500.	T
RPMP	MRGV	-14700.	5200.	T
CINLT	MEGV	-8000.	5300.	T

DPINLT	B+GV	-17600.	-12000.	T
INTLT	BQGV	-12900.	-12000.	T
SINK8	B-GV	-10700.	-12000.	T
1LEAK	M1GV	2800.	-3200.	T
RLEAK	MRGV	6000.	-3200.	T
SEATMLK	MEGV	2800.	-6000.	T
ORFAREA	B+GV	7500.	-5700.	T

CONNECTOR	TYPE	FROM	TO	VERTICES	
S4	BH V	0PS	1RX4		
S6	BH V	1RX4	0P1		
S7	BH V	0PS	1RX1		
S8	BH V	1RX1	RX1		
S9	BH V	1RX1	0P3		
S11	BH V	1H13	0P1		
S13	BH V	0P3	1H13		
S14	BH V	0P3	1H3EX		
S16	BH V	1H3EX	RX2		
S17	BH V	1H3EX	0EX		
S18	BH V	1HEX2	0EX		
S19	BH V	1HEX2	RX3		
S20	BH V	01P2	1HEX2		
S31	BH V	0EX	SEX1		
S12	BH V	1H13	RPQPG		
S15	BH V	0P3	0SFT1		
S30A	BH V	0C1	TFP1		
S29	BM V	TFP1	1SPL		
S23	BM V	1SPL	TFP2		
S24	BM V	1SPL	CWALL1	100.	1000.
S25	BM V	1SPL	CSPL	100.	1300.
S26	BM V	1SPL	ISPL		
S27	BM V	1SPL	RSPL	-400.	1300.
S28	BM V	1SPL	RWALL1	-300.	1000.
A2A	BH V	0SFT1	1SHF2		
A2B	BH V	1SHF2	RSHF2		
S10	BH V	0P1	0C1		
S21	BH V	0P21	01P2		
S22A	BH V	TFP2	0P21		
V3	BH V	0P2	1RSE		
V4	BH V	1RSE	RSE		
V5	BH V	1RSE	SEX3		
V6	BH V	1RSC	RSC		
A	SM V	AREA	TFP1	-1100.	1200.
P2A	BM V	TFPIN2	1PIN2		
P2B	BM V	1PIN2	RFRE2		
P2C	BM V	1PIN2	RPIN2		
P2D	BM V	1PIN2	IPIN2		
P2E	BM V	1PIN2	CPIN2		

P2F	BM V	1PIN2	RFRN2				
A2PIN	BH V	0ARM2	TFPIN2				
A2C	BH V	1SHF2	0ARM2				
P2G	BM V	1PIN2	TFRM2	-2900.	-5500.		
P2H	BH V	TFRM2	SEARM2				
S5	BH V	1RX4	RX4				
S1	BH V	0INLT	0PS	-3800.	-600.	-600.	-600.
V	SG V	VGEN	SUM				
D	SG V	DELAY	SUM				
V2	BH V	1RSC	0P2				
V1	BH V	0P2	01P2				
VC	SG V	SUM	AGEN				
AA	SG V	AGEN	DIST				
A1	SG V	DIST	RSC				
A2A	SG V	DIST	AGEN2				
A2	SG V	AGEN2	RSE				
V7	BH V	0INLT	1RSC	4300.	2500.		
S1D	BH V	0SFT1	CSFT1				
S30	BH V	0C1	C1				
S22	BH V	0P21	C2				
A2E	BH V	0ARM2	CARM2				
E1	SG V	INTSFT	SINK1				
E2	SG V	INTC1	SINK2				
E3	SG V	INTC2	SINK3				
E4	SG V	INTCRM2	SINK4				
DSFTDT	SG V	DSFT	INTSFT				
DC1DT	SG V	DPC1	INTC1				
DC2DT	SG V	DPC2	INTC2				
DRMDT	SG V	DPRM2	INTCRM2				
P1	BH V	SFPMP	0PMP				
P2	BH V	0PMP	RPMP				
SPLY	BH V	0PMP	0INLT				
P3	BH V	0INLT	CINLT				
DINLDT	SG V	DPINLT	INTLT				
E8	SG V	INTLT	SINK8				
EXTLK	BH V	0SFT1	1LEAK	800.	-3200.		
LKFLO	BH V	1LEAK	SEATMLK				
ORIF	BH V	1LEAK	RLEAK				
ORFARE	SG V	ORFAREA	RLEAK	7500.	-4100.		

NODE EQUATIONS

Named_parameters: 43

1	CD	8.00000E-01
2	VISCOS	1.09200E-06
3	RHO	8.50000E-06
4	AIRFRA	3.50000E-02
5	WALDMP	1.50000E+02
6	KWALL	1.00000E+06

7	HSPOOL	1.25000E-03
8	MSPOOL	9.09760E-05
9	ASPOOL	5.01590E-01
10	WIDSPL	2.51060E+00
11	SPLMXX	2.81500E-01
12	KSPOOL	1.80000E+01
13	SPRELO	2.99200E+00
14	DCHMBR	8.01650E-01
15	VOLCH1	3.36960E-02
16	VOLCH2	2.02460E-01
17	DRAFED	4.00000E-01
18	DAMPRT	1.50000E+02
19	PAREA	2.87500E-01
20	KSPRNG	4.00000E+00
21	FPRELD	4.95560E+00
22	PINMAX	3.25000E-01
23	KWALL2	1.00000E+06
24	PMASS	9.89280E-05
25	CNOT	1.70316E+01
26	PATM	1.01400E+01
27	PSUPLY	4.11620E+01
28	NDRAFD	5.00000E-01
29	R1OVLP	9.50000E-02
30	R2OVLP	1.61000E-01
31	HSPL2	1.25000E-03
32	CORNER	1.50000E+01
33	BRK1	1.00000E-01
34	BRK2	2.00000E-01
35	BRK3	3.00000E-01
36	BILDUP	1.03000E-01
37	BLDUP2	2.03000E-01
38	VSHFT	1.72780E+01
39	GAMMA	1.40000E+00
40	EMOD	1.72000E+05
41	PMPCVL	1.72780E+01
42	CREL	5.00000E-01
43	ORIFIC	5.00000E-02

Number of outputs: 50

Node: RX2

Equation: Y = ZZSU70 (X, P) 1 2 6

Y_list	X_list	Parameters
F.S16	Q.S25	HSPL2
	E.S16	R2OVLP
		CD
		VISCOS
		DCHMBR
		RHO

Node: RX3

```
  Equation:   Y = ZZSU71  ( X, P )      1  2  6
    Y_list          X_list          Parameters
    F.S19           Q.S25          HSPOOL
                    E.S19          1.39000E-01
                                   CD
                                   VISCOS
                                   DCHMBR
                                   RHO

Node:  SEX1
  Equation:   Y = CON     ( X, P )      1  0  1
    Y_list          X_list          Parameters
    E.S31                          PATM

Node:  RX1
  Equation:   Y = ZZSU69  ( X, P )      1  2  6
    Y_list          X_list          Parameters
    F.S8            Q.S25          HSPOOL
                    E.S8           R1OVLP
                                   CD
                                   VISCOS
                                   DCHMBR
                                   RHO

Node:  RPQPG
  Equation:   Y = ZZSU76  ( X, P )      1  1  2
    Y_list          X_list          Parameters
    F.S12           E.S12          VISCOS
                                   CORNER

Node:  TFP1
  Equation:   Y = MUL     ( X, P )      1  2  1
    Y_list          X_list          Parameters
    F.S30A          F.S29          1.00000E+00
                    A
  Equation:   Y = MUL     ( X, P )      1  2  1
    Y_list          X_list          Parameters
    E.S29           E.S30A         1.00000E+00
                    A

Node:  TFP2
  Equation:   Y = GAIN    ( X, P )      1  1  1
    Y_list          X_list          Parameters
    F.S22A          F.S23          ASPOOL
  Equation:   Y = GAIN    ( X, P )      1  1  1
    Y_list          X_list          Parameters
    E.S23           E.S22A         ASPOOL

Node:  RSPL
  Equation:   Y = ZZSU62  ( X, P )      1  1  4
    Y_list          X_list          Parameters
```

```
   E.S27          F.S27          VISCOS
                                 1.80000E+00
                                 WIDSPL
                                 HSPOOL

Node:  RWALL1
  Equation:   Y = ZZSU63  ( X, P )      1  2  4
    Y_list         X_list          Parameters
    E.S28          Q.S25           WALDMP
                   F.S25           WALDMP
                                   0.00000E+00
                                   SPLMXX

Node:  CSPL
  Equation:   Y = LIN     ( X, P )      1  1  2
    Y_list         X_list          Parameters
    E.S25          Q.S25           SPRELO
                                   KSPOOL

Node:  CWALL1
  Equation:   Y = ZZSU61  ( X, P )      1  1  4
    Y_list         X_list          Parameters
    E.S24          Q.S24           0.00000E+00
                                   SPLMXX
                                   KWALL
                                   KWALL

Node:  ISPL
  Equation:   Y = ATT     ( X, P )      1  1  1
    Y_list         X_list          Parameters
    F.S26          P.S26           MSPOOL

Node:  RSHF2
  Equation:   Y = ZZSU32  ( X, P )      1  1  3
    Y_list         X_list          Parameters
    F.A2B          E.A2B           DRAFED
                                   5.00000E-01
                                   VISCOS

Node:  RSE
  Equation:   Y = ZZSU64  ( X, P )      1  2  1
    Y_list         X_list          Parameters
    F.V4           A2              CNOT
                   E.V4

Node:  SEX3
  Equation:   Y = CON     ( X, P )      1  0  1
    Y_list         X_list          Parameters
    E.V5                           PATM

Node:  RSC
```

```
  Equation:   Y = ZZSU64  ( X, P )      1  2  1
    Y_list          X_list           Parameters
    F.V6            A1              CNOT
                    E.V6

Node:  AREA
  Equation:   Y = TABLE   ( X, P )      1  1  9

     N  Q.S25          A
      1 -5.00000E+00  3.81760E-01
      2  0.00000E+00  3.81760E-01
      3  1.00000E-08  ASPOOL
      4  1.00000E+01  ASPOOL

    Extend option: OFF

Node:  TFPIN2
  Equation:   Y = GAIN    ( X, P )      1  1  1
    Y_list          X_list           Parameters
    E.P2A           E.A2PIN         PAREA
  Equation:   Y = GAIN    ( X, P )      1  1  1
    Y_list          X_list           Parameters
    F.A2PIN         F.P2A           PAREA

Node:  RFRE2
  Equation:   Y = ZZSU54  ( X, P )      1  2  6
    Y_list          X_list           Parameters
    E.P2B           F.P2B           1.16800E+00
                    F.P2B           1.00000E+00
                                    5.50000E-01
                                    1.00000E+00
                                    3.50000E-03
                                    VISCOS

Node:  RFRN2
  Equation:   Y = ZZSU54  ( X, P )      1  2  6
    Y_list          X_list           Parameters
    E.P2F           F.P2F           9.99100E-01
                    F.P2F           1.00000E+00
                                    7.50000E-01
                                    1.00000E+00
                                    8.50000E-04
                                    VISCOS

Node:  CPIN2
  Equation:   Y = ZZSU19  ( X, P )      1  1  8
    Y_list          X_list           Parameters
    E.P2E           Q.P2E           KSPRNG
                                    FPRELD
                                    KWALL2
                                    KWALL2
```

```
                                  0.00000E+00
                                  PINMAX
                                  1.00000E+00
                                  1.00000E+00

Node: RPIN2
  Equation:  Y = ZZSU20  ( X, P )    1  2  5
    Y_list        X_list             Parameters
    E.P2C         Q.P2E              0.00000E+00
                  F.P2C              DAMPRT
                                     DAMPRT
                                     0.00000E+00
                                     PINMAX

Node: IPIN2
  Equation:  Y = ATT     ( X, P )    1  1  1
    Y_list        X_list             Parameters
    F.P2D         P.P2D              PMASS

Node: TFRM2
  Equation:  Y = GAIN    ( X, P )    1  1  1
    Y_list        X_list             Parameters
    E.P2G         E.P2H              PAREA
  Equation:  Y = GAIN    ( X, P )    1  1  1
    Y_list        X_list             Parameters
    F.P2H         F.P2G              PAREA

Node: SEARM2
  Equation:  Y = CON     ( X, P )    1  0  1
    Y_list        X_list             Parameters
    E.P2H                            PATM

Node: RX4
  Equation:  Y = ZZSU72  ( X, P )    1  2  6
    Y_list        X_list             Parameters
    F.S5          Q.S25              HSPOOL
                  E.S5               5.95000E-01
                                     CD
                                     VISCOS
                                     DCHMBR
                                     RHO

Node: SUM
  Equation:  Y = SUM     ( X, P )    1  2  2
    Y_list        X_list             Parameters
    VC            D                  1.00000E+00
                  V                  1.00000E+00

Node: VGEN
  Equation:  Y = PULSETRN( X, P )    1  1  5
    Y_list        X_list             Parameters
```

```
    V                TIME            BRK1
                                     1.20000E+01
                                     BRK2
                                     0.00000E+00
                                     BRK3

Node:  DELAY
  Equation:   Y = PULSETRN( X, P )       1  1  5
    Y_list           X_list            Parameters
    D                TIME            BRK1
                                    -1.20000E+01
                                     BILDUP
                                     0.00000E+00
                                     BLDUP2

Node:  AGEN
  Equation:   Y = TRANSFER( X, P )       1  1  4
    Y_list           X_list            Parameters
    AA               VC              1.00000E+03
                                     1.00000E+00
                                     8.33333E+01
                                     0.00000E+00

Node:  AGEN2
  Equation:   Y = LIN      ( X, P )      1  1  2
    Y_list           X_list            Parameters
    A2               A2A             1.00000E+00
                                    -1.00000E+00

Node:  CSFT1
  Equation:   Y = ASGN     ( X, P )      1  1  0
    Y_list           X_list            Parameters
    E.S1D            E1

Node:  C1
  Equation:   Y = ASGN     ( X, P )      1  1  0
    Y_list           X_list            Parameters
    E.S30            E2

Node:  C2
  Equation:   Y = ASGN     ( X, P )      1  1  0
    Y_list           X_list            Parameters
    E.S22            E3

Node:  CARM2
  Equation:   Y = ASGN     ( X, P )      1  1  0
    Y_list           X_list            Parameters
    E.A2E            E4

Node:  DSFT
  Equation:   Y = ZZSU12   ( X, P )      1  3  6
```

```
   Y_list          X_list          Parameters
   DSFTDT          F.S1D           VSHFT
                   Q.S25           0.00000E+00
                   E1              GAMMA
                                   1.00000E+00
                                   EMOD
                                   AIRFRA

Node:  DPC1
  Equation:   Y = ZZSU12  ( X, P )     1  3  6
   Y_list          X_list          Parameters
   DC1DT           F.S30           VOLCH1
                   Q.S25           ASPOOL
                   E2              GAMMA
                                   1.00000E+00
                                   EMOD
                                   AIRFRA

Node:  DPC2
  Equation:   Y = ZZSU85  ( X, P )     1  3  6
   Y_list          X_list          Parameters
   DC2DT           F.S22           VOLCH2
                   Q.S25           ASPOOL
                   E3              GAMMA
                                   1.00000E+00
                                   EMOD
                                   AIRFRA

Node:  DPRM2
  Equation:   Y = ZZSU12  ( X, P )     1  3  6
   Y_list          X_list          Parameters
   DRMDT           F.A2C           2.75700E-01
                   Q.P2E           PAREA
                   E4              GAMMA
                                   1.00000E+00
                                   EMOD
                                   AIRFRA

Node:  SFPMP
  Equation:   Y = CON     ( X, P )     1  0  1
   Y_list          X_list          Parameters
   F.P1                            1.02200E+01

Node:  RPMP
  Equation:   Y = TABLE   ( X, P )     1  1 31

    N  E.P1         F.P2
     1  2.16400E+01  0.00000E+00
     2  2.30500E+01  8.20000E-01
     3  2.45800E+01  1.67000E+00
     4  2.68400E+01  2.36500E+00
```

```
      5  3.01600E+01  2.80500E+00
      6  3.48200E+01  3.22000E+00
      7  4.15800E+01  3.69000E+00
      8  4.39500E+01  5.04500E+00
      9  4.58000E+01  6.31000E+00
     10  4.73300E+01  7.44500E+00
     11  4.86100E+01  8.42000E+00
     12  4.96300E+01  9.18000E+00
     13  5.04600E+01  9.74500E+00
     14  5.09400E+01  1.00950E+01
     15  5.11900E+01  1.02200E+01

    Extend option: OFF

Node:  CINLT
  Equation:   Y = ASGN     ( X, P )       1  1  0
    Y_list          X_list            Parameters
    E.P3            E8

Node:  DPINLT
  Equation:   Y = ZZSU12   ( X, P )       1  3  6
    Y_list          X_list            Parameters
    DINLDT          F.P3             PMPCVL
                    Q.S25            0.00000E+00
                    E8               GAMMA
                                     1.00000E+00
                                     EMOD
                                     AIRFRA

Node:  RLEAK
  Equation:   Y = ORIFICE  ( X, P )       1  2  2
    Y_list          X_list            Parameters
    F.ORIF          E.ORIF           CD
                    ORFARE           5.00000E-01

Node:  SEATMLK
  Equation:   Y = CON      ( X, P )       1  0  1
    Y_list          X_list            Parameters
    E.LKFLO                          PATM

Node:  ORFAREA
  Equation:   Y = CON      ( X, P )       1  0  1
    Y_list          X_list            Parameters
    ORFARE                           ORIFIC


SORTED SYSTEM EQUATIONS
    144  145
     48   48   48   48   48   48   48   48   48   48
..........................................................................................
.....
```

```
  121 122 123 124 125 126 127 128 129 130 131 132 133 134 135
  136 137 138 139 140 141 142 143 144


INITIAL CONDITIONS

  QS25          =    -6.2810E-06
  QS24          =    -6.2810E-06
  PS26          =     1.3983E-07
  QP2E          =     3.2500E-01
  PP2D          =     3.2649E-08
  XTF001        =     1.2000E-02
  E1            =     4.1343E+01
  E2            =     4.1341E+01
  E3            =     4.1344E+01
  E4            =     4.1343E+01
  E8            =     4.1344E+01


ALGEBRAIC VARIABLES

  Loops:  0    Nbr vbls:   0


OUTPUT VARIABLES
    1
    QS25


TIME CONTROLS

  Initial time =    0.0000E+00
  Final time   =    9.5000E-02
  Number saved =   951


END-OF-FILE
```

APPENDIX D

NODE DESCRIPTIONS FOR NOMINAL DESIGN MODEL

<table>
<tr><td>Node Name</td><td colspan="3">AREA</td></tr>
<tr><td>Type</td><td colspan="3">SRC (Block)</td></tr>
<tr><td>Power Domain</td><td colspan="3">Hydraulic</td></tr>
<tr><td>Description</td><td colspan="3">Dictates the area available for pressure to act on the left side of the spool. When the spool is hard left (ie, touching the wall), there is almost no surface on which the fluid pressure can act except on a 1mm wide "X" provided on the left face of the spool for this purpose. This block generates an area value for this surface depending on the position of the spool. It is approximated by a table that assumes the full face of the spool is available to act upon only after the spool has moved
1.00E-08 cm away from the left wall.</td></tr>
<tr><td rowspan="3">Equations</td><td>Function</td><td colspan="2">TABLE</td></tr>
<tr><td>Outputs</td><td>Inputs</td><td>Parameters</td></tr>
<tr><td>A:
3.81760E-01
3.81760E-01
ASPOOL
ASPOOL</td><td>QS25:
-5.00
0.00
1.00E-08
10.00</td><td>None</td></tr>
<tr><td>Equation Description</td><td colspan="3">A = Function of QS25(varies from 0.38 to ASPOOL)</td></tr>
</table>

<table>
<tr><td>Node Name</td><td colspan="3">C1</td></tr>
<tr><td>Type</td><td colspan="3">SE</td></tr>
<tr><td>Power Domain</td><td colspan="3">Hydraulic</td></tr>
<tr><td>Description</td><td colspan="3">Even though this is an SE type node, it actually represents the hydraulic compliance of the fluid in the chamber on the left side of the spool. The hydraulic compliance of the fluid depends on the air in the fluid, the bulk modulus of the fluid, and the pressure on the fluid volume. Since there will be both change in volume, and mass of the fluid in the volume the compliance of the fluid will keep changing. So the existing pressure, volume and flow are used to re-compute the final pressure in this chamber. This complex set of computation is achieved with a combination of this SE type node, and a set of signal blocks that are given seperately elsewhere on the system bond graph (to make the graph easier to read). The signal blocks related to this node are DPC1, INTC1 and SINK2.</td></tr>
<tr><td rowspan="3">Equations</td><td>Function</td><td colspan="2">ASSIGN</td></tr>
<tr><td>Outputs</td><td>Inputs</td><td>Parameters</td></tr>
<tr><td>ES30</td><td>E2</td><td>None</td></tr>
<tr><td>Equation Description</td><td colspan="3">ES30 = E2</td></tr>
</table>

Node Name	**C2**		
Type	SE		
Power Domain	Hydraulic		
Description	Even though this is an SE type node, it actually represents the hydraulic compliance of the fluid in the chamber on the right side of the spool. The hydraulic compliance of the fluid depends on the air in the fluid, the bulk modulus of the fluid, and the pressure on the fluid volume. Since there will be both change in volume, and mass of the fluid in the volume the compliance of the fluid will keep changing. So the existing pressure, volume and flow are used to re-compute the final pressure in this chamber. This complex set of computation is achieved with a combination of this SE type node, and a set of signal blocks that are given seperately elsewhere on the system bond graph (to make the graph easier to read). The signal blocks related to this node are DPC2, INTC2 and SINK3.		
Equations	Function	ASSIGN	
	Outputs	Inputs	Parameters
	ES22	E3	NONE
Equation Description	ES22 = E3		

Node Name	CSPL		
Type	C		
Power Domain	Mechanical		
Description	This capacitance element represents the spool spring on the right side of the spool. This spring is preloaded with a certain force and pushes the spool against the left wall in the absence of any other imbalance of forces.		
Equations	Function	LIN	
	Outputs	Inputs	Parameters
	ES25	QS25	SPRELO KSPOOL
Equation Description	ES25 = SPRELO + KSPOOL * QS25		

Node Name	CWALL1		
Type	C		
Power Domain	Mechanical		
Description	Represents the wall on either end of the spool chamber. The wall is modelled as a very stiff spring.		
Equations	Function	ZZSU61	
	Outputs	Inputs	Parameters
	ES24	QS24	0.00 SPLMXX KWALL KWALL
Equation Description	ES24 = ZZSU61 (QS24; Parameters)		

Node Name	DPC1.		
Type	SRC (Block)		
Power Domain	Hydraulic		
Description	This is a computational node directly linked and to support C1. It considers the existing pressure in the C1 chamber , the mass of fluid flowing in/out, and the size of the chamber in order to calculate the pressure difference in the chamber as a result of the fluid flow.		
Equations	Function	ZZSU12	
	Outputs	Inputs	Parameters
	DC1DT	FS30 QS25 E2	VOLCH1 ASPOOL GAMMA 1.00 EMOD AIRFRA
Equation Description	DC1DT = ZZSU12 (FS30, QS25, E2; Parameters)		

Node Name	**DPC2**		
Type	SRC (Block)		
Power Domain	Hydraulic		
Description	This is a computational node directly linked and to support C2. It considers the existing pressure in the C2 chamber , the mass of fluid flowing in/out, and the size of the chamber in order to calculate the pressure difference in the chamber as a result of the fluid flow.		
Equations	Function	ZZSU85	
	Outputs	Inputs	Parameters
	DC2DT	FS22 QS25 E3	VOLCH1 ASPOOL GAMMA 1.00 EMOD AIRFRA
Equation Description	DC2DT = ZZSU85 (FS22, QS25, E3; Parameters)		

Node Name	INTC1		
Type	INT (Block)		
Power Domain	Hydraulic		
Description	This node integrates the output of the DPC1 node to compute the final pressure in the C1 chamber.		
Equations	Function	[is set by software]	
	Outputs	Inputs	Parameters
	E2	DC1DT	None
Equation Description	E2 = INTEGRAL (DC1DT)		

Node Name	INTC2		
Type	INT (Block)		
Power Domain	Hydraulic		
Description	This node integrates the output of the DPC2 node to compute the final pressure in the C2 chamber.		
Equations	Function	[is set by software]	
	Outputs	Inputs	Parameters
	E3	DC2DT	None
Equation Description	E3 = INTEGRAL (DC2DT)		

Node Name	ISPL		
Type	I		
Power Domain	Mechanical		
Description	Represents the inertia of the spool body. The mass of the spool is calculated from the density of the material and the volume of the spool.		
Equations	Function	ATT	
	Outputs	Inputs	Parameters
	FS26	PS26	MSPOOL
Equation Description	FS26 = (1/MSPOOL) * PS26		

Node Name	**RPQPG**		
Type	R		
Power Domain	Hydraulic		
Description	This is the resistance to fluid flow in the pressure equalizing passage that connects the chamber on the left hand side of the spool to the control port chamber of the spool valve. The side view (as seen in various figures of the spool valve) of this passage is like a "T". This passage is considered as three different resistance paths in series. Since the fluid turns a corner, the corner resistance is estimated as being a multiple of the least resistance.		
Equations	Function	ZZSU76	
	Outputs	Inputs	Parameters
	FS12	ES12	VISCOS CORNER
Equation Description	FS12 = ZZSU76 (ES12; Parameters)		

<table>
<tr><td>Node Name</td><td colspan="3">RSPL</td></tr>
<tr><td>Type</td><td colspan="3">R</td></tr>
<tr><td>Power Domain</td><td colspan="3">Mechanical</td></tr>
<tr><td>Description</td><td colspan="3">This is the translational resistance on the spool. It is a fluid friction effect. Fluid layers are sheared when the spool moves within the chamber filled with oil. So this resistnace is proprotional to fluid viscosity.</td></tr>
<tr><td rowspan="3">Equations</td><td>Function</td><td colspan="2">ZSSU62</td></tr>
<tr><td>Outputs</td><td>Inputs</td><td>Parameters</td></tr>
<tr><td>ES27</td><td>FS27</td><td>VISCOS
1.800
WIDSPL
HSPOOL</td></tr>
<tr><td>Equation Description</td><td colspan="3">ES27 = ZZSU62 (FS27; Parameters)</td></tr>
</table>

Node Name	**RWALL1**		
Type	R		
Power Domain	Mechanical		
Description	This resistive element represents the damping by a wall when an object hits the wall. Since the walls in the spool chamber are modeled as very stiff springs, some amount of bounce may be seen when the spool hits against the walls. This is damped out by this R element. The nature of the resistance is such that it damps only when the spool moves into the wall and not when it moves out. The damping co-efficient is a named parameter that can be tuned to obtain realistic responses of damping and bounce as observed in experiments.		
Equations	Function	ZZSU63	
	Outputs	Inputs	Parameters
	ES28	QS25 FS25	WALDMP WALDMP 0.00 SPLMXX
Equation Description	ES28 = ZZSU63 (QS25, FS25; Parameters)		

<table>
<tr><td>Name</td><td colspan="3">RX1</td></tr>
<tr><td>Type</td><td colspan="3">R</td></tr>
<tr><td>Power Domain</td><td colspan="3">HYDRAULIC</td></tr>
<tr><td>Description</td><td colspan="3">This is the resistance between the inlet port and the control port of the spool valve. This R changes as the spool moves...the opening seen by the oil coming through the inlet gets bigger as the spool moves to the `left' wall of the chamber. The nature of the resistance changes from an orifice flow to be an annular type of flow. The flow calculations depending on the position of the spool and the pressure difference between the two regions are done in a subroutine. There is a transition region that is defined so that the two kinds of flow curves are smoothly patched up together.</td></tr>
<tr><td rowspan="3">Equations</td><td>Function</td><td colspan="2">ZZSU69</td></tr>
<tr><td>Outputs</td><td>Inputs</td><td>Parameters</td></tr>
<tr><td>FS8</td><td>QS25
ES8</td><td>HSPOOL
R1OVLP
CD
VISCOS
DCHMBR
RHO</td></tr>
<tr><td>Equation Description</td><td colspan="3">FS8 = ZZSU69 (QS25, ES8; Parameters)</td></tr>
</table>

Node Name	**RX2**		
Type	R		
Power Domain	Hydraulic		
Description	This is the resistance to flow of oil between the control port and the drain port. The nature of the resistance is the same as RX1. The flow calculations depending on the spool position and the pressure difference between the two regions are made in a subroutine. Again there is a transition region that is defined so that the two kinds of flow curves are smoothly patched up together.		
Equations	Function	ZZSU70	
	Outputs	Inputs	Parameters
	FS16	QS25 ES16	HSPL2 R2OVLP CD VISCOS DCHMBR RHO
Equation Description	FS16 = ZZSU70 (QS25, ES16; Parameters)		

Node Name	**RX3**		
Type	R		
Power Domain	Hydraulic		
Description	This is the resistance between the control port and the port that talks to the solenoid valve part of the Solenoid-Spool valve combination. The flow through this resistance never becomes an orifice type by virtue of the geometry of the spool valve; it is always annular flow and allows a very small flow. The flow calculations according to the pressure difference between the chambers are made by a subroutine.		
Equations	Function	ZZSU71	
	Outputs	Inputs	Parameters
	FS19	QS25 ES19	HSPOOL 1.39E-01 CD VISCOS DCHMBR RHO
Equation Description	FS19 = ZZSU71 (QS25, ES19; Parameters)		

<table>
<tr><td>Node Name</td><td colspan="3">RX4</td></tr>
<tr><td>Type</td><td colspan="3">R</td></tr>
<tr><td>Power Domain</td><td colspan="3">Hydraulic</td></tr>
<tr><td>Description</td><td colspan="3">This is the resistance to flow between the inlet port and the chamber on the left of the spool. By virtue of the geometry this will always be an annular type of flow, with the length of the passage changing with spool position. The flow calculations are made by a subroutine.</td></tr>
<tr><td rowspan="3">Equations</td><td>Function</td><td colspan="2">ZZSU72</td></tr>
<tr><td>Outputs</td><td>Inputs</td><td>Parameters</td></tr>
<tr><td>FS5</td><td>QS25
ES5</td><td>HSPOOL
5.95E-01
CD
VISCOS
DCHMBR
RHO</td></tr>
<tr><td>Equation Description</td><td colspan="3">FS5 = ZZSU72 (QS25, ES5; Parameters)</td></tr>
</table>

<table>
<tr><td>Node Name</td><td colspan="3">SEX1</td></tr>
<tr><td>Type</td><td colspan="3">SE</td></tr>
<tr><td>Power Domain</td><td colspan="3">Hydraulic</td></tr>
<tr><td>Description</td><td colspan="3">Represents a drain. It is considered to be a port which is at atmospheric pressure. It is assumed to be a pressure source that can handle infinite flow.</td></tr>
<tr><td rowspan="3">Equations</td><td>Function</td><td colspan="2">CON</td></tr>
<tr><td>Outputs</td><td>Inputs</td><td>Parameters</td></tr>
<tr><td>ES31</td><td>None</td><td>PATM</td></tr>
<tr><td>Equation Description</td><td colspan="3">ES31 = PATM</td></tr>
</table>

Node Name	**TFP1**		
Type	TF		
Power Domain	Hydraulic <-> Mechanical		
Description	This transformer represents the interface between the hydraulic and mechanical domains on the left side of the spool. It converts the pressure acting on the left side of the spool into a force acting on the left side of the spool. The area on which this pressure acts is determined by the AREA block described above.		
Equations	Function	MUL	
	Outputs	Inputs	Parameters
	FS30A ES29	FS29, A ES30A, A	1.00 1.00
Equation Description	FS30A = 1.00 * A * FS29 ES29 = 1.00 * A * ES30A		

<table>
<tr><td>Node Name</td><td colspan="3">TFP2</td></tr>
<tr><td>Type</td><td colspan="3">TF</td></tr>
<tr><td>Power Domain</td><td colspan="3">Hydraulic <-> Mechanical</td></tr>
<tr><td>Description</td><td colspan="3">This transformer represents the interface between the hydraulic and mechanical domains on the right side of the spool. It converts the pressure acting on the right side of the spool into a force acting on the right side of the spool. The area on which this pressure acts is constant.</td></tr>
<tr><td rowspan="3">Equations</td><td>Function</td><td colspan="2">GAIN</td></tr>
<tr><td>Outputs</td><td>Inputs</td><td>Parameters</td></tr>
<tr><td>FS22A
ES23</td><td>FS23
ES22A</td><td>ASPOOL
ASPOOL</td></tr>
<tr><td>Equation Description</td><td colspan="3">FS22A = ASPOOL * FS23
ES23 = ASPOOL * ES22A</td></tr>
</table>

Node Name	AGEN		
Type	FCN (Block)		
Power Domain	Hydraulic		
Description	Generates the area for the orifice functions RSC and RSE. What we know (from COLTECH) is that the ports open and close in a certain amount of time, once the command is given. The two openings of RSE and RSC are inversely related. When one closes, the other opens. This block generates the area curve for one of them according to a first order lag. The area for the other resistance is generated by a block AGEN2.		
Equations	Function	TRANSFER	
	Outputs	Inputs	Parameters
	AA	VC	1.00E+03 1.00 83.333 0.00
Equation Description	AA = VC * 83.33/(s+1000)		

<table>
<tr><td>Node Name</td><td colspan="3">AGEN2</td></tr>
<tr><td>Type</td><td colspan="3">FCN (Block)</td></tr>
<tr><td>Power Domain</td><td colspan="3">Hydraulic</td></tr>
<tr><td>Description</td><td colspan="3">This block is directly tied to the block AGEN. Once AGEN generates a curve for the area for one of the resistances (RSC or RSE), since the other resistance is inversely tied to it, this block generates an inverse curve to that generated by AGEN.</td></tr>
<tr><td rowspan="3">Equations</td><td>Function</td><td colspan="2">LIN</td></tr>
<tr><td>Outputs</td><td>Inputs</td><td>Parameters</td></tr>
<tr><td>A2</td><td>A2A</td><td>1.00
-1.00</td></tr>
<tr><td>Equation Description</td><td colspan="3">A2 = 1.00 - 1.00*A2A</td></tr>
</table>

<table>
<tr><td>Node Name</td><td colspan="3">DELAY</td></tr>
<tr><td>Type</td><td colspan="3">SRC (Block)</td></tr>
<tr><td>Power Domain</td><td colspan="3">Electrical</td></tr>
<tr><td>Description</td><td colspan="3">When there is a moded switch from the regulation mode to the high pressure mode of the spool valve, the solenoid valve opens the port between the supply and the control form nearly zero to maximum; and the port between supply and exhaust is closed simultaneously. There is a 3 millisecond flux build-up time required by the coil in the solenoid valve to build up the neccessary force to move the valve. This 3 millisecond delay is artificially built up by this DELAY node. It has to be mentioned that the delay is rigidly coupled with the pulsetrain from the VGEN block and hence any changes to the width of the pulse or the magnitudes in VGEN should be accompanied by a corresponding change in this block.</td></tr>
<tr><td rowspan="3">Equations</td><td>Function</td><td colspan="2">PULSETRN</td></tr>
<tr><td>Outputs</td><td>Inputs</td><td>Parameters</td></tr>
<tr><td>D</td><td>TIME</td><td>BRK1
-12.0
BILDUP
0.0
BRK3</td></tr>
<tr><td>Equation Description</td><td colspan="3">D = Function of (Time; Breakpoints, -12.0, 0.0)</td></tr>
</table>

Node Name	RSC		
Type	R		
Power Domain	Hydraulic		
Description	The resitance between the supply to the solenoid valve and the control port that talks to the spool valve. Assumed to be an orifice type of flow through this resistance. The orifice equation is tuned according to actual flow numbers obtained on a real solenoid valve by COLTECH engineers. We knew the maximum flow through the valve at a certain pressure of the supply. The flow is determined by the area of the orifice, which in turn is dictated by an area generating block called AGEN, where the area changes by a first order lag.		
Equations	Function	ZZSU64	
	Outputs	Inputs	Parameters
	FV6	A1 EV6	CNOT
Equation Description	FV6 = ZZSU64 (A1,EV6; CNOT)		

Node Name	RSE		
Type	R		
Power Domain	Hydraulic		
Description	The resitance between the supply to the solenoid valve and the exhaust port that talks to the drain. Assumed to be an orifice type of flow through this resistance. The orifice equation is tuned according to actual flow numbers obtained on a real solenoid valve by COLTECH engineers. We knew the maximum flow through the valve at a certain pressure of the supply. The flow is determined by the area of the orifice, which in turn is dictated by an area generating block called AGEN2, where the area changes by a first order lag.		
Equations	Function	ZZSU64	
	Outputs	Inputs	Parameters
	FV4	A2 EV4	CNOT
Equation Description	FV4 = ZZSU64(A2, EV4; CNOT)		

Node Name	SEX3		
Type	SE		
Power Domain	Hydraulic		
Description	This represents the drain. The drain is assumed to be at atmospheric pressure.		
Equations	Function	CON	
	Outputs	Inputs	Parameters
	EV5	None	PATM
Equation Description	EV5 = PATM		

<table>
<tr><td>Node Name</td><td colspan="3">VGEN</td></tr>
<tr><td>Type</td><td colspan="3">SRC (Block)</td></tr>
<tr><td>Power Domain</td><td colspan="3">Electrical</td></tr>
<tr><td>Description</td><td colspan="3">Generates a pulse train of 50 milliseconds long of 0 volts and 12 volts alternately. It is meant only to switch between the two modes of the spool valve. This is not part of the real solenoid valve design. It has been included only so that various runs can be conducted between the two modes of operation of the VDE.</td></tr>
<tr><td rowspan="3">Equations</td><td>Function</td><td colspan="2">PULSETRN</td></tr>
<tr><td>Outputs</td><td>Inputs</td><td>Parameters</td></tr>
<tr><td>V</td><td>TIME</td><td>BRK1
12.00
BRK2
0.00
BRK3</td></tr>
<tr><td>Equation Description</td><td colspan="3">V = Function of (Time; Breakpoints, 12, 0)</td></tr>
</table>

Node Name	CSFT1		
Type	SE		
Power Domain	Hydraulic		
Description	It is like a hydraulic C element and represents the compliance effects of the fluid in the rocker shaft. The rocker shaft is considered to be a relatively large volume with no other effects. The compliance calculations are made in a similar manner to the C1 and C2 elements mentioned in the Spool valve description. There is no moving piston here and hence no volume changes need to be considered when computing the pressure due to fluid flow in/out. The signal block that does the computation for this node are DSFT, INTSFT and SINK1.		
Equations	Function	ASGN	
	Outputs	Inputs	Parameters
	ES1D	E1	None
Equation Description	ES1D = E1		

Node Name	**DSFT**		
Type	SRC (Block)		
Power Domain	Hydraulic		
Description	This is a computational node directly linked and to support CSFT1. It considers the existing pressure in the C1 chamber , the mass of fluid flowing in/out, and the size of the chamber in order to calculate the pressure difference in the chamber as a result of the fluid flow.		
Equations	Function	ZZSU12	
	Outputs	Inputs	Parameters
	DSFTDT	FS1D QS25 E1	VSHFT 0.000 GAMMA 1.00 EMOD AIRFRA
Equation Description	DSFTDT = ZZSU12 (FS1D,QS25,E1; Parameters) *Note: The same function (ZZSU12) as in DPC1 is used here to compute the change in pressure; the physical volume of the Rocker Shaft remains constant(VSHFT). In ZZSU12 the physical volume of the chamber is computed as: Vt = VSHFT + P(2)*QS25, where the 1st term on the right is the initial volume and the 2nd term accounts for the geometric change in volume. So to maintain a constant volume for all computations by this subroutine for this node, we pass 0.0 as the area in the above equation - thus P(2)=0.0.*		

Node Name	INTSFT		
Type	INT (Block)		
Power Domain	Hydraulic		
Description	This node integrates the output of the DSFT node to compute the final pressure in the ROKER SHAFT chamber.		
Equations	Function	[is set by software]	
	Outputs	Inputs	Parameters
	E1	DSFTDT	None
Equation Description	E1 = INTEGRAL (DSFTDT)		

Node Name	**CARM2 (CARM3)**		
Type	SE		
Power Domain	Hydraulic		
Description	This is the hydraulic compliance element for the fluid in the rocker arm. The details of the modelling are the same as in the case of C1. Except that in this case moving piston is the pin. The computing blocks related to this node are DPRM(2), INTCRM2(INTCRM3) and SINK4 (SINK5).		
Equations	Function	ASGN	
	Outputs	Inputs	Parameters
	EA2E (EA3E)	E4 (E5)	None
Equation Description	EA2E = E4		

Node Name	CPIN2 (CPIN3)	
Type	C	
Power Domain	Mechanical	
Description	Models the pin spring. This spring has a preload which pushes the pin to the "left" wall such that the pin tends to stay in an engaged position with the other half of the rocker arm in the absence of any unbalanced force.	
Equations	Function	ZZSU19

Outputs	Inputs	Parameters
EP2E (EP3E)	QP2E (QP3E)	KSPRING FPRELD KWALL2 KWALL2 0.00 PINMAX 1.0 1.0

Equation Description	EP2E = ZZSU19 (QP2E; Paramaters)

Node Name	**DPRM2 (DPRM3)**		
Type	SRC (Block)		
Power Domain	Hydraulic		
Description	This is a computational node directly linked and to support CARM2(CARM3). It considers the existing pressure in the rocker arm chamber , the mass of fluid flowing in/out, and the size of the chamber in order to calculate the pressure difference in the chamber as a result of the fluid flow.		
Equations	Function	ZZSU12	
	Outputs	Inputs	Parameters
	DRMDT	FA2C (FA3C) QP2E (QP3E) E4 (E5)	2.757E-01 PAREA GAMMA 1.00 EMOD AIRFRA
Equation Description	DRMDT = ZZSU12 (FA2C,QP2E,E4; Parameters)		

Node Name	INTCRM2 (INTCRM3)		
Type	INT (Block)		
Power Domain	Hydraulic		
Description	This node integrates the output of the DPRM2 (DPRM3) node to compute the final pressure in the rocker arm chamber.		
Equations	Function	[is set by software]	
	Outputs	Inputs	Parameters
	E4 (E5)	DRMDT	None
Equation Description	E4 - INTEGRAL(DRMDT)		

Node Name	IPIN2		
Type	I		
Power Domain	Mechanical		
Description	Represents the inertial effects due to the mass of the pin.		
Equations	Function	ATT	
	Outputs	Inputs	Parameters
	FP2D	PP2D	PMASS
Equation Description	FP2D - (1/PMASS) * PP2D		

Node Name	**RFRE2**		
Type	R		
Power Domain	Hydraulic		
Description	This is the hydrodynamic damping force on the engagement length of the pin. It is similar to RSPL in its physics.		
Equations	Function	ZZSU54	
	Outputs	Inputs	Parameters
	EP2B	FP2B FP2B	1.168 1.00 5.5E-01 1.00 3.5E-03 VISCOS
Equation Description	EP2B = ZZSU54(FP2B; Parameters)		

<table>
<tr><td>Node Name</td><td colspan="3">RFRN2</td></tr>
<tr><td>Type</td><td colspan="3">R</td></tr>
<tr><td>Power Domain</td><td colspan="3">Mechanical</td></tr>
<tr><td>Description</td><td colspan="3">This is the hydrodynamic damping force on the non-engagement length of the pin. It is similar to RSPL in its physics.</td></tr>
<tr><td rowspan="3">Equations</td><td>Function</td><td colspan="2">ZZSU54</td></tr>
<tr><td>Outputs</td><td>Inputs</td><td>Parameters</td></tr>
<tr><td>EP2F</td><td>FP2F
FP2F</td><td>9.991E-01
1.00
7.5E-01
1.00
8.5E-04
VISCOS</td></tr>
<tr><td>Equation Description</td><td colspan="3">EP2F = ZZSU54 (FP2F; Parameters)</td></tr>
</table>

Node Name	**RPIN2**		
Type	R		
Power Domain	Mechanical		
Description	This effect is exactly the same as RWALL1 in the solenoid-spool. In this case the damping is meant for the bounding walls of the pin.		
Equations	Function	ZZSU20	
	Outputs	Inputs	Parameters
	EP2C	QP2E FP2C	0.00 DAMPRT DAMPRT 0.0 PINMAX
Equation Description	EP2C = ZZSU20 (QP2E, FP2C; Parameters)		

Node Name	**SEARM2**		
Type	SE		
Power Domain	Hydraulic		
Description	Represents the atmospheric pressure acting on the mixture of oil and air on the "right" side of the pin.		
Equations	Function	CON	
	Outputs	Inputs	Parameters
	EP2H	---	PATM
Equation Description	EP2H = PATM		

Node Name	**TFPIN2**		
Type	TF		
Power Domain	Hydraulic <-> Mechanical		
Description	Transforms the pressure acting inside the pin chamber to a force on the pin piston according to the area of the pin(piston) face .		
Equations	Function	GAIN	
	Outputs	Inputs	Parameters
	EP2A FA2PIN	EA2PIN FP2A	PAREA PAREA
Equation Description	EP2A = PAREA * EA2PIN FA2PIN = PAREA * FP2A		

Node Name	**TFRM2**		
Type	TF		
Power Domain	Mechanical <-> Electrical		
Description	The interface between the pin piston and the oil and air on the far ("right") side of the pin. Essentially atmospheric pressure acts on the pin from this side.		
Equations	Function	GAIN	
	Outputs	Inputs	Parameters
	EP2G FP2H	EP2H FP2G	PAREA PAREA
Equation Description	EP2G = PAREA * EP2H FP2H = PAREA * FP2G		

NAMED PARAMETERS

The following is a listing of all the named parameters used in the model. The names, what they represent and the pertinent calculations (if required) are shown. A spread sheet in EXCEL that will automatically do all these calculations is also provided together with the model.

Fixed Value NAMED PARAMETERS:

1. **AIRFRA**
   The fraction (per 100 parts) of air in the oil.

   3.5%

2. **BRK1**
   This is a parameter developed only for simulation runs. Sets the length of the pulse train of the signals that switch between modes. In the current version, it was chosen as **50 milliseconds** in each mode.

3. **CD**
   The coefficient of discharge for all the various orifices. It is assumed to be a constant

   8.00E-01

4. **CORNER**
   The tuning factor for the corner resistance in RPQPG:

   15 times R1(resistance of the shorter passage)

5. **CNOT**
   The constant multiplier for the orifice flow in the solenoid valve. Knowing the maximum flow at a given pressure and assuming the area to be 1 unit, this constant is computed.

   170

6. **DAMPRT**
   The damping coefficient of the pin chamber walls:

   150 N sec/cm

7. **DCHMBR**
   The diameter of the spool chamber:
   8.0165E-01 cm

8. **DSPOOL**
Spool diameter: (Larger section)
7.9915E-01 cm

9. **DRAFED**
The diameter of the feed hole that feeds oil into the DRA. This hole is in the rocker shaft:

4.00E-01 cm

10. **EMOD**
The bulk modulus of the oil (10 W 30) :

1.7200E+05 N/cm^2

11. **FPRELD**
The preload on the pin spring:

4.9556 N (the equivalent of 25psig acting on the pin area)

12. **GAMMA**
The ratio of specific heats for air:

1.4

13. **KSPOOL**
The stiffness of the spool spring. Given by COLTECH as

18 N/cm

14. **KSPRING**
The stiffness of the pin spring:

4.00 N/cm

15. **KWALL**
The stiffness of the wall (which is modeled as a very stiff spring).
1.000E+06 N/cm

16. **KWALL2**
The stiffness of the wall in the pin chamber:

1.000E+06 N/cm

17. **MSPOOL**
This mass of the spool was calculated knowing the spool geometry and the spool material density.

Volume of spool = 1.137198 cm^3
Material - SS 303: 18% Cr, 8% Ni
Density = 8 grams / cm^3 = 8.00E-05 N sec^2/cm^4

Mass = **9.09760E-05 N sec^2/cm**

18. **NDRAFD**
The diameter of the feed hole that feeds oil into the DRA. This hole is in the rocker shaft:

5.00E-01 cm

19. **PATM**
The atmospheric pressure:

10.14 N/cm^2

20. **PMASS**
The mass of the pin:

9.89280E-05 N sec^2/cm

21. **PSUPLY**
The supply pressure from the pump:

41.162 N/cm^2 (equivalent of 45 psig)

22. **RHO**
The density of oil.

0.85 grams/ cm^3 = **8.5 E-06 N sec^2 /cm**

23. **SPRELO**
The preload on the spool spring.

2.992 N

24. **VISCOS**

The viscosity of the oil. It is temperature dependent. A table of viscosity VS temperature

Temperature (°F)	**Viscosity(Nsec/cm^2)**
100	5.64 E-06
150	2.37 E-06
200	1.092 E-06

25. **WALDMP**

The damping coefficient of the wall.

150 N sec/cm

Derived NAMED PARAMETERS:

1. **ASPOOL**
   The area of the spool face:

   5.0159E-01 cm^2

2. **BILDUP**
   BRK1 + 3 millisec = **5.3E-02 sec.**
   (where 3 ms is the time for flux buildup)

3. **BRK2**
   The 2nd breakpoint for the pulsetrain:

   2 * BRK1 = **100 millisec**

4. **BRK3**
   The 3rd breakpoint for the pulsetrain:

   3 * BRK1 = 150 millisec

5. **HSPL2**
   The clearance between the spool and its chamber at the RX2 end:

   1.25E-03 cm

6. **HSPOOL**
   The clearance between the spool O.D and the spool chamber I.D. Calculated from spool and chamber diameters:

   1.2500E-03 cm

7. **PAREA**
   The area of the pin face:

   2.875E-01 cm^2

8. **PINMAX**
   The maximum distance that the pin can travel between walls:

   3.25E-01 cm^2

9.

10.

11.

12.

13.

14

15

9. **R1OVLP**
The distance the spool travels till RX1 enters into the transition region from orifice flow to annular flow. This is the distance that the spool travels before the larger diameter of the spool completely overlaps the inlet port:

9.5E-02 cm

10. **R2OVLP**
The same concept as in R1OVLP. Except that inthis case the flow regime changes from an annular to an orifice type, with a transition in between:

1.61E-01 cm

11. **SPLMXX**
The maximum distance spool can travel between walls:

2.815E-01 cm

12. **VOLCH1**
The volume of the chamber on the left side of the spool when the spool is hard left (the "X" on this face):

3.3696E-02 cm^3

13. **VOLCH2**
The volume of the chamber on the right side of the spool when the spool is hard left:

2.0246E-01 cm^3

14. **VSHFT**
The volume of the rocker shaft:

1.7278E+01 cm^3

15. **WIDSPL**
The cicumference of the spool's maximum diameter.

2.5106 cm

APPENDIX E

APPENDIX E

USER DEFINED SUBROUTINE DEFINITIONS FOR NOMINAL DESIGN

```
C ZZSU12 >>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
C
C  calculation of DP/Dt for liquid with air entrained
C  Version 1.0- 3/29/90 pss/jal
C
        SUBROUTINE ZZSU12(TIME,X,P,Y,STAT)
C
C    PROGRAMMING:
C   1) Version 1.0- 3/29/90 pss/jal
C
C   2.0) Converted code to interface with ENPORT/PC 5.1
C        G. DeRose Jr.        02/07/94
C
C   2.0) Changed print statment.
C        G. DeRose Jr.        02/22/94
C
C
C    DESCRIPTION: This is the driver subroutine for enport
C        computes dp/dt from f.xx for fluid with air entrained.
C        (assumes isentropic compression of air, P(3)=1.4)
C
C    INPUTS:
C   X(1) = Net hydraulic flow f.xx  --  (cm**3/sec)
C   X(2) = Piston displacement (Xp) --  (cm)
C   X(3) = Pressure                 --  (N/cm**2)
C
C   P(1) = Initial chamber vol (Vi) --  (cm**3)
C   P(2) = Area of piston (Ap)      --  (cm**2)
C   P(3) = Gas constant (Cp/Cv)     --
C   P(4) = Constant defining Vt, i.e.
C          Vt = Vi + P(4)*Ap*Xp
C
C   P(5) = Fluid bulk modulus       --  (N/cm**2)
C   P(6) = Volume fraction of air   --
C
C
C
C    OUTPUTS:
C   Y(1) = dP/dT or d(E.xx)/dt, from f.xx
C
C    MAIN SUBROUTINE
C
C    DECLARATIONS:
        DOUBLE PRECISION  X(20), Y(20), P(20), TIME
        integer STAT(10)
        DOUBLE PRECISION F_xx, Emod, Beff, Vi, press, VT, Xair
        DOUBLE PRECISION Xp, Ap, Patm, Pabs, gamma, a, b, c, d,  t1

        CHARACTER      STR*80
        EXTERNAL       ZZWRIT
C
C
C     Evaluation section
C
C
C  Variables:
C
C     F_xx  = Net hydraulic flow (cm**3/sec)
C     Emod  = Bulk modulus of fluid (N/cm**2)
C     Beff  = Effective bulk modulus (N/cm**2)
C     Vi    = Initial volume of chamber (cm**3)
C     press = pressure (N/cm**2)
C     VT    = Total volume being compressed (cm**3)
C     Xair  = Volume fraction of air in fluid
C     Xp    = Piston displacement (cm)
C     Ap    = Piston area (cm**2)
C     Patm  = Atmospheric pressure (N/cm**2)
C           = 10.14 N/cm**2
C     gamma = Gas constant (Cp/Cv)
C           = 1.4 for isentropic compression of air
C           = 1.0 for isothermal compression of air
C
C     a, b, c, d, t1 --> Temporary Variables

      IF( STAT(10) .EQ. 1 ) THEN
          STR = ' User Sub - zzsu12 - Version 2.0 - 02/22/94'
          CALL ZZWRIT(STR)
      ENDIF

              F_xx  = X(1)
              Xp    = X(2)
              press = X(3)

              Vi    = P(1)
              Ap    = P(2)
              gamma = P(3)
              Emod  = P(5)
              Xair  = P(6)

              Patm = 10.14d0
              VT   = Vi + P(4)*Xp*Ap

              a  = (Emod)/(1.d0-Xair)
              t1 = Patm**(1.d0/gamma)
              b  = (Xair*Emod*t1)/(gamma-gamma*Xair)
              c  = -1.d0 - 1.d0/gamma
              d  = Patm

              Pabs = press + Patm
              Pabs = max(Pabs, 1.d-4) ! Prevent undefined P**c
              Beff = a / (1.d0 + b*Pabs**c)
              Y(1) = F_xx * ( Beff / VT )
          return
          end
CEND:ZZSU12<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<
```

```
FZNU19>>>>>>>>>>>>>>>>>>>>>>>>>ZZNU19<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<C
DOUBLE PRECISION TIME, X(20), P(20), Y(20)
INTEGER STAT(10)
```

```
ZZSU19>>>>>>>>>>>>>>>>>>>>>>ZZSU19<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<C
      SUBROUTINE ZZSU19(TIME,X,P,Y,STAT)
C
C THIS SUBROUTINE WAS COPIED FROM ZZSU18 AND ZZSU05
C
C--- PROGRAMMING:
C 1)  ZZSU05 provides the nonlinear GAIN function for a spring with limits
C     on max and min displacement.  When limits are reached, spring stiffness
C     is set to a large value specified by parameter P(2).
C
C 2)  ZZSU05 extended to cover both nonlinear gain fuction for spring and damper
C     for impact moDELing.  Both spring and damper gains are changed at TIME
C     of impact so that a damping ratio of z=0.3-0.7 is maintained.  Note it is
C     up to the user to calculate the proper spring constants and damping
C     coefficients to maintain the above damping ratio. (8/7/87 J.A. LORUSSO)
C
C 3)  Improved file headers and DESCriptors for diagnostics (Ver. 3.0  1/16/89)
C
C 3.1) SW variable properly declared as integer
C
C 3.2) General Fortran cleanup, PSS 4/90.
C
C 3.3) streamlined if-else-if block
C
C 4.0) Converted to interface with EMPORT/PC 5.1.
C         G. DeRose Jr.        01/18/94
C
C 4.1) Removed damping when mass is moving away from the wall.
C         G. DeRose Jr.        01/18/94
C
C 4.2) Added control parameters for displacements outside of
C      the Qmin to Qmax range.
C         G. DeRose Jr.
C         T. Bertcher          02/09/94
C
C 5.0) Removed the switch and made a spring function only.
C         G. DeRose Jr.        02/21/94
C
C 5.0) Changed the print statement.
C         G. DeRose Jr.        02/22/94
C
C 6.0) Changed parameter list to added different spring constants and
C      possible spring preloads.
C         G. DeRose Jr.        02/22/94
C
C
C--- Description:  ZZSU05: SPRING LIMIT IMPACT MODEL.
C                              --STIFFNESS --
C                  (similar to BACKLASH except shifted)
C
C--- INPUTS:  X(1) = displacement
C
C             P(1) = spring stiffness within limits
C
C             P(2) = spring within limits preload.
C
C             P(3) = spring stiffness DISPL < Qmin
C
C             P(4) = spring stiffness DISPL > Qmax
C
C             P(5) = minimum displacement
C
C             P(6) = maximum displacement
C
C             P(7) = scaling factor for displacement <= Qmin
C
C             P(8) = scaling factor for displacement > Qmax
C
C
C--- OUTPUTS: Y(1) = force, N.xx
C
C--- DECLARATIONS:
        DOUBLE PRECISION TIME, X(20), P(20), Y(20)
        INTEGER STAT(10)
        CHARACTER    STR*80
        DOUBLE PRECISION K1, K2, K3, QMIN, QMAX, DISPL, PRELD
        DOUBLE PRECISION CONTR1, CONTR2

        EXTERNAL     ZZWRIT
C
C***ZZSU19*****************************************************************
C---- Description section
      IF (STAT(10).EQ.1) THEN
         STR= ' This is  zzsu19, Defines R for the PIN .'
         CALL ZZWRIT(STR)
         STR= ' This is the last line- 05/13/94.'
         CALL ZZWRIT(STR)
         RETURN
      ENDIF

C     Define variables and parameters based on input lists

      K1     = P(1)          ! spring stiffness within limits
      PRELD  = P(2)          ! spring preload

      K2     = P(3)          ! spring stiffness DISPL < Qmin
      K3     = P(4)          ! spring stiffness DISPL > Qmax

      QMIN   = P(5)          ! minimum displacement
      QMAX   = P(6)          ! maximum displacement

      CONTR1 = P(7)          ! For q <= Qmin
      CONTR2 = P(8)          ! For q > Qmax

      DISPL  = X(1)          ! displacement

C  case 1... displacement within specified limits

      if ( (DISPL .GE. QMIN) .and. (DISPL .LE. QMAX) ) then

         Y(1) = K1 * DISPL + PRELD

C  case 2... displacement exceeds max limit QMAX

      else if (DISPL .GT. QMAX) then

         Y(1) = CONTR2 * (  K1 * DISPL + PRELD
     *                   +  K3 * (DISPL - QMAX) )

C  case 3... displacement is below minimum limit QMIN

      else if (DISPL .LT. QMIN) then

         Y(1) = CONTR1 * (  K1 * DISPL + PRELD
     *                   +  K2 * (DISPL - QMIN) )

      else

         print*,'Error encountered in ZZSU19 ....'

      end if
C
      RETURN
      END

CEND:ZZSU19<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<
```

```
ZZSU20>>>>>>>>>>>>>>>>>>>>>>>>ZZSU20<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<
C
      SUBROUTINE ZZSU20(TIME,X,P,Y,STAT)
C
C THIS SUBROUTINE WAS COPIED FROM ZZSU18 AND ZZSU05
C
C--- PROGRAMMING:
C 1)  ZZSU05 provides the nonlinear GAIN function for a spring with limits
C     on max and min displacement.  When limits are reached, spring stiffness
C     is set to a large value specified by parameter P(2).
C
C 2)  ZZSU05 extended to cover both nonlinear gain fuction for spring and damper
C     for impact moDELing.  Both spring and damper gains are changed at TIME
C     of impact so that a damping ratio of z=0.3-0.7 is maintained.  Note it is
C     up to the user to calculate the proper spring constants and damping
C     coefficients to maintain the above damping ratio. (8/7/87 J.A. LORUSSO)
C
C 3)  Improved file headers and DEScriptors for diagnostics (Ver. 3.0  1/16/89)
C
C 3.1) SW variable properly declared as integer
C
C 3.2) General Fortran cleanup, PSS 4/90.
C
C 3.3) streamlined if-else-if block
C
C 4.0) Converted to interface with EMPORT/PC 5.1.
C         G. DeRose Jr.       01/18/94
C
C 4.1) Removed damping when mass is moving away from the wall.
C         G. DeRose Jr.       01/18/94
C
C 4.2) Added control parameters for displacements outside of
C      the Qmin to Qmax range.
C         G. DeRose Jr.
C         T. Bertcher         02/09/94
C
C 5.0) Removed the spring efects.
C         G. DeRose Jr.       02/21/94
C
C 5.0) Added Control parameters and changed print statment.
C         G. DeRose Jr.       02/22/94
C
C
C
C--- Description:  ZZSU05: SPRING LIMIT IMPACT MODEL.
C                               --DAMPING--
C                  (similar to BACKLASH except shifted)
C
C--- INPUTS:  X(1) = displacement
C
C             X(2) = velocity
C
C             P(1) = damping coeff. within limits
C
C             P(2) = damping coeff.  DISPL < Qmin
C
C             P(3) = damping coeff.  DISPL > Qmax
C
C             P(4) = minimum displacement
C
C             P(5) = maximum displacement
C
C
C--- OUTPUTS: Y(1) = force, E.xx
C
C--- DECLARATIONS:
       CHARACTER             STR*80
       EXTERNAL              ZZWRIT
       DOUBLE PRECISION TIME, X(20), P(20), Y(20)
       INTEGER STAT(10)
       DOUBLE PRECISION CON1, CON2, CON3, QMIN, QMAX, DISPL, XDOT
C
C***ZZSU20**************************************************************
C
      IF( STAT(10) .EQ. 1 ) THEN
          STR=' User Sub - zzsu20 - Version 5.0 - 02/22/94'
          CALL ZZWRIT(STR)
      ENDIF

C    Define variables and parameters based on input lists


      CON1   = P(1)          ! damping coeff. within limits

      CON2   = P(2)          ! damping coeff. DISPL < Qmin
      CON3   = P(3)          ! damping coeff. DISPL > Qmax

      QMIN   = P(4)          ! minimum displacement
      QMAX   = P(5)          ! maximum displacement

      DISPL  = X(1)          ! displacement
      XDOT   = X(2)          ! velocity


C  case 1... displacement within specified limits

      if ( (DISPL .GE. QMIN) .and. (DISPL .LE. QMAX) ) then
             Y(1) = CON1 * XDOT

C  case 2... displacement exceeds QMAX

          elseif ( DISPL .GT. QMAX ) then

             IF( XDOT .LE. 0.0 ) THEN
                 Y(1) = 0.0
             ELSE
                 Y(1) = CON3 * XDOT
             ENDIF
C case 3... displacement is below QMIN

          else

             IF( XDOT .GE. 0.0 ) THEN
                Y(1) = 0.0
             ELSE
                Y(1) = CON2 * XDOT
             ENDIF

      endif

      RETURN

      END
```

ZZ8U54 >>
viscous damping force calculation for hydrodynamic

```
ZZSU32 >>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
C
      SUBROUTINE ZZSU32(TIME,X,P,Y,STAT)
C
C---- PROGRAMMING:  G. DeRose Jr.                     03/29/94
C
C VERSION:
C      1.0  Initial subroutine
C              G. DeRose Jr.                          03/29/94
C
C
C---- DESCRIPTION:  This function will calculate the flow for laminar
C                        in a tube with a circular cross section.
C
C
C                       SOURCE: Hydraulic Control Systems
C                               Herbert E. Merritt
C                               Copyright 1967
C
C
C---- INPUTS:
C              X(1) = Pressure Drop                      [N/cm^2]
C
C              P(1) = Diameter                           [cm]
C
C              P(2) = Length                             [cm]
C
C              P(3) = Dynamic Viscosity                  [N sec/cm^2]
C
C
C              STAT(1), =1 iff 1ST time subrtn is called,  =0 else
C              STAT(2), =1 iff last time subrtn is called, =0 else
C              STAT(3), =1 iff last time subrtn is called
C                          for this storage interval, =0 else
C
C---- OUTPUTS: Y(1) = Flow Rate                          [cm^3/sec]
C
C              STAT(4)  =1, stop the integration,  =0 continue
C
C---- DECLARATIONS:
      CHARACTER      STR*80
      EXTERNAL                   ZZWRIT

      DOUBLE PRECISION TIME, X(20), P(20), Y(20)
      INTEGER          STAT(10)
      DOUBLE PRECISION DELTAP, DVISC, DIA, LENGTH
C
C***ZZSU32*************************************************************
C
C
C
      IF( STAT(10) .EQ. 1 ) THEN
         STR=' User Sub - zzsu32 - Version 5.0 - 03/29/94'
         CALL ZZWRIT(STR)
      ENDIF

C Copy input variables
      DELTAP = X(1)              ! Pressure Drop

      DIA =    P(1)              ! Diameter
      LENGTH = P(2)              ! Length
      DVISC =  P(3)              ! Dynamic viscosity

C Calculate the flow rate

      Y(1) = (3.14 * (DIA/2.0 )**4)/(8.0*DVISC*LENGTH) * DELTAP

      RETURN
      END
CEND:ZZSU32<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<
```

```
ZZSU54 >>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
C Description:  Viscous damping force calculation for hydrodynamic
C               lubrication
C
C     Authors - J.A. LoRusso & P.S. Szpak
C
C     Reference : Introduction to Fluid Mechanics
C                 Fox & McDonald
C                 1973
C                 p. 323
C
      SUBROUTINE ZZSU54(TIME,X,P,Y,STAT)
C
C---- PROGRAMMING:
C   1.0) Base version  1/26/90   J. A. LoRusso
C
C   1.1) Switch added for clearity  P.S. Szpak  4/18/90
C
C   2.0) input list modified -- 3/16/92 j.a. lorusso
C
C   2.1) revised for latest version of ENPORT  10/12/92 jal
C
C   3.0) Converted to interface with ENPORT/PC 5.1
C          G. DeRose Jr.        01/18/94
C
C   3.0) Changed print statement.
C          G. DeRose Jr.        02/22/94
C
C
C---- INPUTS:  TIME,     current time
C              X(1) = f.xx  -- piston velocity  [cm/sec]
C              X(2) = L     -- variable len. of leak path [cm]
C
C              P(1) = D     -- diameter                  [cm]
C
C              P(2) = CONST -- number of pistons
C
C              P(3) = L     -- constant len. of leak path [cm]
C
C              P(4) = Sw
C                     = 1  -->  L = P(3)
C                     = 2  -->  L = X(4)
C
C              P(5) = H     -- radial clearance  [cm]
C
C              P(6) = XMU   -- dynamic viscosity [N sec/cm**2]
C
C              STAT(1), =1 iff first time subroutine is called,
C                       =0 otherwise
C              STAT(2), =1 iff last time subroutine is called,
C                       =0 otherwise
C              STAT(3), =1 iff last time subroutine is called
C                          for this storage interval,
C                       =0 otherwise
C
C---- OUTPUTS: Y(1) = B.xx = damping force'
C                     = f.xx * CONST * (XMU*PI*D*L/H)      [N]
C
C              STAT(4)  =1, stop the integration,
C                       =0, continue
C
C---- DECLARATIONS:

      CHARACTER          STR*80
      EXTERNAL                ZZWRIT
      DOUBLE PRECISION TIME, X(20), P(20), Y(20)
      INTEGER          STAT(10)
      INTEGER SW
      DOUBLE PRECISION PI
      DOUBLE PRECISION VELOCITY, D, CONST, XMU, L, H, W, FORCE
C
C***ZZSU54*************************************************************
```

```
C
      IF( STAT(10) .EQ. 1 ) THEN
          STR=' User Sub - zzsu54 - Version 3.0 - 02/22/94'
          CALL ZZWRIT(STR)
      ENDIF

C ..... define input variables
C
          PI = 3.141592654d0
          VELOCITY= X(1)

          D       = P(1)
          CONST   = P(2)
          SW      = nint(P(4))
          H       = P(5)
          XMU     = P(6)

          if (SW.eq.1)then
                L = P(3)
            else
                L = X(2)
          end if
C
C ..... calculate hydrodynamic damping force
C
          w = PI * D

          FORCE  = VELOCITY * CONST * (XMU*w*L/H)
          Y(1)   = FORCE

      RETURN
      END
CZZSU54 >>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
```

```
ZZSU61 >>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
C
      SUBROUTINE ZZSU61(TIME,X,P,Y,STAT)
C
C---- PROGRAMMING:  Basil Joseph    (Jan 18, 1994.)
C
C---- DESCRIPTION:  Creating a fxn. to act as a hard stop- as encounterd at
C                   a wall. Essentially a very stiff spring is to be
C                   encountered when you hit either of two limiting walls.
C                   Written for a piston in a cylinder....
C
C---- INPUTS:  TIME,     current time
C              X,        input_variable values
C              P,        parameter values
C              STAT(1), =1 iff 1ST time subrtn is called,  =0 else
C              STAT(2), =1 iff last time subrtn is called, =0 else
C              STAT(3), =1 iff last time subrtn is called
C                           for this storage interval, =0 else
C
C---- OUTPUTS: Y,        output_variable values
C              STAT(4)  =1, stop the integration,  =0 continue


C
C---- DECLARATIONS:
      CHARACTER         STR*80
      DOUBLE PRECISION TIME, X(20), P(20),Y(20)
      INTEGER           STAT(10)

      EXTERNAL ZZWRIT
C
C     Added checks for v.small nos.     02/19/94   BJ
C     Removed these checks              04/22/94   BJ
C     Changed these checks to 1.00E-09 05/18/94   BJ
C***ZZSU61*************************************************************
      IF(STAT(10).EQ.1)THEN
          STR= 'ZZSU61...modified 05/18/94 BJJ'
          CALL ZZWRIT(STR)
          RETURN
      ENDIF

C ......define input variable
C
C      POSITION = X(1)
C
C.....define limits of travel
C
C      LEFT_WALL  = P(1)
C      RIGHT_WALL = P(2)
C
C.....define spring stiffness for the walls
C
C     K_left  = P(3)
C     K_right = P(4)
C
C.....when hitting left wall...
C
      if( X(1).LT.P(1) )then
C......avoid small numbers
c         if ( ABS( X(1) - P(1) ) .LT. 1.000E-09) then
c             Y(1) = 0.0
c         else
          Y(1) = P(3) *( X(1) -P(1) )
c         endif
C.....between walls...
C
      else if( X(1).LE.P(2) )then
          Y(1) = 0
C
C.....when hitting right wall...
C
      else
```

```
C.......avoid small numbers
C
        if ( ABS( X(1) - P(2) ) .LT. 1.000E-09) then
           Y(1) = 0.0
```

```
ZZSU62 >>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
C
      SUBROUTINE ZZSU62(TIME,X,P,Y,STAT)
```

```
C.......avoid small numbers
c        if ( ABS( X(1) - P(2) ) .LT. 1.000E-09) then
c                 Y(1) = 0.0
c        else
         Y(1) = P(4) * ( X(1) - P(2) )
c        endif

      end if
c
      RETURN
      END
c
c
CEND:ZZSU61<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<
```

```
ZZSU62 >>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
C
      SUBROUTINE ZZSU62(TIME,X,P,Y,STAT)
C
C---- PROGRAMMING:  (Basil Jacob Joseph)     (January 30, 1994)
C
C---- DESCRIPTION:  Subroutine to calculate viscous friction force
C                   exerted on a flat plate sliding on fluid film
C                   over another flat plate. It is assumed that the
C                   moving plate will have oscillations(i.e; it is
C                   compressing a spring when it has a positive
C                   velocity and vice-versa...).The drag effects due
C                   to pressure differences are neglected here...
C
C---- INPUTS:  TIME,     current time
C              X,        Input Variables
C              P,        parameter values
C              STAT(1),  =1 iff 1ST time subrtn is called,  =0 else
C              STAT(2),  =1 iff last time subrtn is called, =0 else
C              STAT(3),  =1 iff last time subrtn is called
C                              for this storage interval, =0 else
C
C---- OUTPUTS: Y,        output_variable values
C              STAT(4)   =1, stop the integration,  =0 continue

C
C---- DECLARATIONS:
      CHARACTER      STR*80
      DOUBLE PRECISION TIME, X(20), P(20), Y(20)
      DOUBLE PRECISION U, mu, l, w, h, F
      INTEGER           STAT(10)
C

      EXTERNAL ZZWRIT

C     Changed the numerical limits to 1.0E-09  BJ
C***ZZSU62****************************************************************
      IF (STAT(10).EQ.1) THEN
          STR= 'ZZSU62....MODIFIED 05/18/94  BJJ'
          CALL ZZWRIT(STR)
        RETURN
      ENDIF

C-----
C     U   Velocity of moving plate
C     mu  Average Viscosity of fluid
C     l   length of the moving plate
C     w   width of the moving plate
C     h   Distance between the two plates
C     F   Friction force on the moving plate
C
      U    =   X(1)
      mu   =   P(1)
      l    =   P(2)
      w    =   P(3)
      h    =   P(4)

C
C     when the spring is being compressed...or extended...
C
C      IF (ABS(U).GT. 1.0E-09) THEN
      F  =  (mu*U/h) * l * w          !Ignore drag effects
C
C
C     plate is not moving...
C
C      ELSE
C         F = 0
C
C      END IF
      Y(1) = F
C
```

```
      RETURN
      END
```

```
ZZSU63 >>>>>>>>>>>>>>>>>>>>>> ZZSU63 <<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<
C
      SUBROUTINE ZZHU63(TIME,X,P,Y,STAT)
```

```
      RETURN
      END
CEND:ZZSU62<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<
```

```
ZZSU63 >>>>>>>>>>>>>>>>>>>>>> ZZSU63 <<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<
C
       SUBROUTINE ZZSU63(TIME,X,P,Y,STAT)
C
C--- PROGRAMMING:  B.Joseph
C
C
C--- Description:  Modified routine from ZZSU05. Will apply a large friction
C                  force to a spool-like body when it moves into a bounding
C                  wall...
C
C--- INPUTS:  X(1) = displacement
C
C             X(2) = velocity
C
C             P(1) = damping coeff. beyond QMAX
C
C             P(2) = damping coeff. below QMIN
C
C             P(4) = minimum displacement
C
C             P(5) = maximum displacement
C
C
C--- OUTPUTS: Y(1) = force, N.xx
C

C
C--- DECLARATIONS:

       CHARACTER        STR*80
       DOUBLE PRECISION TIME, X(20), P(20), Y(20)
       INTEGER  STAT(10)
       DOUBLE PRECISION CON1, CON2, QMIN, QMAX, DISPL, VEL
C
       EXTERNAL  ZZWRIT
C***ZZSU63*****************************************************************
      IF (STAT(10).EQ.1) THEN
         STR= 'ZZSU63....MODIFIED 05/18/94  BJJ'
         CALL ZZWRIT(STR)
         RETURN
      ENDIF

C
C    Define variables and parameters based on input lists


      CON1   = P(1)          ! damping coeff. beyond QMAX

      CON2   = P(2)          ! damping coeff. below QMIN

      QMIN   = P(3)          ! minimum displacement

      QMAX   = P(4)          ! maximum displacement

      DISPL  = X(1)          ! displacement

      VEL    = X(2)          ! velocity

C  Avoiding very small numbers...

c      if (ABS(VEL) .LT. 1.0E-09) then
c         VEL = 0.0
c      end if

c      if (ABS(DISPL) .LT. 1.0E-09) then
c         DISPL = 0.0
c      end if


C  case 1... displacement exceeds max limit QMAX
```

```
if ( (DISPL .GT. QMAX) ) then
```

```
ZZHU64 >>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
```

```
      if ( (DISPL .GT. QMAX)    ) then

             if (VEL .GT. 0.0) then
                    Y(1) = CON1 * VEL
             else if (VEL .LE. 0.0) then
                    Y(1) = 0.0
             end if


C  case 2... displacement is below minimum limit QMIN

      else if ( (DISPL .LT. QMIN)  ) then

             if (VEL .LT. 0.0) then
                    Y(1) = CON2 * VEL
             else if (VEL .GE. 0.0) then
                    Y(1) = 0.0
             end if


C  case 3... displacement within specified limits

      else if ( (DISPL .GE. QMIN) .and. (DISPL .LE. QMAX)) then


             Y(1) = 0.0

      else
             print*,'Error encountered in ZZSU63 ....'

      end if

C
      RETURN
      END
CEND: ZZSU63<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<
```

```
ZZSU64 >>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
C
      SUBROUTINE ZZSU64(TIME,X,P,Y,STAT)
C
C---- PROGRAMMING:  Basil Joseph    (Jan 18, 1994.)
C
C---- DESCRIPTION:  Creating a fxn. to act as a resistance to flow...
C                   area is an input...written for the solenoid valve
C                   control....
C---- INPUTS:  TIME,     current time
C              X,        input_variable values
C              P,        parameter values
C              STAT(1),  =1 iff 1ST time subrtn is called,  =0 else
C              STAT(2),  =1 iff last time subrtn is called, =0 else
C              STAT(3),  =1 iff last time subrtn is called
C                            for this storage interval, =0 else
C
C---- OUTPUTS: Y,        output_variable values
C              STAT(4)   =1, stop the integration,  =0 continue


cC
C---- DECLARATIONS:
      CHARACTER STR*80
      DOUBLE PRECISION TIME, X(20), P(20),Y(20)
      DOUBLE PRECISION AREA, PRESS, CD, DELTAP, FLOW
      INTEGER          STAT(10)

      EXTERNAL  ZZWRIT
C   ***************************************************************
      IF (STAT(10).EQ.1) THEN
          STR= 'ZZSU64....MODIFIED 05/18/94  BJJ'
          CALL ZZWRIT(STR)
          RETURN
      ENDIF

      AREA  = X(1)
      PRESS = X(2)
      CD    = P(1)
      DELTAP= ABS(PRESS)

c      IF (DELTAP .LT. 1.0E-09) THEN
c         DELTAP = 0.0
c      ENDIF

      FLOW = AREA * CD * SQRT(DELTAP)

      IF (PRESS .LT. 0.0) THEN
          Y(1) = -1 * FLOW
      ELSE
          Y(1) = FLOW
      ENDIF

      RETURN
      END
C
C
CEND:ZZSU64<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<
```

D = P(5) ! Diameter of Mixed Chamber

```
ZZSU69 >>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
C
      SUBROUTINE ZZSU69(TIME,X,P,Y,STAT)
C
C---- PROGRAMMING:
C               Basil Joseph            February 12, 1994.
C               Michael K Hales         June 8, 1994
C
C---- DESCRIPTION:
C                  This subroutine is to compute the hydraulic resistances
C       in the VVLS model. The routine was written with the spool valve in
C       mind. The resistances are assumed to act in either of 2 modes-
C       orifice flow or annular flow. The equations for the two kinds of
C       flows have been taken from the Fluid Power Control book by Blackburn
C       et al. Instead of an abrupt change from orifice to annular mode
C       or vice-versa, a transition region is defined.  The length of the
C       transition region is based on tests of the resistance perfomance
C       in this region. It was found that the annular flow equation blows
C       up at the transition point.  The transition length is just long
C       enough for the annular flow values to become valid.
C
C---- INPUTS:  TIME,     current time
C              X,        input_variable values
C              P,        parameter values
C              STAT(1), =1 iff 1ST time subrtn is called,  =0 else
C              STAT(2), =1 iff last time subrtn is called, =0 else
C              STAT(3), =1 iff last time subrtn is called
C                            for this storage interval, =0 else
C
C---- OUTPUTS: Y,        output_variable values
C              STAT(4)  =1, stop the integration,  =0 continue

C
C---- DECLARATIONS:
      CHARACTER      STR*80
      EXTERNAL       ZZWRIT

      DOUBLE PRECISION TIME, X(20), P(20), Y(20)
      DOUBLE PRECISION Xspl, a, dP, h, Cd, Mu, D, Riovlp, Rho
      DOUBLE PRECISION Q, Pi, b, G, T1, T2, Qorif, Qann, alpha
      parameter (Pi = 3.141592654d+00)
      INTEGER    STAT(10)
C
C     Added checks for v.small nos.                        02/19/94
C     Adding clause for -ve Xspl and using pr.diff.
C       directly from BG                                   02/22/94
C     Re-writing the whole from scratch                    05/22/94   BJ
C     Made the overlap an MP... to make it a
C      changeable parameter in the solver...               05/22/94   BJ
C     Changed the transition region def to be
C       del-pressure dependent...refer notes               05/24/94   BJ
C     Used a different approach to define transition
C       region                                             08-Jun-94  mkh
C***ZZSU69*****************************************************************
C
      TIME = TIME
      IF (STAT(10).EQ.1) THEN
          STR= 'ZZSU69....Last change: 22-Jun-94 - mkh'
          CALL ZZWRIT(STR)
          RETURN
      ENDIF
C
C     Inputs...
      Xspl      = X(1)            ! Spool position
      dP        = X(2)            ! Pressure difference
C
C     Parameters...
      h         = P(1)            ! Distance between spool and chamber
      Riovlp    = P(2)            ! Length of spool land- cutoff point
C                                          between orif. & transition
      Cd        = P(3)            ! Co-efficient of discharge
      Mu        = P(4)            ! Kinematic Viscosity
      D         = P(5)            ! Diameter of Spool Chamber
      Rho       = P(6)            ! density of oil
C
      T2 = 0.0015
      G = Riovlp + T2             !Orifice region + transition region
C                                 !as determined from tests
C.....ORIFACE REGION
C
      IF ( Xspl .LE. Riovlp) THEN                        !orifice regn
          IF ( Xspl .LT. 0.0 ) Xspl = 0.0                 !ignore -ve def
          b       = Riovlp - Xspl                         !opening
          a       = Pi * D * SQRT( b**2 + h**2)           !area

          Qorif   = Cd * a * SQRT(2*ABS(dP)/Rho)
          Q       = Qorif

      ELSEIF ( (Xspl .GT. Riovlp) .AND. (Xspl .LE. G) ) THEN
C
C.....TRANSITION REGION
C        The transition region is divided into two equal parts.
C        For the 1st half, the flow is the same as the smallest oriface
C        flow.  For the 2nd half, the flow is a weighted average of the
C        smallest oriface flow(dependant only on dP) and the annular flow
C        (dependant on dP and Xspl).  The weight of each variable depends
C        on the spool position.
C
          Qorif   = Cd * Pi * D * h * SQRT( 2*ABS(dP)/Rho )
          T1      = Riovlp + T2/2            !1st half of transition region
          IF (Xspl.LT.T1) THEN
            Q     =  Qorif
          ELSE                               !2nd half of transition region
            Qann  = Pi * D * h**3 * ABS(dP) / (12 * Mu * (Xspl - Riovlp))
            alpha = (Xspl - T1)/(G-T1)
            Q     = (1-alpha)*Qorif + alpha*Qann
          END IF
C
      ELSE IF (Xspl.GT.G) THEN
C
C.....ANNULAR REGION
C
          Qann    = Pi * D * h**3 * ABS(dP) / (12 * Mu * (Xspl - Riovlp))
          Q       = Qann
      ENDIF
C.....Outputs...
C      IF (ABS(Q).GT.26) Q=26        ! Pump Flow Limitations
      IF (dP .LT. 0.0) THEN
                 Y(1) = -Q
      ELSE
                 Y(1) =  Q          ! Flow thru the Hydr. Resistance
      ENDIF
C
      RETURN
      END
CEND:ZZSU69<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<
```

```
ZZSU70>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
C
      SUBROUTINE ZZSU70(TIME,X,P,Y,STAT)
C
C---- PROGRAMMING:
C               Basil Joseph            February 12, 1994.
C               Michael K Hales         June 9, 1994.
C
C---- DESCRIPTION:
C  This subroutine is to compute the hydraulic resistances
C  in the VVLS model. The routine was written with the spool valve in
C      mind. The resistances are assumed to act in either of 2 modes-
C      orifice flow or annular flow. The equations for the two kinds of
C      flows have been taken from the Fluid Power Control book by Blackburn
C      et al.  Instead of an abrupt change from orifice to annular mode
C      or vice-versa, a transition region is defined.  The length of the
C      transition region is based on tests of the resistance perfomance
C      in this region. It was found that the annular flow equation blows
C      up at the transition point.  The transition length is just long
C      enough for the annular flow values to become valid.
C
C---- INPUTS:  TIME,     current time
C              X,        input_variable values
C              P,        parameter values
C              STAT(1),  =1 iff 1ST time subrtn is called,  =0 else
C              STAT(2),  =1 iff last time subrtn is called, =0 else
C              STAT(3),  =1 iff last time subrtn is called
C                             for this storage interval, =0 else
C
C---- OUTPUTS: Y,        output_variable values
C              STAT(4)   =1, stop the integration,  =0 continue
C
C---- DECLARATIONS:
      CHARACTER       STR*80
      EXTERNAL        ZZWRIT

      DOUBLE PRECISION TIME, X(20), P(20), Y(20)
      DOUBLE PRECISION Xspl, a, h, Cd, Mu, D, R2ovlp, Rho
      DOUBLE PRECISION Q, Pi, b, dP, G, T1, T2, Qorif, Qann, alpha
      parameter (Pi = 3.141592654d+00)
      INTEGER          STAT(10)
C
C     Adding clause for -ve Xspl                          02/22/94  BJJ
C       and using pr. diff. dirctly from BG.
C     Added transition region to avoid large flow.        09-Jun-94 mkh
C***ZZSU70*************************************************************
      TIME = TIME
      IF (STAT(10).EQ.1) THEN
          STR= 'ZZSU70....Last Modified 22-Jun-94  mkh'
          CALL ZZWRIT(STR)
          RETURN
      ENDIF
C
C     Inputs...
      Xspl       = X(1)           ! Spool position
      dP         = X(2)           ! Pressure difference(from  Bond Graph)
C
C     Parameters...
      h          = P(1)           ! Distance between spool and chamber
      R2ovlp     = P(2)           ! Length of spool land - cut-off between
C                                 ! transition and Orifice regions
      Cd         = P(3)           ! Co-efficient of discharge
      Mu         = P(4)           ! Kinematic Viscosity
      D          = P(5)           ! Diameter of Spool Chamber
      Rho        = P(6)           ! density of oil
C
      T2 = 0.0015
      G = R2ovlp - T2             ! Oriface region - Transition region
                                          ! (value determined by testing)
C
C.....ANNULAR REGION
C
      IF (Xspl.LE.G) THEN
          IF (Xspl.LT.0.0) Xspl = 0.0         !ignore negative Xspl
          Qann = Pi * D * (h**3) * ABS(dP)/(12 * Mu * (R2ovlp-Xspl))
          Q    = Qann
C
      ELSE IF ((Xspl.GT.G).AND.(Xspl.LE.R2ovlp)) THEN
C
C.....TRANSITION REGION
C       The transition region is divided into two equal parts.
C       For the 1st half, the flow is a weighted average of the smallest
C       oriface flow, and the annular flow.  The weight depends on the
C       spool position. For the second half, the flow is a constant,
C       based on the smallest orifice flow.
C
          Qorif = Cd * Pi * D * h * SQRT (2*ABS(dP)/Rho)
          T1    = G + T2/2
C
          IF (Xspl.LT.T1) THEN                 !1st half of transition region
            Qann  = Pi * D * (h**3) * ABS(dP)/(12 * Mu * (R2ovlp-Xspl))
            alpha = (Xspl-G)/(T1-G)
            Q     = (1-alpha)*Qann + alpha*Qorif
          ELSE
            Q     = Qorif
          END IF
C
      ELSE IF (Xspl.GT.R2ovlp) THEN
C
C.....ORIFACE REGION
C
          b     = Xspl - R2ovlp
          a     = Pi * D * SQRT (b**2 + h**2)
          Qorif = Cd * a * SQRT (2*ABS(dP)/Rho)
          Q     = Qorif
      END IF
C
C.....Outputs
      IF (dP .LT. 0.0) THEN
                     Y(1) = -Q         ! -ve flow
      ELSE
                     Y(1) = Q          ! Flow thru the Hydr. Resistance
      ENDIF
C
      RETURN
      END
CEND:ZZSU70<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<
```

```
zzsu71>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
C
      SUBROUTINE zzsu71(TIME,X,P,Y,STAT)
C
C---- PROGRAMMING:
C               Basil Joseph            February 13, 1994.
C
C---- DESCRIPTION:
C                This subroutine is to compute the hydraulic resistances
C       in the VVLS model. The routine was written with the spool valve in
C       mind. The resistances are assumed to act in either of 2 modes-
C       orifice flow or annular flow. The equations for the two kinds of
C       flows have been taken from the Fluid Power Control book by Blackburn
C       et al.
C
C---- INPUTS:  TIME,     current time
C              X,        input_variable values
C              P,        parameter values
C              STAT(1), =1 iff 1ST time subrtn is called,  =0 else
C              STAT(2), =1 iff last time subrtn is called, =0 else
C              STAT(3), =1 iff last time subrtn is called
C                           for this storage interval, =0 else
C
C---- OUTPUTS: Y,        output_variable values
C              STAT(4)  =1, stop the integration,  =0 continue


C
C---- DECLARATIONS:
      CHARACTER         STR*80
      EXTERNAL                  ZZWRIT
      DOUBLE PRECISION TIME, X(20), P(20), Y(20), Rho, Q, Pi
      DOUBLE PRECISION  Xspl, dP, h, Cd, Mu, D, SplLand
      parameter (Pi = 3.141592654d+00)
      INTEGER           STAT(10)
C
C***zzsu71**********************************************************
      IF (STAT(10).EQ.1) THEN
         STR= 'zzsu71....MODIFIED 05/18/94  BJJ'
         CALL ZZWRIT(STR)
         RETURN
      ENDIF
C
C     Inputs...
      Xspl       = X(1)          ! Spool position
      dP          = X(2)          ! Pressure difference

C
C     Parameters...
      h           = P(1)          ! Distance between spool and chamber
      SplLand     = P(2)          ! Length of spool land
      Cd          = P(3)          ! Co-efficient of discharge
      Mu          = P(4)          ! Kinematic Viscosity
      D           = P(5)          ! Diameter of Spool Chamber
      Rho         = P(6)          ! density of oil
C
C
C      IF (ABS(dP) .LT. 1.00E-09) THEN
C      dP= 0.0
C      ENDIF
C
C----Always annular flow...
      Q = Pi * D * (h**3) * dP/(12 * Mu * (SplLand + Xspl))
C
C
C     Outputs...
      Y(1)        = Q          ! Flow thru the Hydr. Resistance
      RETURN
      END
CEND:zzsu71<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<
```

```
zzsu76 >>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
C
      SUBROUTINE zzsu76(TIME,X,P,Y,STAT)
C
C---- PROGRAMMING:  Michael K Hales              June 22, 1994
C
C---- DESCRIPTION:  This subroutine calculates the hyraulic resistance
C     to flow through the spool valve ports.  There are three different
C     resistance effects that act in series:
C               1) laminar flow through 2 pipes in parallel,
C               2) change of the flow direction at the T-junction,
C               3) laminar flow through 1 pipe.
C     The equations for 1) and 3) are standard for laminar flow.
C     The resistance of 2) is estimated as a tuning factor times R1.
C
C---- INPUTS:  TIME,     current time
C              X(1),     ES12(dP): pressure drop across the 3 resistances
C              P(1),     VISCOS:   fluid viscosity
C              P(2),     CORNER:   tuning factor for corner friction
C              STAT(1), =1 iff 1ST time subrtn is called,  =0 else
C              STAT(2), =1 iff last time subrtn is called, =0 else
C              STAT(3), =1 iff last time subrtn is called
C                           for this storage interval, =0 else
C
C---- OUTPUTS: Y(1),     FS12(Q):  total flow through resistances
C              STAT(4)  =1, stop the integration,  =0 continue
C
C---- DECLARATIONS:
      CHARACTER        STR*80
      DOUBLE PRECISION TIME, X(20), dP, R1, R2, R3, RTOTAL
      DOUBLE PRECISION P(20), VISCOS, CORNER, Pi, Y(20), Q
      INTEGER          STAT(10)
      PARAMETER        (Pi=3.14159d0)
C
      EXTERNAL         ZZWRIT
C
C***zzsu76**********************************************************
C
      IF (STAT(10).EQ.1) THEN
         STR= 'Last Modification: June 22, 1994 - mkh'
         CALL ZZWRIT(STR)
         RETURN
      ENDIF
      TIME = TIME
C
C---- Inputs
C
      dP     = X(1)                    ! [N/cm^2]
      VISCOS = P(1)                    ! [N s/cm^2]
      CORNER = P(2)                    ! []
C
C---- Calculate the resistance values
C
      R1     = (VISCOS * 0.17 * 128)/(Pi * 0.15**4)
      R2     = CORNER * R1
      R3     = (VISCOS * 1.23 * 128)/(Pi * 0.20**4)
      RTOTAL = 0.5*R1 + R2 + R3
C
C---- Output
C
      Q      = (1.0/RTOTAL)*dP
      y(1)   = Q                       ! [cm^3/s]
C
      RETURN
      END
CEND:zzsu00<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<
```

```
C zzsu85 >>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
c
c  calculation of DP/Dt for liquid with air entrained
c  Version 1.0- 3/29/90 pas/jal
c
        SUBROUTINE zzsu85(TIME,X,P,Y,STAT)
c
c    PROGRAMMING:
c   1) Version 1.0- 3/29/90 pas/jal
c
c   2.0) Converted code to interface with ENPORT/PC 5.1
c        G. DeRose Jr.        02/07/94
c
c   2.0) Changed print statment.
c        G. DeRose Jr.        02/22/94
c
c
c    DESCRIPTION: This is the driver subroutine for enport
c        computes dp/dt from f.xx for fluid with air entrained.
c        (assumes isentropic compression of air, P(3)=1.4)
c         ZZSU85 is a slight modification of ZZSU12 - to handle a
c         decreasing volume....in the P2 chamber of the VDE...this had
c         to be done bcause the vol is max when Xpistn is 0.
c
c
c    INPUTS:
c   X(1) = Net hydraulic flow f.xx  --  (cm**3/sec)
c   X(2) = Piston displacement (Xp) --  (cm)
c   X(3) = Pressure                 --  (N/cm**2)
c
c   P(1) = Initial chamber vol (Vi) --  (cm**3)
c   P(2) = Area of piston (Ap)      --  (cm**2)
c   P(3) = Gas constant (Cp/Cv)     --
c   P(4) = Constant defining Vt, i.e.
c            Vt = Vi + P(4)*Ap*Xp
c
c   P(5) = Fluid bulk modulus       --  (N/cm**2)
c   P(6) = Volume fraction of air   --
c
c
c
c    OUTPUTS:
c   Y(1) = dP/dT or d(E.xx)/dt, from f.xx
c
c    MAIN SUBROUTINE
c
c    DECLARATIONS:
         DOUBLE PRECISION  X(20), Y(20), P(20), TIME
         integer STAT(10)
         DOUBLE PRECISION F_xx, Emod, Beff, Vi, press, VT, Xair
         DOUBLE PRECISION Xp, Ap, Patm, Pabs, gamma, a, b, c, d,  t1

         CHARACTER      STR*80
         EXTERNAL       ZZWRIT
c
c
c     Evaluation section
c
c
c  Variables:
c
c    F_xx  = Net hydraulic flow (cm**3/sec)
c    Emod  = Bulk modulus of fluid (N/cm**2)
c    Beff  = Effective bulk modulus (N/cm**2)
c    Vi    = Initial volume of chamber (cm**3)
c    press = pressure (N/cm**2)
c    VT    = Total volume being compressed (cm**3)
c    Xair  = Volume fraction of air in fluid
c    Xp    = Piston displacement (cm)
c    Ap    = Piston area (cm**2)
c    Patm  = Atmospheric pressure (N/cm**2)
c          = 10.14 N/cm**2
c    gamma = Gas constant (Cp/Cv)
c          = 1.4 for isentropic compression of air
c          = 1.0 for isothermal compression of air
c
c    a, b, c, d, t1 --> Temporary Variables

      IF( STAT(10) .EQ. 1 ) THEN
         STR = ' User Sub - zzsu85 - Version 1.0 - 08/02/94 -bjj'
         CALL ZZWRIT(STR)
      ENDIF

             F_xx  = X(1)
             Xp    = X(2)
             press = X(3)

             Vi    = P(1)
             Ap    = P(2)
             gamma = P(3)
             Emod  = P(5)
             Xair  = P(6)

             Patm = 10.14d0
             VT   = Vi - P(4)*Xp*Ap

             a  = (Emod)/(1.d0-Xair)
             t1 = Patm**(1.d0/gamma)
             b  = (Xair*Emod*t1)/(gamma-gamma*Xair)
             c  = -1.d0 - 1.d0/gamma
             d  = Patm

             Pabs = press + Patm
             Pabs = max(Pabs, 1.d-4) ! Prevent undefined P**c

             Beff = a / (1.d0 + b*Pabs**c)
             Y(1) = F_xx * ( Beff / VT )

         return
         end
CEND:zzsu85<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<
```