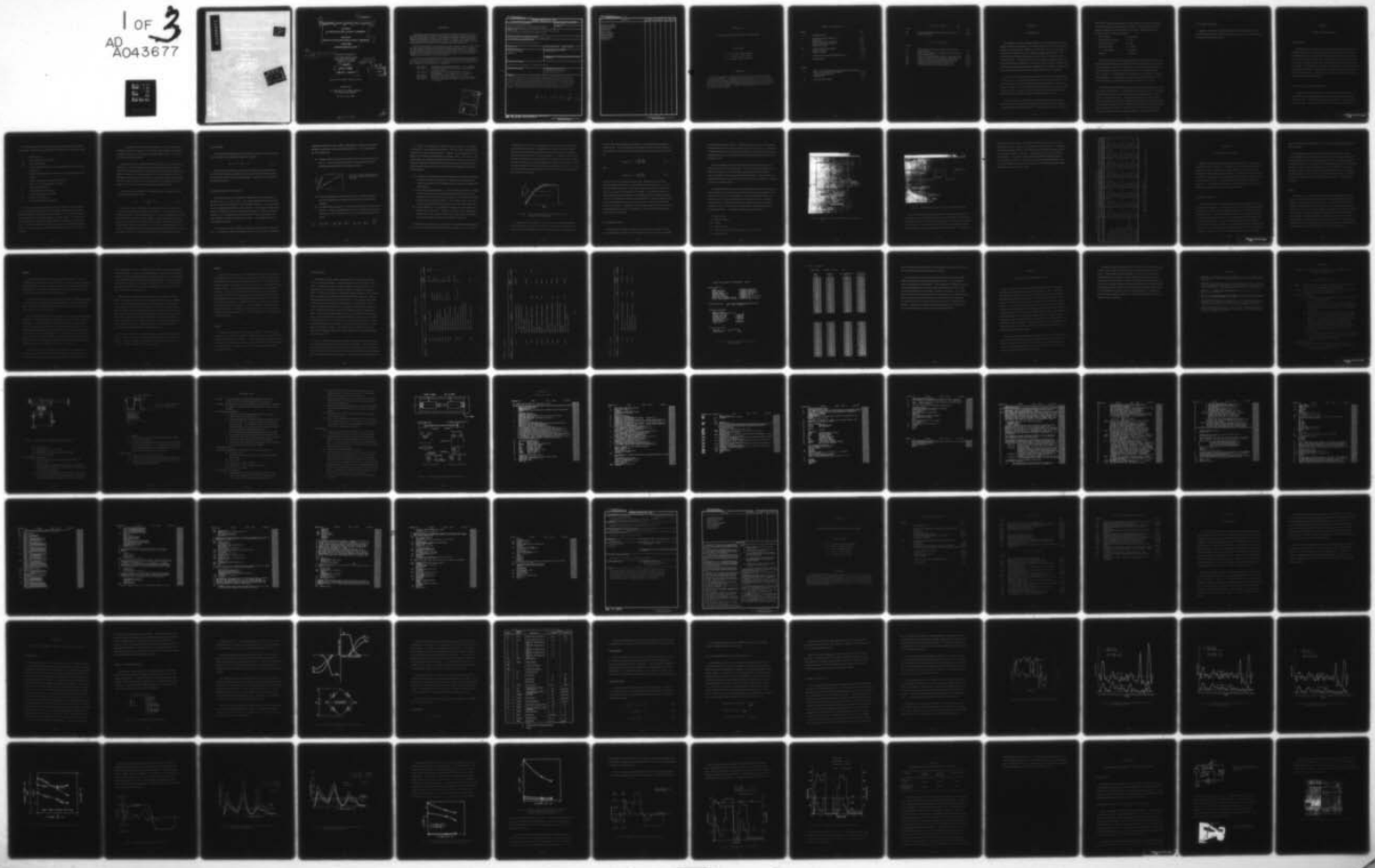
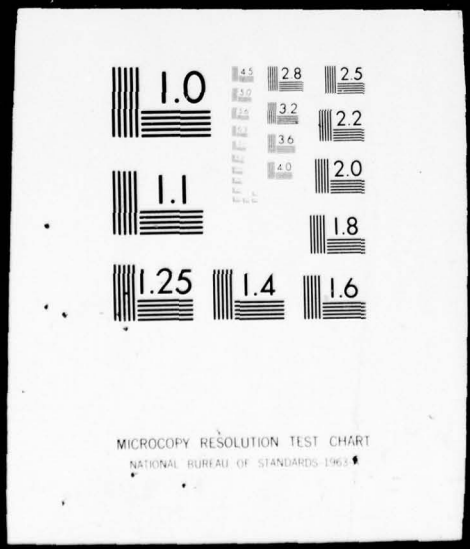
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- FOREWORD -

This report was prepared by the staff of the Fluid Power Research Center of the Division of Engineering, Technology & Architecture, Oklahoma State University of Agriculture and Applied Sciences. The study was initiated by the Mobility Equipment Research and Development Command, Fort Belvoir, Virginia. Authorization for the study reported herein was granted under Contract No. DAAK02-75-C-0137. The time period covered by this report is from 1 February 1976 to 31 January 1977.

The Contracting Officer's Representative was Mr. Hansel Y. Smith, and Mr. John M. Karhnak served as the Contracting Officer's Technical Representative. In addition, Mr. Paul Hopler has effectively represented the Contracting Officer both technically and administratively through various phases of this contract. The active participation of Messrs. Smith, Karhnak, and Hopler during critical phases of work contributed significantly to the overall success of the program.

The studies represented by this report were conducted under the general guidance of Dr. E. C. Fitch, Program Director. The details of each study are presented in a self-contained section of this report. The titles of the various sections together with their respective Project Managers are listed below:

SECTION I.	HYDRAULIC NOISE ATTENUATION — G. E. Maroney
SECTION II.	CYLINDER STRUCTURAL INTEGRITY ASSESSMENT — S. K. R. Iyengar
SECTION III.	HYDRAULIC SYSTEM OPERATIONAL SEVERITY ASSESSMENT — R. L. Decker/S. K. R. Iyengar
SECTION IV.	ON-BOARD MONITOR STUDY — R. L. Decker
SECTION V.	HYDRAULIC SYSTEM DIAGNOSTICS — R. K. Tessman
SECTION VI.	PUMP CONTAMINANT TOLERANCE VERIFICATION — L. E. Bensch



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13. ABSTRACT

This report presents an account of the activities of the MERADCOM-OSU System Reliability Program in the area of hydraulic cylinder structural integrity assessment. A dynamic mathematical model of the locked-rod or impulse testing is developed and the effects of changing test setup parameters are also demonstrated. A computer program for simulating locked-rod testing is presented along with a user's guide. Draft procedures for both stroking (endurance) and locked-rod (impulse) tests are included in an appendix. Results of experimentation with the locked-rod setup are also presented.

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Locked-Rod Test						
Impulse Test						

SECTION II

CYLINDER STRUCTURAL INTEGRITY ASSESSMENT

Project Staff

S. K. R. Iyengar, Project Manager

R. F. Sharp, Project Engineer

N. M. Hamdan, Project Associate

FOREWORD

This section presents a detailed account of the project activities in the area of cylinder dynamic testing. A mathematical analysis of locked-rod or impulse testing is developed and the effects of changing test setup parameters are also demonstrated. A computer program for simulating locked-red testing is presented along with a program user's guide. Draft procedures for both stroking (endurance) and locked-rod (impulse) tests are included in an appendix. Results of experimentation with the locked-rod test setup are also presented.

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CHAPTER I

INTRODUCTION

The reliability of hydraulic equipment depends to a considerable extent on the proper selection of individual components. For various reasons, most of which were indicated by Hopler at the 29th National Conference on Fluid Power, Ref. [1], the end-item user should exercise significant control over individual component specifications. Such specifications should address themselves to the performance of the component rather than design details. The objective of the U.S. Army Mobility Equipment Research and Development Command (MERADCOM) - Fluid Power Research Center program over the past five years has been directed towards implementing this philosophy by developing and appraising test methods and procurement specifications for hydraulic components.

Hydraulic cylinders are important components on a vast majority of mobile equipment and function not only as fluid power components but also as structural elements. Recognizing the importance of assessing the structural integrity of hydraulic cylinders under dynamic loading the U.S. Army MERADCOM initiated a study of two currently used test procedures in 1975. Results of the first year's effort were presented in the Annual Report on MERD/OSU Hydraulic System Reliability Program, Ref. [2].

The current project was undertaken as the continuation of the previous year's effort to establish a rational basis for appraising the structural integrity of hydraulic cylinders under static and dynamic loading. The effort has been done as a Technology

Development Project and has gained the active participation of six industrial companies having strong interests in mobile hydraulic cylinders. The following is a list of the industrial sponsors and their monitors for the Technology Development Project on Cylinder Structural Integrity Assessment.

Allis Chalmers	L. Stikeleather
Bruning Division of Gould	K. Koch
Deere and Company	D. Malm
Eaton Corporation	R. Lindgren
J. I. Case Company	E. Falendysz
Koehring	J. Parrett

Since some of the monitors were assigned primarily for administrative control, the sponsoring companies have maintained technical liaison through persons actively involved in cylinder design and selection. These persons, who have made valuable technical inputs to the program, both at review meetings as well as in correspondence include Dr. G. Ekstrom, C. Brundidge and E. Esser (Eaton), M. Beck (Drott), D. Hancock (Allis-Chalmers), W. Snyder (Deere & Co.), and J. Fairbairn (Koehring). The U.S. Army MERADCOM was represented at the technical meetings by H. Y. Smith.

The effort has been divided into two phases, namely, the Static Analysis Phase and the Dynamic Analysis Phase. The results of the Static Analysis Phase, which consists of verification fo the joint flexure theory of hydraulic cylinder deflection, will be presented in a self-contained report. This section is devoted to the Dynamic Analysis Phase whose objective was to examine the effect of test parameters on locked-rod testing. The next chapter presents the results of dynamic stress analysis as well as a parameter sensitivity analysis. Chapter III includes the user's guide for the digital computer program for simulating the locked-rod test in addition to a listing of the FORTRAN

source code for the program.

Appendix A contains the draft procedures for stroking and locked-rod testing. These procedures incorporate modification to reflect the results of the parameter sensitivity analysis and simulation results.

CHAPTER II

DYNAMIC STRESS ANALYSIS

INTRODUCTION

The main objective of this effort was to examine the effects of pin clearances, frame stiffness, and flow rate on stress cycles in stroking and impulse testing of cylinders. Experimental effort was to be devoted to measuring dynamic strain and pressure during cyclic loading on a locked-rod test setup. Based on the analysis and review of experimental data, revised test procedures for conducting stroking and locked-rod tests were to be drafted. The following sections will discuss the effect of test frame parameters and present experimental data on locked-rod testing. General conclusions on both facets will be presented at the end. Appendices A and B contain drafts of the revised procedures for both impulse and stroking tests.

EFFECT OF TEST FRAME PARAMETERS

The effect of test frame parameters (e.g., frame stiffness, pin clearances, pump flow rate) all can be best explained by developing mathematical models of the setups under discussion. The locked-rod setup will be analyzed below. A parallel analysis for stroking tests was furnished in the report on the previous year's effort, Ref. [2].

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The following symbols will be used in the various equations comprising the mathematical model. Time derivatives of quantities will be indicated by a dot over the symbol.

P = System pressure

A = Cross section area of the cylinder

Q_{in} = Flow rate of the pump

V = Volume of the test cylinder which is being pressurized during one half of the test cycle

x = Displacement of the piston with respect to a given reference mark on the cylinder

v = Velocity of the piston with respect to the cylinder

I = Inertia of the piston and attached moving parts

K = Stiffness of the test frame

B = Drag coefficient for the piston rod

C_L = Leakage coefficient for the cylinder

P_r = Relief valve set pressure

β = Effective bulk modulus of system fluid

It will be assumed that the directional control valve used for cycling the pressure switches instantaneously and that the system relief valve opens when the set pressure is attained and insures that the pressure is not exceeded. It will also be assumed that the directional control valve and piping offer no resistance to flow. The net result of these assumptions is to slightly overestimate the pressure rise and decay rates for the cycle. Though the assumptions can be lifted by developing more elaborate mathematical models, such a course of action is not considered necessary for the majority of testing situations.

It is sufficient to consider only half of a complete cycle since the analysis is precisely the same for the other half. The half cycle under consideration consists of a pressure rise period, a dwell period, and a pressure decay period (i.e., the waveform is approximately trapezoidal).

The pressure rise is not instantaneous for three reasons: firstly, the fluid and the conductors (i.e., hoses, tubing) are elastic and a finite amount of fluid is needed to make up for the compressibility of the system volume as well as the dilation of the hoses, tubing, etc.; secondly, the cylinder, especially if it has worn-out seals, will leak at a rate generally increasing with pressure and this leakage fluid reduces the flow available to raise the system pressure; lastly, because of the flexure and slack of the frame the piston rod will move just enough to take up flexure and slack in the frame.

The following equation establishes the relationship between the pump flow and the various quantities referred to above:

$$Q_{in} = Av + \frac{V}{\beta}\dot{P} + PC_L \qquad (2\text{-}1)$$

The first term on the right hand side of the equation is the flow rate needed to fill up the volume rendered void by movement of the piston rod. The second term expresses the flow rate needed to raise system pressure (i.e., it is the "compressibility flow rate"), while the last term accounts for cylinder leakage. It should be noted that in this equation Q_{in} is the inflow to the system volume and is obtained by subtracting from the pump outflow whatever passes over the relief valve. It may also be noted that once the relief valve is opened and the frame has flexed sufficiently to develop the necessary reaction, the pressure rise rate, $\dot{P}$, goes to zero and the only inflow is that needed to handle

cylinder leakage.

The second equation needed to describe the locked-rod setup is a force balance equation for the piston rod and attached moving parts, as follows:

$$PA = I\dot{v} + Bv + Kx \qquad (2\text{-}2)$$

The first term on the right hand side is the force needed to overcome the inertia of the moving parts (piston + attachments, if any), while the second is the force needed to overcome the friction drag at the piston and gland. The last term is the reaction of the frame due to flexure.

PARAMETER SENSITIVITY ANALYSIS

The following parameters can be generally changed with more or less ease for any test setup: Q_{in}, P_r, I, B, C_L, and K. Q_{in} can be changed by using different pumps, operating a pump at various speeds or using a variable volume pump. P_r can be changed easily if an adjustable relief valve is used in the circuit. The last four parameters cited above are characteristic of the test cylinder and the test frame. Of these, the leakage coefficient, C_L, will generally increase in the course of a test, while changes in the drag coefficient, B, depend on the design of the seals. Frame stiffness is, perhaps, the most difficult to change.

It is instructive to examine the effect of changing the above parameters on the test cycle. Even though the effects can be quantitized by simulating the system using different

combinations of parameter values, a better understanding of the influence of a specific parameter is obtained by examining the pertinent equations. Thus, an inspection of Eq. (2-1) indicates that:

(i) A larger pump flow rate will result in higher pressure rise rates, as shown in Fig. 2-1. Too low a pump flow may result in the directional control valve switching flow before the relief valve setting is reached.

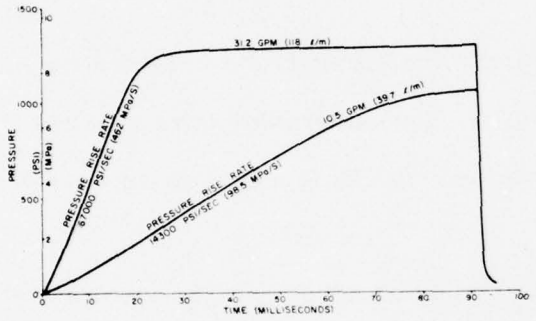


Fig. 2-1. Effect of Pump Flow Rate on Pressure Rise Rate and Final Pressure

(ii) As may be anticipated, the relief valve setting, P_r, controls the pressure level, and consequently, the stress level to which the test cylinder will be subjected.

(iii) The effect of piston rod inertia, I, is hard to ascertain directly from Eqs. (2-1) and (2-2). However, by differentiating Eq. (2-2) with respect to time and substituting for P and $\dot{P}$ in terms of x, v, $\dot{v}$, and $\ddot{v}$, the following equation is obtained:

$$Q_{in} = \left(\frac{V}{\beta} \cdot \frac{I}{A}\right) \ddot{v} + \left(\frac{V}{\beta} \cdot \frac{B}{A} + \frac{I}{A}\right) \dot{v} + \left(\frac{V}{\beta} \cdot \frac{K}{A} + \frac{B}{A}\right) v + \frac{K}{A} x \qquad (2\text{-}3)$$

If $\ddot{v}$ is zero, it is seen that, for a constant, Q_{in}, any increase in I will result in a reduction of $\dot{v}$, other quantities being constant. From Eq. (2-2) it can be seen that a reduction of $\dot{v}$ implies a lesser value of P. However, Eq. (2-1) requires that a reduction in P will need to be compensated by increases in either v or $\dot{P}$ or both. The overall effect, thus, cannot be summarized as an increase or decrease in the rise rate. Simulation results have indicated that for the common range size of cylinders and flow rates, piston rod inertia has a rather small impact on both the pressure rise rate and the final pressure.

(iv) The effect of the cylinder drag is equally complex and hard to generalize without numerical values for other parameters. Simulation using selected sizes of cylinders has indicated that this parameter has little impact on the waveform for inpulse testing.

(v) The cylinder leakage coefficient, C_L, is an important parameter since it affects both the pressure rise rate and the final pressure attained in the test cycle. Inspection of Eq. (2-1) shows that an increase of C_L reduces both the pressure rise rate as well as the final pressure. If the cylinder leakage is excessive, all the pump flow may leak past the seal and none over the system relief valve.

(vi) The frame stiffness, K, mainly affects the pressure rise rate--a stiffer frame leading to higher rise rates. This effect is, however, not very significant if the test frame is made of material having a high Youngs modulus and designed so that lateral deflection of load-carrying elements is minimized.

The effect of pin clearances can be ascertained for any specified test setup by assigning a value of zero to the frame stiffness until the slack is taken up. From Eq. (2-2),

it can be seen that if K is zero, a given pressure will result in a higher acceleration and velocity for the piston rod. Qualitatively, the pressure rise rate will be small until the piston rod has moved far enough to overcome the slack due to pin clearances, and after that the pressure will rise exactly as before. The computer program written for digital simulation and discussed in Chapter III, includes provisions for simulating the behavior of a test frame with variable stiffness and a variety of pin clearances. Figure 2-2 presents the effect of chagning pin clearances on the pressure rise rate. It is seen that large clearances lead to lower pressure rise rates, while very small clearances can result in pressure overshoots.

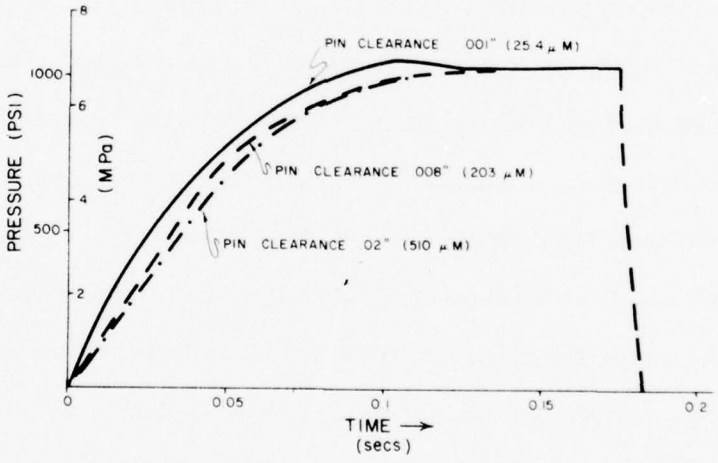


Fig. 2-2. Effect of Pin Clearance on Pressure Rise During Locked-Rod Test (Simulated)

The mathematical model presented in Eqs. (2-1) and (2-2) can be used to predict the value of pressure at any time in the course of an impulse test on a cylinder with a rod fixed at any specified position. Using this value of pressure, the stresses in the

cylinder, rod or any other load carrying member can be established using standard formulas, Ref. [3]. Thus, for example, the hoop stress at the inner and outer surfaces of the cylinder wall, in terms of the internal pressure and the cylinder dimensions are given by:

$$S_{\text{Hoop int.}} \triangleq p \frac{(R^2 + r^2)}{(R^2 - r^2)} \tag{2-4}$$

and:

$$S_{\text{Hoop ext.}} \triangleq p \frac{2r^2}{(R^2 - r^2)} \tag{2-5}$$

where R and r are the external and internal radii, respectively, of the cylinder. Since the cylinder wall thickness is almost always within the range 0.1" to 1" (2.5 mm to 25 mm) the time required for a stress wave to travel from the internal surface to the outer, or vice versa is of the order of 10^{-6} seconds. Since pressure rise rates in inpulse tests rarely exceed 100,000 psi/sec (690 MPa/s), the time needed for pressure to rise from 0 to 3000 psi (0-21 MPa) is 0.03 seconds which is orders of magnitude larger than the time needed for the stress wave to travel from the inside to the outside of the cylinder or vice versa. Consequently, for all practical purposes, the stress rise accompanying the pressure rise occurs simultaneously. Experimental data presented subsequently confirm this deduction.

EXPERIMENTAL EFFORT

The final report on the previous year's activity in the area of cylinder structural integrity assessment presented the results of dynamic pressure and strain measurements

on a locked-rod test setup, Ref. [2]. It showed that the pressure rise rate correlated well with strain rate in the cylinder in both the axial and hoop directions. Consequently, in conducting fatigue tests (either impulse or stroking) it is sufficient to measure cylinder pressure dynamically and to calculate the hoop and longitudinal stresses using standard formulas, Ref. [3].

Figure 2-3 presents traces of cylinder hoop strain and pressure for one half of a complete impulse cycle in a locked-rod test. The strain rise is seen to occur synchronously with the pressure rise, which affirms the validity of Eqs. (2-4) and (2-5). Figure 2-4 presents similar traces of pressure and axial strain. Once again the correlation between pressure rise and axial strain rise is seen to be very good, thus, obviating the need for strain measurements.

It should be noted that the actual rise rate and the final pressure for a cycle depend on the pump flow rate, characteristics of the system relief valve, switching speed of the directional control valve, and capacitance (i.e., elasticity) of the tubing hoses, etc., connecting the test cylinder to the directional control valve and pump. In addition, it also depends on the stiffness of the test frame--a stiffer frame resulting in higher pressure rise rates. Table 2-1 summarizes the effect of changing some of the parameters mentioned above. The following parameters were kept constant:

(i) pump flow rate

(ii) test frame stiffness

(iii) cylinder

(iv) fluid bulk modulus

(v) relief valve gradient (slope of pressure flow characteristics)

(vi) upstream volume

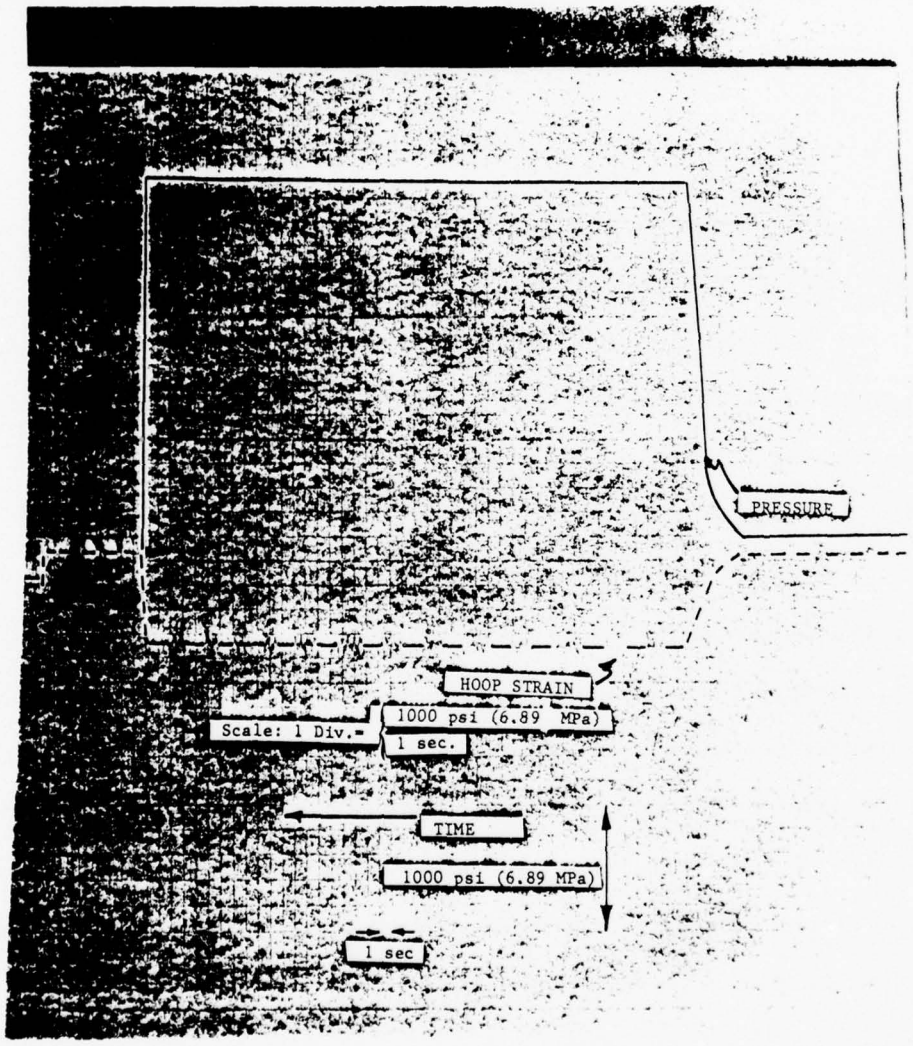


Fig. 2-3. Dynamic Pressure and Hoop Strain for Locked-Rod Test

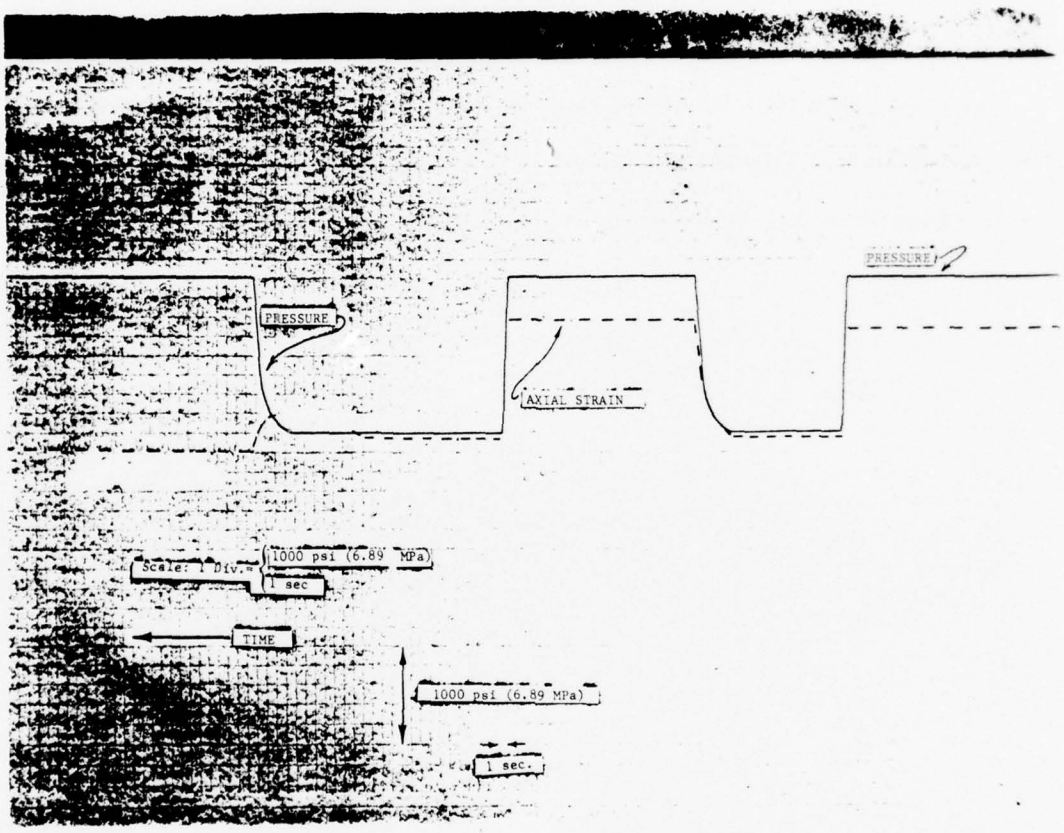


Fig. 2-4. Dynamic Pressure and Axial Strain for Locked-Rod Test

Since the locked-rod test setup is essentially a first-order dynamic system, its transient behavior can be adequately described by its time constant--a larger time constant implying a "spongy" system with low pressure rise rate and a small time constant a "stiff" system. Table 2-1 indicates that a 250% change in the slack in the frame (caused mainly by pin clearances) changes the time constant only 7%. Change in the

relief valve cracking pressure, and consequently, the pressure at which the cycling is performed, on the other hand, significantly affects the pressure rise rate. Consequently, high pressure cylinders tested at the same flow rate will be subjected to higher pressure rise rates than low pressure cylinders. An inspection of Figs. 2-3 and 2-4 confirm this conclusion. It is seen that in both cases the time taken to reach final pressure is approximately one second. Since the final pressure is 3000 psi (20.691 MPa) in the first case and 1000 psi (6.897 MPa) in the second, the rise rate is approximately tripled due to the increase in relief valve setting.

TABLE 2-1. SUMMARY OF PARAMETERS FOR LOCKED-ROD CYLINDER TEST

TEST SYSTEM PARAMETER*	NUMERICAL VALUE FOR COMPUTER RUN NO.							
	770114.1	770114.3	770114.4	770114.5	770114.6	770114.7	770114.8	770114.9
Pump Flow	40.425	40.425	40.425	40.425	40.425	40.425	40.425	40.425
Frame Stiffness	1.57×10^{6}	1.57×10^{6}	1.57×10^{6}	1.57×10^{6}	1.57×10^{6}	1.57×10^{6}	1.57×10^{6}	1.57×10^{6}
Drag Coefficient	133.44	133.44	133.44	133.44	133.44	133.44	13.34	1.334
Cylinder Area	19.63	19.63	19.63	19.63	19.63	19.63	19.63	19.63
Velocity Coefficient	10^{-3}	10^{-3}	10^{-3}	10^{-3}	10^{-3}	10^{-3}	10^{-3}	10^{-3}
Upstream Volume	363	363	363	363	363	363	363	363
Fluid Bulk Modulus	200×10^{3}	200×10^{3}	200×10^{3}	200×10^{3}	200×10^{3}	200×10^{3}	200×10^{3}	200×10^{3}
Piston Rod Inertia	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Total Slack in Frame	8×10^{-3}	10^{-3}	0.02	0.02	10^{-3}	8×10^{-3}	8×10^{-3}	8×10^{-3}
Relief Valve Cracking Pressure	1000	1000	1000	3000	3000	3000	3000	3000
Relief Valve Gradient	0.404	0.404	0.404	0.404	0.404	0.404	0.404	0.404
Time Constant **	43.5×10^{-3}	44×10^{-3}	46×10^{-3}	75×10^{-3}	77×10^{-3}	75×10^{-3}	76×10^{-3}	72×10^{-3}
Final Pressure	1029	1029	1029	1453	1453	1453	1453	1453

* Units: See computer print-out reproduced.

** Defined as the time in seconds needed for the pressure to rise to 63% of its final value.

CHAPTER III

USER'S GUIDE FOR LCKROD

LOKROD is a digital computer program, written in FORTRAN IV, for simulating a locked-rod hydraulic cylinder test. It takes into account the compressibility of the system fluid, inertia and drag of moving parts, leakage in the test cylinder and pin clearances in establishing the pressure waveform. The program can be used to examine the influence of changing not only the above parameters but also the hydraulic test circuit pump and system relief valve. Mathematical details of the analysis are reported in Chapter II. The remainder of this chapter is devoted to explaining the structure and usage of the computer program, which is included in Appendix C.

PROGRAM STRUCTURE

The locked-rod hydraulic cylinder test setup is treated in the program as a lumped parameter dynamic system. It is modeled by a third-order vector nonlinear differential equation with a step change in flow (caused by switching of the directional valve) being the forcing function. Any other type of forcing function can be imposed on the mathematical model by appropriate changes in one of the subroutines to described subsequently. Since the system is nonlinear, a numerical integration method is used to develop the time-histories of the dynamic quantities (i.e., system pressure, piston rod displacement, and its velocity). The numerical integration method calculates the values of the dynamic quantities at a specific point in time by extrapolating from the values of the points in

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time prior to the time under consideration. The process is iterated to develop the complete time-history.

The time step between two consecutive points on the trajectories of the dynamic variables depends not only on the dynamics of the system being simulated but also on the numerical integration method. Since the time step, which may be variable, influences the speed of simulation, it is important to match the integration method to the system being simulated. LOKROD uses Gear's algorithm for numerical integration, a fairly recent development which is suited for the system under consideration, Ref. [4]. In order to use Gear's algorithm, which is included in a subroutine called DIFSUB, it is necessary to furnish a main program as well as certain auxiliary programs. These will now be discussed.

MAIN

The main program is used primarily for controlling input and output (I/O) for the computer. All the system parameters as well as the integration parameters are read off data cards and printed out by the main program. The initialization of the dynamic variables is also performed in the main program prior to calling the integration subroutine DIFSUB. Each call to DIFSUB advances the trajectories of the dynamic variables by one time step. Between repeated calls to time DIFSUB, the main program checks if the integration is proceeding satisfactorily and stores the results of the numerical integration after a specified number of time steps have been taken. Finally, the main program prints out the time-histories of the dynamic variables and any messages pertaining to abnormal termination of the integration, if any such terminations occur.

DIFFUN

This subroutine contains the mathematical model for the system in the form prescribed by Gear's integration subroutine DIFSUB. The dynamic quantities are referred to in this subroutine as "State Variables," in conformity with the terminology of modern control theory. The listing for this subroutine shows how the mathematical model for the system is written in the form of FORTRAN statements.

It is instructive to examine how information about the behavior of different components in the test circuit is incorporated in the mathematical model. This will be done briefly below. Reference will be made to the line numbers of the FORTRAN program, which are printed at the right edge of the listing.

Lines 2890 through 2920 of the listing in Appendix C contain the model for the system relief valve. If the system relief valve cracking pressure, there is no flow through the relief valve--i.e., all the pump flow is directed into the cylinder. However, if the relief valve cracking pressure (RELFCR) is exceeded by the system pressure (Y (1,1)), part of the pump flow goes over the relief valve (RVFLO). The quantity of this flow is determined by the relief valve gradient (XM). An ideal valve would have a infinite gradient (i.e., the pressure is always equal to the cracking pressure, no matter what the flow through the valve). In actual practice relief valves have a finite gradient which can be ascertained during tests of regulation characteristics, Refs. [5,6].

FORTRAN statements in lines 2960 through 3050 describe the dynamic behavior of the test cylinder as well as the frame. This is done by furnishing expressions for the rate of change of the state variables (system pressure, rod displacement and rod

velocity, respectively). Thus, in line 2960, the rate of change of pressure is expressed in terms of the inflow, rod velocity, and cylinder leakage. Note that the fluid bulk modulus (BETA) as well as the upstream volume of the test setup (VA) enter in the expression. It is seen that increasing the bulk modulus and pump inflow tends to increase the pressure rise rate while increasing the cylinder volume tends to reduce it. It may also be noted that when the inflow (QA) is exactly equal to the leakage flow, and the rod velocity is zero, the pressure rise rate falls to zero.

Statements in lines 2970 through 3000 describe the dynamic flexure of the test frame. The pressure in the test cylinder causes the test frame, pins, etc., to deflect--the exact amount of deflection depending upon the effective stiffness of the test setup. For a given pressure a stiff system would deflect less than one which is less stiff. In order to account for the fact that there will generally be clearances in the cylinder rod-end and eye, the mathematical model incorporates expressions for taking such clearances into account. Basically, the mathematical model assumes that the frame stiffness is zero until the slack due to pin clearance is taken up (i.e., the cylinder rod moves freely until the clearance is taken up). Beyond that point the frame deflects, building up a resisting force which ultimately balances the cylinder pressure.

DIFFUN is called by DIFSUB a number of times during the numerical integration process. After each call DIFFUN returns the values of the derivative vector DY to DIFSUB. Parameters needed for calculating these derivatives are communicated via the labeled COMMON block BLK1 from the MAIN program.

DIFSUB

This subroutine performs the numerical integration to develop the time-histories of the state variables (i.e., system pressure, rod displacement, and rod velocity) using the mathematical model furnished in the subroutine DIFFUN. It is called by the main program repeatedly until the desired time-history is developed or integration fails due to abnormal conditions. The attached listing explains the significance of all quantities of interest. The subroutine has three options for performing numerical integration, of which only the third (M = 2) is actually used in the locked-rod simulation program. Complete details of the mathematical basis for DIFSUB is given by Gear, Ref. [4], and will not be discussed here. In addition to DIFFUN, DIFSUB requires two subroutines called MATINV and PEDERV. The first is needed for inverting a matrix generated by DIFSUB. The second is really needed only for the option in numerical integration method corresponding to MF = 1 and is consequently a dummy subroutine in the present package.

MATINV

This subroutine is needed by DIFSUB to invert a matrix. The actual inversion is carried out in a subroutine called MINV, contained in the IBM Scientific Subroutine Package (SSP) and written in FORTRAN. The SSP subroutine called ARRAY is used to arrange both the matrix to be inverted and the matrix after inversion in forms suitable for further processing. Both MINV and ARRAY can be substituted by functionally equivalent subroutines.

PROGRAM USAGE

The program is setup to read pertinent data off the card reader, designated as until 5 in the READ statements. Output is directed to unit 6 in the WRITE statements. No scratch files, tapes or auxiliary storage facilities are required. It is assumed that the SSP subroutines MINV and ARRAY are available in the system library. If this is not so, source or object decks of these subprograms can be concatenated to the program or substituted by functionally equivalent subprograms. Source listings of these subprograms can be found in Ref. [7]. The remainder of this section is devoted to explaining the data input for the program and interpreting the output. Table I presents the description, units, and computer names anf format specifications for all variables and parameters needed for simulating the locked-rod cylinder test setup. In accordance with the standard practice in using FORTRAN, all real quantities (i.e., those whose computer names start with letters A through H, and O through Z) should conform to the F, E, or D formats, and all integer quantities (i.e., those whose computer names start with letters I through N) should conform to the I format and be right justified in the field. The computer program, written for use on the IBM 360/370 or equivalent systems uses double precision for all real quantities except those starting with "P".

Figure 3-1 includes excerpts from the computer print-out for an example simulation. The first part gives the title of the test system and its parameters. The next part indicates the numerical integration method used and the integration parameters. The third part of the output includes the initial values for the state variables (i.e., system pressure, piston rod displacement and piston rod velocity). All of the above mentioned parts of the

TABLE 3-1. INPUTS TO LOKROD

Card No.	Columns	Quantity	Units	Computer Name	Format
1	1-72	Description of Test System		PTITLE	18A4
2	1-10	Pump Flow	*cu. in/sec*	QP	F10.3
	11-20	Frame Stiffness	lbsf.in.	STIFF	"
	21-30	Cylinder Drag Coefficient	lbsf sec/in	DRAG	"
	31-40	Cylinder Cross-section Area	square in.	AA	"
	41-50	Upstream Volume	cu. in.	VA	"
	51-60	Fluid Effective Bulk Modulus	psi	BETA	"
	61-70	Inertia of Piston Rod	lbsf sec^2/in	XI	"
3	1-10	Total Slack in Frame (including pin clearances)	ins	CLRNCE	"
	11-20	Relief Valve Cracking Pressure	psi	RELFCR	"
	21-30	Relief Valve Gradient	cu. in/sec psi	XM	"
4	1-5	Order of System (always equal to 3 for the set of equations included in DIFFUN for the model developed in this report)		N	I5
	6-10	*Method Number* (always equal to 2)		MF	I5

TABLE 3-1. Continued.

Card No.	Columns	Quantity	Units	Computer Name	Format
	11-15	Maximum Order of Integration (A maximum value of 5 may be assigned to this parameter. Values between 3 and 5 give good results.)		MAXDER	I5
	16-20	Print-out Interval (suggested value: between 5 and 20)		MULTSP	I5
5	1-10	Initial Step Size (suggested value: 0.0001)	sec.	H	F10.3
	11-20	Minimum Step Size (suggested value: 0.00001)	sec.	HMIN	"
	21-30	Maximum Step Size (suggested value: 0.01)	sec.	HMAX	"
	31-40	Fractional Allowable Error (suggested value: 0.2)		EPS	"
	41-50	Initial Time for Integration (suggested value: 0)	sec.	TINTL	"
	51-60	Time for Which Cylinder Is Pressurized (suggested value: "on" time for switching value)	sec.	TPRESS	"
	61-67	Final Time for Integration (suggested value: same as TPRESS)	sec.	TFINAL	"

TABLE 3-1. Continued.

Card No.	Columns	Quantity	Units	Computer Name	Format
6	1-10	Initial Value of Pressure (suggested value: 14.7)	psi	YYINT(1)	F10.3
	11-20	Initial Value of Piston Rod Position (suggested value: 0)	ins.	YYINT(2)	"
	21-30	Initial Value of Piston Rod Velocity (suggested value: 0)	ins/sec.	YYINT(3)	"

```
LOCKED ROD CYLINDER TEST SIMULATION     770113


SYSTEM PARAMETERS

      INFLOW                              4.0425D+01 CU.IN./SEC
      FRAME STIFFNESS                     1.5704D+06 LBS.F/IN.
      DRAG COEFFICIENT                    1.3344D+02 LBS.F*SEC/IN
      CYLINDER AREA                       1.9630D+01 SQ. IN.
      LEAKAGE COEFFICIENT,                1.4170D-03 IN./SEC*PSI
      UPSTREAM VOLUME                     3.6300D+02 CU. IN.
      FLUID BULK MODULUS                  2.0000D+05 PSI
      TOTAL SLACK IN FRAME                8.0000D-03 IN..F*SEC**2/IN./
      RELIEF VALVE CRACKING PRESSURE      1.9000D+03 PSI
      RELIEF VALVE CRACKING GRADIENT      4.0425D-01 CU.IN./SEC*PSI


INTEGRATION METHOD:   GEAR'S (WITH NUMERICAL DIFFERENTIATION)
                      STIFF SYSTEM INTEGRATION


INTEGRATION PARAMETERS

      ORDER OF SYSTEM                                3
      MAXIMUM ORDER OF INTEGRATION                   3
      PRINT-OUT INTERVALS                            5
      INITIAL STEP SIZE                   1.0000D-06
      MINIMUM STEP SIZE                   1.0000D-07
      MAXIMUM STEP SIZE                   2.5000D-01
      ALLOWABLE ERROR                     1.0000D-01
      MAX. NUMBER OF STEPS                  10250000
      INITIAL TIME                        0.0
      TIME AT PRESSURE                    1.0000D+01
      FINAL TIME                          1.0000D+01


INITIAL STATE VECTOR

      PRESSURE              1.4700D+01 PSI
      ROD DISPLACEMENT      0.0        IN.
      ROD VELOCITY          0.0        IN/SEC
```

Fig. 3-1. Computer Print-Out for Locked-Rod Test Simulation

Fig. 3-1. Continued.

TRAJECTORIES NUMBER OF POINTS: 193

TIME (SEC)	PRESSURE (PSI)	ROD DISPLACEMENT (INS)	ROD VELOCITY (INS/SEC)
1.0000D-06	1.4722D+01	2.8894D-10	2.8895D-04
5.2304D-04	2.5498D+01	6.2789D-05	2.0320D-01
1.2336D-03	3.7041D+01	3.6997D-04	5.9559D-01
2.1668D-03	4.7827D+01	1.2914D-03	1.2678D+00
3.4423D-03	5.1242D+01	3.5111D-03	2.1694D+00
4.3225D-03	4.9077D+01	5.4616D-03	2.0513D+00
5.0297D-03	5.4025D+01	6.4096D-03	4.3263D-01
5.5556D-03	6.7264D+01	6.2239D-03	-1.0613D+00
6.1335D-03	8.8446D+01	5.3918D-03	-1.6065D+00
6.8319D-03	1.1289D+02	4.4696D-03	-8.7428D-01
7.5985D-03	1.2999D+02	4.3342D-03	5.5919D-01
8.6241D-03	1.3560D+02	5.7329D-03	1.8700D+00
9.3753D-03	1.3881D+02	6.8377D-03	6.7341D-01
9.8470D-03	1.4871D+02	6.7984D-03	-7.2705D-01
1.0311D-02	1.6371D+02	6.2642D-03	-1.4223D+00
1.0659D-02	1.7585D+02	5.7743D-03	-1.3180D+00
1.1086D-02	1.8861D+02	5.3620D-03	-7.1877D-01
1.1489D-02	1.9742D+02	5.2677D-03	1.1595D-01
1.1738D-02	2.0099D+02	5.3795D-03	6.5435D-01
1.1898D-02	2.0260D+02	5.5139D-03	9.6295D-01
1.2382D-02	2.0491D+02	6.1571D-03	1.5392D+00
1.2907D-02	2.0669D+02	6.9208D-03	1.1893D+00
1.3196D-02	2.0966D+02	7.1558D-03	4.3523D-01
1.3423D-02	2.1396D+02	7.1574D-03	-2.5604D-01
1.3710D-02	2.2153D+02	6.9605D-03	-9.0260D-01
1.4137D-02	2.3470D+02	6.4831D-03	-1.2024D+00
1.4821D-02	2.5326D+02	5.9389D-03	-2.0267D-01
1.5472D-02	2.6182D+02	6.2510D-03	1.0827D+00
1.6020D-02	2.6437D+02	6.9380D-03	1.2030D+00
1.6580D-02	2.7053D+02	7.3106D-03	3.5182D-03
1.6922D-02	2.7833D+02	7.1597D-03	-7.1897D-01
1.7256D-02	2.8758D+02	6.8587D-03	-9.8418D-01
1.7606D-02	2.9719D+02	6.5450D-03	-7.5368D-01
1.8187D-02	3.0907D+02	6.3930D-03	2.9710D-01
1.8519D-02	3.1277D+02	6.5889D-03	8.5290D-01
1.9035D-02	3.1604D+02	7.1192D-03	1.0524D+00
3.5517D-02	5.6408D+02	7.7114D-03	3.2710D-01
3.6934D-02	5.7993D+02	8.0090D-03	-2.7640D-02
3.8119D-02	5.9741D+02	7.8404D-03	-9.5981D-02
4.1091D-02	6.3369D+02	7.9857D-03	5.6059D-02
1.1954D-01	1.2173D+03	8.2588D-03	1.3219D-01
1.1970D-01	1.2163D+03	8.4029D-03	1.4490D+00
1.2002D-01	1.2097D+03	9.1262D-03	2.6516D+00
1.2037D-01	1.2045D+03	9.7270D-03	6.3263D-01
1.2053D-01	1.2056D+03	9.6810D-03	-9.6668D-01
1.2071D-01	1.2093D+03	9.3971D-03	-2.0477D+00
1.2092D-01	1.2154D+03	8.9110D-03	-2.2417D+00
1.2109D-01	1.2193D+03	8.6011D-03	-1.5309D+00
1.2142D-01	1.2218D+03	8.4867D-03	9.1614D-01
1.2185D-01	1.2146D+03	9.2888D-03	2.1254D+00
1.2232D-01	1.2129D+03	9.6108D-03	-1.0963D+00
1.2264D-01	1.2202D+03	9.0442D-03	-2.1775D+00
1.2303D-01	1.2277D+03	8.4795D-03	-2.3315D-01
1.2344D-01	1.2242D+03	8.9266D-03	2.1051D+00
1.2370D-01	1.2195D+03	9.4536D-03	1.7009D+00
1.2388D-01	1.2179D+03	9.6553D-03	4.0204D-01
1.2405D-01	1.2192D+03	9.5895D-03	-8.6223D-01
1.2423D-01	1.2228D+03	9.3231D-03	-1.7475D+00
1.2447D-01	1.2283D+03	8.8858D-03	-1.7475D+00
1.2473D-01	1.2324D+03	8.5891D-03	-5.0285D-01
1.2484D-01	1.2329D+03	8.5782D-03	2.1660D-01
1.2501D-01	1.2321D+03	8.7123D-03	1.1375D+00
1.2525D-01	1.2289D+03	9.0793D-03	1.7739D+00
1.2558D-01	1.2251D+03	9.5409D-03	6.8887D-01
1.2585D-01	1.2266D+03	9.4864D-03	-1.0588D+00
1.2617D-01	1.2330D+03	8.9919D-03	-1.6342D+00
1.2647D-01	1.2376D+03	8.6624D-03	-3.8684D-01
1.2683D-01	1.2365D+03	8.8728D-03	1.4072D+00
1.2716D-01	1.2321D+03	9.3806D-03	1.2977D+00
1.2759D-01	1.2326D+03	9.4689D-03	-9.5854D-01

print-out present the input information so that the program user may easily verify that the correct information is being furnished to the computer.

The last part of the print-out includes the time-histories for the state variables printed out in increments of the print-out interval MULTSP. The total number of points in the trajectory is also indicated. Digital simulations is essentially a discrete process and establishes the values of the state variables at discrete points in time. Values at other points in time can be easily obtained by interpolation. The common practice is to plot the data points graphically, either manually or via a digital computer. From the print-out it can be seen that the time increments between the data points increases from $.523 \times 10^{-3}$ seconds at the beginning to 2.9×10^{-3} seconds at 0.3811 seconds. This change in step size is automatically brought about by the integration algorithm and ensures that simulation is done efficiently and quickly.

CHAPTER IV

CONCLUSIONS AND RECOMMENDATIONS

Hydraulic cylinders are important components of mobile hydraulic systems and need to be carefully evaluated to ensure reliable operation in the field. Apart from being hydraulic components, cylinders are also structural elements and consequently need to be appraised for structural integrity. Structural failure of hydraulic cylinders may occur due to static overloading (usually buckling failure) or due to cyclic loading (fatigue). The joint flexure theory, developed by the Fluid Power Research Center, for static analysis of hydraulic cylinders has been computerized and used for analyzing a variety of cylinders, not only at the Fluid Power Research Center but also industrial companies sponsoring the Technology Development Program on Cylinder Integrity Assessment. Dynamic analysis of locked-rod (impulse) testing has been presented and computerized for digital simulation. Test results confirm that it is sufficient to measure pressure and deduce the cylinder and rod stresses by applying standard formulas, rather than to strain gage the cylinders.

Digital simulation of the test setup for locked-rod cylinder tests indicate that within certain limits the pin clearance does not significantly affect the pressure rise rate. However, the pressure setting of the system relief valve significantly influences the pressure rise rate and consequently caution should be exercised in comparing test results on cylinders of different pressure ratings.

A survey of cylinder test reports listed in Ref. [2], Section I, Appendix B, indicate that pin and rod-eye failures are the more common modes of failure in impulse testing. Since the effect of pin-eye clearance is to cause cyclic impact loading, these elements must be designed for dynamic loading rather than just static loads. Even design for fatigue stregth using classical S/N diagrams may be inadequate since such curves are usually generated from sinusoidal loading rather than impact loading. Fatigue tests conducted to failure on rod-eye arrangements subjected to impact loads are recommended as a method of acquiring a reliable data base. Investigation of stress concentration effects on both static as well as dynamic loading is also recommended for future investigation.

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APPENDIX A

DRAFT TEST PROCEDURE FOR IMPULSE AND STROKING TESTS ON HYDRAULIC CYLINDERS

IMPULSE (LOCKED-ROD) TEST

1. Scope: This test procedure is intended to be applicable to all hydraulic cylinders which are not integral parts of other components.
2. Purpose: The objective of the test described herein is to ascertain the capability of a hydraulic cylinder to repeated pressure cycles.
3. Materials & Test Apparatus
   - 3.1 Test fluid shall be that designated for use in the hydraulic system in which the cylinder is used.
   - 3.2 The test frame in which the cylinder is installed for this test should be sufficiently stiff so that the relative motion between the piston and the cylinder does not exceed 0.1% of the stroke of the test cylinder.
   - 3.3 The test cylinder shall be mounted using the mounts (i.e., pins, trunnions, etc.) used in installing the cylinder in the intended application. Pin material, clearances and lubrications arrangements shall conform to that used in the intended application.
   - 3.4 The test frame shall have provisions to adjust and measure eccentricity of the test cylinder to the center line of loading.
   - 3.5 The test frame shall not impose side loads or torque on the test cylinder.
   - 3.6 The hydraulic circuit shall be as shown in Fig. A-1 or equivalent. The system should be capable of maintaining the prescribed pressure waveform for the entire test duration.
4. Measurement Accuracy

   All physical quantities shall be measured to the accuracies given below:
   - 4.1 Pressure: ± 2%. The pressure transducer shall have been a flat frequency response from 0-5 kHz.

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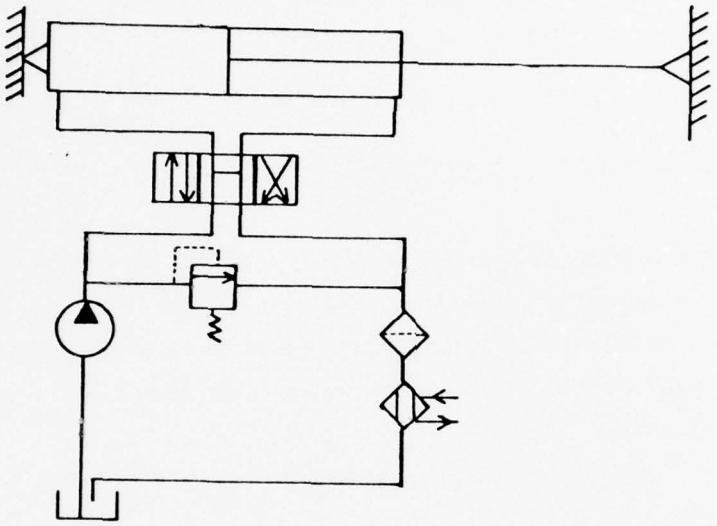


Fig. A-1. Hydraulic Circuit Schematic for Blocked-Rod Test

4.2 Flow: ± 2%.

4.3 Temperature: ± 5° F (±2.8°C).

4.4 Eccentricity: ± 0.05% of stroke of test cylinder.

4.5 Time: ± 0.05 seconds

5. Test Conditions & Definitions

5.1 Test system fluid shall be at a temperature of 180°F ± 5°F (82°C ± 2.8°C).

5.2 Test fluid shall be maintained clean and shall have a particulate matter content of not more than 1500 particles per milliliter of size greater than 10 micrometers.

5.3 Test waveform shall conform to particulars given in Fig. A-2.

5.4 Packing drag is defined as the pressure needed to move the piston with all external forces (mechanical or hydraulic) removed or in

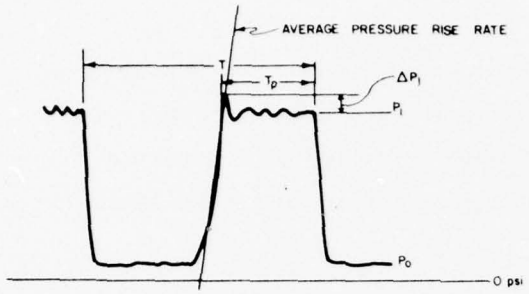


Fig. A-2. Pressure Waveform for Cylinder Impulse Test

T Time Period for One Cycle (= 60/N)(sec.)
N Cycling Frequency (cycles per minute)
T_p Time "On Pressure" (sec.)
P_i Maximum Test Pressure (psi/MPa)
P_o Minimum Test Pressure (psi/MPa)
ΔP_i Pressure Overshoot (psi/MPa)
$\dot{P}$ Average Pressure Rise Rate Between 15% and 90% of P_i (psi/Sec or MPa/sec)
N Shall Be Between 29 and 31 Cycles Per Minute

$0.045T \leq T_p \leq 0.55T$ $\quad 20{,}000 \leq \dot{P} \leq 80{,}000$ (psi/sec)

$\Delta P_i \leq 0.1P_i$

$P_o \leq 0.1P_i$

balance.

5.5 Piston dirft is the measure of internal leakage of the cylinder at the specified pressure.

5.6 Failure is any condition which precludes the use of the cylinder for its intended application. It is evidenced by excessive leakage--internal or external, structural deformation or breakage of any part of the cylinder and its mountings.

6. Test Procedure

6.1 Install the test cylinder in the test frame.

6.2 Adjust pump flow and relief valve setting to prescribed values.

6.3 Adjust the timer for the solenoid directional control valve so as to obtain the prescribed waveform.

STROKING TEST

1. Scope: This test procedure is intended to be applicable to all hydraulic cylinders which are not integral parts of other components.

2. Purpose: The objective of the test described herein is to ascertain the capability of a hydraulic cylinder to piston rod stroking under realistic loading conditions.

3. Materials & Test Apparatus

   3.1 Test fluid shall be that designated for use in the hydraulic system in which the cylinder is used.

   3.2 The test cylinder shall be installed in a test frame and test circuit as shown in Fig. A-3. The slave cylinder may be identical to the test cylinder. If it is different it should have a stroke and piston rod length, at least equal to the test cylinder's and shall not exceed 110% of the above mentioned values.

   3.3 The connecting piece between the piston rods for the test and slave cylinders shall not exceed 10% of the test cylinder stroke.

   3.4 The test frame shall have privisions to adjust and measure eccentricity of the test cylinder to the center line of loading.

   3.5 The test and slave cylinders shall be mounted so as not to impose any side loads on the test or slave cylinders.

4. Measurement Accuracy

   All physical quantities shall be measured to the accuracies given below.

   4.1 Pressure: ± 2%.

   The pressure transducer shall have a flat frequency response from 0-5 kHz.

   4.2 Flow: ± 2%.

   4.3 Temperature: ± 5°F (· ± 2.8°C)

   4.4 Eccentricity: ± 0.05% of stroke of test cylinder.

   4.5 Time: ± 0.05 seconds.

5. Test Conditions & Definitions

   5.1 Test system fluid shall be at a temperature of 180°F ± 5°F (82°C ± 2.8°C) during the first 10% of total cycles and 150°F 5°F (63° ± 2.8°C) during the balance of the test run.

5.2 Test system fluid shall be maintained clean and shall have a particulate matter content of not more than 1500 particles per milliliter of size greater than 10 micrometers.

5.3 The average pressure rise rate, as measured between 15% and 90% of the maximum operating pressure of the cycle, shall not be less than 20,000 psi/sec.

5.4 Packing drag is defined as the pressure needed to move the piston with all external forces (mechanical or hydraulic) removed or in balance.

5.5 Piston drift is the measure of internal leakage of the cylinder at the specified pressure.

5.6 Failure is any condition which precludes the use of the cylinder for its intended application. It is evidenced by excessive leakage--internal or external, structural deformation or breakage of any part of the cylinder and its mountings.

6. Test Procedure

6.1 Install the test cylinder in the test frame. Connect the test cylinder to the slave cylinder and check and adjust alignment.

6.2 Adjust pump flows and relief valve settings so as to attain the prescribed maximum operating pressure and the pressure rise rate. The latter can generally be adjusted by changing the pump flow rate, the length and volume of connecting lines and the speed of the directional control valve.

6.3 Perform piston drift and packing drag tests.

6.4 Stroke the cylinder, in accordance with the prescribed schedule, by switching the directional control valve. The pressure rise rate and the maximum operating pressure shall be recorded at least twice during the test; once at the beginning of the test and once at the end. Additional records of pressure waveform should be taken when any irregular operation or malfunction is observed. Stroking shall be done for the prescribed number of cycles or until failure. No repairs or modifications shall be carried out on the test cylinder at any time in the course of the cycling.

6.5 Perform piston drift and packing drag tests at the termination of the cycling.

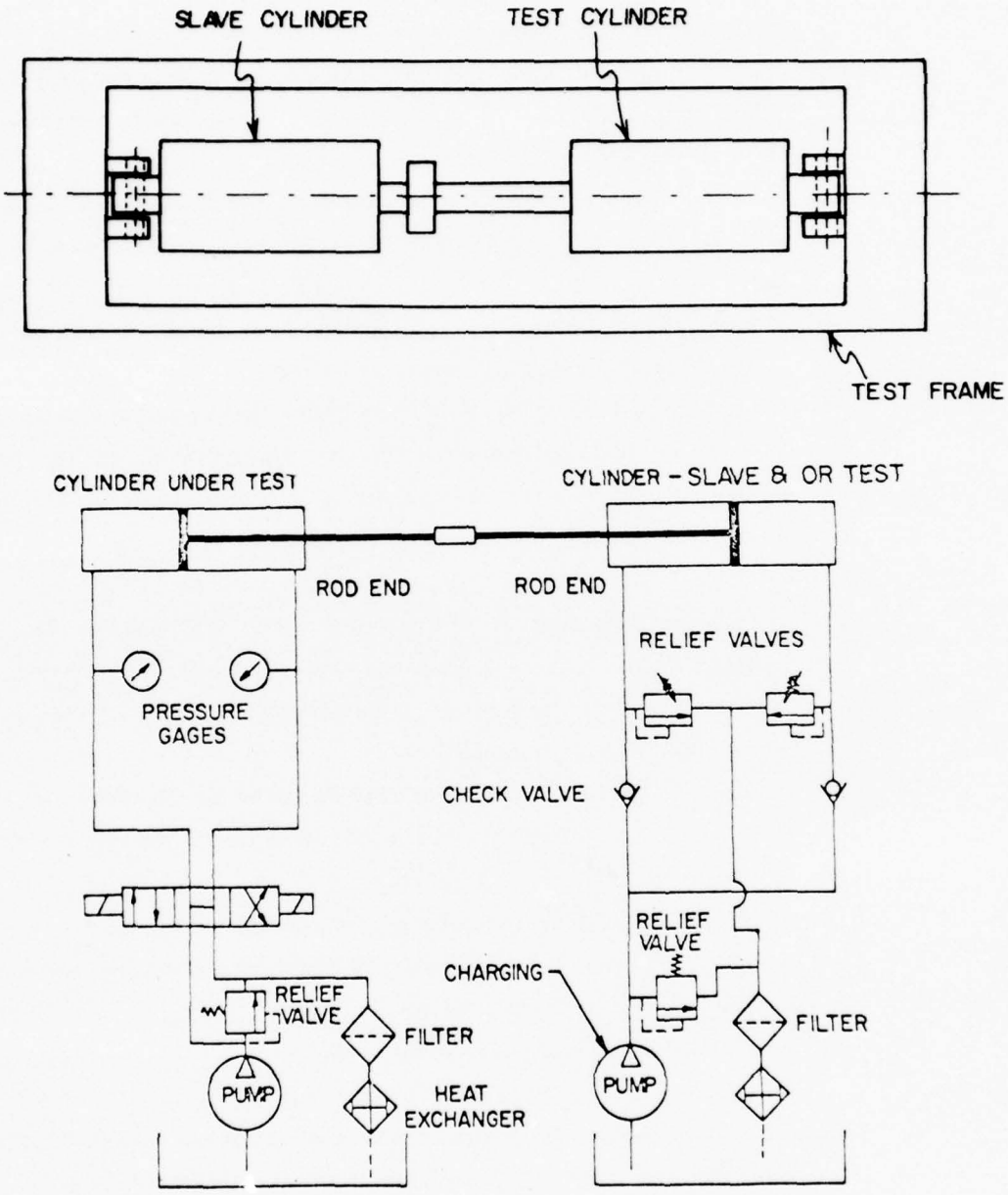


Fig. A-3. Test Frame and Test Circuit for Stroking Test

APPENDIX B

LISTING FOR LOKROD

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RELEASE 2.0              MAIN              DATE = 77014          15/09/38

      C                                                                                00001000
      C  LOCKED ROD CYLINDER TEST SIMULATION  770113                                   00001010
      C                                                                                00001020
      C*********************************************************************************00001030
            IMPLICIT REAL*8(A-H,O-Z)                                                   00001040
            COMMON/INIT/YYINT(10)                                                      00001050
            COMMON/ORDER/N                                                             00001060
            COMMON/BLK1/ QP,STIFF,DRAG,AA,CL,VA,BETA,XI,CLRNCE,RELFCR,XM,              00001070
           1TPRESS                                                                     00001080
      C                                                                                00001090
            DIMENSION Y(8,10)                                                          00001100
            DIMENSION PTITLE(18)                                                       00001110
            DIMENSION TRAJ(10,1200)                                                    00001120
            DIMENSION SAVE(10,10), YMAX(10), ERROR(10), PW(10,10)                      00001130
            DIMENSION DERIV(10)                                                        00001140
            DATA YMAX/10*1.0D0/,ERROR/10*1.0D-1/,J/-1/                                 00001150
            READ(5,1) PTITLE                                                           00001160
      1     FORMAT(18A4)                                                             00001170
            WRITE(6,2) PTITLE                                                          00001180
      2     FORMAT(1H1,/////,5X,18A4,////)                                           00001190
            READ(5,10) QP,STIFF,DRAG,AA,CL,VA,BETA,XI,CLRNCE,RELFCR,XM                 00001200
            WRITE(6,3) QP,STIFF,DRAG,AA,CL,VA                                          00001210
            WRITE(6,4) BETA,XI,CLRNCE,RELFCR,XM                                        00001220
      3     FORMAT(1H ,T5,17HSYSTEM PARAMETERS,//1H ,                                00001230
           1 T10,6HINFLOW,T40,1PE13.4,11H CU.IN./SEC,/1H ,                           00001240
           2 T10,15HFRAME STIFFNESS,T40,1PE13.4,10H LBS.F/IN,/1H ,                   00001250
           3 T10,16HDRAG COEFFICIENT,T40,1PE13.4,13H LBS.F*SEC/IN,/1H ,              00001260
           4 T10,13HCYLINDER AREA,T40,1PE13.4,8H SQ. IN.,/1H ,                       00001270
           5 T10,20HLEAKAGE COEFFICIENT,T40,1PE13.4,12H IN./SEC*PSI,/1H ,            00001280
           6 T10,15HUPSTREAM VOLUME,T40,1PE13.4,8H CU. IN.)                          00001290
      4     FORMAT(1H ,T10,18HFLUID BULK MODULUS,T40,1PE13.4,4H PSI,/1H ,            00001300
           1 T10,18HPISTON ROD INERTIA,T40,1PE13.4,18H LBS.F*SEC**2/IN,/1H ,         00001310
           2 T10,20HTOTAL SLACK IN FRAME,T40,1PE13.4,4H IN.,/1H ,                    00001320
           3 T10,30HRELIEF VALVE CRACKING PRESSURE,T40,1PE13.4,4H PSI,/1H ,          00001330
           4 T10,30HRELIEF VALVE CRACKING GRADIENT,T40,1PE13.4,                      00001340
           5 15H CU.IN./SEC*PSI,////)                                                00001350
      C                                                                              00001360
      C     INTEGRATION PARAMETERS:                                                  00001370
      C     N          ORDER OF SYSTEM                                               00001380
      C     MF         METHOD NUMBER                                                 00001390
      C     MAXDER     MAXIMUM ORDER OF INTEGRATION                                  00001400
      C     MULTSP     PRINT-OUT INTERVALS                                           00001410
      C     H          INITIAL STEP SIZE                                             00001420
      C     HMIN       MINIMUM STEP SIZE                                             00001430
      C     HMAX       MAXIMUM STEP SIZE                                             00001440
      C     EPS        ALLOWABLE ERROR                                               00001450
      C     NSTEPS     MAXIMUM NUMBER OF STEPS                                       00001460
      C     TINTL      INITIAL TIME                                                  00001470
      C     TPRESS     TIME AT PRESSURE                                              00001480
      C     TFINAL     FINAL TIME                                                    00001490
      C                                                                              00001500
            READ(5,9) N,MF,MAXDER,MULTSP                                           00001510
      9     FORMAT(8I5)                                                              00001520
            READ(5,10) H,HMIN,HMAX,EPS,TINTL,TPRESS,TFINAL                         00001530
            READ(5,10)  (YYINT(J),J=1, N)                                          00001540
      10    FORMAT(7F10.3)                                                           00001550
            TRAJ(1,1)= TINTL                                                       00001560
            NP1= N+1                                                               00001570
```

```
C                                                                       00001580
C     INITIALIZE TRAJECTORY VECTORS                                     00001590
      DO 50 JJ=2, NP1                                                   00001600
50    TRAJ(JJ,1)= YYINT(JJ-1)                                           00001610
      T=TINTL                                                           00001620
      IF(HMAX.GT.TFINAL) HMAX=TFINAL                                    00001630
      NSTEPS=(TFINAL+HMAX)/H                                            00001640
      JSTART=0                                                          00001650
      DO 30 JJ=1, N                                                     00001660
30    Y(1,JJ)= YYINT(JJ)                                                00001670
      IF(MF.EQ.0) WRITE(6,15)                                           00001680
15    FORMAT(1H ,T5,27HINTEGRATION METHOD:   ADAMS,////)                 00001690
      IF(MF.EQ.1) WRITE(6,16)                                           00001700
16    FORMAT(1H ,T5,46HINTEGRATION METHOD:   GEAR'S (WITH ANALYTICAL ,  00001710
     112HDERIVATIVES),/1H ,T27,24HSTIFF SYSTEM INTEGRATION,////)        00001720
      IF(MF.EQ.2) WRITE(6,17)                                           00001730
17    FORMAT(1H ,T5,45HINTEGRATION METHOD:   GEAR'S (WITH NUMERICAL ,   00001740
     116HDIFFERENTIATION),/1H ,T27,24HSTIFF SYSTEM INTEGRATION,////)    00001750
      WRITE(6,20) N,MAXDER,MULTSP                                       00001760
20    FORMAT(1H ,T5,22HINTEGRATION PARAMETERS,//1H ,                    00001770
     1 T10,15HORDER OF SYSTEM,T43,I5,/1H ,                              00001780
     2 T10,28HMAXIMUM ORDER OF INTEGRATION,T43,I5,/1H ,                 00001790
     3 T10,19HPRINT-OUT INTERVALS,T43,I5)                               00001800
      WRITE(6,21) H,HMIN,HMAX,EPS                                       00001810
21    FORMAT(1H ,T10,17HINITIAL STEP SIZE,T30,1PE18.4,/1H ,             00001820
     1 T10,17HMINIMUM STEP SIZE,T30,1PE18.4,/1H ,                       00001830
     2 T10,17HMAXIMUM STEP SIZE,T30,1PE18.4,/1H ,                       00001840
     3 T10,15HALLOWABLE ERROR,T30,1PE18.4)                              00001850
      WRITE(6,22) NSTEPS,TINTL,TPRESS,TFINAL                            00001860
22    FORMAT(1H ,T10,20HMAX. NUMBER OF STEPS,T33,I15,/1H ,              00001870
     1 T10,12HINITIAL TIME,T30,1PE18.4,/1H ,                            00001880
     2 T10,16HTIME AT PRESSURE,T30,1PE18.4,/1H ,                        00001890
     2 T10,10HFINAL TIME,T30,1PE18.4,////)                              00001900
      WRITE(6,23) (YYINT(JJ), JJ=1, N)                                  00001910
23    FORMAT(1H ,T5,20HINITIAL STATE VECTOR,//,1H ,                     00001920
     1 T10,8HPRESSURE,T27,1PE12.4,1X,3HPSI,/1H ,                        00001930
     2 T10,16HROD DISPLACEMENT,T27,1PE12.4,1X,3HIN.,/1H ,               00001940
     3 T10,12HROD VELOCITY,T27,1PE12.4,1X,6HIN/SEC,////)                00001950
C                                                                       00001960
C     MULTSP = NUMBER OF STEPS BETWEEN PRINTOUT                         00001970
      KOUNT = MULTSP                                                    00001980
      DO 100 NNN=1,NSTEPS                                               00001990
      NNNP1= NNN+1                                                      00002000
      IF(T.GT.TFINAL) GO TO 9120                                        00002010
      IF(NNN.GT.1) JSTART=1                                             00002020
101   CONTINUE                                                          00002030
C                                                                       00002040
      CALL DIFSUB(N,T,Y,SAVE,H,HMIN,HMAX,EPS,MF,YMAX,ERROR,KFLAG,JSTART,00002050
     1MAXDER,PW)                                                        00002060
C                                                                       00002070
      IF(KFLAG.NE.1) GO TO 9120                                         00002080
      IF(KOUNT.LT.MULTSP) GO TO 109                                     00002090
      ICOL = 1+ NNNP1/MULTSP                                            00002100
      IF(ICOL.GE.1200) GO TO 9120                                       00002110
      TRAJ(1,ICOL)=T                                                    00002120
      DO 111 JJ=2, NP1                                                  00002130
111   TRAJ(JJ,ICOL)= Y(1,JJ-1)                                          00002140
109   CONTINUE                                                          00002150
```

```
0064                    KOUNT = KOUNT -1                                                00002160
0065                    IF(KOUNT.EQ.0) KOUNT= MULTSP                                    00002170
0066              100   CONTINUE                                                        00002180
                  C                                                                     00002190
                  C                                                                     00002200
                  C                                                                     00002210
0067              9120  CONTINUE                                                        00002220
0068                    WRITE(6,9130) ICOL                                              00002230
0069              9130  FORMAT(///,1H ,T5,12HTRAJECTORIES,5X,17HNUMBER OF POINTS:,I8,////,00002240
                 11H ,T9,4HTIME,T25,8HPRESSURE,T41,16HROD DISPLACEMENT,T62,            00002250
                 212HROD VELOCITY,/1H ,T9,5H(SEC),T26,5H(PSI),T46,5H(INS),            00002260
                 3T63,9H(INS/SEC),/)                                                    00002270
0070                    DO 9210 JJ=1, ICOL                                              00002280
0071                    WRITE(6,9220) (TRAJ(NR,JJ), NR=1, NP1)                          00002290
0072              9210  CONTINUE                                                        00002300
0073              9220  FORMAT(T5,1PE13.4,T21,1PE13.4,T42,1PE13.4,T59,1PE13.4)          00002310
0074                    IF(KFLAG.EQ.1) GO TO 9999                                       00002320
0075                    WRITE(6,9140) T                                                 00002330
0076              9140  FORMAT(////1H ,T5,44H**** SIMULATION STOPPED ABNORMALLY AT TIME =,00002340
                 1 2X,1PD15.4)                                                          00002350
0077                    IF(KFLAG.EQ.-1) WRITE(6,9141)                                   00002360
0078              9141  FORMAT(1H ,T10,46HSTEP WAS TAKEN WITH H=HMIN,BUT REQUESTED ERROR,00002370
                 118H WAS NOT ACHIEVED.)                                                00002380
0079                    IF(KFLAG.EQ.-2) WRITE(6,9142)                                   00002390
0080              9142  FORMAT(1H ,T10,44HTHE MAXIMUM ORDER SPECIFIED WAS FOUND TO BE , 00002400
                 110HTOO LARGE.)                                                        00002410
0081                    IF(KFLAG.EQ.-3) WRITE(6,9143)                                   00002420
0082              9143  FORMAT(1H ,T10,44HCORRECTOR CONVERGENCE COULD NOT BE ACHIEVED , 00002430
                 113HFOR H.GT.HMIN)                                                     00002440
0083                    IF(KFLAG.EQ.-4) WRITE(6,9144)                                   00002450
0084              9144  FORMAT(1H ,T10,43HTHE REQUESTED ERROR IS SMALLER THAN CAN BE ,  00002460
                 125HHANDLED FOR THIS PROBLEM.)                                         00002470
0085              9999  CONTINUE                                                        00002480
0086                    WRITE(6,9980)                                                   00002490
0087              9980  FORMAT(/////)                                                   00002500
0088                    STOP                                                            00002510
0089                    END                                                             00002520
```

```
RELEASE 2.0                DIFFUN              DATE = 77014          15/09/38

      SUBROUTINE DIFFUN(T,Y,DY)                                                 00002530
      IMPLICIT REAL*8(A-H,Q-Z)                                                  00002540
C     THIS SUBROUTINE EVALUATES THE DERIVATIVES OF THE DEPENDENT VARIAB-        00002550
C     LES STORED IN Y(1,I) FOR I=1 TO N, AND STORES THE DERIVATIVES IN          00002560
C     ARRAY DY.  N= NUMBER OF FIRST ORDER DIFFERENTIAL EQUATIONS                00002570
C     T=INDEPENDENT VARIABLE                                                    00002580
      COMMON/INIT/YYINT(10)                                                     00002590
      COMMON/ORDER/N                                                            00002600
      COMMON/BLK1/ QP,STIFF,DRAG,AA,CL,VA,BETA,XI,CLRNCE,RELFCR,XM,             00002610
     1TPRESS                                                                    00002620
      DIMENSION Y(8,3), DY(10)                                                  00002630
C                                                                               00002640
C     EQUATIONS IN 'DIFFUN' FOR SIMULATING LOCKED ROD FATIGUE TEST              00002650
C     MODELED AS A THIRD-ORDER SYSTEM                                           00002660
C                                                                               00002670
C     STATE VARIABLES:                                                          00002680
C     Y(1,1)          PRESSURE                                                  00002690
C     Y(1,2)          ROD DISPLACEMENT                                          00002700
C     Y(1,3)          ROD VELOCITY                                              00002710
C                                                                               00002720
C     INPUTS:                                                                   00002730
C     QP              INFLOW                                                    00002740
C                                                                               00002750
C     PARAMETERS                                                                00002760
C     STIFF           ULTIMATE FRAME STIFFNESS                                  00002770
C     XKF             FRAME STIFFNESS                                           00002780
C     DRAG            DRAG COEFFICIENT                                          00002790
C     AA              CYLINDER AREA                                             00002800
C     CL              LEAKAGE COEFFICIENT                                       00002810
C     VA              UPSTREAM VOLUME                                           00002820
C     BETA            FLUID BULK MODULUS                                        00002830
C     XI              PISTON ROD INERTIA                                        00002840
C     CLRNCE          TOTAL SLACK IN FRAME                                      00002850
C     RELFCR          RELIEF VALVE CRACKING PRESSURE                            00002860
C     XM              RELIEF VALVE GRADIENT                                     00002870
C                                                                               00002880
      IF(T.GT.TPRESS) GO TO 20                                                  00002890
      IF( Y(1,1).LT.RELFCR) GO TO 10                                            00002900
      RVFLO= XM*(Y(1,1) - RELFCR)                                               00002910
      QA= QP - RVFLO                                                            00002920
      GO TO 11                                                                  00002930
10    QA= QP                                                                    00002940
11    CONTINUE                                                                  00002950
      DY(1)= (QA-AA*(Y(1,3) + CL*Y(1,1)) )  * BETA/VA                           00002960
      DY(2)=  Y(1,3)                                                            00002970
      IF( Y(1,2).GE.CLRNCE) XKF=STIFF                                           00002980
      XKF= (Y(1,2)/CLRNCE)**4 * STIFF                                           00002990
      DY(3)= ( Y(1,1)*AA -DRAG*Y(1,3) -XKF*Y(1,2) ) /XI                         00003000
C                                                                               00003010
C                                                                               00003020
      RETURN                                                                    00003030
20    CONTINUE                                                                  00003040
      QA= 0.0D+0                                                                00003050
      RETURN                                                                    00003060
      END                                                                       00003070
```

```
*RELEASE 2.0                MATINV              DATE = 77014          15/09/38

      SUBROUTINE MATINV(PW,N,M,J)                                          00003080
C     THIS SUBPROGRAM INVERTS AN N BY N MATRIX STORED IN ARRAY PW          00003090
C     THE FOLLOWING SSP SUBROUTINES ARE CALLED BY THIS SUBROUTINE:         00003100
C                                                                          00003110
C     AKRAY    INTERCONVERSION OF SINGLE AND DOUBLE DIMENSION ARRAYS       00003120
C     MINV     MATRIX INVERSION                                            00003130
C                                                                          00003140
C     THEY MAY BE REPLACED BY APPROPRIATE SUBROUTINES                      00003150
C                                                                          00003160
      DIMENSION PW(M,M)                                                    00003170
      DIMENSION DUMMY(10,10),S(100),L(20),MM(20)                           00003180
      DATA DUMMY/100*0.0/,S/100*0.0/                                       00003190
      DO 10 NROW=1, N                                                      00003200
      DO 10 NCOL=1, N                                                      00003210
      DUMMY(NROW,NCOL)= PW(NROW,NCOL)                                      00003220
10    CONTINUE                                                             00003230
      MODE=2                                                               00003240
      CALL ARRAY(MODE,N,N,10,10,S,DUMMY)                                   00003250
      CALL MINV(S,N,DET,L,MM)                                              00003260
      IF(DET.EQ.0.0)  GO TO 50                                             00003270
      J=1                                                                  00003280
      MODE=1                                                               00003290
      CALL ARRAY(MODE,N,N,10,10,S,DUMMY)                                   00003300
      DO 20 NROW=1, N                                                      00003310
      DO 20 NCOL=1, N                                                      00003320
      PW(NROW,NCOL)= DUMMY(NROW,NCOL)                                      00003330
20    CONTINUE                                                             00003340
      RETURN                                                               00003350
50    J=-1                                                                 00003360
      RETURN                                                               00003370
      END                                                                  00003380
```

```
RELEASE 2.0                 PEDERV              DATE = 77014          15/09/38

      SUBROUTINE PEDERV(T,Y,PW,M)                                          00003390
C     THIS SUBPROGRAM EVALUATES THE PARTIAL DERIVATIVES OF THE DIFFERENT   00003400
C     TIONS WITN RESPECT TO THE Y' S                                       00003410
      IMPLICIT REAL*8(A-H,O-Z)                                             00003420
      DIMENSION PW(M,M)                                                    00003430
      RETURN                                                               00003440
      END                                                                  00003450
```

```
      SUBROUTINE DIFSUB(N,T,Y,SAVE,H,HMIN,HMAX,EPS,MF,YMAX,ERROR,KFLAG,  00003460
     1JSTART,MAXDER,PW)                                                  00003470
C*********************************************************************00003480
C     THIS IS THE IMPLICIT INTEGRATION PROGRAM AS GIVEN BY C.W.GEAR IN  00003490
C     "NUMERICAL INITIAL VALUE PROBLEMS IN ORDINARY DIFFERENTIAL        00003500
C     EQUATIONS", PUB. PRENTICE-HALL,INC. 1971.                         00003510
C*********************************************************************00003520
C     THIS SUBROUTINE INTEGRATES A SET OF N ORDINARY DIFFERENTIAL FIRST  00003530
C     ORDER EQUATIONS OVER ONE STEP OF LENGTH H AT EACH CALL.  H CAN BE  00003540
C     SPECIFIED BY THE USER FOR EACH STEP, BUT IT MAY BE INCREASED OR    00003550
C     DECREASED BY DIFSUB WITHIN THE RANGE HMIN TO HMAX IN ORDER TO      00003560
C     ACHIEVE AS LARGE A STEP AS POSSIBLE WHILE NOT COMMITTING A SINGLE  00003570
C     STEP ERROR WHICH IS LARGER THAN EPS IN THE L-2 NORM, WHERE EACH    00003580
C     COMPONENT OF THE ERROR IS DIVIDED BY THE COMPONENTS OF YMAX.       00003590
C                                                                        00003600
C     THIS PROGRAM REQUIRES THREE SUBROUTINES NAMED                      00003610
C        DIFFUN(T,Y,DY)                                                  00003620
C        MATINV(PW,N,M,J)                                                00003630
C        PEDERV(T,Y,PW,M)                                                00003640
C     THE FIRST, DIFFUN, EVALUATES THE DERIVATIVES OF THE DEPENDENT      00003650
C     VARIABLES STORED IN Y(1,I) FOR I=1 TO N, AND STORES THE            00003660
C     DERIVATIVES IN THE ARRAY DY.  THE SECOND IS CALLED ONLY IF THE     00003670
C     METHOD FLAG MF IS SET TO 1 OR 2 FOR STIFF METHODS.  IT MUST INVERT 00003680
C     THE N BY N MATRIX STORED IN THE ARRAY PW(M,M).  IF THE INVERSION I 00003690
C     SUCCESFUL, J SHOULD BE SET TO 1, OTHERWISE IT SHOULD BE SET TO -1. 00003700
C     PEDERV IS USED ONLY IF MF IS 1, AND COMPUTES THE PARTIAL           00003710
C     DERIVATIVES OF THE DIFFERENTIAL EQUATIONS AS DESCRIBED UNDER THE   00003720
C     MF PARAMETER.                                                      00003730
C                                                                        00003740
C     THE PROGRAM USES DOUBLE PRECISION ARITHMETIC FOR ALL FLOATING      00003750
C     POINT VARIABLES EXCEPT THOSE STARTING WITH P   THE FORMER ARE      00003760
C     SINGLE PRECISION TO SAVE TIME AND SPACE.                           00003770
C                                                                        00003780
C     THE TEMPORARY STORAGE SPACE IS PROVIDED BY THE CALLER IN THE       00003790
C     SINGLE PRECISION ARRAY PW AND THE COUBLE PRECISION ARRAY SAVE.     00003800
C     THE ARRAY PW IS USED ONLY TO HOLD THE MATRIX OF THE SAME NAME, BUT 00003810
C     SAVE IS USED TO HOLD SEVERAL ARRAYS.  THE REGIONS USED ARE         00003820
C        SAVE(J,I)    1.LE.J.LE.8  AND 1.LE.I.LE.N  IS USED TO SAVE THE 00003830
C                     VALUES OF Y IN CASE A STEP HAS TO BE REPEATED.     00003840
C        SAVE(9,I)    IS USED MAINLY TO HOLD THE CORRECTION TERMS IN THE 00003850
C                     CORRECTOR LOOP.                                    00003860
C        SAVE(10,I)   IS USED TO SAVE THE VALUES OF THE SUMS OF ALL OF T00003870
C                     CORRECTION TERMS IN THE PREVIOUS STEP AFTER THEY   00003880
C                     HAVE BEEN ACCUMULATED IN THE ARRAY ERROR IN THE    00003890
C                     CURRENT STEP.  THIS ENABLES THE BACKWARDS DIFFERENC00003900
C                     OF ERROR TO BE FORMED.  IT IS USED TO ESTIMATE THE 00003910
C                     STEP SIZE FOR ONE ORDER HIGHER THAN CURRENT.       00003920
C        SAVE(N1+I,1)  IS USED TO STORE THE DERIVATIVES WHEN THEY ARE    00003930
C                     COMPUTED BY DIFFUN.  IT IS ALSO ACCESSED AS        00003940
C                     SAVE(N2,1) AS A COMPLETE ARRAY.                    00003950
C        SAVE(N5+I,1)  HOLDS THE DERIVATIVES DURING JACOBIAN EVALUATIONS00003960
C                     IT IS REFERENCED AS SAVE(N6,1) AS A COMPLETE ARRAY.00003970
C                                                                        00003980
C     THE PARAMETERS TO THE SUBROUTINE DIFSUB HAVE                       00003990
C     THE FOLLOWING MEANINGS..                                           00004000
C                                                                        00004010
C       N       THE NUMBER OF FIRST ORDER DIFFERENTIAL EQUATIONS.  N     00004020
C               MAY BE DECREASED ON LATER CALLS IF THE NUMBER OF         00004030
```

```
C                ACTIVE EQUATIONS REDUCES, BUT IT MUST NOT BE                00004040
C                INCREASED WITHOUT CALLING WITH JSTART = 0.                  00004050
C          T     THE INDEPENDENT VARIABLE.                                   00004060
C          Y     AN 8 BY N ARRAY CONTAINING THE DEPENDENT VARIABLES AND      00004070
C                THEIR SCALED DERIVATIVES.  Y(J+1,I)CONTAINS                 00004080
C                THE J-TH DERIVATIVE OF Y(I) SCALED BY                       00004090
C                H**J/FACTORIAL(J) WHERE H IS THE CURRENT                    00004100
C                STEP SIZE.  ONLY Y(1,I) NEED BE PROVIDED BY                 00004110
C                THE CALLING PROGRAM ON THE FIRST ENTRY.                     00004120
C                  IF IT IS DESIRED TO INTERPOLATE TO NON MESH POINTS        00004130
C                THESE VALUES CAN BE USED.  IF THE CURRENT STEP SIZE         00004140
C                IS H AND THE VALUE AT T + E IS NEEDED, FORM                 00004150
C                S = E/H, AND THEN COMPUTE                                   00004160
C                                  NQ                                        00004170
C                  Y(I)(T+E) = SUM Y(J+1,I)*S**J                             00004180
C                                 J=0                                        00004190
C          SAVE  A BLOCK OF AT LEAST 12*N FLOATING POINT LOCATIONS           00004200
C                USED BY THE SUBROUTINES.                                    00004210
C          H     THE STEP SIZE TO BE ATTEMPTED ON THE NEXT STEP.             00004220
C                H MAY BE ADJUSTED UP OR DOUN BY THE PROGRAM                 00004230
C                IN ORDER TO ACHEIVE AN ECONOMICAL INTEGRATION.              00004240
C                HOWEVER, IF THE H PROVIDED BY THE USER DOES                 00004250
C                NOT CAUSE A LARGER ERROR THAN REQUESTED, IT                 00004260
C                WILL BE USED.  TO SAVE COMPUTER TIME, THE USER IS           00004270
C                ASVISED TO USE A FAIRLY SMALL STEP FOR THE FIRST            00004280
C                CALL.  IT WILL BE AUTOMATICALLY INCREASED LATER.            00004290
C          HMIN  THE MINIMUM STEP SIZE THAT WILL BE USED FOR THE             00004300
C                INTEGRATION.  NOTE THAT ON STARTING THIS MUST               00004310
C                BE MUCH SMALLER THAN THE AVERAGE H EXPECTED SINCE           00004320
C                A FIRST ORDER METHOD IS USED INITIALLY.                     00004330
C          HMAX  THE MAXIMUM SIZE TO WHICH THE STEP WILL BE INCREASED        00004340
C          EPS   THE ERROR TEST CONSTANT.  SINGLE STEP ERROR ESTIMATES       00004350
C                DIVIDED BY YMAX(I) MUST BE LESS THAN THIS                   00004360
C                IN THE EUCLIDEAN NORM.  THE STEP AND/OR ORDER IS            00004370
C                ADJUSTED TO ACHEIVE THIS.                                   00004380
C          MF    THE METHOD INDICATOR.  THE FOLLOWING ARE ALLOWED.           00004390
C                0 AN ADAMS PREDICTOR CORRECTOR IS USED.                     00004400
C                1 A MULTI-STEP METHOD SUITABLE FOR STIFF SYSTEMS IS USED.   00004410
C                  IT WILL ALSO WORK FOR NON-STIFF SYSTEMS.  HOWEVER         00004420
C                  THE USER MUST PROVIDE A SUBROUTINE PEDERV WHICH           00004430
C                  EVALUATES THE PARTIAL DERIVATIVES OF THE DIFFERENTIAL     00004440
C                  EQUATIONS WITH RESPECT TO THE Y'S.  THIS IS DONE BY       00004450
C                  CALL PEDERV(T,Y,PW,M).  PW IS AN N BY N ARRAY WHICH       00004460
C                  MUST BE SET TO THE PARTIAL OF THE I-TH EQUATION WITH      00004470
C                  RESPECT TO THE J DEPENDENT VARIABLE IN PW(I,J).  PW IS    00004480
C                  ACTUALLY STORED IN AN M BY M ARRAY WHERE M IS THE         00004490
C                  VALUE OF N USED ON THE FIRST CALL TO THE PROGRAM.         00004500
C                2 THE SAME CASE AS 1, EXCEPT THAT THIS SUBROUTINE           00004510
C                  COMPUTES THE PARTIAL DERIVATIVES BY NUMERICAL             00004520
C                  DIFFERENCING OF THE DERIVATIVES.  HENCE PEDERV IS NOT     00004530
C                  CALLED.                                                   00004540
C          YMAX  AN ARRAY OF N LOCATIONS WHICH CONTAINS THE MAXIMUM          00004550
C                OF EACH Y SEEN SO FAR.  IT SHOULD NORMALLY BE SET TO        00004560
C                1 IN EACH COMPONENT BEFORE THE FIRST ENTRY.  (SEE THE       00004570
C                DESCRIPTION OF EPS.)                                        00004580
C          ERROR AN ARRAY OF N ELEMENTS WHICH CONTAINS THE ESTIMATED         00004590
C                ONE STEP ERROR IN EACH COMPONENT.                           00004600
C          KFLAG A COMPLETION CODE WITH THE FOLLOWING MEANINGS..             00004610
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C              +1  THE STEP WAS SUCCESSFUL.                                    00004620
C              -1  THE STEP WAS TAKEN WITH H=HMIN, BUT THE                     00004630
C                  REQUESTED ERROR WAS NOT ACHIEVED.                           00004640
C              -2  THE MAXIMUM ORDER SPECIFIED WAS FOUND TO                    00004650
C                  BE TOO LARGE.                                               00004660
C              -3  CORRECTOR CONVERGENCE COULD NOT BE                          00004670
C                  ACHIEVED FOR H.GT.HMIN.                                     00004680
C              -4  THE REQUESTED ERROR IS SMALLER THAN CAN                     00004690
C                  BE HANDLED FOR THIS PROBLEM.                                00004700
C        JSTART AN INPUT INDICATOR WITH THE FOLLOWING MEANINGS..               00004710
C              -1  REPEAT THE LAST STEP WITH A NEW H                           00004720
C               0  PERFORM THE FIRST STEP.  THE FIRST STEP                     00004730
C                  MUST BE DONE WITH THIS VALUE OF JSTART                      00004740
C                  SO THAT THE SUBROUTINE CAN INITIALIZE                       00004750
C                  ITSELF.                                                     00004760
C              +1  TAKE A NEW STEP CONTINUING FROM THE LAST.                   00004770
C                JSTART IS SET TO NQ, THE CURRENT ORDER OF THE METHOD          00004780
C                AT EXIT.  NQ IS ALSO THE ORDER OF THE MAXIMUM                 00004790
C                DERIVATIVE AVAILABLE.                                         00004800
C        MAXDER  THE MAXIMUM DERIVATIVE THAT SHOULD BE USED IN THE             00004810
C                METHOD.  SINCE THE ORDER IS EQUAL TO THE HIGHEST              00004820
C                DERIVATIVE USED, THIS RESTRICTS THE ORDER.  IT MUST           00004830
C                BE LESS THAN 8 FOR ADAMS AND 7 FOR STIFF METHODS.             00004840
C        PW      A BLOCK OF AT LEAST N**2 FLOATING POINT LOCATIONS.            00004850
C*********************************************************************       00004860
C                                                                              00004870
C                                                                              00004880
      IMPLICIT REAL*8(A-H,Q-Z)                                                 00004890
      REAL*4 AMAX1                                                             00004900
C                                                                              00004910
C                                                                              00004920
      DIMENSION Y(8,1),YMAX(1),SAVE(10,1),ERROR(1),PW(1),                      00004930
     1 A(8),PERTST(7,2,3)                                                      00004940
C                                                                              00004950
C     THE COEFFICIENTS IN PERTST ARE USED IN SELECTING THE STEP AND            00004960
C     ORDER, THEREFORE ONLY ABOUT ONE PERCENT ACCURACY IS NEEDED.              00004970
C                                                                              00004980
      DATA PERTST/2.0,4.5,7.333,10.42,13.7,17.15,1.0,                          00004990
     1             2.0,12.0,24.0,37.89,53.33,70.08,87.97,                      00005000
     2            3.0,6.0,9.167,12.5,15.98,1.0,1.0,                            00005010
     3            12.0,24.0,37.89,53.33,70.08,87.97,1.0,                       00005020
     4            1.,1.,0.5,0.1667,0.04133,0.008267,1.0,                       00005030
     5            1.0,1.0,2.0,1.0,.3157,.07407,.0139/                          00005040
      DATA A(2)/-1.0D+0/                                                       00005050
      IRET=1                                                                   00005060
      KFLAG=1                                                                  00005070
      IF (JSTART.LE.0) GO TO 140                                               00005080
C                                                                              00005090
C     BEGIN BY SAVING INFORMATION FOR POSSIBLE RESTARTS AND CHANGING           00005100
C     H BY THE FACTOR R IF THE CALLER HAS CHANGED H.  ALL VARIABLES            00005110
C     DEPENDENT ON H MUST ALSO BE CHANGED.                                     00005120
C     E IS A COMPARISON FOR ERRORS OF THE CURRENT ORDER NQ. EUP IS             00005130
C     TO TEST FOR INCREASING THE ORDER, EDWN FOR DECREASING THE ORDER.         00005140
C     HNEW IS THE STEP SIZE THAT WAS USED ON THE LAST CALL.                    00005150
C                                                                              00005160
100   DO 110 I=1, N                                                            00005170
      DO 110 J=1, K                                                            00005180
110   SAVE(J,I)= Y(J,I)                                                        00005190
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      HOLD= HNEW                                                        00005200
      IF(H.EQ.HOLD) GO TO 130                                           00005210
120   RACUM= H/HOLD                                                     00005220
      IRET1 = 1                                                         00005230
      GO TO 750                                                         00005240
130   NQOLD=NQ                                                          00005250
      TOLD= T                                                           00005260
      RACUM= 1                                                          00005270
      IF (JSTART.GT.0) GO TO 250                                        00005280
      GO TO 170                                                         00005290
140   IF( JSTART.EQ.-1) GO TO 160                                       00005300
C                                                                       00005310
C     ON THE FIRST CALL, THE ORDER IS SET TO 1 AND THE INITIAL          00005320
C     DERIVATIVES ARE CALCULATED.                                       00005330
C                                                                       00005340
      NQ= 1                                                             00005350
      N3= N                                                             00005360
      N1= N*10                                                          00005370
      N2= N1+ 1                                                         00005380
      N4= N**2                                                          00005390
      N5= N1 + N                                                        00005400
      N6= N5 + 1                                                        00005410
      CALL DIFFUN( T,Y,SAVE(N2,1))                                      00005420
      DO 150 I=1, N                                                     00005430
150   Y(2,I)= SAVE(N1 + I,1) *H                                         00005440
      HNEW= H                                                           00005450
      K=2                                                               00005460
      GO TO 100                                                         00005470
C                                                                       00005480
C     REPEAT LAST STEP BY RESTORING SAVED INFORMATION.                  00005490
C                                                                       00005500
160   IF(NQ.EQ.NQOLD) JSTART= 1                                         00005510
      T= TOLD                                                           00005520
      NQ= NQOLD                                                         00005530
      K= NQ + 1                                                         00005540
      GO TO 120                                                         00005550
C                                                                       00005560
C     SET THE COEFFICIENTS THAT DETERMINE THE ORDER AND THE METHOD      00005570
C     TYPE.  CHECK FOR EXCESSIVE ORDER.  THE LAST TWO STATEMENTS OF     00005580
C     THIS SECTION SET IWEVAL.GT.0 IF PW IS TO BE RE-EVALUATED          00005590
C     BECAUSE OF THE ORDER CHANGE, AND THE REPEAT THE INTEGRATION       00005600
C     STEP IF IT HAS NOT YET BEEN DONE (IRET = 1) OR SKIP TO A FINAL    00005610
C     SCALING BEFORE EXIT IF IT HAS BEEN COMPLETED (IRET = 2).          00005620
C                                                                       00005630
170   IF(MF.EQ.0) GO TO 180                                             00005640
      IF(NQ.GT.6) GO TO 190                                             00005650
      GO TO (221,222,223,224,225,226), NQ                               00005660
180   IF(NQ.GT.7) GO TO 190                                             00005670
      GO TO (211,212,213,214,215,216,217), NQ                           00005680
190   KFLAG=-2                                                          00005690
      RETURN                                                            00005700
C                                                                       00005710
C     THE FOLLOWING COEFFICIENTS SHOULD BE DEFINED TO THE MAXIMUM       00005720
C     ACCURACY PERMITTED BY THE MACHINE.  THEY ARE, IN THE ORDER USED.  00005730
C     -1,-1/2,-1/2,-5/12,-3/4,-1/6,-3/8,-11/12,-1/3,-1/24               00005740
C     -251/720,-25/24,-35/72,-5/48,-1/120,-95/288,-137/120,-5/8         00005750
C     -17/96,-1/40,-1/720,-19087/60480,-49/40,-203/270,-49/192          00005760
C     -7/144,-7/1440,-1/5040,-1,-2/3,-1/3,-6/11,-6/11,-1/11,-12/25      00005770
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C      -7/10,-1/5,-1/50,-120/274,-225/274,-85/274,-15/274,-1/274                00005780
C      -180/441,-58/63,-15/36,-25/252,-3/252,-1/1764                            00005790
C                                                                               00005800
211    A(1)= -1.0D+0                                                            00005810
       GO TO 230                                                                00005820
212    A(1)= -.50000000D+0                                                      00005830
       A(3)= -.50000000D+0                                                      00005840
       GO TO 230                                                                00005850
213    A(1)= -.41666666666666670+0                                              00005860
       A(3)= -.75000000000+0                                                    00005870
       A(4)= -.16666666666666670+0                                              00005880
       GO TO 230                                                                00005890
214    A(1)= -0.375000000D+0                                                    00005900
       A(3)= -0.916666666666666670+0                                            00005910
       A(4)= -0.333333333333333D+0                                              00005920
       A(5)= -0.0416666666666666670+0                                           00005930
       GO TO 230                                                                00005940
215    A(1)= -0.34861111111111111D+0                                            00005950
       A(3)= -1.0416666666666667D+0                                             00005960
       A(4)= -0.48611111111111111D+0                                            00005970
       A(5)= -0.1041666666666667D+0                                             00005980
       A(6)=-0.00833333333333333D+0                                             00005990
       GO TO 230                                                                00006000
216    A(1)= -0.32986111111111111D+0                                            00006010
       A(3)= -1.1416666666666667D+0                                             00006020
       A(4)= -0.625000000D+0                                                    00006030
       A(5)= -0.17708333333333330+0                                             00006040
       A(6)= -0.025000000D+0                                                    00006050
       A(7)= -0.00138888888888889D+0                                            00006060
       GO TO 230                                                                00006070
217    A(1)= -0.31559193121693120+0                                             00006080
       A(3)= -1.235000000D+0                                                    00006090
       A(4)=-0.75185185185185190+0                                              00006100
       A(5)= -0.25520833333333330+0                                             00006110
       A(6)=-0.04861111111111111D+0                                             00006120
       A(7)=-0.00486111111111111D+0                                             00006130
       A(8)= -0.00019841269841269840+0                                          00006140
       GO TO 230                                                                00006150
221    A(1)= -1.000000000D+0                                                    00006160
       GO TO 230                                                                00006170
222    A(1)= -0.666666666666666670+0                                            00006180
       A(3)= -0.333333333333333D+0                                              00006190
            GO TO 230                                                           00006200
223    A(1)=-0.54545454545455D+0                                                00006210
       A(3)=A(1)                                                                00006220
       A(4)=-0.090909090909091D+0                                               00006230
       GO TO 230                                                                00006240
224    A(1)= -0.480000000000D+0                                                 00006250
       A(3)=-0.700000000000D+0                                                  00006260
       A(4)=-0.200000000000D+0                                                  00006270
       A(5)=-0.020000000000D+0                                                  00006280
       GO TO 230                                                                00006290
225    A(1)=-0.437956204379562D+0                                               00006300
       A(3)=-0.821167883211678D+0                                               00006310
       A(4)=-0.310218978102189D+0                                               00006320
       A(5)=-0.054744525547445260+0                                             00006330
       A(6)=-0.003649635036496350+0                                             00006340
       GO TO 230                                                                00006350
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  226   A(1)=-0.40816326530612245D+0                                    00006360
        A(3)=-0.92063492063492063D+0                                    00006370
        A(4)=-0.41666666666666667D+0                                    00006380
        A(5)=-0.09920634920634920D+0                                    00006390
        A(6)=-0.01190476190476190D+0                                    00006400
        A(7)=-0.00056689342403628D+0                                    00006410
  230   K=NQ+1                                                          00006420
        IDOUB=K                                                         00006430
        MTYP=(4-MF)/2                                                   00006440
        ENQ2=.5/DFLOAT(NQ+1)                                            00006450
        ENQ3=.5/DFLOAT(NQ+2)                                            00006460
        ENQ1=0.5/DFLOAT(NQ)                                             00006470
        PEPSH=EPS                                                       00006480
        EUP=(PERTST(NQ,MTYP,2)*PEPSH)**2                                00006490
        E=(PERTST(NQ,MTYP,1)*PEPSH)**2                                  00006500
        EDWN=(PERTST(NQ,MTYP,3)*PEPSH)**2                               00006510
        IF(EDWN.EQ.0)GO TO 780                                          00006520
        BND=EPS*ENQ3/DFLOAT(N)                                          00006530
  240   IWEVAL=MF                                                       00006540
        GO TO (250,680),IRET                                            00006550
  C                                                                     00006560
  C  THIS SECTION COMPUTES THE PREDICTED VALUES BY EFFECTIVELY          00006570
  C  MULTIPLYING THE SAVED INFORMATION BY THE PASCAL TRIANGLE           00006580
  C  MATRIX.                                                            00006590
  C                                                                     00006600
  250   T=T+H                                                           00006610
        DO 260 J=2,K                                                    00006620
        DO 260 J1=J,K                                                   00006630
        J2=K-J1+J-1                                                     00006640
        DO 260 I=1,N                                                    00006650
  260   Y(J2,I)=Y(J2,I)+Y(J2+1,I)                                       00006660
  C                                                                     00006670
  C  UP TO 3 CORRECTOR ITERATIONS ARE TAKEN.  CONVERGENCE IS TESTED     00006680
  C  BY REQUIRING CHANGES TO BE LESS THAN BND WHICH IS DEPENDENT ON     00006690
  C  THE ERROR TEST CONSTANT.                                           00006700
  C     THE SUM OF THE CORRECTIONS IS ACCUMULATED IN THE ARRAY          00006710
  C  ERROR(I).  IT IS EQUAL TO THE K-TH DERIVATIVE OF Y MULTIPLIED      00006720
  C  BY H**K/(FACTORIAL(K-1)*A(K)), AND IS THEREFORE PROPORTIONAL       00006730
  C  TO THE ACTUAL ERRORS TO THE LOWEST POWER OF H PRESENT. (H**K)      00006740
  C                                                                     00006750
        DO 270 I=1,N                                                    00006760
  270   ERROR(I)=0.0                                                    00006770
        DO 430 L=1,3                                                    00006780
        CALL DIFFUN(T,Y,SAVE(N2,1))                                     00006790
  C                                                                     00006800
  C  IF THERE HAS BEEN A CHANGE OF ORDER OR THERE HAS BEEN TROUBLE      00006810
  C  WITH CONVERGENCE, PW IS RE-EVALUATED PRIOR TO STARTING THE         00006820
  C  CORRECTOR ITERATION IN THE CASE OF STIFF METHODS.  IWEVAL IS       00006830
  C  THEN SET TO -1 AS AN INDICATOR THAT IT HAS BEEN DONE.             00006840
  C                                                                     00006850
        IF(IWEVAL.LT.1) GO TO 350                                       00006860
        IF(MF.EQ.2) GO TO 310                                           00006870
        CALL PEDERV(T,Y,PW,N3)                                          00006880
        R=A(1)*H                                                        00006890
        DO 280 I=1,N4                                                   00006900
  280   PW(I)=PW(I)*R                                                   00006910
  C                                                                     00006920
  C  ADD THE IDENTITY MATRIX TO THE JACOBIAN AND INVERT TO GET PW.      00006930
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C                                                                       00006940
290   DO 300 I=1,N                                                      00006950
300   PW(I*(N3+1)-N3)=1.0+PW(I*(N3+1)-N3)                               00006960
      IWEVAL=-1                                                         00006970
      CALL MATINV(PW,N,N3,J1)                                           00006980
      IF(J1.GT.0) GO TO 350                                             00006990
      GO TO 440                                                         00007000
C                                                                       00007010
C  EVALUATE THE JACOBIAN INTO PW BY NUMERICAL DIFFERENCING.  R IS THE   00007020
C  CHANGE MADE TO THE ELEMENT OF Y.  IT IS EPS RELATIVE TO Y WITH       00007030
C  A MINIMUM OF EPS**2.                                                 00007040
C                                                                       00007050
310   DO 320 I=1,N                                                      00007060
320   SAVE(9,I)=Y(1,I)                                                  00007070
      DO 340 J=1,N                                                      00007080
      R=EPS*DMAX1(EPS,DABS(SAVE(9,J)))                                  00007090
      Y(1,J)=Y(1,J)+R                                                   00007100
      D=A(1)*H/R                                                        00007110
      CALL DIFFUN(T,Y,SAVE(N6,1))                                       00007120
      DO 330 I=1,N                                                      00007130
330   PW(I+(J-1)*N3)=(SAVE(N5+I,1)-SAVE(N1+I,1))*D                      00007140
340   Y(1,J)=SAVE(9,J)                                                  00007150
      GO TO 290                                                         00007160
350   IF (MF.NE.0)  GO TO 370                                           00007170
      DO 360 I=1,N                                                      00007180
360   SAVE(9,I)=Y(2,I)-SAVE(N1+I,1)*H                                   00007190
      GO TO 410                                                         00007200
370   DO 380 I= 1,N                                                     00007210
380   SAVE(N5+I,1)=Y(2,I)-SAVE(N1+I,1)*H                                00007220
      DO 400 I=1,N                                                      00007230
      D=0.0                                                             00007240
      DO 390 J=1,N                                                      00007250
390   D=D+PW(I+(J-1)*N3)*SAVE(N5+J,1)                                   00007260
400   SAVE(9,I)=D                                                       00007270
410   NT=N                                                              00007280
C                                                                       00007290
C  CORRECT AND SEE IF ALL CHANGES ARE LESS THAN BNE RELATIVE TO YMAX.   00007300
C  IF SO, THE CORRECTOR IS SAID TO HAVE CONVERGED.                      00007310
C                                                                       00007320
      DO 420 I=1,N                                                      00007330
      Y(1,I)=Y(1,I)+A(1)*SAVE(9,I)                                      00007340
      Y(2,I)=Y(2,I)-SAVE(9,I)                                           00007350
      ERROR(I)=ERROR(I)+SAVE(9,I)                                       00007360
      IF(DABS(SAVE(9,I)).LE.(BND*YMAX(I)))NT=NT-1                       00007370
420   CONTINUE                                                          00007380
      IF (NT.LE.0) GO TO 490                                            00007390
430   CONTINUE                                                          00007400
C                                                                       00007410
C  THE CORRECTOR ITERATION FAILED TO CONVERGE IN 3 TRIES.  VARIOUS      00007420
C  POSSIBILITIES ARE CHECKED FOR.  IF H IS ALREADY HMIN AND             00007430
C  THIS IS EITHER ADAMS METHOD OR THE STIFF METHOD IN WHICH THE         00007440
C  MATRIX PW HAS ALREADY BEEN RE-EVALUATED, A NO CONVERGENCE EXIT       00007450
C  IS TAKEN.  OTHERWISE THE MATRIX PW IS RE-EVALUATED AND/OR THE        00007460
C  STEP IS REDUCED TO TRY AND GET CONVERGENCE.                          00007470
C                                                                       00007480
440   T=TOLD                                                            00007490
      IF((H.LE.(HMIN*1.00001)).AND.((IWEVAL-MTYP).LT.-1)) GO TO 460     00007500
      IF((MF.EQ.0).OR.(IWEVAL.NE.0))RACUM=RACUM*0.2500                  00007510
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      IWEVAL=MF                                                          00007520
      IRET1=2                                                            00007530
      GO TO 750                                                          00007540
460   KFLAG=-3                                                           00007550
470   DO 480 I=1,N                                                       00007560
      DO 480 J=1,K                                                       00007570
480   Y(J,I)=SAVE(J,I)                                                   00007580
      H=HOLD                                                             00007590
      NQ=NQOLD                                                           00007600
      JSTART=NQ                                                          00007610
      RETURN                                                             00007620
C                                                                        00007630
C  THE CORRECTOR CONVERGED AND CONTROL IS PASSED TO STATEMENT 520        00007640
C  IF THE ERROR TEST IS O.K., AND TO 540 OTHERWISE.                      00007650
C  IF THE STEP IS O.K. IT IS ACCEPTED.  IF IDOUB HAS BEEN REDUCED        00007660
C  TO ONE, A TEST IS MADE TO SEE IF THE STEP CAN BE IN REASED            00007670
C  AT THE CURRENT ORDER OR BY GOING TO ONE HIGHER OR ONE LOWER.          00007680
C  SUCH A CHANGE IS ONLY MADE IF THE STEP CAN BE INCREASED BY AT         00007690
C  LEAST 1.1.  IF NO CHANGE IS POSSIBLE IDOUB IS SET TO 10 TO           00007700
C  PREVENT FUTHER TESTING FOR 10 STEPS.                                  00007710
C  IF A CHANGE IS POSSIBLE, IT IS MADE AND IDOUB IS SET TO               00007720
C  NQ + 1 TO PREVENT FURTHER TESTING FOR THAT NUMBER OF STEPS.           00007730
C  IF THE ERROR WAS TOO LARGE, THE OPTIMUM STEP SIZE FOR THIS OR         00007740
C LOWER ORDER IS COMPUTED, AND THE STEP RETRIED.  IF IT SHOULD          00007750
C  FAIL TWICE MORE IT IS AN INDICATION THAT THE DERIVATIVES THAT         00007760
C  HAVE ACCUMULATED IN THE Y ARRAY HAVE ERRORS OF THE WRONG ORDER        00007770
C  SO THE FIRST DERIVATIVES ARE RECOMPUTED AND THE ORDER IS SET          00007780
C  TO 1.                                                                 00007790
C                                                                        00007800
490   D=0.0                                                              00007810
      DO 500 I=1,N                                                       00007820
500   D=D+(ERROR(I)/YMAX(I))**2                                          00007830
      IWEVAL=0                                                           00007840
      IF (D.GT.E) GO TO 540                                              00007850
      IF(K.LT.3) GO TO 520                                               00007860
C                                                                        00007870
C  COMPLETE THE CORRECTION OF THE HIGHER ORDER DERIVATIVES AFTER A       00007880
C  SUCCESFUL STEP.                                                       00007890
C                                                                        00007900
      DO 510 J=3,K                                                       00007910
      DO 510 I=1,N                                                       00007920
510   Y(J,I)=Y(J,I)+A(J)*ERROR(I)                                        00007930
520   KFLAG=+1                                                           00007940
      HNEW=H                                                             00007950
      IF(IDOUB.LE.1) GO TO 550                                           00007960
      IDOUB=IDOUB -1                                                     00007970
      IF(IDOUB.GT.1) GO TO 700                                           00007980
      DO 530 I=1,N                                                       00007990
530   SAVE(10,I)=ERROR(I)                                                00008000
      GO TO 700                                                          00008010
C                                                                        00008020
C  REDUCE THE FAILURE FLAG COUNT TO CHECK FOR MULTIPLE FAILURES.         00008030
C  RESTORE T TO ITS ORIGINAL VALUE AND TRY AGAIN UNLESS THERE HAVE       00008040
C THREE FAILURES.  IN THAT CASE THE DERIVATIVES ARE ASSUMED TO HAVE     00008050
C  ACCUMULATED ERRORS SO A RESTART FROM THE CURRENT VALUES OF Y IS       00008060
C  TRIED.                                                                00008070
C                                                                        00008080
540   KFLAG=KFLAG-2                                                      00008090
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      IF (H.LE.(HMIN*1.00001)) GO TO 740                                00008100
      T=TOLD                                                            00008110
      IF (KFLAG.LE.-5) GO TO 720                                        00008120
C                                                                       00008130
C   PR1,PR2,AND PR3 WILL CONTAIN THE AMOUNTS BY WHICH THE STEP SIZE     00008140
C   SHOULD BE DIVIDED AT ORDER ONE LOWER, AT THIS ORDER, AND AT ORDER   00008150
C   ONE HIGHER RESPECTIVELY.                                            00008160
C                                                                       00008170
550   PR2 =(D/E)**ENQ2*1.2                                              00008180
      PR3=1.E+20                                                        00008190
      IF ((NQ.GE.MAXDER).OR.(KFLAG.LE.-1)) GO TO 570                    00008200
      D=0.0                                                             00008210
      DO 560 I=1,N                                                      00008220
560   D=D+((ERROR(I)-SAVE(10,I))/YMAX(I))**2                            00008230
      PR3=(D/EUP)**ENQ3*1.4                                             00008240
570   PR1=1.E+20                                                        00008250
      IF(NQ.LE.1) GO TO 590                                             00008260
      D=0.0                                                             00008270
           DO 580 I=1,N                                                 00008280
580   D=D+(Y(K,I)/YMAX(I))**2                                           00008290
      PR1=(D/EDWN)**ENQ1*1.3                                            00008300
590   CONTINUE                                                          00008310
      IF (PR2.LE.PR3)  GO TO 650                                        00008320
      IF (PR3.LT.PR1) GO TO 660                                         00008330
600   R=1.0/AMAX1(PR1,1.E-4)                                            00008340
      NEWQ=NQ-1                                                         00008350
610   IDOUB=10                                                          00008360
      IF((KFLAG.EQ.1).AND.(R.LT.(1.1))) GO TO 700                       00008370
      IF(NEWQ.LE.NQ) GO TO 630                                          00008380
C                                                                       00008390
C  COMPUTE ONE ADDITIONAL SCALED DERIVATIVE IF ORDER IS INCREASED.      00008400
C                                                                       00008410
      DO 620 I=1,N                                                      00008420
620   Y(NEWQ+1,I)=ERROR(I)*A(K)/DFLOAT(K)                               00008430
630   K=NEWQ+1                                                          00008440
      IF(KFLAG.EQ.1)  GO TO 670                                         00008450
      RACUM=RACUM*R                                                     00008460
      IRET1=3                                                           00008470
      GO TO 750                                                         00008480
640   IF(NEWQ.EQ.NQ) GO TO 250                                          00008490
      NQ= NEWQ                                                          00008500
      GO TO 170                                                         00008510
650   IF (PR2.GT.PR1) GO TO 600                                         00008520
      NEWQ = NQ                                                         00008530
      R=1.0/AMAX1(PR2,1.E-4)                                            00008540
      GO TO 610                                                         00008550
660   R=1.0/AMAX1(PR3,1.E-4)                                            00008560
      NEWQ=NQ+1                                                         00008570
      GO TO 610                                                         00008580
670   IRET=2                                                            00008590
      R=DMIN1(R,HMAX/DABS(H))                                           00008600
      H=H*R                                                             00008610
      HNEW=H                                                            00008620
      IF (NQ.EQ.NEWQ) GO TO 680                                         00008630
      NQ=NEWQ                                                           00008640
      GO TO 170                                                         00008650
680   R1=1.0                                                            00008660
      DO 690 J=2,K                                                      00008670
```

```
      R1=R1*R                                                          00008680
      DO 690 I=1,N                                                     00008690
  690 Y(J,I)=Y(J,I)*R1                                                 00008700
      IDOUB=K                                                          00008710
  700 DO 710 I=1,N                                                     00008720
  710 YMAX(I)=DMAX1(YMAX(I),DABS(Y(1,I)))                              00008730
      JSTART=NQ                                                        00008740
      RETURN                                                           00008750
  720 IF(NQ.EQ.1) GO TO 780                                            00008760
      CALL DIFFUN(T,Y,SAVE(N2,1))                                      00008770
      R=H/HOLD                                                         00008780
      DO 730 I=1,N                                                     00008790
      Y(1,I)=SAVE(1,I)                                                 00008800
      SAVE(2,I)=HOLD*SAVE(N1+I,1)                                      00008810
  730 Y(2,I)=SAVE(2,I)*R                                               00008820
      NQ=1                                                             00008830
      KFLAG=1                                                          00008840
      GO TO 170                                                        00008850
  740 KFLAG=-1                                                         00008860
      HNEW=H                                                           00008870
      JSTART=NQ                                                        00008880
      RETURN                                                           00008890
C   THIS SECTION SCALES ALL VARIABLES CONNECTED WITH H AND RETURNS     00008900
C   TO THE ENTERING SECTION.                                           00008910
C                                                                      00008920
  750 RACUM=DMAX1(DABS(HMIN/HOLD),RACUM)                               00008930
      RACUM=DMIN1(RACUM,DABS(HMAX/HOLD))                               00008940
      R1=1.0                                                           00008950
      DO 760 J=2,K                                                     00008960
      R1=R1*RACUM                                                      00008970
      DO 760 I=1,N                                                     00008980
  760 Y(J,I)=SAVE(J,I)*R1                                              00008990
      H=HOLD*RACUM                                                     00009000
      DO 770 I=1,N                                                     00009010
  770 Y(1,I)=SAVE(1,I)                                                 00009020
      IDOUB=K                                                          00009030
      GO TO (130,250,640),IRET1                                        00009040
  780 KFLAG=-4                                                         00009050
      GO TO 470                                                        00009060
      END                                                              00009070
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This report presents an account of the activities of the MERADCOM-OSU System Reliability Program in the area of hydraulic system operational severity assessment. An appraisal of changes in component performance due to degradation is presented and their effect on overall system performance examined. Data acquired by the Statistical Analog Monitor on systems working under controlled conditions is also analyzed.

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SECTION III

HYDRAULIC OPERATIONAL SEVERITY ASSESSMENT

PROJECT STAFF

S. K. R. Iyengar, Co-Project Manager
R. L. Decker, Co-Project Manager
R. F. Sharp, Project Engineer
R. L. Brown, Project Engineer
M. T. Yokley, Project Engineer

FOREWORD

This section presents the results of the project on hydraulic system operational severity assessment. The principal objectives of this year's effort were to examine the changes in component performance parameters due to their degradation and relate them to cumulative data of the type acquired by the Statistical Analog Monitor (STAM). Effort was also to be expended on collecting STAM data on selected machines to examine the influence of operational duty cycles on STAM profiles. This report presents a summary of data so collected.

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CHAPTER I

INTRODUCTION

The assessment of performance degradation is of vital importance to both equipment manufacturers and users of hydraulic equipment, since the drop in performance capabilities of a machine can almost always be traced to degradation of one or more components. Significant improvement in overall system reliability can be achieved by monitoring the performance of individual components and repairing or replacing them when needed. Even though the degradation of a component can usually be ascertained by disassembly and inspection, this process is generally time-consuming, and often impracticable for field-maintenance units. Consequently, the development of non-intrusive diagnostics, wherein the state of a component is assessed without removing components from a system and if possible, even disturbing normal operation of the equipment, hold much promise for improving overall system reliability.

Non-intrusive diagnostics depends on the measurement of physical quantities like pressure, temperature, flow rate, etc., by permanently installing the requisite transducers in the system. Hitherto, such instrumentation had been accomplished only on experimental vehicles and needed the use of elaborate recording or transmitting equipment. The development of the Statistical Analog Monitor (STAM) has obviated the need for much real-time data acquisition. Details of construction and operation of STAM have been presented in earlier reports [1,2,3] as well as a number of papers [4,5,6].

Even though the collection of cumulative data is a challenging task, such data, by themselves, reveal little information about the state of a specific component on a machine. The development of data interpretation algorithms which can furnish qualitative or quantitative information about the state of the system or any component therein needs, as a prerequisite, an analysis of the system. Examples of such analysis have been presented in earlier reports [7,8]. Results of some STAM data interpretation are given in Ref. [2]. The effort reported in this document is a continuation of the earlier work and focuses on individual component degradation.

Chapter II examines the behavior of a system in which components are exchanged for those of larger or smaller size. It is shown that both power output and overall efficiency may be significantly altered by such component changes. Chapter III reports on component performance changes due to degradation. A relief valve was chosen for experimentation, since such valves are critical components on many mobile hydraulic systems.

CHAPTER II

EFFECT OF COMPONENT CHANGES ON OPERATIONAL SEVERITY

INTRODUCTION

Fluid power equipment, like any other piece of machinery, is designed to perform in a prescribed manner under the range of specified operating conditions. Even though the end-item company is generally responsible for the call-out of individual components, the equipment buyer should exercise some control over component selection [9]. In order to exercise such control effectively and efficiently, and also to be able to undertake or guide "commercial modification" to suit specific operational requirements, it is desirable that the effect of changing circuit components be evaluated. In the case of simple hydraulic circuits, the effect of sizing changes can be estimated by quick hand calculations. Thus, in a circuit comprised of a fixed displacement pump, a cylinder, and a four-way, two-position directional control valve, enlarging the pump displacement or reducing the cylinder will increase the piston velocity proportionately. However, if the circuit becomes complex due to aggregation of a number of actuators and use of flow modulation through the use of various types of flow and pressure controls, hand calculations become cumbersome and time-consuming, if not altogether impossible; under such circumstances, it is advantageous to develop appropriate mathematical models of individual components and assemble them to obtain a mathematical model for the entire system under investigation. The mathematical model for the system can, then, be used to study the effect of changing components on the operational severity

of the system under prescribed operating conditions. Performance appraisal using mathematical models of components can be very efficiently and economically done with the help of digital computers. An example of such analysis is presented below, primarily to indicate the scope of effort involved and the type of appraisal information generated by such analysis. Numerical values for various design parameters (e.g., pump and cylinder sizes, duty cycles, etc.) were chosen so as to illustrate the methodology and do not reflect any actual operating conditions.

EXAMPLE SYSTEM DESCRIPTION

The open center system consisting of a fixed displacement pump, a directional control valve, and two hydraulic cylinders in parallel, as shown in Fig. 2-1, was chosen as the test circuit. This type of system is not only common to many mobile hydraulic systems but also the basic subsystem in many large and complex hydraulic machinery. It also illustrates the kind of trade-offs which system designers and equipment users need to consider in selecting components.

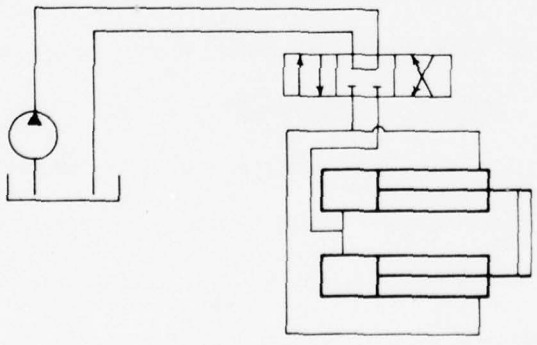


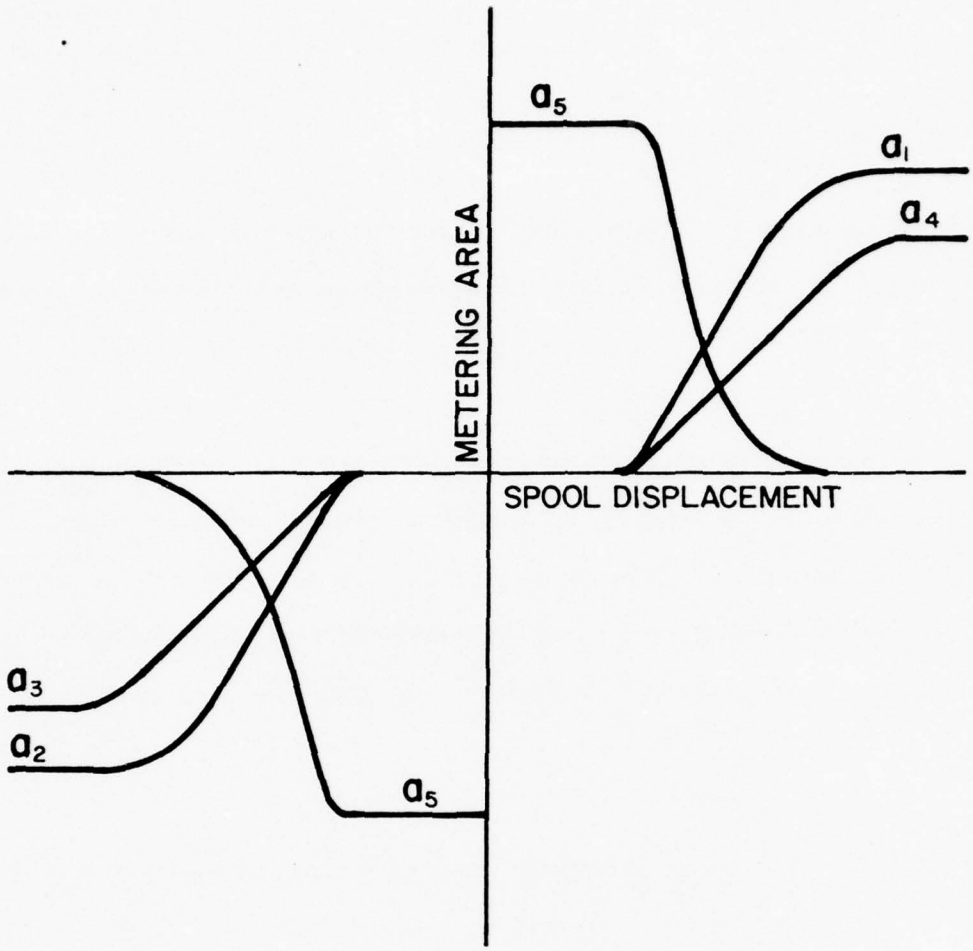
Fig. 2-1. Circuit Schematic of Open Center System

The dotted lines in Fig. 2-1 demarcate subsystems; each of which in turn is comprised of subsystems. Details of modeling the subsystems and individual components are discussed only briefly, since they have been presented elsewhere [10,11].

The positive displacement pump is assumed to operated at a constant speed. Its flow rate is assumed to drop linearly, so that its mathematical model consists of an equation relating the flow rate to the delivery pressure. The filter and heat exchanger though shown in Fig. 2-1 do not enter into the mathematical model for Subsystem 1--an assumption which can be lifted if the flow-pressure characteristics of the component are known.

The directional control valve comprises Subsystem 2 and is shown to manually operated and infinitely positioning. It could just as well be pilot operated or electrically actuated. Anti-cavitation checks and cross-over relief valves, which are often present in open center systems, have been excluded in the modeling. The valve is described mathematically by a set of graphs which show how the various metering orifices change with spool displacement, Fig. 2-2. Such graphs can be developed from test data generated in metering characteristics tests [12].

The actuators comprise Subsystem 3 and are mechanically connected so that they share the external load equally and move in unison. It is also assumed that the actuators do not leak and do not cause any significant drag. Pressure drops in the various lines are also considered negligible.



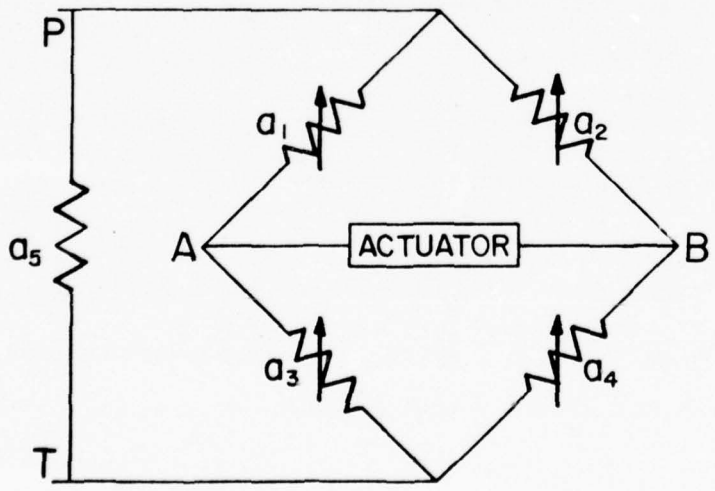


Fig. 2-2. Metering Characteristics of an Open Center Valve

In order to keep the mathematical models as simple as possible, all dynamic considerations have been excluded. Thus, the effects of fluid compressibility and inertia of moving parts in the cylinders and elsewhere have been ignored. The end result is that the mathematical models of all components are in the form of algebraic equations or in graphic form, in the case of the directional control valve. The system model obtained by assembling the subsystem model is called a static model to distinguish it from one which portrays dynamic behavior. It should be noted that, even though it is called a "static" model, it still depicts the motion of the actuators and the changes in the various flows and pressures when a time-history of inputs is given.

The mathematical model for any system can be thought of as a black box which accepts certain input information and generates the desired output information. In the case of the open center system under consideration, the following quantities are considered as inputs: pump theoretical flow, valve spool position, external load, and tank pressure. Of those, pump flow and tank pressure are treated as constants, while the other two vary with time in accordance with the prescribed operational cycle.

Using the nomenclature of Table 2-1, the mathematical models for the subsystems can be shown to be as follows:

Pump Subsystem

$$Q_s = Q_{th} - k_p P_s \qquad (2\text{-}1)$$

TABLE 2-1. Nomenclature for Open Center System Analysis

SYMBOL	COMPUTER NAME	DESCRIPTION	VALUE	
			U.S. UNITS	S. I. UNITS
A_{hc}	CYLH	Cylinder Effective Area, Head End	@ sq. ins.	mm^2
A_{rc}	CYLR	Cylinder Effective Area, Rod End	@ sq. ins.	mm^2
a_1	A1	Open-Center Valve Metering Orifice Area	sq. in.	"
a_2	A2	Open-Center Valve Metering Orifice Area	sq. in.	"
a_3	A3	Open-Center Valve Metering Orifice Area	sq. in.	"
a_4	A4	Open-Center Valve Metering Orifice Area	sq. in.	"
a_5	A5	Open-Center Valve Metering Orifice Area	sq. in.	"
HP_{in}	HPIN	Input Horsepower		
HP_{out}	HPOUT	Output Horsepower		
$\overline{HP}_{in}$		Average Input Horsepower		
$\overline{HP}_{out}$		Average Output Horsepower		
k_p	XK1	Pump Slip Coefficient		
P_a	PA	Port A Pressure	psi	MPa
P_b	PB	Port B Pressure	psi	MPa
P_s		Supply Pressure	psi	MPa
P_t	PTANK	Tank Port Pressure	50 psi	0.345 Pa
Q_{hc}	QHC	Flow to Head End of Cylinders (inflow positive)	gpm	litres/minute
Q_{rc}	QRC	Flow from Rod End of Cylinders (outflow positive)	gpm	litres/minute
Q_s	FLOWIN	Pump Flow	gpm	litres/minute
Q_t	QTANK	Flow Through a_5	gpm	litres/minute
Q_{th}	TFLOW	Theoretical Pump Flow	gpm	litres/minute
v	VELOC	Actuator Velocity Extension Positive	in/sec	mm/s
W*	ELOAD	Load on Cylinders (positive if resisting extension)	lbsf	N
x *	SPOOL	Spool Displacement	ins.	mm
ρ	RHO	Fluid Density	lbsf sec^2/in^4	kg/ℓ
	CYLDIA	Cylinder Diameter	@ ins.	mm
	ROD2	Rod Diameter	2.5 ins.	63.5 mm

@ Parameter (constant for a given operational cycle)

* Variable

This equation indicates that at any time the actual outflow from the pump is equal to the theoretical flow less the slip flow which is proportional to the supply pressure.

Valve Subsystem

Figure 2-2 presented the valve metering characteristics graphically. Since it is rarely practicable to describe such characteristics in the form of equations, a numerical representation is used in the analysis. Such representation takes the form of arrays of numbers from which the metering areas corresponding tc a given spool displacement can be read off either directly or by a process of interpolation. The numerical form of representation is particularly well-adapted to computerization [7,8].

Actuator Subsystem

Three equations are needed to describe the actuator operation. The first is a force balance equation and relates the external load to the pressures on either side of the actuator; the other two equations relate the actuator velocity to the inflow and outflow of the cylinder.

$$P_a A_{hc} - P_b A_{rc} = W/2 \tag{2-2}$$

$$v = Q_{hc}/(2 A_{hc}) \tag{2-3}$$

$$v = Q_{rc}/(2 A_{rc}) \tag{2-4}$$

It may be noted that these equations are algebraic and imply that the actuator subsystem has been described by a static model.

TOTAL SYSTEM REPRESENTATION AND SIMULATION

Equations (2-2) through (2-4), in conjunction with the numerical model for the directional control valve, comprise the mathematical model for the entire system. It should be noted that the equations are "coupled"; i.e., some quantities appear in more than one equation. Consequently, the entire set of equations has to be solved simultaneously for each set of inputs. Since a typical operational duty cycle will involve continuously changing spool displacement and loads, it is necessary to solve the set of equations representing the total system for a number of sets of inputs. By doing so, it will be possible to establish the output quantities--namely, actuator velocity, cylinder port pressures, flows, and supply pressure corresponding to each set of inputs. Once the values of the above-mentioned outputs are established, it is relatively easy to calculate supplementary quantities which may be of interest. Thus:

$$\text{Hydraulic Power Input } (HP_{in}) = \frac{P_s Q_s}{6599} \quad HP$$

$$\text{Output Power } (HP_{out}) = \frac{W.v}{6600} \quad HP$$

$$\text{Hydraulic System Efficiency} = HP_{out}/HP_{in}$$

It may be noted that all of the above quantities change from instant to instant during an operational duty cycle, and average values need to be calculated by accounting for the time period at each level.

Apart from calculating instantaneous values of pressures, flows, velocities, power, etc., the digital computer can be used to generate cumulative data, such as that acquired by the Statistical Analog Monitor (STAM) [10]. Simulation of STAM is especially useful, since it can be used for the rational selection of transducer range and location, gate levels, and scale factors for counters.

PARAMETER SENSITIVITY

Once a component has been selected, the parameters associated with it are fixed, no matter what the operational duty cycle. Thus, selection of a pump fixes the theoretical flow rate, while selection of a cylinder determines, once for all, the ratio of head end to rod end flow and the rod velocity for a given flow. If the system designer or the equipment buyer wishes to ascertain how a change in component specifications will affect the overall performance, one method is to actually carry out the change on the hardware and measure output quantities under both circumstances. The expense and time involved in such experimentation is not inconsiderable. On the other hand, substantially the same information can be obtained by performing what is known as parameter sensitivity analysis. One method of doing such analysis, and often the only one when the system is complex, consists of modifying the mathematical models for the components to reflect the parameter changes and compare the results of simu-

tion. Due to the general availability of digital computers and the downward trend in computational costs, the total cost of such computer-aided analysis is generally orders of magnitude less than equivalent experimental work. The remainder of this section will present the results of varying cylinder bore and the effect of incorporating a relief valve in the open center system.

In order to examine the effect of changing a parameter, it is necessary to keep all other parameters, as well as the operational duty cycle, invariant. It is important to emphasize that any trends observed by changing a parameter in the above manner are, strictly speaking, valid only for the duty cycle used in the simulation. For the other duty cycles, the entire analysis has to be repeated. Such iterative analysis is, however, easily performed on the digital computer.

Figure 2-3 presents one of the input time-histories used in the simulation. Only two input quantities are depicted, since the other two--pump theoretical flow and tank pressure--are invariant. Figures 2-4a, b, and c depict the instantaneous values of the input and output power as well as their average values for three cylinder bore diameters. The actual average input power is shown in addition to that indicated by STAM. It is seen that the STAM estimates are close to the actual average.

The sensitivity of any specified output quantity to the parameter under study is best presented graphically, plotting the parameter value on the x-axis and the output on the y-axis. Figure 2-5 is such a graph and shows the variation of input and output power and efficiency with cylinder bore for a specified operational duty cycle.

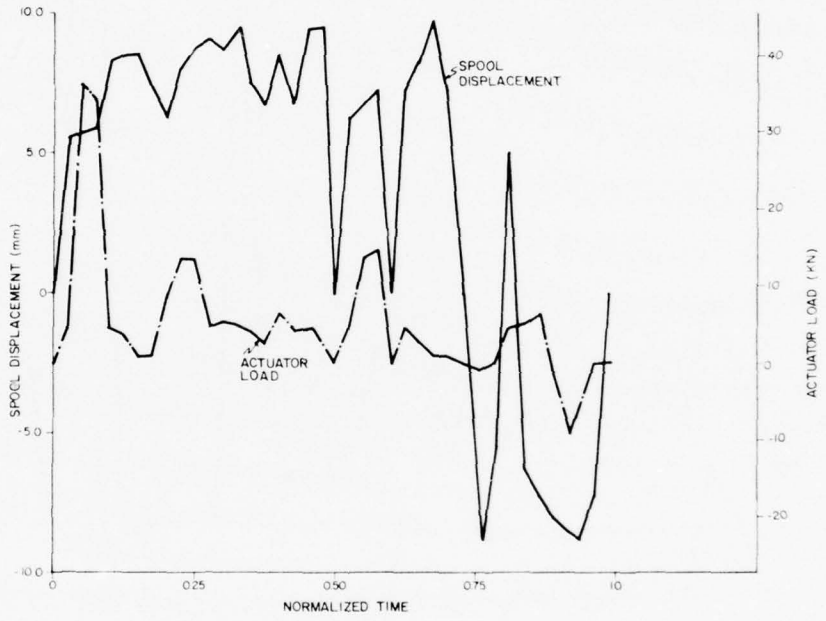


Fig. 2-3. Typical Input Time-Histories used for Simulation

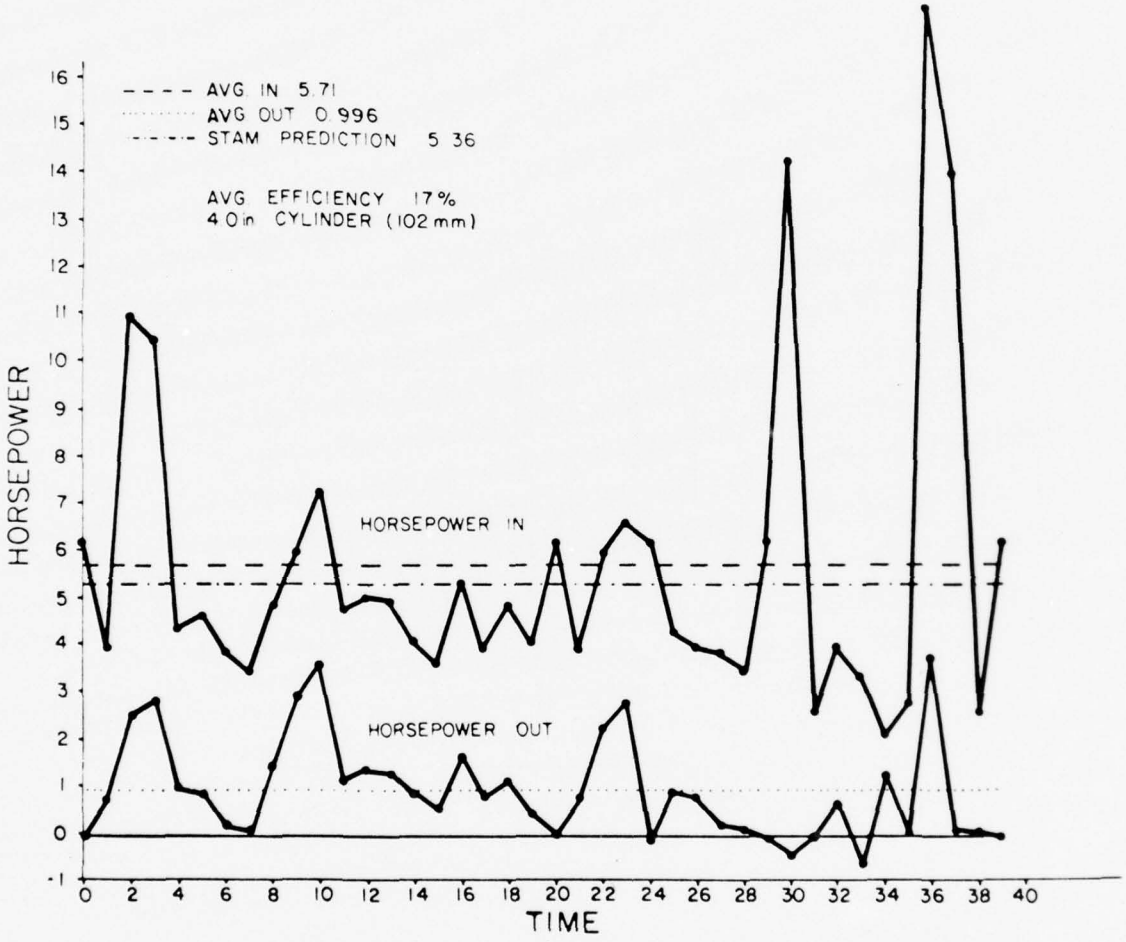


Fig. 2-4a. Time-Histories of Input and Output Power for a System with 4" (102mm) Cylinders

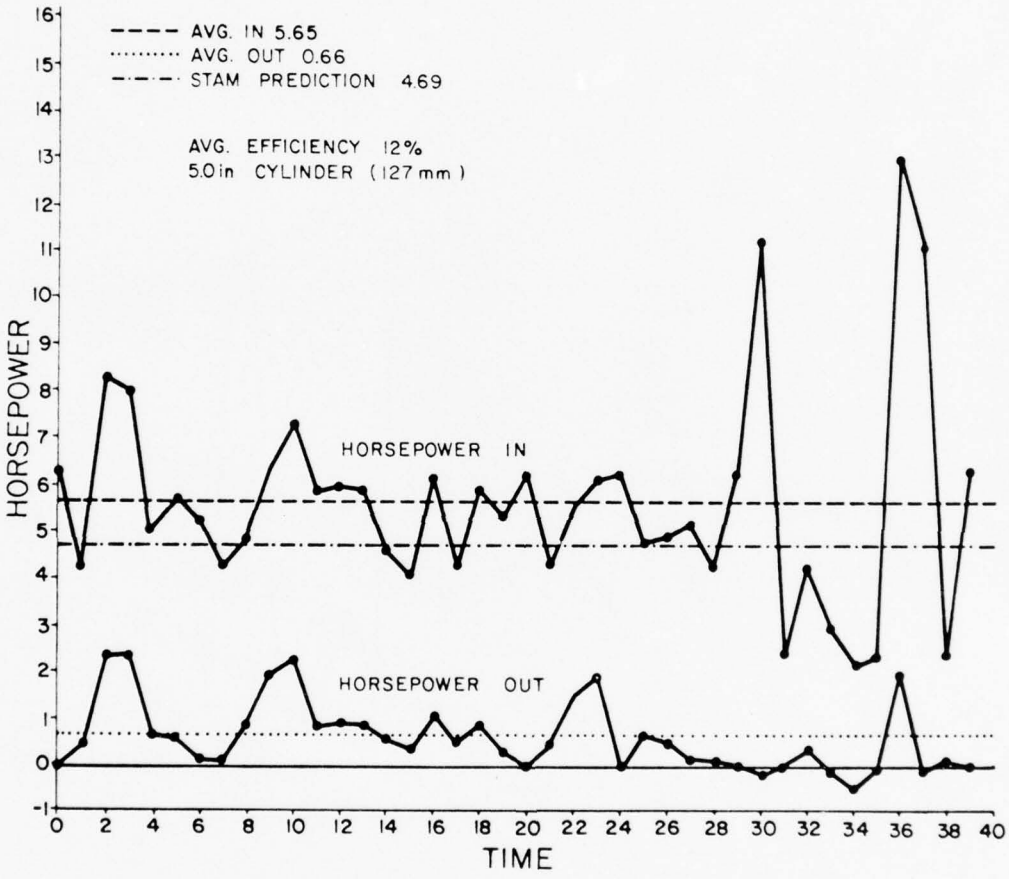


Fig. 2-4b. Time-Histories of Input and Output Power for a System with 5" (127mm) Cylinders

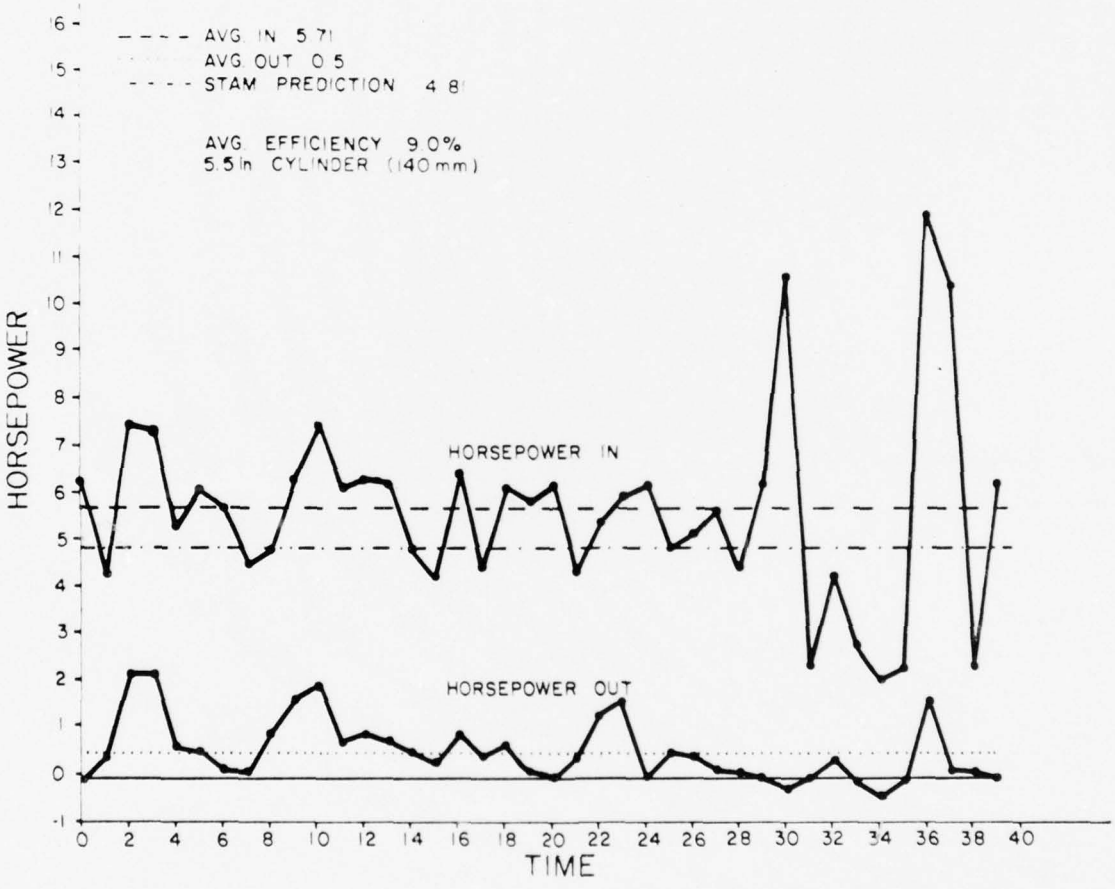


Fig. 2-4c. Time-Histories of Input and Output Power for a System with $5\frac{1}{2}$" (140mm) Cylinders

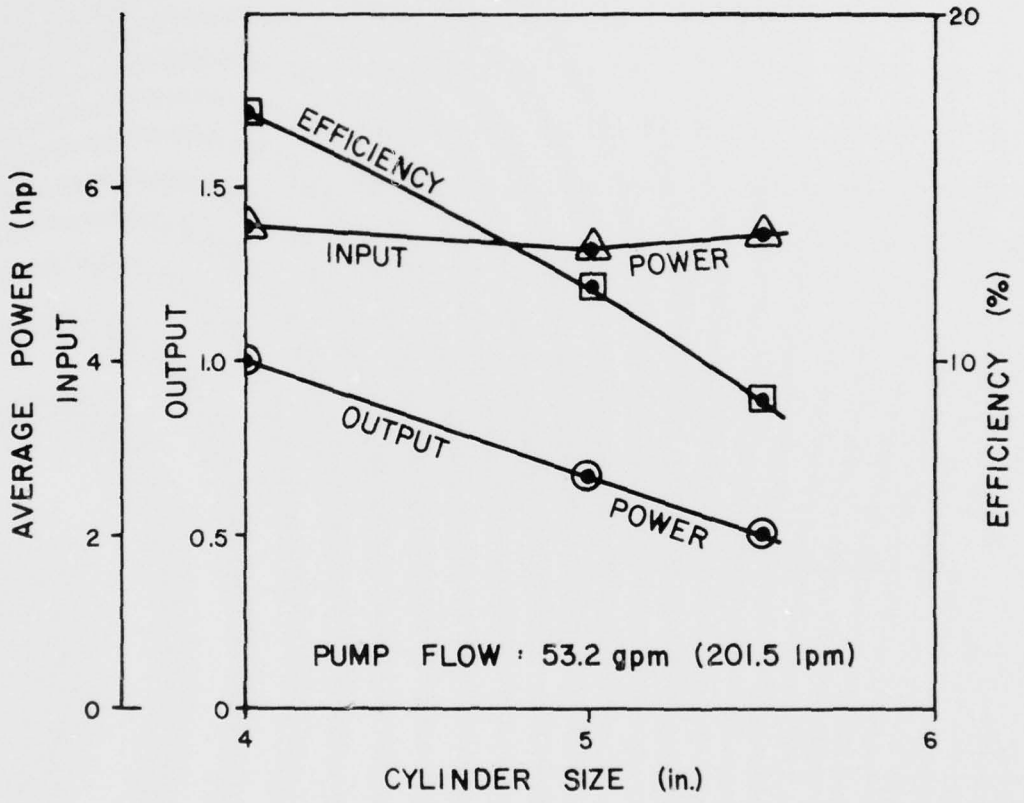


Fig. 2-5. Efficiency and Output Power Variations with Cylinder Size

Figure 2-6 shows another operational cycle--one in which the valve spool is maintained at one or the other extreme position--with the result that all pump flow is directed to either the head end or rod end of the cylinder. Three different pump flow rates, 3.89, 7.79, and 77.9 gpm (14.7, 29.4, and 294 liters per minute, respectively), and three cylinder bores, 4", 5", and $5\frac{1}{2}$" (102 mm, 127 mm, and 140 mm, respectively), were used. Figures 2-7 and 2-8 depict the output power and efficiency time-histories for a pump flow rate of 7.7 gpm (29.4 lpm); similar trajectories were obtained for the other flow rates.

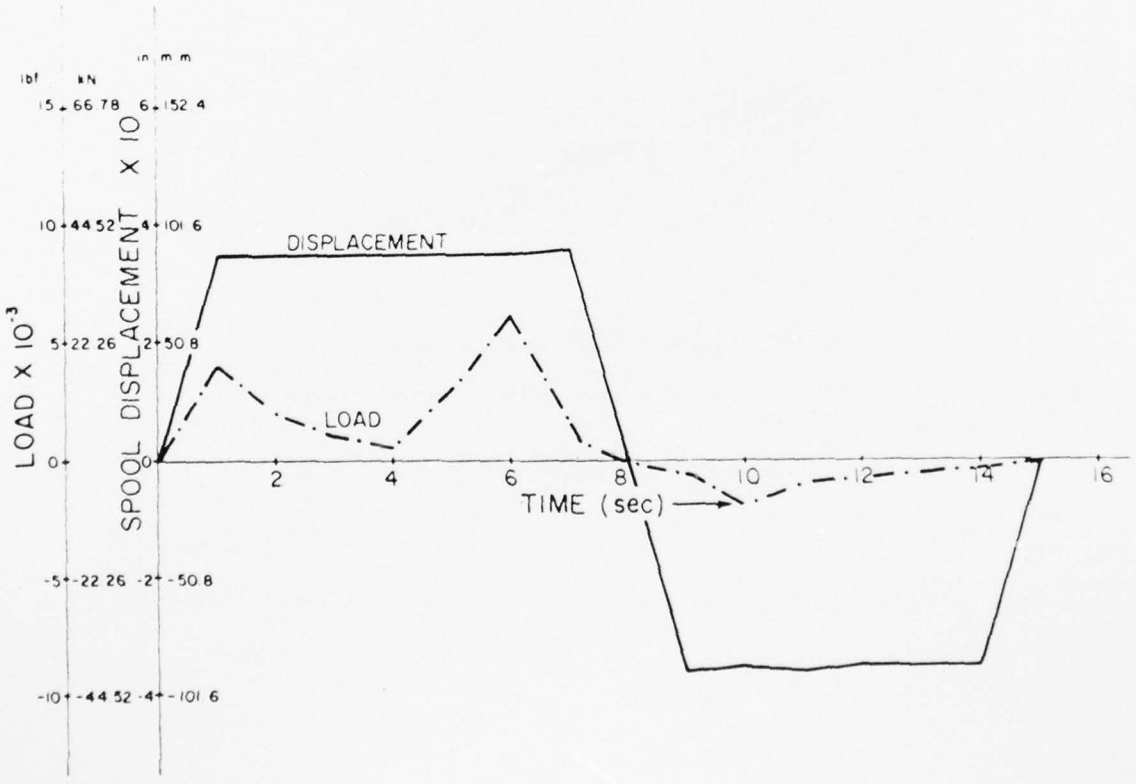


Fig. 2-6. Operational Cycle with Spool in Extreme Position

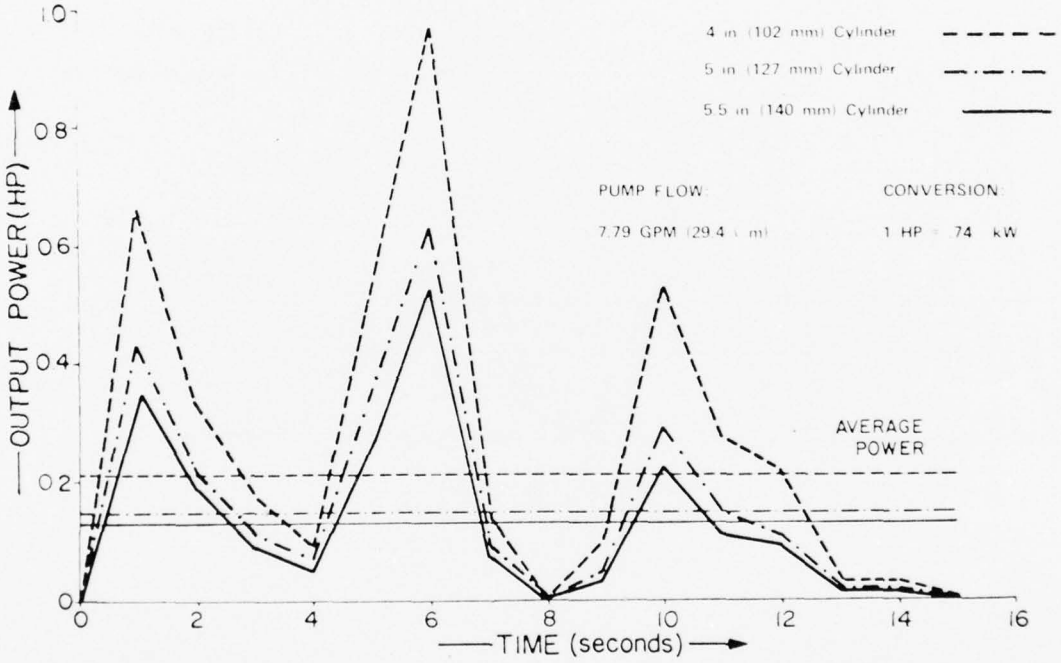


Fig. 2-7. Output Power Trajectories for Open Center System with Three Different Cylinder Sizes

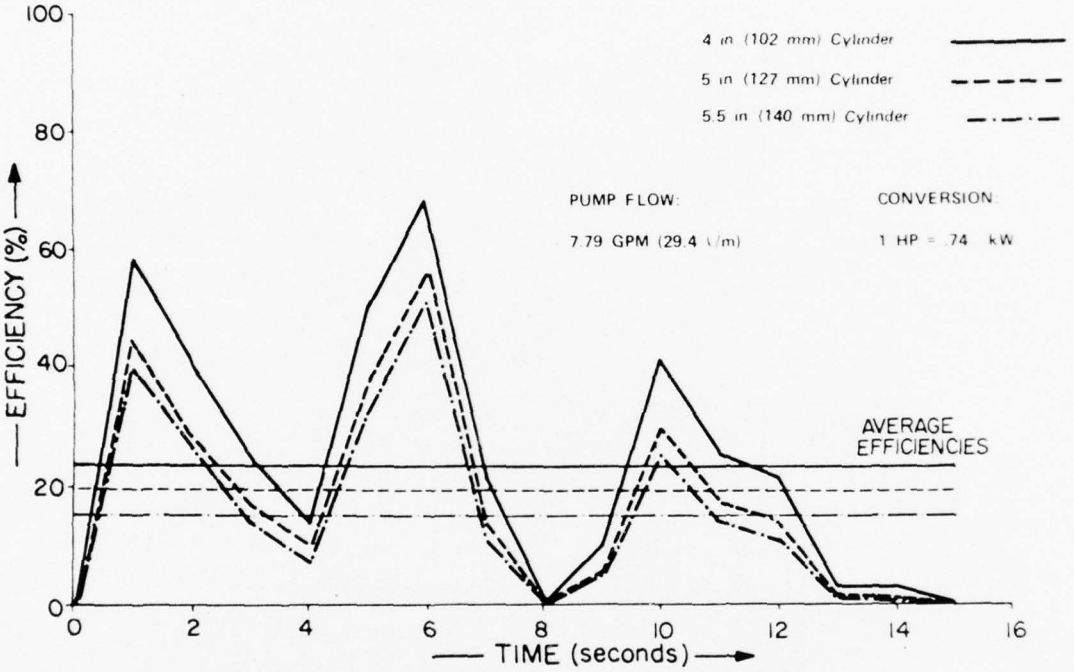


Fig. 2-8. Efficiency Trajectories for Open Center System with Three Different Cylinder Sizes

For this particular operational duty cycle, the power and efficiency trajectories have the same general shape as the load trajectory. This is not surprising in view of the fact that the valve spool was moved to one extremity or the other; and, consequently, the cylinder velocity was dependent solely on the pump flow rate and the cylinder bore. Consequently, for a given flow rate and cylinder size, the output power would increase with load. Since the power loss in the valve is constant, the efficiency correlates with output power. It is also of interest to note that the smaller cylinder size results in higher output power and efficiency. This can be ascribed to higher load velocities and, therefore, higher output power for the same losses. Figures 2-9 and 2-10 depict the sensitivity of cycle efficiency and output power to both cylinder bore and pump flow rate. Such graphs are useful in appraising the

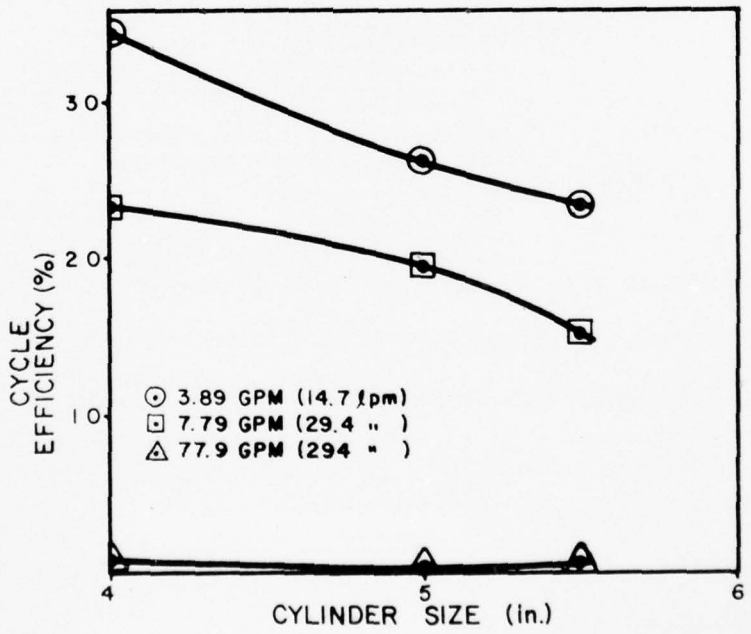


Fig. 2-9. Variation of Open Center System Cycle Efficiency due to Changes in Cylinder Size and Pump Flow Rate

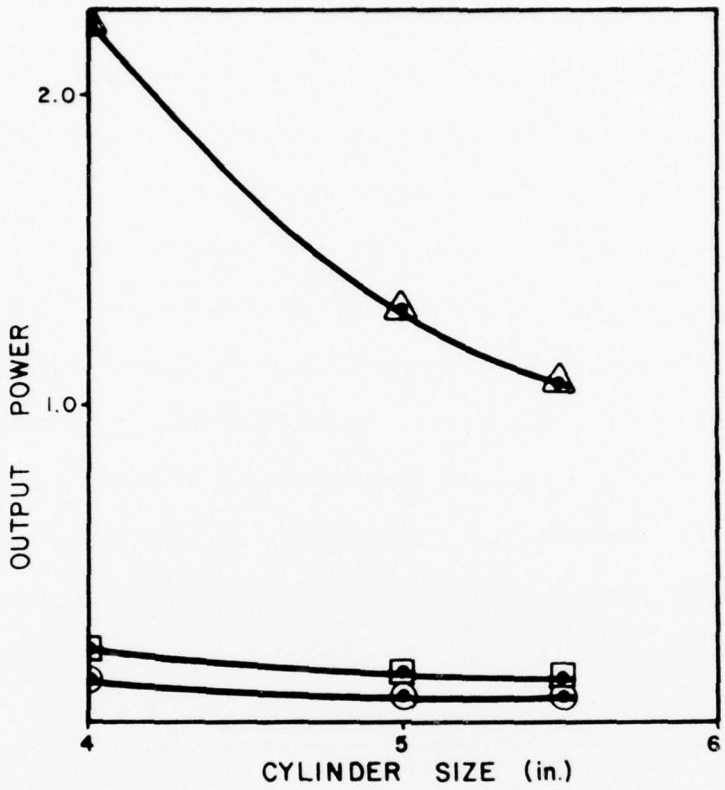


Fig. 2-10. Variation of Open Center System Power Output due to Changes in Cylinder Size and Pump Flow Rate (See Fig. 2-9 for symbol explanation.)

effects of simultaneous changes in two variables. It should be emphasized that such graphs are valid only for the operational duty cycle used in the analysis; and, if a machine is subjected to a number of distinct duty cycles, such an analysis may be repeated for every cycle.

The above discussion illustrates the methodology for systematically analyzing the effect of component changes on operational severity. In view of the number of variables and parameters involved in the mathematical model, the results expose only some of the trade-offs in component selection and system operations. Thus,

for example, if the circuit shown in Fig. 2-1 was augmented with an adjustable circuit relief valve, the mathematical model for the relief valve is all that is needed to appraise its impact on the system behavior.

Figure 2-11 shows an operational duty cycle in which the spool displacement has a large enough absolute value, such that all the pump flow is directed to the cylinder.

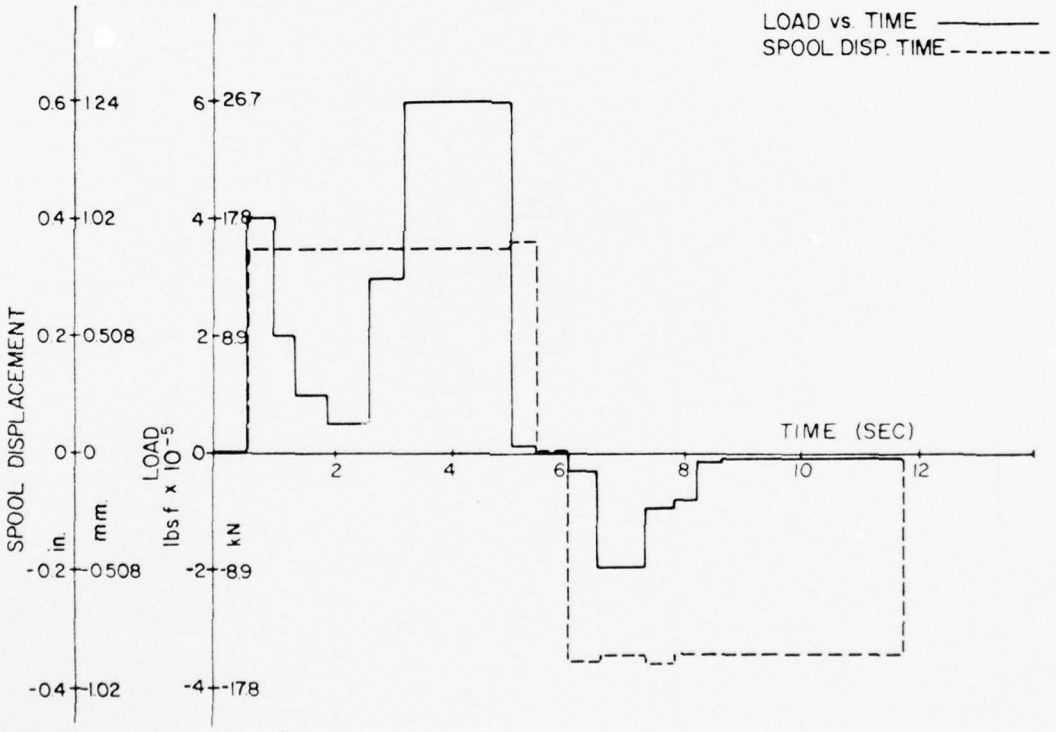


Fig. 2-11. Operational Duty Cycle for an Open Center System

Figure 2-12 depicts the corresponding time-histories for input power, output power, and efficiency for the circuit shown in Fig. 2-1; i.e., one without a relief valve. Figure 2-13 presents the same information when a relief valve, set at 1100 psi (7.59 MPa) is installed in the pump outlet line. The relief valve has a positive gradient of 26 gpm/psi (14.25 lpm/kPa); i.e., it passes the total pump flow of 1.95 gpm

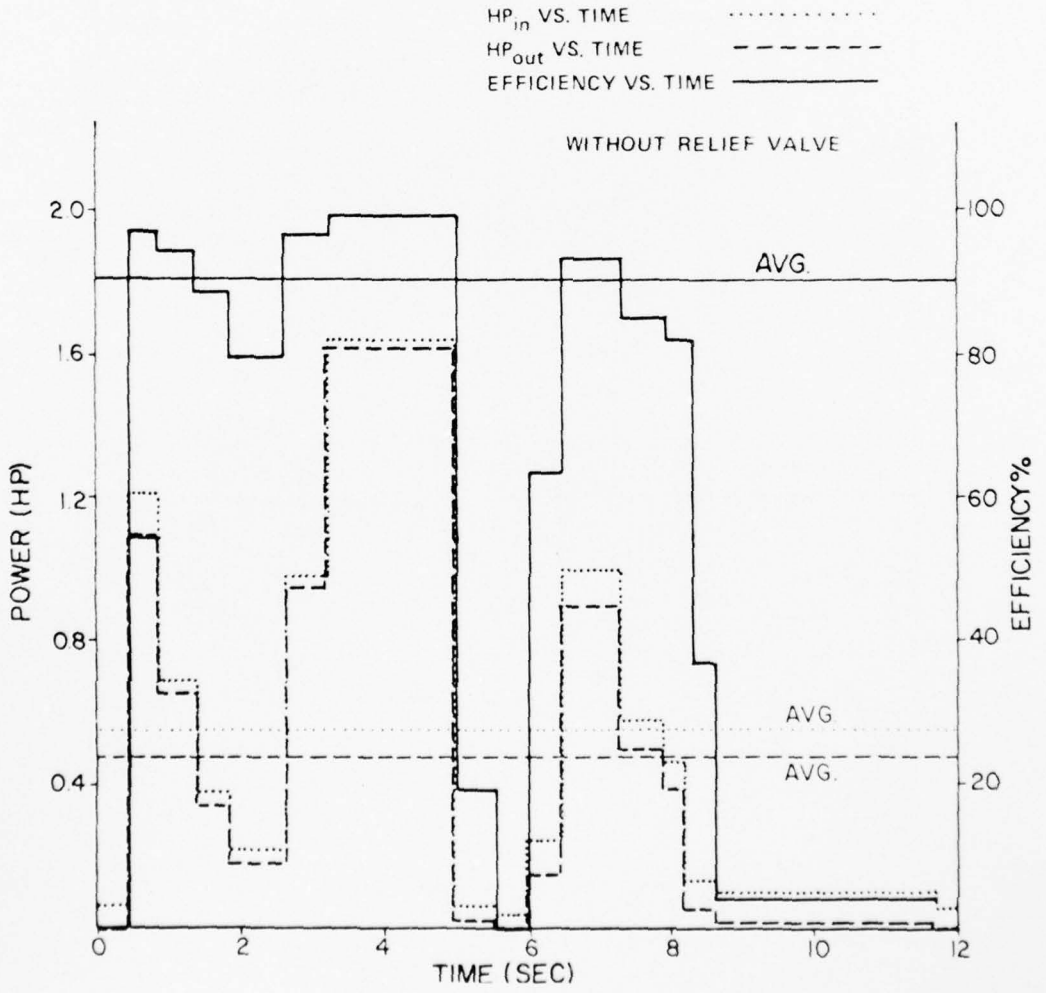


Fig. 2-12. Time-Histories for a System Without a Relief Valve

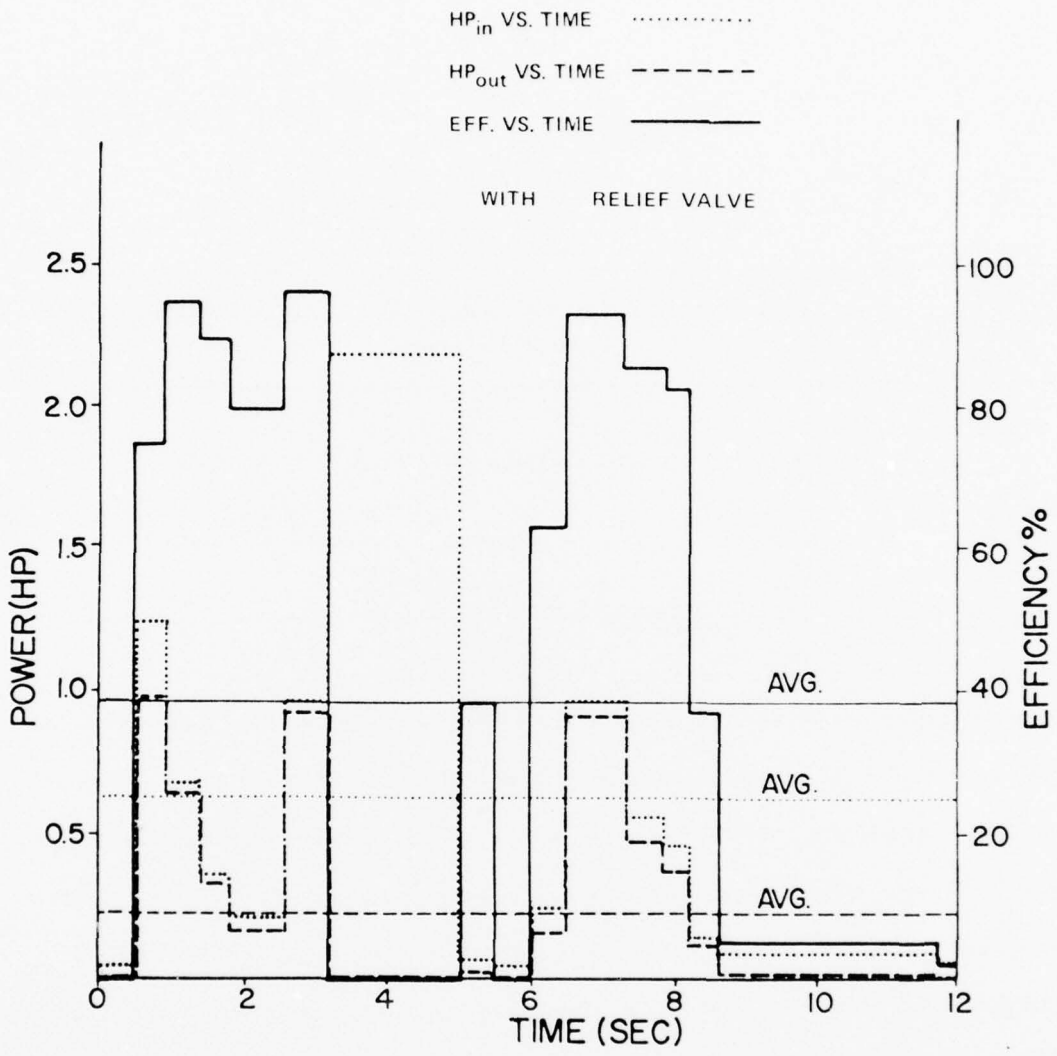


Fig. 2-13. Time-Histories for a System with a Relief Valve

(7.38 lmp) at substantially the cracking pressure. Consequently, when the relief valve opens, no flow is available to the actuator and the output work is zero. The net result on the operational cycle is a drastic reduction in outpower as well as efficiency, as summarized below:

TABLE 2-2.

Comparison of Average Input and Output Power and Efficiency

System	Average Input Power	Average Output Power	Cycle Efficiency
Without relief valve	0.54 HP	0.48 HP	89%
With relief valve set at 1100 psi (7.59 MPa)	0.65 HP	0.24 HP	38%

A method has been developed to examine the effect of component changes on operational severity of hydraulic systems used on mobile hydraulic equipment. It does not require extensive testing of actual hardware, since it uses mathematical models which can be developed from standard performance evaluation tests. By consolidating the mathematical models for the components or subsystems comprising a system, it is possible to simulate its behavior under any specified operating conditions and for any specified operational duty cycle. Since it is generally far easier to change or insert a component mathematical model than to implement the change on the actual hardware, it is possible to ascertain the impact of changing component parameters even on complex systems efficiently and quickly by simulation. An open center hydraulic system has been analyzed for sensitivity of power input and output and efficiency to changes in actuator size, as well as introduction of a relief valve in the pump delivery line. Similar sensitivity analysis can be performed on any system for which component mathematical models are available. Such models should include in them the specific parameter (e.g., cylinder bore, relief valve, cracking pressure, etc.) relative to which

sensitivity analysis is to be performed. Since the results of such analysis are, strictly speaking, valid only for the specific operational duty cycle used in the simulation, it is advisable in the case of multi-task machines to iterate such analysis for the different operational duty cycles the machine is likely to encounter.

CHAPTER III

EXPERIMENTAL ASSESSMENT OF OPERATIONAL SEVERITY

INTRODUCTION

Since relief valves are among the most critical components in hydraulic systems and their degradation could lead to poor overall performance or even malfunctioning of the equipment, it was decided that experimental effort would be focussed on them. The objective was to develop a methodology for correlating performance degradation under controlled operating conditions with real time and STAM histograms.

OPERATIONAL SEVERITY EFFECTS ON CYCLIC TEST RESULTS

Figure 3-1 presents the circuit schematic for the test system. The fixed displacement pump is operated at a constant speed of 1750 RPM. The cycling valve is a relief valve set at a high pressure and vented through a solenoid directional control valve. The solenoid is energized by a cycle timer so as to control the "on" time and "off" time portions of the cycle. The test valve has a needle bypass which is used to control the flow going through the test valve. When the bypass is completely closed, all the pump flow is directed through the test valve. A flowmeter and fluid conditioning equipment (filters and heat exchangers) make up the remainder of the test circuit.

A two-stage relief valve with adjustable pressure setting was used as the test valve. Cycling was performed with a "new" valve and an "old" valve. The new and old valves

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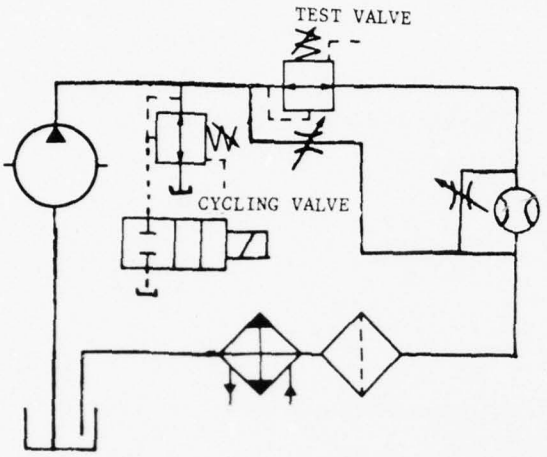


Fig. 3-1. Hydraulic Circuit Schematic for Valve Performance Assessment

were obtained by assembling, respectively, a good and a degraded main stage in the same housing and using the same pilot stage and springs. Switchover of the main stage was performed without disturbing either the pilot stage or the pressure setting. Consequently, any change in the performance can be attributed to the main stage degradation. Visual inspection of the degraded main stage revealed significant wear of the seating cone. Other surfaces were macroscopically unaffected. Figure 3-2 shows the seating cone and the region of wear.

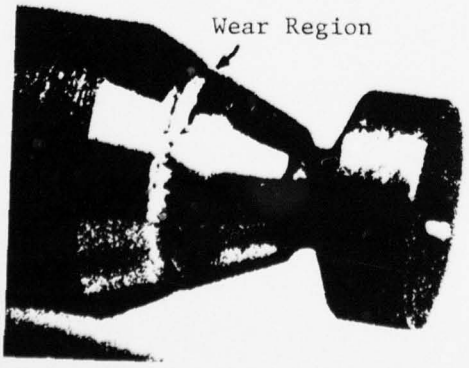


Fig. 3-2. Wear Region on Main Stage of Relief Valve

Figures 3-3 through 3-8 depict the pressure wave forms obtained for the new and old valves at two different flow rates. The lower flow rate was obtained by adjusting the bypass valve so that only the requisite flow passes through the test valve for the "on" time of the cycle. Table 3-1 summarizes the salient features of the pressure wave forms for the old and new valves.

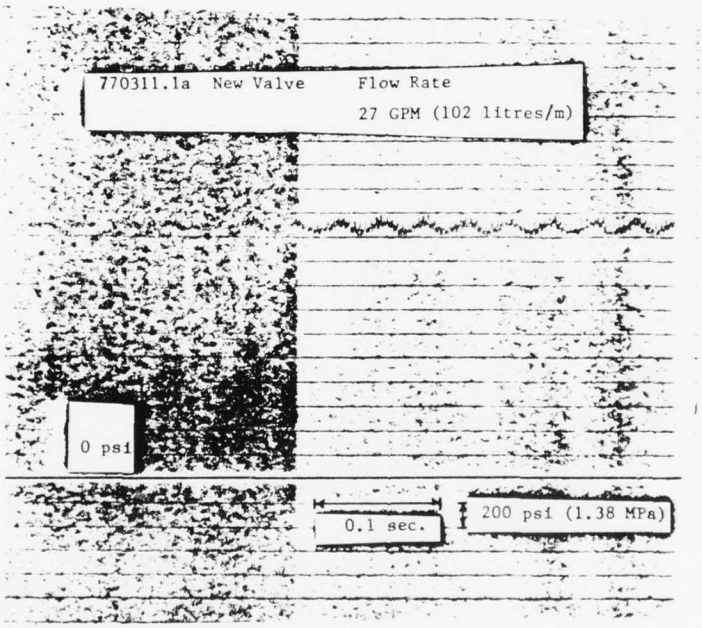
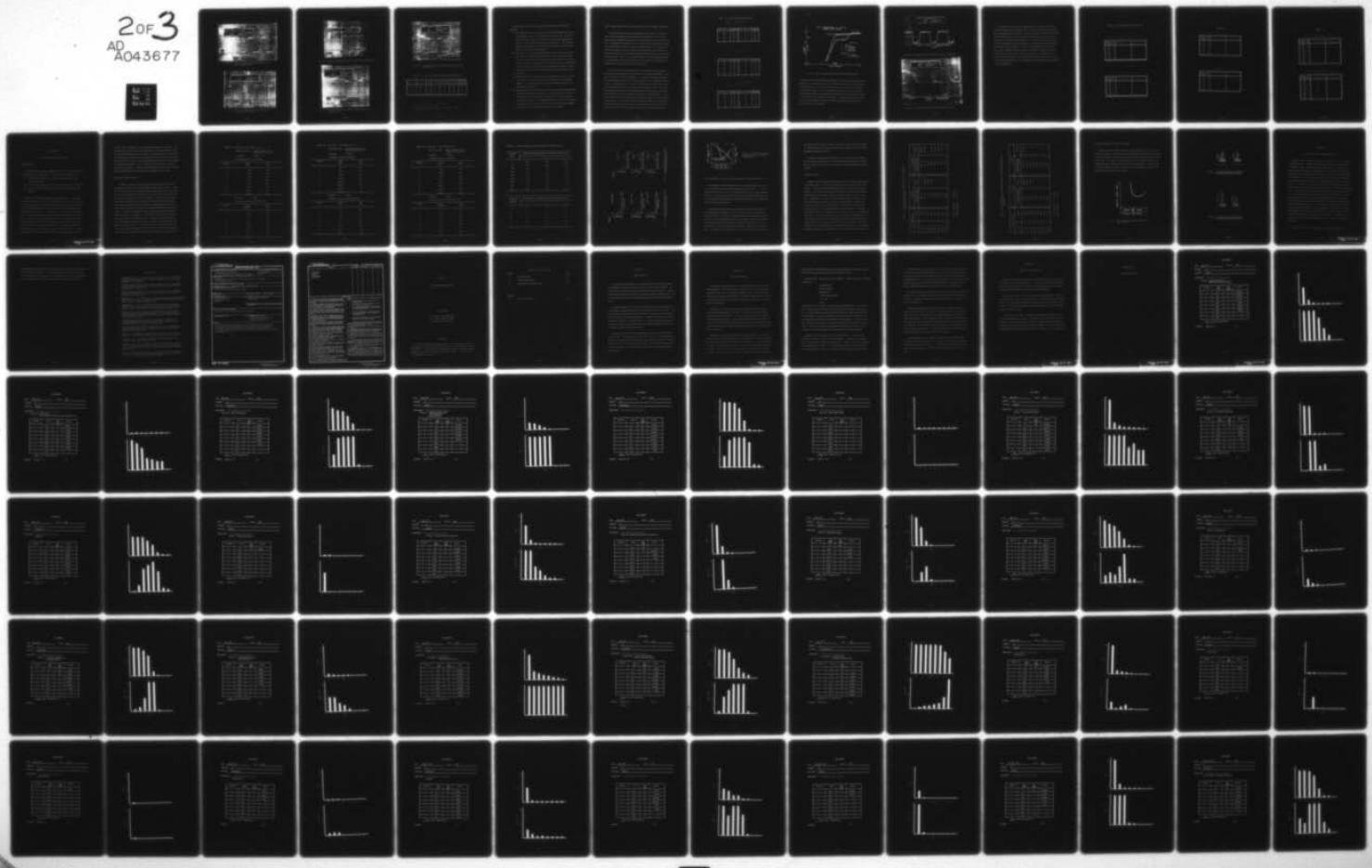


Fig. 3-3. Pressure "Signature" for a New Relief Valve at Rated Flows

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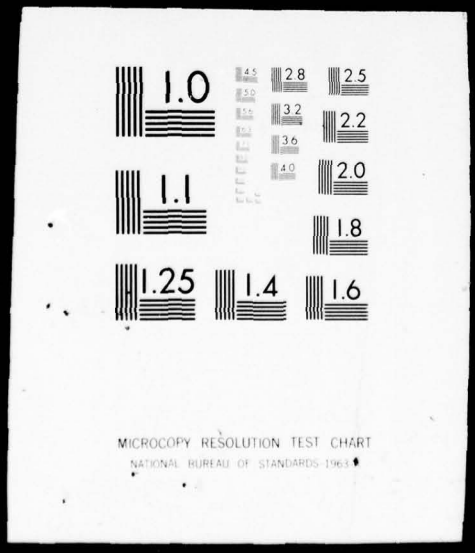
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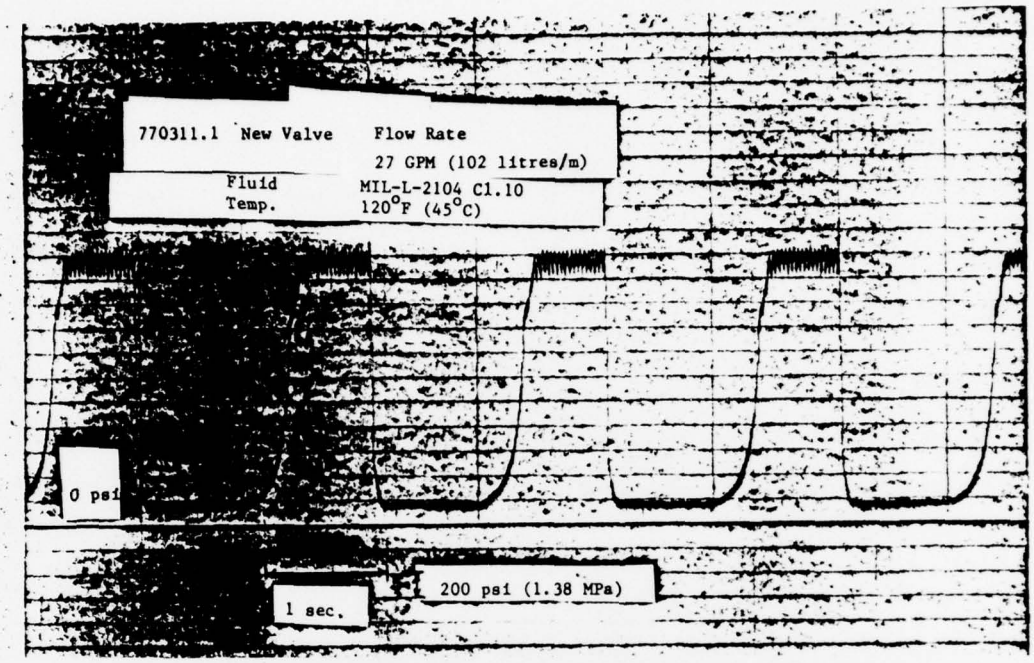


Fig. 3-4. Pressure Waveform for New Relief Valve with Cycling at Rated Flow

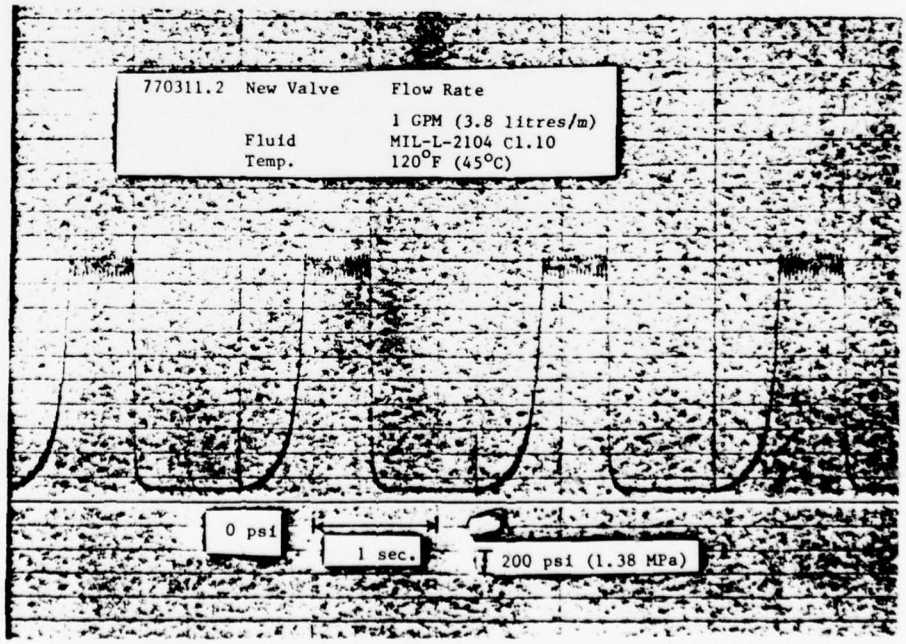


Fig. 3-5. Pressure Waveform for New Relief Valve with Cycling at Low Flow Rate

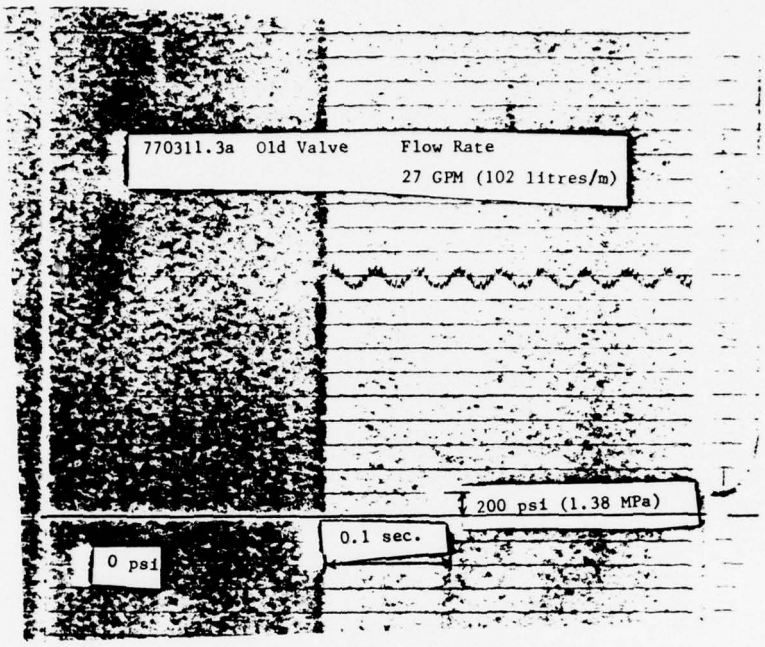


Fig. 3-6. Pressure "Signature" for an Old Relief Valve at Rated Flow

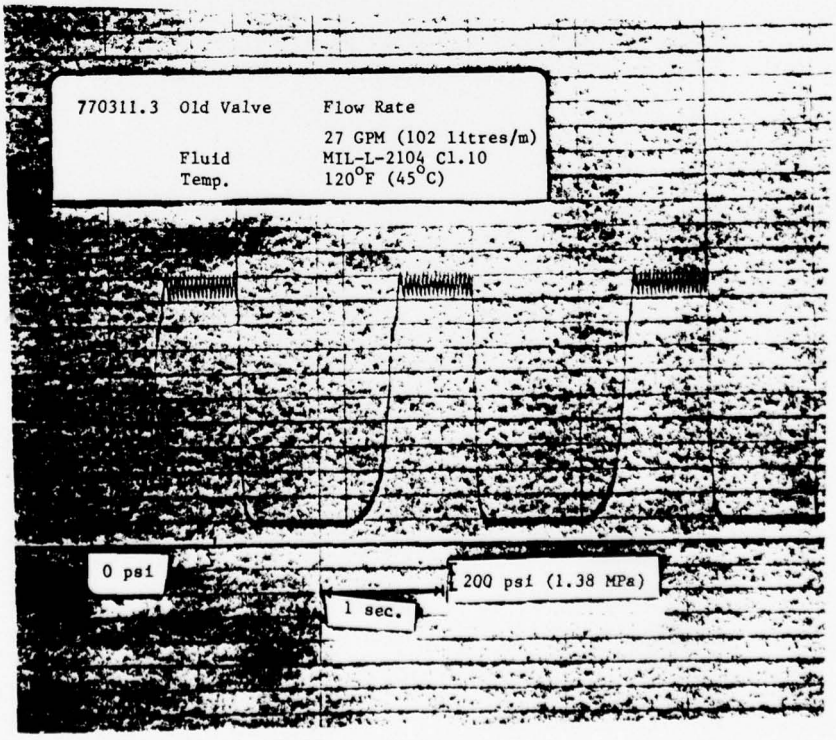


Fig. 3-7. Pressure Waveform for Old Relief Valve with Cycling at Rated Flow

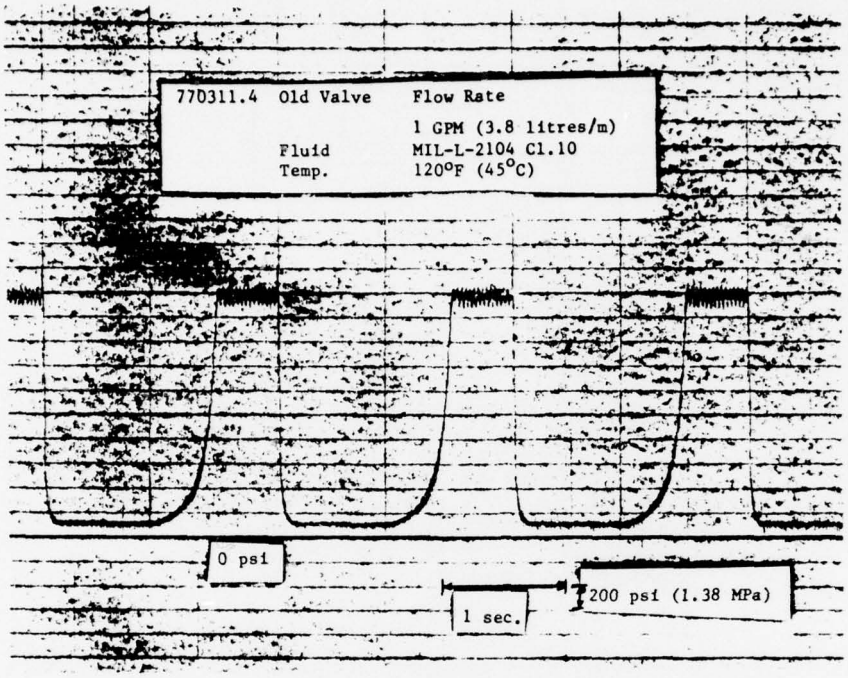


Fig. 3-8. Pressure Waveform for Old Relief Valve with Cycling at Low Flow

TABLE 3-1. Summary of Cyclic Performance of Relief Valves

CYCLE I.D.	VALVE CONDITION	FLOW RATE GPM	FINAL PRESSURE (psi)	PRESSURE RISE TIME (sec)*	PRESSURE RISE RATE (psi/sec)	PRESSURE RIPPLE peak to peak (psi)
770311.1	NEW	27	2150	0.46	8820	180
770311.2	NEW	1	1950	0.52	12500	
770311.3	OLD	27	2130	0.44	9925	230
773011.4	OLD	1	1950	0.54	12500	

FLUID: MIL-L-2104 C&.10 TEMP. 120°F (45°C)

CONVERSION: 1 GPM = 3.785 Liters/minute

* AS MEASURED FROM THE TIME SOLENOID FOR CYCLING VALVE IS SWITCHED ON TO THE TIME FINAL PRESSURE IS ATTAINED.

A scrutiny of the pressure wave forms and the table leads to the following conclusions:

(1) The system pressure at the high flow rate is slightly reduced due to wear of the main stage. There is no reduction for the low flow rate. This is not surprising considering that, at the low flow rate, the main stage does not open--i.e., all the flow goes through the pilot stage only. Since the pilot stage is exactly the same for both new and old valves, the invariance of the pressure at low flow is understandable.

(2) The pressure rise rate remains substantially the same, whether the valve is new or old. The difference between the rise rates for low and high flows can be attributed in part to the load valve being partly open for the low flow cycle. Since the load valve functions as a nonlinear orifice, the flow through it bears a complex relationship to the pressure; and, consequently, the test valve is not subjected to a step change in flow like that encountered at high flow cycling.

(3) The wave forms for low flow cycling are substantially the same for both the old and new valves; whereas, for high flow rates, they are significantly different. For example, the new valve does not exhibit the pressure overshoot shown by the old valve.

(4) The pressure ripple as measured peak to peak at the test valve is significantly less for the new valve than the old valve. Inspection of Figs. 3-3 and 3-6 reveals that the fundamental and first harmonic of the pressure ripple are unchanged in frequency. The fundamental frequency of 29.17 Hz corresponds to the shaft speed (1750 rpm) while the first harmonic (233 Hz) corresponds to the number of pumping elements (gear teeth, in this case).

OPERATIONAL SEVERITY EFFECTS ON STATIC AND DYNAMIC BEHAVIOR

The "old" valve used in the above-mentioned tests was artificial in that the test valve contained a degraded main stage operated in conjunction with a "new" pilot stage, and this combination is not likely to be met under normal field operating conditions. Consequently, additional tests were conducted using the degraded main stage with the degraded pilot with which it was originally equipped. Since the pressure adjustment mechanism had to be dismantled to reach the pilot, it was impractical to ensure that the pilot spring compression would be maintained the same, with the "old" and "new" pilots. Hence, it was decided to conduct tests with the pressure setting screw adjusted so that the valve maintained the same pressure at the rated flow of 27 gpm (102 liters/m), with both the old and new pilots.

Table 3-2 and Fig. 3-9 present the static characteristics of valves equipped with new and old pilot stages used in conjunction with a degraded main stage, as also that of a new valve, to serve as reference. It is seen that a degraded main stage does not manifest itself unless the flow rate is fairly low--i.e., 12% of the rated flow or less. A degraded valve (i.e., one with old pilot and main stage) is seen to lose its regulation characteristics over most of the flow range of the valve. This valve also exhibited erratic behavior in that repeated pressure measurements at the same flow resulted, in one case, in pressures as far apart as 100 psi (690 kPa). A more serious failing of the valve with degraded main and pilot stages was its poor dynamic characteristics. The response time for step changes in flow was so large that the one-second on/one-second off cycle which was used for earlier tests (See Figs. 3-3 through 3-8.) did not allow the pressure to stabilize in the "on" part of the cycle.

TABLE 3-2. Flow-Pressure Characteristics

VALVE I.D.: DT WITH "NEW" MAIN STAGE & "NEW" PILOT
PRESSURE SETTING: 2000 PSI (13.79 MPa)
FLUID: MIL-L-2104C Ck. 10
TEMPERATURE: 110°F (42°C)

Daytronic Reading	Flow Liters/M	Pressure PSI	Pressure MPa	Daytronic Reading	Flow Liters/M	Pressure PSI	Pressure MPa
90	106	1920	13.59	8	27.8	1915	13.21
70	92	1960	13.51	6	23.6	1915	13.21
50	78	1950	13.45	5	21.2	1910	13.17
30	57.5	1940	13.38	4	19	1910	13.17
20	46	1925	13.28	3	16	1910	13.17
10	31.3	1920	13.24	2	13.2	1910	13.17
				1	8.6	1910	13.17
				0.5	6	1905	13.14

VALVE I.D.: DT WITH "OLD" MAIN STAGE & "OLD" PILOT
PRESSURE SETTING: 1960 PSI (13.52 MPa)*
FLUID: MIL-L-2104C Ck. 10
TEMPERATURE: 110°F (42°C)

Daytronic Reading	Flow Liters/M	Pressure PSI	Pressure MPa	Daytronic Reading	Flow Liters/M	Pressure PSI	Pressure MPa
90	106	1940	13.38	5	21.2	1610	11.10
70	92	1960	13.52	4	19	1610	11.10
50	78	2100	14.48	3	16	1610	11.10
		12880	88.80				
30	57.5	2010	13.86	2	13.2	1610	11.10
20	46	1960	13.52	1	8.6	1210	8.35
10	31.3	1610	11.10	0.5	6	800	5.52
8	27.8	1610	11.10				
6	23.6	1610	11.10				

* PRESSURE SETTING ADJUSTED TO BE 2000 PSI (13.79 MPa) AT 27 GPM (102 LITERS/M)

VALVE I.D.: DT WITH "OLD" MAIN STAGE & "NEW" PILOT
PRESSURE SETTING: 2000 PSI (13.79 MPa) (UNCHANGED)
FLUID: MIL-L-2104C Ck. 10
TEMPERATURE: 110°F (42°C)

Daytronic Reading	Flow Liters/M	Pressure PSI	Pressure MPa	Daytronic Reading	Flow Liters/M	Pressure PSI	Pressure MPa
90	106	1965	13.55	5	21.2	1960	13.10
70	92	1940	13.38	4	19	1965	13.07
50	78	1960	13.89	3	16	1965	14.00
30	57.5	1935	13.35	2	13.2	1965	13.07
20	46	1925	13.28	1	8.6	1400	9.66
10	31.3	1920	13.24	0.5	6	700	4.83
8	27.8	1910	13.17				
6	23.6	1910	13.17				

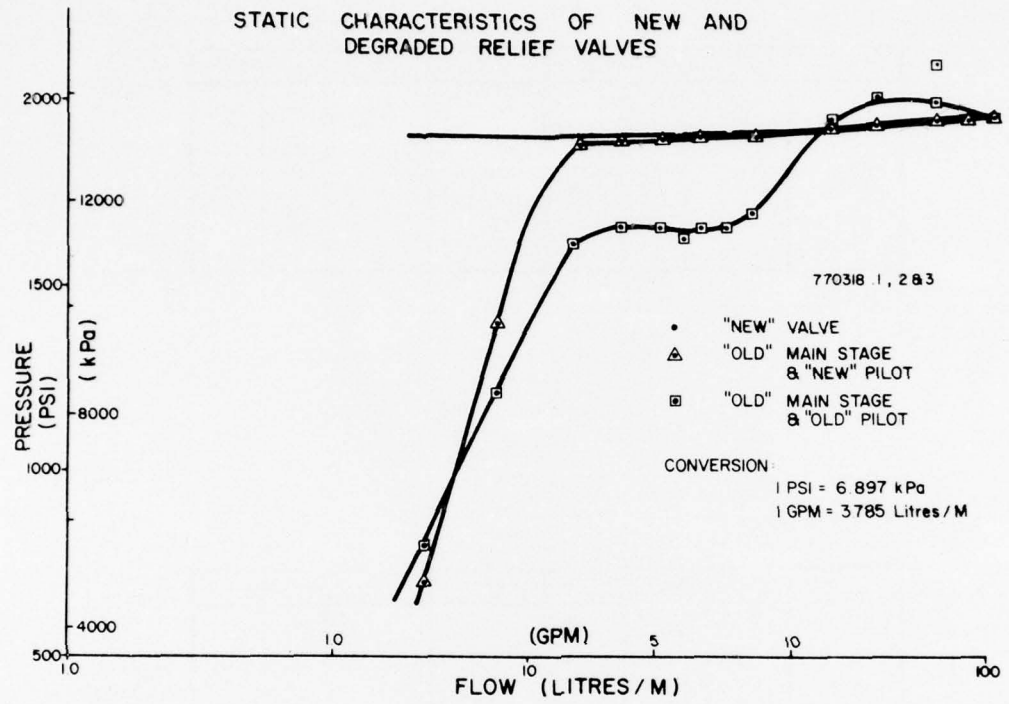


Fig. 3-9. Static Characteristics of "Old" and "New" Relief Valves

Consequently, the "on" time had to be lengthened to 1.5 seconds to permit steady state operation for one-third of the "on" time. Figures 3-10 through 3-11 present the wave forms obtained for cyclic operation with both old and new pilot stages in conjunction with the old main stage. It can be seen that the wave form for low flow operation is not significantly different from that obtained earlier for the new valve, though it should be noted that the maximum pressure is much less. The wave form for high flow, however, exhibits overshoots of the order of 100%, and steady state operation is not reached for at least 0.5 seconds.

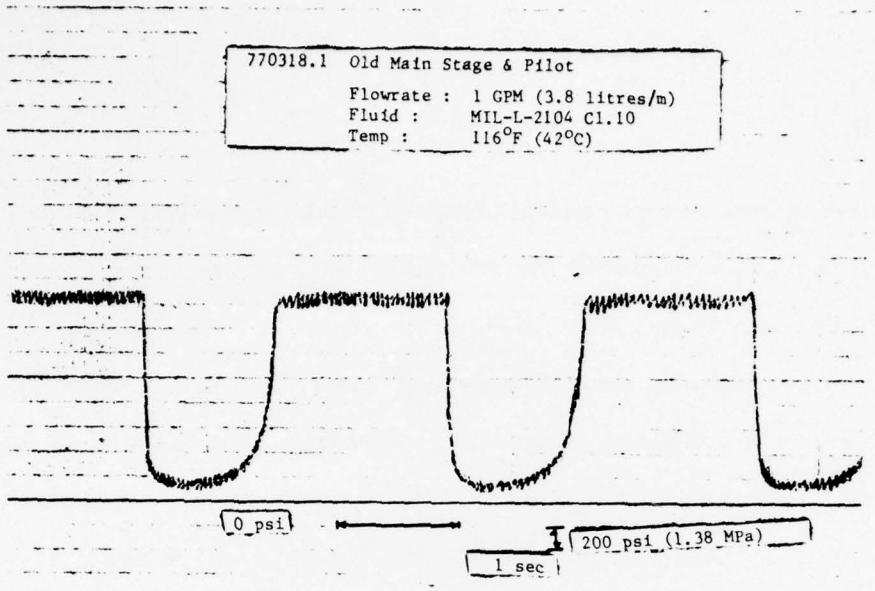


Fig. 3-10. Pressure Wave Form for "Old" Valve at Low Flow Rate

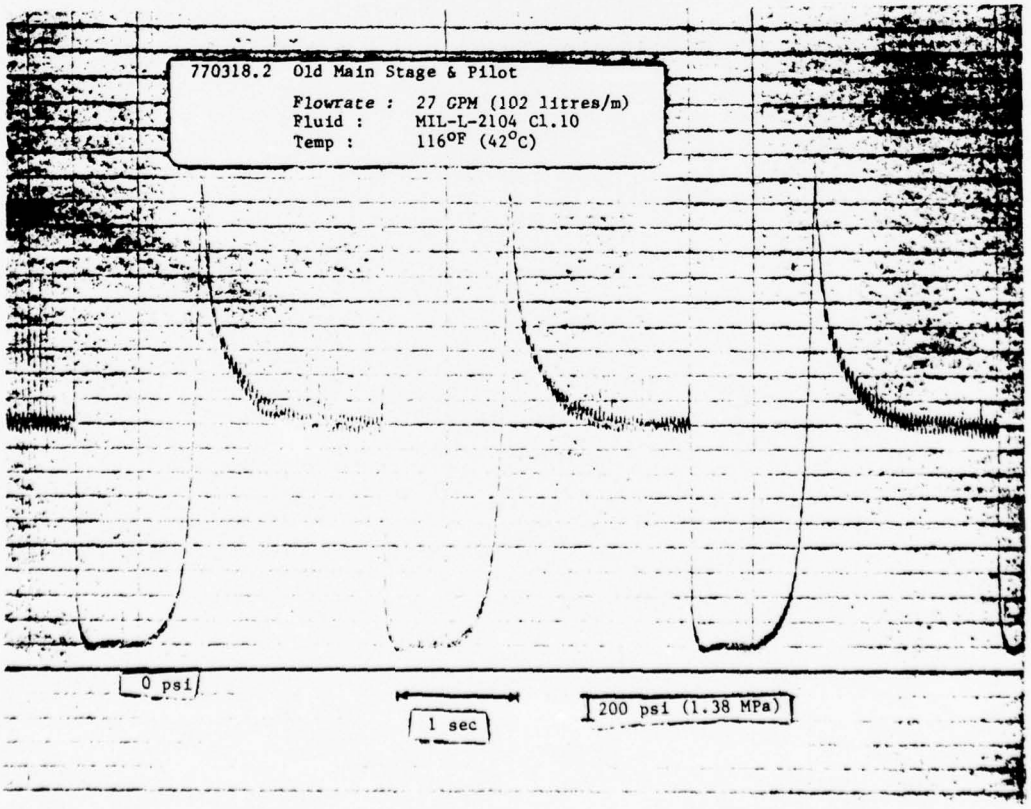


Fig. 3-11. Pressure Wave Form for "Old" Valve at Rated Flow

It is instructive to examine how cumulative data, such as that acquired by the Statistical Analog Monitor or equivalent devices, portray the change in performance due to degraded pilot and main stages. Tables 3-3 through 3-5 present the time above pressure and number of crossings for eight pressure levels, just as they would be obtained from the Statistical Analog Monitor. It is seen that the cumulative data do not differ appreciably when the main stage only is degraded but deviate significantly when the pikot stage is degraded. Hence, it is concluded that, for the design of valve tested, degradation of the pilot stage is more readily evidenced in cumulative data than that of the main stage. Since in actual practice degradation of a valve in the field entails changes in both the pilot and main stages, cumulative data can be used to discriminate between new and degraded valves, provided bench-mark profiles have been established.

TABLE 3-3. Cumulative Data on Cycling Tests

VALVE I.D.: D1 WITH "NEW" MAIN STAGE & "NEW" PILOT

HIGH FLOW CYCLING

Pressure		Fraction of Time Level Is Exceeded Per Cycle	Number of Upward Crossings Per Cycle
PSI	MPa		
200	1.379	53 %	1
500	3.449	41 %	1
1000	6.897	37 %	1
1500	10.345	35 %	1
2000	13.794	27 %	1
2500	17.242	0 %	0
3000	20.69	0 %	0
3500	24.139	0 %	0

VALVE I.D.: D1 WITH "NEW" MAIN STAGE & "NEW" PILOT

LOW FLOW CYCLING

Pressure		Fraction of Time Level Is Exceeded Per Cycle	Number of Upward Crossings Per Cycle
PSI	MPa		
200	1.379	42 %	1
500	3.449	35 %	1
1000	6.897	32 %	1
1500	10.345	29 %	1
2000	13.794	25 %	1*
2500	17.242	0 %	0
3000	20.69 *	0 %	0
3500	24.139	0 %	0

* These are average values based on observed waveform.

TABLE 3-4.

VALVE I.D.: D1 WITH "OLD" MAIN STAGE & "NEW" PILOT
HIGH FLOW CYCLING

Pressure		Fraction of Time Level Is Exceeded Per Cycle	Number of Upward Crossings Per Cycle
PSI	MPa		
200	1.379	59%	1
500	3.449	45%	1
1000	6.89	39%	1
1500	10.345	38%	1
2000	13.794	34%	1
2500	17.242	0%	0
3000	20.69	0%	0
3500	24.139	0%	0

VALVE I.D.: D1 WITH "OLD" MAIN STAGE & "NEW" PILOT
LOW FLOW CYCLING

Pressure		Fraction of Time Level Is Exceeded Per Cycle	Number of Upward Crossings Per Cycle
PSI	MPa		
200	1.379	47%	1
500	3.449	34%	1
1000	6.89	30%	1
1500	10.345	28%	1
2000	13.794	26%	1*
2500	17.242	0%	0
3000	20.69	0%	0
3500	24.139	0%	0

* These are average values based on observed waveforms.

TABLE 3-5.

VALVE I.D.: D1 WITH "OLD" MAIN STAGE AND PILOT
LOW FLOW CYCLING

Pressure		Fraction of Time Level Is Exceeded Per Cycle	Number of Upward Crossings Per Cycle
PSI	MPa		
200	1.379	74 %	1
500	3.449	63 %	1
1000	6.897	58 %	1
1500	10.345	56 %	1
2000	13.794	0 %	0
2500	17.242	0 %	0
3000	20.69	0 %	0
3500	24.139	0 %	0

VALVE I.D.: D1 WITH "OLD" MAIN STAGE AND PILOT
HIGH FLOW CYCLING

Pressure		Fraction of Time Level Is Exceeded Per Cycle	Number of Upward Crossings Per Cycle
PSI	MPa		
200	1.379	98 %	1
500	3.449	66 %	1
1000	6.897	65 %	1
1500	10.345	63 %	1
2000	13.794	57 %	1
2500	17.242	11 %	1
3000	20.69	5 %	1
3500	24.139	2 %	1

CHAPTER IV

FIELD DATA INTERPRETATIONS

INTRODUCTION

The assessment of performance degradation of hydraulic system components is of vital importance to equipment users. Examples of such degradation are:

(i) a pump losing its output flow for a given speed and pressure, due to increase of slip flow,

(ii) a relief valve cracking at a lower pressure than the original setting, and

(iii) a hydraulic cylinder moving slower than designed for, due to internal leakage.

A major cause of component degradation is contaminant wear. It is usually possible to assess the extent of such wear by disassembling the component. However, such a procedure is not always practicable or desirable, and hence, the need for non-intrusive diagnostics (i.e., methods of assessing component degradation without disturbing the system). In principle this can be done by installing transducers at selected locations in the hydraulic system and monitoring pertinent variables. The task of selecting the quantities to be monitored, locating the sites for transducer installation and interpreting the data requires analysis of the specific system and cannot be discussed in general terms. However, it is possible to deduce conclusions as to the operational severity of a specific task or mix of tasks from such data. Chapter III presented results on operational severity assess-

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ment of a type of component (i.e., relief valves) under laboratory conditions. The remainder of this chapter will present interpretation of test data acquired on actual machines doing different tasks or mix of tasks. The data was acquired by Statistical Analog Monitors (STAM) which were developed by the Fluid Power Research Center, Oklahoma State University, for storing cumulative data from electrical analog signals of a variety of transducers [1, 2, 7]. Details of data collection can be found in Section IV of this report. The first set of data pertains to a backhoe loader system while the second pertains to a wheeled tractor assigned for various tasks.

BACKHOE LOADER SYSTEM

Pump delivery pressure, swash plate angle and outlet temperature were the parameters measured on a closed center backhoe loader hydraulic system. STAM units for each parameter were capable of measuring time above level for eight levels. Duration of data acquisition was 90 hours for the first set, which included 74 hours of operation as a loader and 16 hours as a backhoe. For the other two data sets, test duration was 100 hours, with 50 hours each of backhoe and loader operation for the second, and 40 hours loader and 60 hours backhoe operation for the third. Tables 4-1a, 4-1b and 4-1c include data as read off the STAM units installed on the system. For purposes of comparison, data has been normalized and presented in Table 4-2 and Figs. 4-1 through 4-3. Normalization is performed by dividing the time above a level by the total test duration. Histograms convert the cumulative data into range data and depict the level of the parameter at eight or less discrete steps, which may be unequal. It should be noted that if the lowest level does not have a 100% reading, the shortfall has to be assigned to a transducer output of zero. Such is the case in the pressure data on all three operational cycles, and hence,

TABLE 4-1a. Data Sheet - Operational Cycle #1

Cycle Description: Loader Operation 74 hrs
Backhoe Operation 16 hrs

Parameter: Pressure

Transducer Location: Pump Outlet

Channel	Level (psi)	Time (hrs)
1	158	80.5
2	560	36.9
3	952	34.6
4	1,352	28.9
5	1,752	28.2
6	2,168	23.8
7	2,552	21.4
8	2,944	21.4

Parameter: Angle

Transducer Location: Pump Swash Plate

Channel	Level (degrees)	Time (hrs)
1	1.13	132.6
2	3.09	132.3
3	5.0	60.5
4	6.91	57.2
5	8.87	57.1
6	10.78	54.5
7	12.7	45.5
8	14.65	1.5

TABLE 4-1b. Data Sheet - Operational Cycle #2

Cycle Description: Loader Operation 50 hrs
Backhoe Operation 50 hrs

Parameter: Pressure

Transducer Location: Pump Outlet

Channel	Level (psi)	Time (hrs)
1	117.7	88.6
2	510.1	30.4
3	894.6	22.9
4	1,279.0	18.6
5	1,663.0	13.7
6	2,048.0	10.2
7	2,432.0	7.2
8	2,817.0	3.0

Parameter: Angle

Transducer Location: Pump Swash Plate

Channel	Level (psi)	Time (hrs)
1	1.5	100
2	3.3	100
3	5.2	100
4	7.1	100
5	9.0	100
6	10.9	98.1
7	12.8	75.1
8	14.7	52.1

TABLE 4-1c. Data Sheet - Operational Cycle #3

Cycle Description: Loader Operation 40 hrs
Backhoe Operation 60 hrs

Parameter: Pressure

Transducer Location: Pump Outlet

Channel	Level (psi)	Time (hrs)
1	158.0	61.8
2	560.0	42.7
3	952.0	40.6
4	1,352.0	36.2
5	1,752.0	32.8
6	2,168.0	25.8
7	2,552.0	18.6
8	2,944.0	17.3

Parameter: Angle

Transducer Location: Pump Swash Plate

Channel	Level (degrees)	Time (hrs)
1	1.1	100
2	3.1	100
3	5.0	100
4	6.9	100
5	8.0	100
6	10.8	100
7	12.7	96.2
8	14.7	72.9

TABLE 4-2. Cumulative Data for 100 Hour Operation of a Backhoe Loader

Pressure (bars)	Percent of Total Time Spent at Value for Operational Cycle		
	1	2	3
0	19.5	11.4	38.2
11.0	43.6	58.2	19.1
38.6	2.3	7.5	2.3
65.7	5.7	4.5	6.2
93.3	0.7	4.7	1.4
121.0	4.4	3.5	7.0
150.0	2.4	3.0	7.4
176	0	4.2	1.1
203	21.4	3.0	17.3

Swash Plate Angle (degrees)	Percent of Total Time Spent at Value for Operational Cycle		
	1	2	3
3	55	0	0
5	2	0	0
9	2	2	0
11	7	23	4
13	33	23	23
5	1	52	73

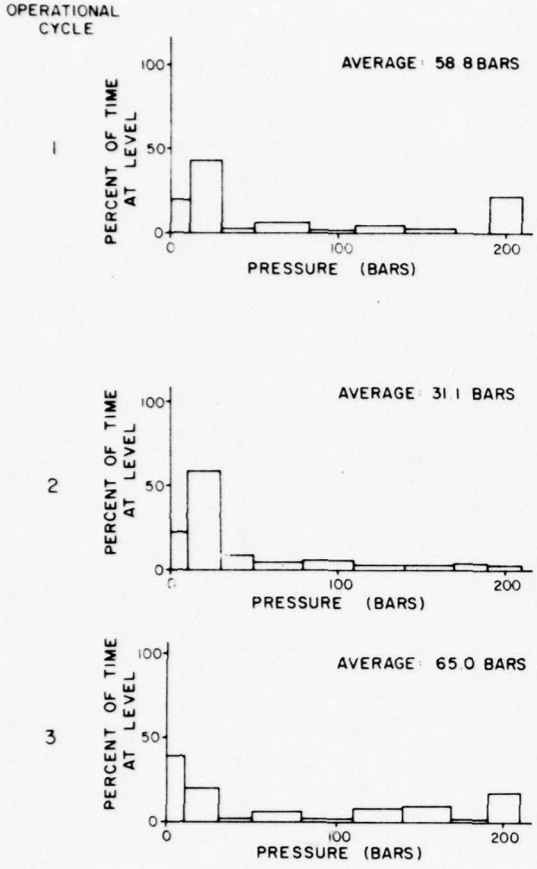


Fig. 4-1. Histograms for Pump Outlet Pressure for Three Operational Cycles

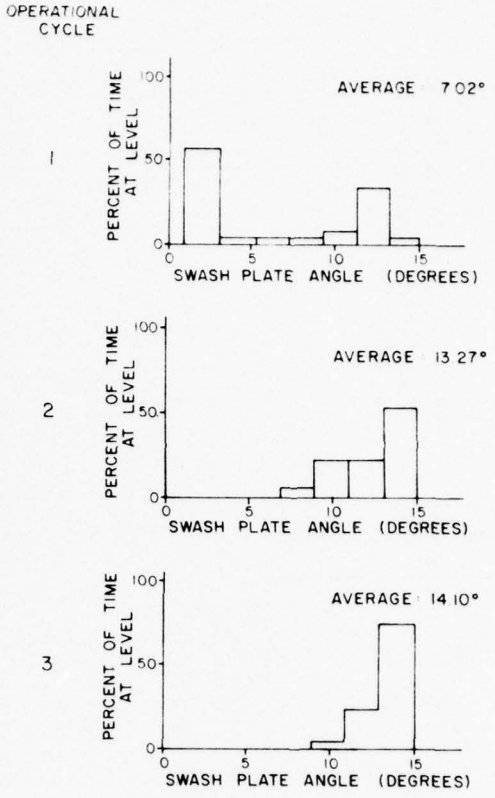


Fig. 4-2. Histograms for Swash Plate Angle for Three Operational Cycles

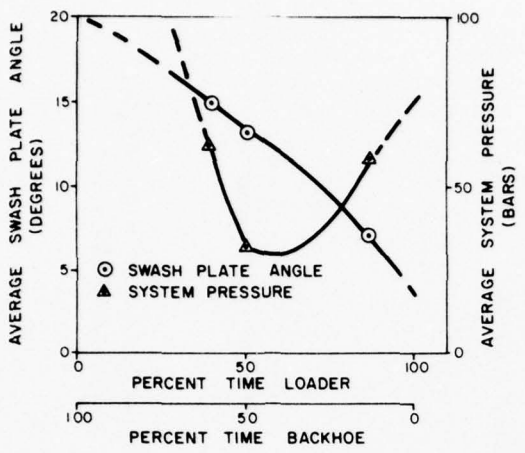


Fig. 4-3. Average Pressures and Swash Plate Angle for Different Mixes of Tasks

the inclusion of zero as a level in the pressure data in Table 4-2 and Fig. 4-1.

From the above mentioned table and figure, it is seen that Operational Cycle #2 shows a substantially lower average pressure than Cycles #1 and #2. It is also seen that in the latter two cycles, a substantial fraction of time is spent at 2940 psi (203 bars). From Fig. 4-2 it is seen that as the fraction of time the machine performs as a backhoe increases the average flow demand increases, as evidenced by the trend of the swash plate angle.

From the data on pump outlet pressure and swash plate angle, the change in mean values of these parameters, as the mix of tasks changes, can be plotted as shown in Fig. 4-3. If the pump is assumed to rotated at constant speed, the pump delivery can be considered proportional to the swash plate angle, and consequently, the product of the average pressure and the average swash plate angle is a good approximation to the average output hydraulic power. Figure 4-4 is a plot of this power, normalized for a 50:50 task mix (i.e., the power is taken to be unity when

the machine works as a loader 50% of the time and a backhoe for the remaining 50%). It is seen that operation of the machine as a backhoe is more severe from an energy standpoint than usage as a loader.

It needs to be emphasized that all data were collected during controlled tests and the conclusions drawn above are valid for operating conditions which resemble the test conditions. Deviation from the latter could result in significantly different test data.

TRACTOR SYSTEM

Tables 4-3 and 4-4 present data collected by STAM on a tractor system engaged in two different tasks. Pressures were measured at the pump outlet as well as an actuator. The data illustrates the need for selecting the location of transducers carefully. Thus, in both cycles the fractions of total time spent by pump pressure above 29.42 bars is significant, whereas for cylinder pressure the valve is much less. Consequently, pump delivery pressure measurement would not give a true picture of the severity to which the cylinder is being subjected. In the case of Cycle #2, the counts for the pump pressure are significantly higher than for the cylinder pressure. Pump ripple would be part of the explanation. It should be noted that the STAM has a round-off error which results in a very small number being read as zero. This is the explanation for the zero counts for cylinder pressure in Cycle #2 even though the machine has spent a finite time above each pressure level. Another inference from Table 4-4 is that the time above a pressure of 62.35 bars is probably due to a large transient which exceeds 258 bars (3740 psi). Such periodic transients would result in cumulative time at all intermediate levels but would show

TABLE 4-3. Tractor Pump Pressure Cumulative Data for Two Different Operational Duty Cycles

Pressure Level		Cycle #1		Cycle #2	
PSI	BARS	Fraction of Time Level is Exceeded	Counts	Fraction of Time Level is Exceeded	Counts
60.3	4.16	100 %	0	99 %	169,823
426.5	29.42	25 %	210,000	21 %	373,800
787.0	54.3	2.7 %	30,066	4.0 %	
1154.0	79.6	1.4 %	3,482	2.0 %	31,212
1515.0	104.5	0.9 %	0	1.0 %	13,330
1882.4	129.8	0.9 %	0	1.0 %	4,534
2242.7	154.7	0.7 %	0	1.0 %	4,799
2603.0	179.5	0.5 %	0	0.3 %	0

Cycle #1 Duration - 103.9 hrs

Cycle #2 Duration - 65.7 hrs

TABLE 4-4. Cylinder Pressure Cumulative Data for Two Different Operational Duty Cycles

Pressure Level		Cycle #1		Cycle #2	
PSI	BARS	Fraction of Time Level is Exceeded	Counts	Fraction of Time Level is Exceeded	Counts
433	29.9	2.6 %	26,292	3.0 %	66,430
904	62.35	2.1 %	10,333	0.76 %	0
1,375	94.83	1.3 %	3,999	0.61 %	0
1,846	127.3	1.2 %	0	0.61 %	0
2,317	159.8	0.8 %	0	0.61 %	0
2,789	192.4	0.8 %	0	0.61 %	0
3,269	225.4	0.8 %	0	0.61 %	0
3,740	258.0	0.8 %	0	0.61 %	0

Cycle #1 Duration - 103.9 hrs

Cycle #2 Duration - 65.7 hrs

an identical count for the number of crossings.

Figures 4-5 and 4-6 present histograms of system temperature for four different operating conditions. Since the tractor was performing two types of jobs for each data set, it is not possible to use this data to develop typical temperature profiles for each kind of task. It is, however, seen that Operational Cycle #2 not only results in the highest temperature attained but also the highest mean temperature. Additional data on ambient conditions and power input and output are needed before an assessment of thermal behavior of the system can be done.

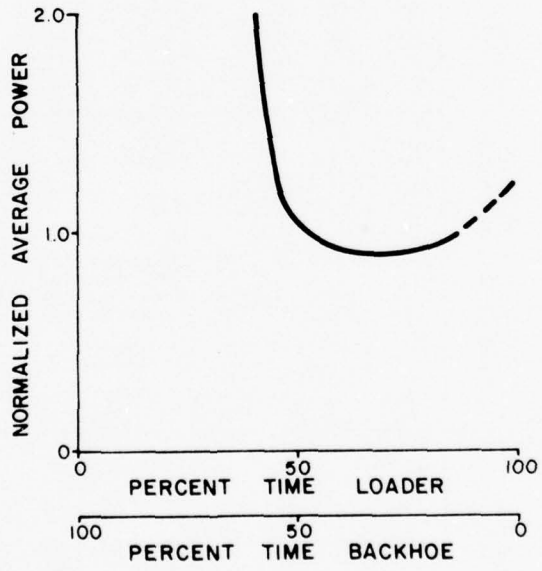


Fig. 4-4. Normalized Average Power for Different Mixes of Tasks

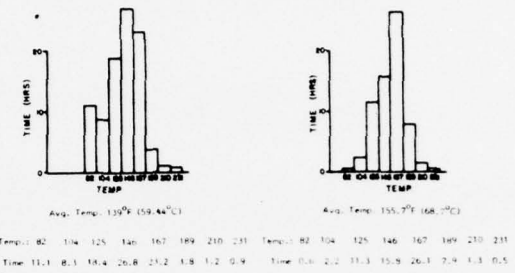


Fig. 4-5. Histograms for System Temperature for Operational Cycles #1 and #2

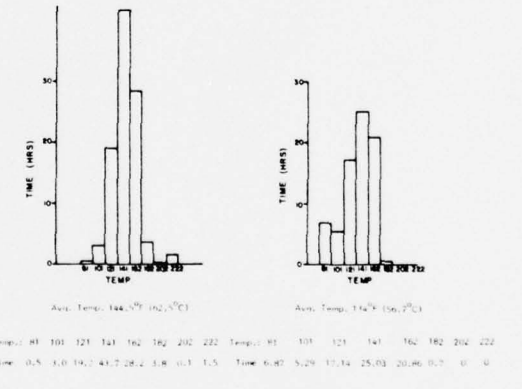


Fig. 4-6. Histograms for System Temperature for Operational Cycles #3 and #4

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Hydraulic system components are subject to degradation, primarily as a result of contaminant wear. It is often impractical or undesirable to dismantle systems in the field to examine the state of system components and take remedial action. Since component degradation is manifested as a change in operational performance parameters, a monitoring of the latter, in principle, permits one to assess the state of any component. The continuous monitoring and recording of system parameters as a machine operates in the field is rarely feasible due to technical or economic reasons. To alleviate this situation the Fluid Power Research Center, Oklahoma State University, developed a Statistical Analog Monitor (STAM) to record cumulative data. Since such data cannot, by themselves, be used to generate time-histories of the various parameters over the period of data acquisition, alternative schemes of data acquisition and alternative schemes of interpretation had to be developed. These techniques depend on mathematical models in simulating operational severity has been explained in Chapter II. The chapter also indicates how modeling can be used to predict the effect of changing components on a given system. The subsequent chapter has presented experimental work which reveals the effect of contaminant wear on operational performance of a component. Typical field data collected on machines operating under controlled conditions has been presented in Chapter IV.

This phase of the reliability project has demonstrated the importance of

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mathematical analysis of a system in order to evolve a rational non-intrusive diagnostic method based on field data. The interpretation of such data depends crucially on a thorough analysis of the system. Even the installation of sensors for measuring physical variables and STAM threshold settings should be based on such analysis.

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13. ABSTRACT

This report presents the data obtained from the On-Board Monitor activities. These data are a result of endeavors on two projects--On-Board Monitor and Operational Severity. STAM units were installed on a variety of vehicles. As many as five parameters per vehicle were monitored with several tests repeated with multiple runs.

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12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring *(paying for)* the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS)*, *(S)*, *(C)*, or *(U)*.

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.

SECTION IV

ON-BOARD MONITOR STUDY

Project Staff

R. L. Decker, Program Manager
M. T. Yokley, Project Engineer
T. Herron, Project Assistant

FOREWORD

This section presents the data obtained from the On-Board Monitor activities. These data are a result of endeavors on two projects--On-Board Monitor and Operational Severity. As many as five Statistical Analog Monitor (STAM) units were installed on a single vehicle measuring a variety of parameters. Some of the tests were repeated on the same vehicle.

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CHAPTER I

INTRODUCTION

The Statistical Analog Monitor is a device developed to obtain long-term information regarding the operation of hydraulic systems in actual field environments. It is a small, low-cost device ideally suited for installation on mobile equipment. The device operates unattended while gathering information, typically in 100-hour tests. The theory of operation, design, and data reduction techniques are discussed in previous reports.

A cooperative program was initiated in 1974 involving 15 major companies which are producers of mobile equipment similar to the type utilized by the U.S. Army. This was directed primarily toward obtaining temperature and pressure characteristics of hydraulic systems on construction equipment. A report of the results of this program through January, 1975, is contained in Ref. [1]. At that time several units were still in the field. Rather than recall these units and possibly invalidate tests, the STAM monitors were allowed to remain in the field.

This report documents the results obtained from activities utilizing the STAM during this year. Two projects utilized the STAM this year. The On-Board Monitor Project is a continuation of the cooperative program previously initiated. The Operational Severity Project utilized the STAM to collect data to be used for assessing the operational severity. The interpretation of these results is contained in Section II of this report.

CHAPTER II

DATA ACQUISITION

The scope of the programs for this year required that two activities be simultaneously pursued. The STAM units in the field at the time of the completion of the cooperative program were to be allowed to complete the tests. These units were, then, to be interrogated and reconditioned. In addition, sponsorship for a program involving a concentrated acquisition effort required for operational severity assessment was to be obtained.

Units which were returned from companies participating in the cooperative program were interrogated and recalibrated. Many of these companies had been active through the entire program. In order to broaden the data base, units were returned to selected companies. These companies had demonstrated an aggressive role in the utilization of the STAM monitor for the acquisition of information. During the year, several of these companies incorporated the STAM into an integral part of their own programs.

Sponsorship for acquisition efforts was solicited and obtained. An extensive program to obtain a large amount of information about specific machines was initiated. As many as five STAM units were installed on a single vehicle. Tests were run with the machine in a typical field environment. Runs were made to obtain repeatability of results. Also tests were run to investigate the effect of altering the machines work cycle. This was performed on several different vehicles, some of which were

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of similar model. Because of the commonalities existing between the hydraulic systems, both industrial equipment and agricultural tractors were allowed.

During the year, more than 45 units were shipped. Companies participating included the following:

Allis-Chalmers

Massey-Ferguson

Bucyrus-Erie

International Harvester

J. I. Case

Eaton

In addition, units were supplied to various areas within MERADCOM. The reliability of the STAM was excellent during this program with only one electronic failure occurring. Previous reports documented logistical and technical problems associated with the STAM system. The two important ones are damaged cables and tranducer as a result of abuse and electromagnetic interference (EMI) susceptibility. During this year, the first of these has not been prevalent while the latter was only a problem in isolated cases. These cases have been readily identified and only exist on certain vehicles. Experience has shown that vehicles utilizing solenoids are a particular problem.

Appendix A catalogs selected results from these activities. Some of the data have been marked with a vehicle numerical designation. In these cases an alphabetic suffix has been added to distinquish individual tests. Section II of this report contains interpretations of these results. A few additional comments are in order regarding the data obtained from the STAM. The following paragraphs discuss several of these.

The STAM monitor is an analog process. The accuracy of the STAM is a function of several factors including transducer accuracy, internal scaling, changes in internal scaling caused by time, changes in internal scaling caused by temperature, and read-out accuracy. An overall accuracy of one percent of full scale for the entire system (including accuracy of all intermediate processes as a result of all factors) would be considered excellent with a five percent accuracy considered good.

The evaluation of the data must include considering the uncertainities associated with the data. The standard scaling for the STAM is 100 hours and 75,000 counts full scale. Assuming a one percent accuracy, uncertainties of ± 1 hour and ± 750 counts exist in the data.

An often overlooked aspect in evaluating the data is considering the physical location of the transducers in the system. A pressure transducer mounted directly on the outlet of a pump will result in the pump ripple affecting the data--both time above level and counts. If the transducer has been installed at the end of the line which had the net effect of attenuating this ripple, the data could possibly be significantly different. The "correct" location of the transducer will be dependent on the needs of a particular application. Test setups which count pump ripple may only provide little information about the actual work of the pump.

The evaluation of the data presented in Appendix A should be performed with an awareness of these considerations. The data have been rounded to the nearest hour and to the nearest 1,000 counts. The uncertainities associated with the data result in the possibility of zero time with a non-zero number of counts at a given level.

CHAPTER III

SUMMARY AND CONCLUSIONS

During this year technical and logistical support was provided in order to receive late returns from the cooperative program. Several units initially committed during the program were returned to the field in order to increase data bases. Units were supplied to satisfy the needs of several areas within MERADCOM.

During this year support for the program was solicited and obtained. Extensive investigations were performed on several vehicles. The results of this were excellent. Many of the previous logistical problems were solved as a result of the format of this program. Participants demonstrated an active and aggressive role which resulted in a mutually beneficial program.

The STAM has, in the past, demonstrated its importance in gathering long-term information about hydraulic systems. The results from this year reinforce these conclusions. The STAM has been utilized reliably to obtain information needed for the evaluation of the operation of vehicles in field environments. STAM has, indeed, been accepted by industry as demonstrated by the financial support it has received this year.

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APPENDIX A

SELECTED RESULTS

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DATA SHEET

DATE: May, 1976 UNIT NO.: 1094

COMPANY: D

UNIT TYPE: Pressure

APPLICATION: *(Type of Vehicle and Location of Sensors)*

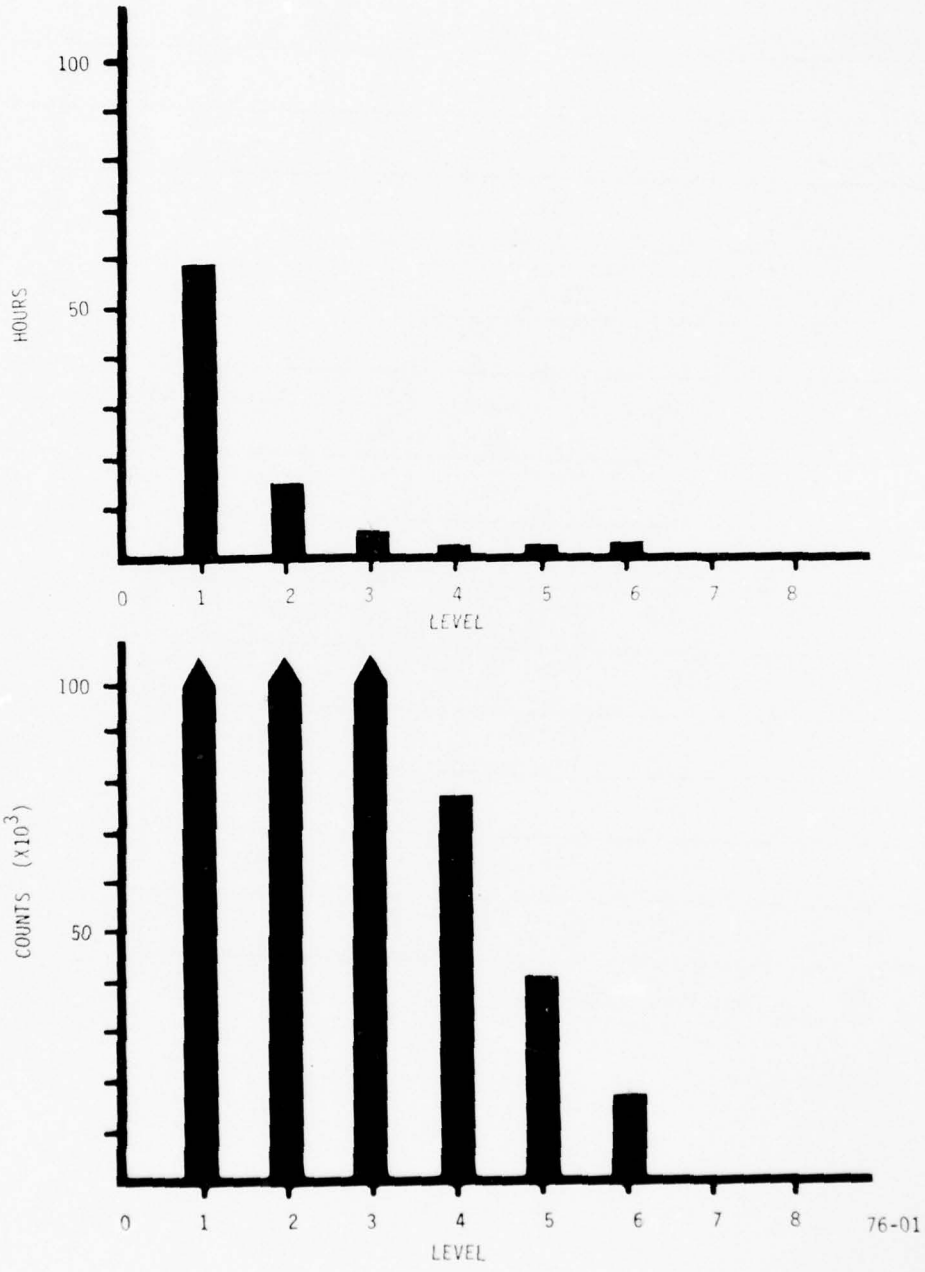
Ag Tractor - Steering and Clutch Pressure
Open Center with Low Pressure Regulator

CHANNEL	LEVEL (PSI)	TIME (HRS.)	COUNTS
1	170	57	>210,000
2	520	14	>210,000
3	880	3	>210,000
4	1240	1	76,000
5	1600	1	40,000
6	1960	1	16,000
7	2320	0	0
8	2690	0	0

90 (Hrs.) Total Operation Time

REMARKS: Vehicle No. 1-A 76-1

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100
50
HOURS
0
1
2
3
4
5
6
7
8
LEVEL
100
50
COUNTS (X10^3)
0
1
2
3
4
5
6
7
8
LEVEL
76-01

DATA SHEET

DATE: May, 1976 UNIT NO.: 1094

COMPANY: D

UNIT TYPE: Pressure

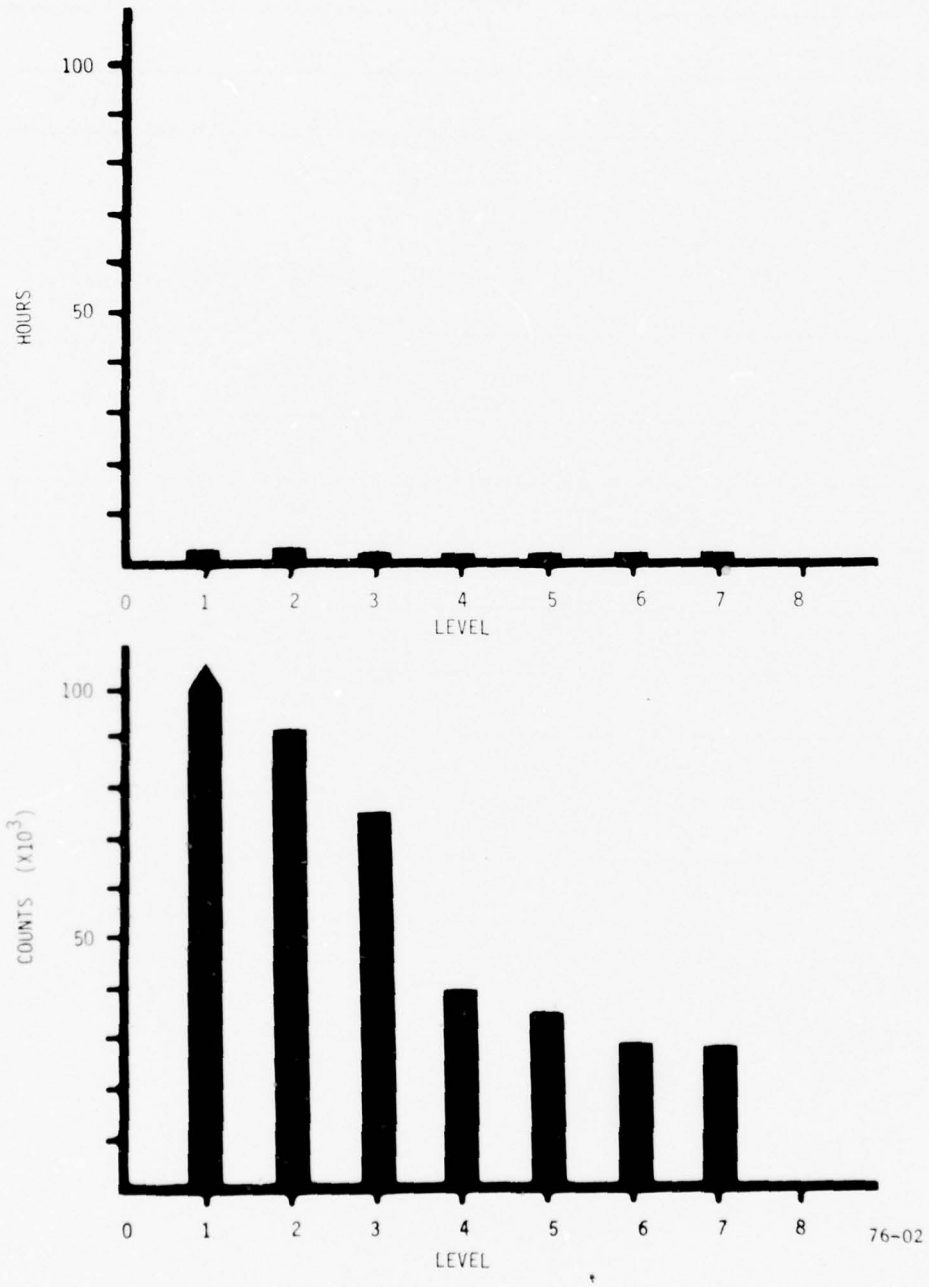
APPLICATION: *(Type of Vehicle and Location of Sensors)*

Ag Tractor – Hitch Pressure
Hitch Automatically Adjusting for Constant Draft Load

CHANNEL	LEVEL	TIME (HRS.)	COUNTS
1	400	2	144,000
2	710	2	91,000
3	1010	1	75,000
4	1320	0.5	39,000
5	1630	0.5	34,000
6	1940	0.5	27,000
7	2250	0.5	27,000
8	2550	0	0

90 (Hrs.) Total Operation Time

REMARKS: Vehicle No. 1-A 76-2


100
50
HOURS
0
1
2
3
4
5
6
7
8
LEVEL
100
50
COUNTS (X10^3)
0
1
2
3
4
5
6
7
8
LEVEL
76-02

DATA SHEET

DATE: May, 1976 UNIT NO.: 1080

COMPANY: D

UNIT TYPE: Temperature

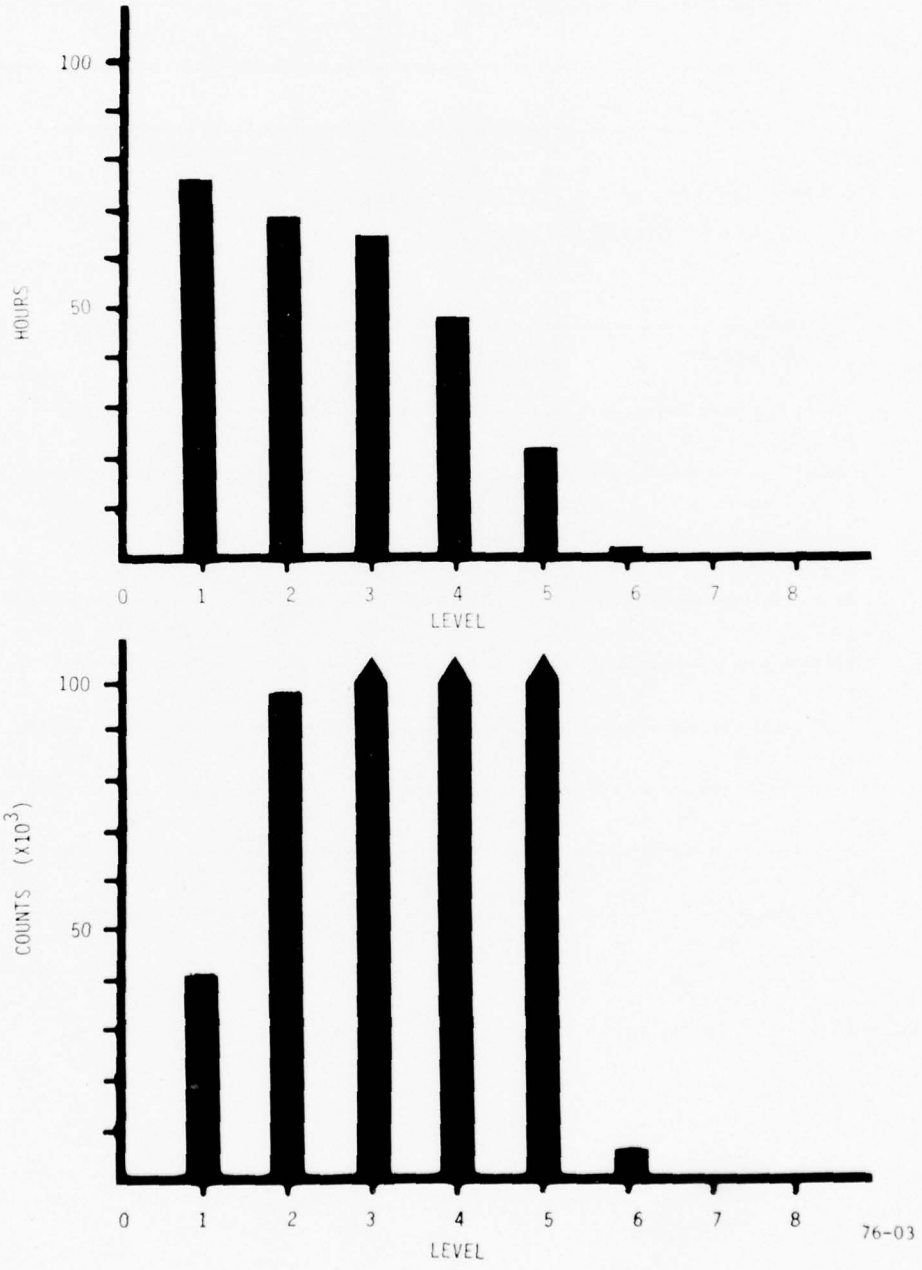
APPLICATION: *(Type of Vehicle and Location of Sensors)*

Ag. Tractor – Reservoir Temperature

CHANNEL	LEVEL	TIME (HRS.)	COUNTS
1	81	76	41,000
2	101	69	99,000
3	121	64	145,000
4	141	47	173,000
5	162	22	183,000
6	182	1	3,000
7	202	0	0
8	222	0	0

90 (Hrs.) Total Operation Time

REMARKS: Vehicle No. 1-A 76-3


100
50
HOURS
0
1
2
3
4
5
6
7
8
LEVEL
100
50
COUNTS (X10^3)
0
1
2
3
4
5
6
7
8
LEVEL
76-03

DATA SHEET

DATE: May, 1976 UNIT NO.: 1080

COMPANY: D

UNIT TYPE: Pressure

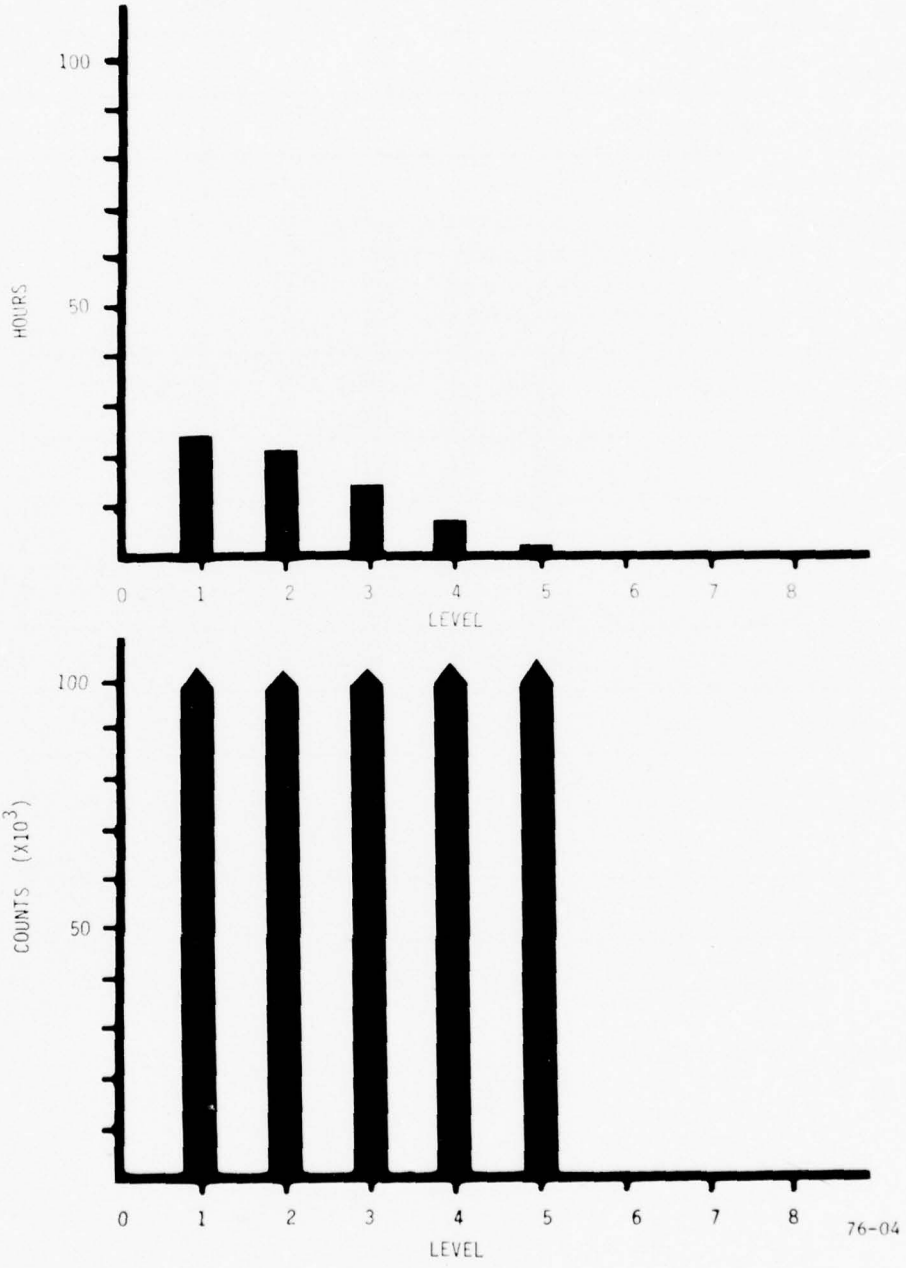
APPLICATION: *(Type of Vehicle and Location of Sensors)*

Ag Tractor – Auxiliary Hydraulic System
Valve Outlet Pressure
Various Operations

CHANNEL	LEVEL (PSI)	TIME (HRS.)	COUNTS
1	570	23	>210,000
2	970	21	>210,000
3	1380	14	>210,000
4	1780	8	>210,000
5	2180	1	145,000
6	2600	0	0
7	3000	0	0
8	3410	0	0

90 (Hrs.) Total Operation Time

REMARKS: Vehicle No. 1-A 76-4


100
50
HOURS
0
1
2
3
4
5
6
7
8
LEVEL
100
50
COUNTS (X10^3)
0
1
2
3
4
5
6
7
8
LEVEL
76-04

DATA SHEET

DATE: July, 1976 UNIT NO.: 1080

COMPANY: D

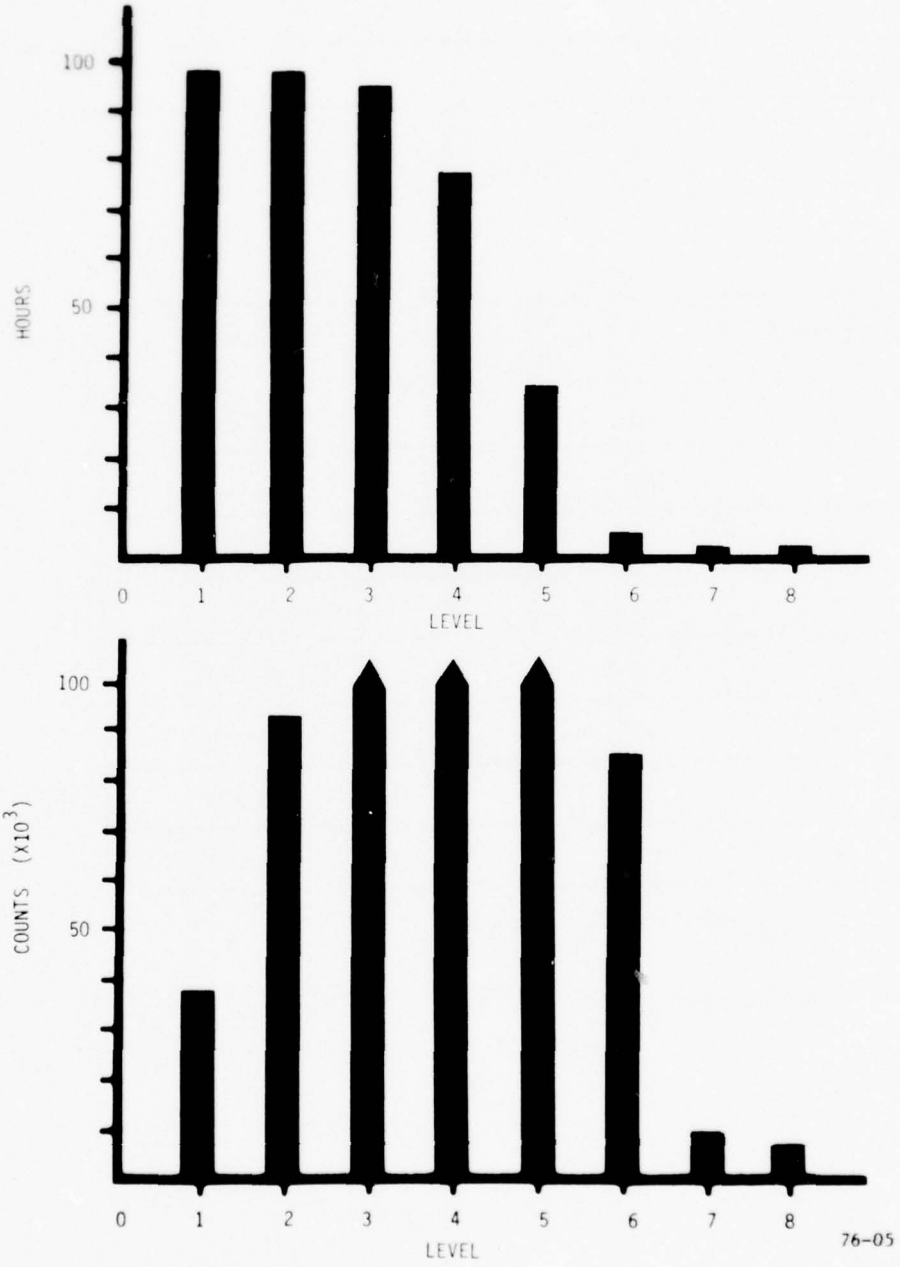
UNIT TYPE: Temperature

APPLICATION: *(Type of Vehicle and Location of Sensors)*

CHANNEL	LEVEL	TIME (HRS.)	COUNTS
1	81	99	38,000
2	101	99	93,000
3	121	97	119,000
4	141	77	>210,000
5	162	34	>210,000
6	182	5	86,000
7	202	2	10,000
8	222	2	8,000

100 (Hrs.) Total Operation Time

REMARKS: Vehicle No. 1-B 76-5


100
50
HOURS
0
1
2
3
4
5
6
7
8
LEVEL
100
50
COUNTS (X10^3)
0
1
2
3
4
5
6
7
8
LEVEL
76-05

DATA SHEET

DATE: July, 1976 UNIT NO.: 1080

COMPANY: D

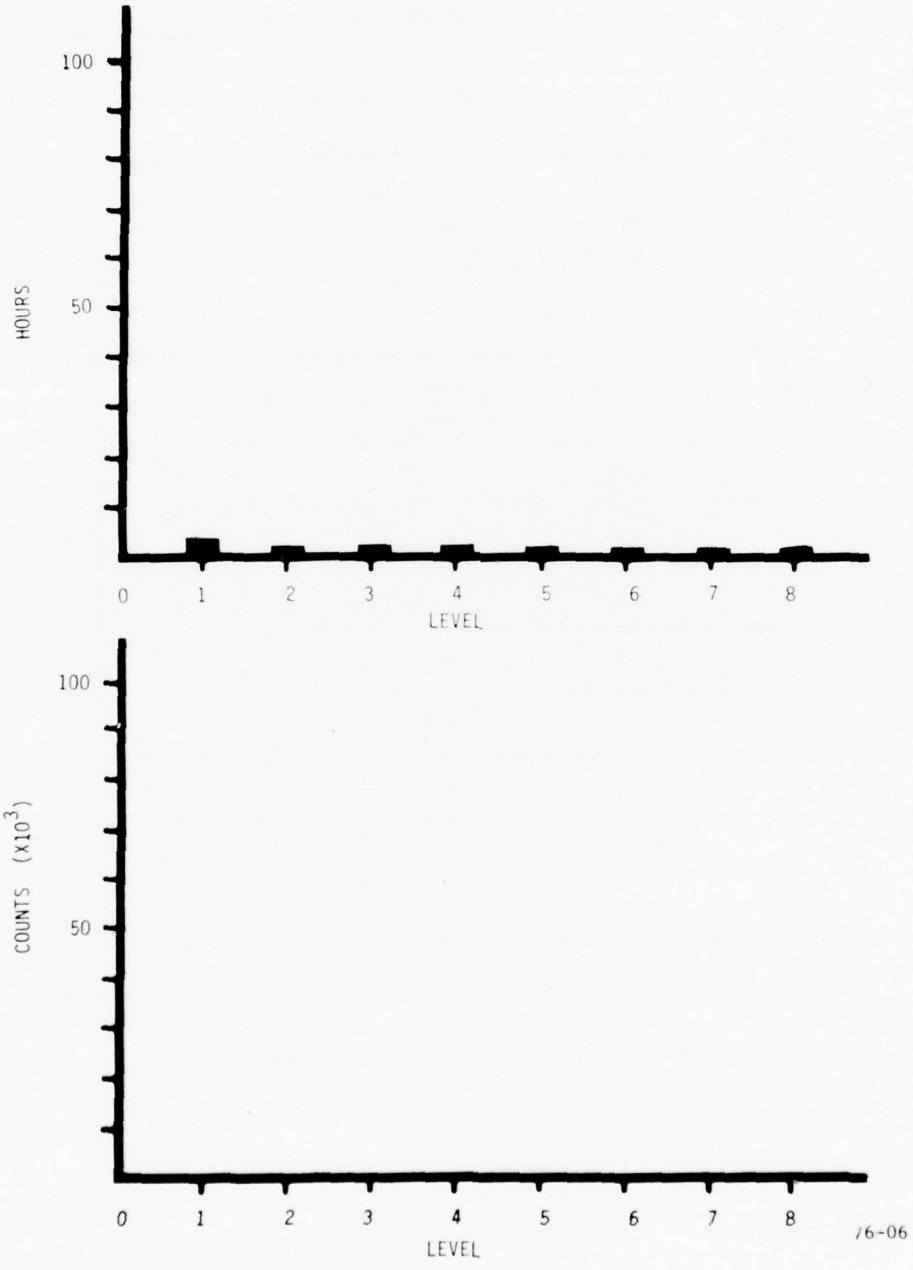
UNIT TYPE: Pressure

APPLICATION: *(Type of Vehicle and Location of Sensors)*
Ag Tractor – Hitch Cylinder Pressure

CHANNEL	LEVEL	TIME (HRS.)	COUNTS
1	470	2	≈0
2	960	1	0
3	1440	1	0
4	1930	1	0
5	2400	1	0
6	2910	1	0
7	3400	1	0
8	3880	1	0

100 (Hrs.) Total Operation Time

REMARKS: Vehicle No. 1-B 76-6


100
50
HOURS
0
1
2
3
4
5
6
7
8
LEVEL
100
50
COUNTS (X10^3)
0
1
2
3
4
5
6
7
8
LEVEL
76-06

DATA SHEET

DATE: July, 1976 UNIT NO.: 1094

COMPANY: D

UNIT TYPE: Pressure

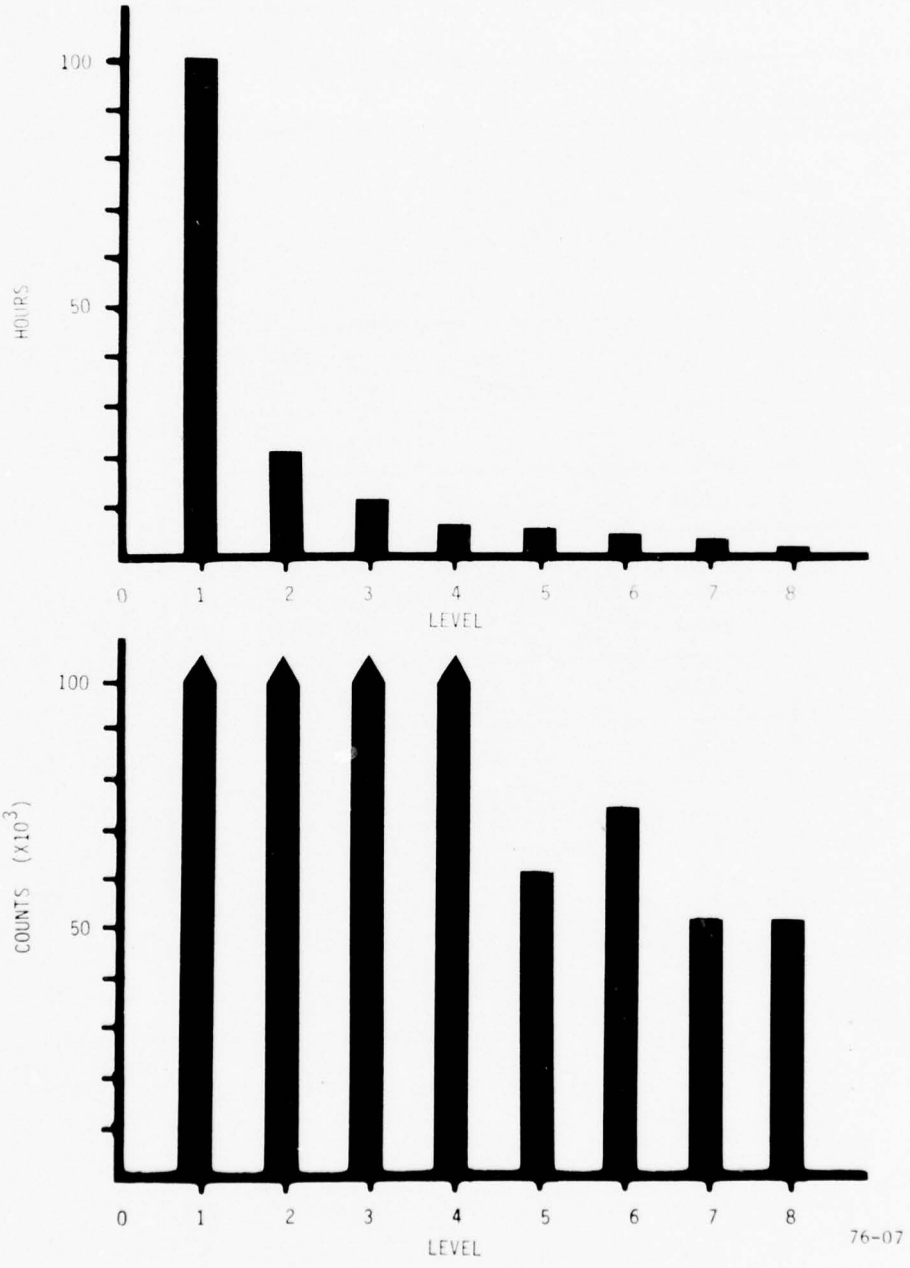
APPLICATION: *(Type of Vehicle and Location of Sensors)*

Ag Tractor – Auxiliary Pump Pressure

CHANNEL	LEVEL	TIME (HRS.)	COUNTS
1	50	100	>210,000
2	420	21	>210,000
3	790	11	208,000
4	1160	7	155,000
5	1520	6	61,000
6	1880	4	74,000
7	2250	3	52,000
8	2620	1	51,000

100 (Hrs.) Total Operation Time

REMARKS: Vehicle No. 1-B 76-7


100
50
HOURS
0
1
2
3
4
5
6
7
8
LEVEL
100
50
COUNTS (X10^3)
0
1
2
3
4
5
6
7
8
LEVEL
76-07

DATA SHEET

DATE: July, 1976 UNIT NO.: 1094

COMPANY: D

UNIT TYPE: Pressure

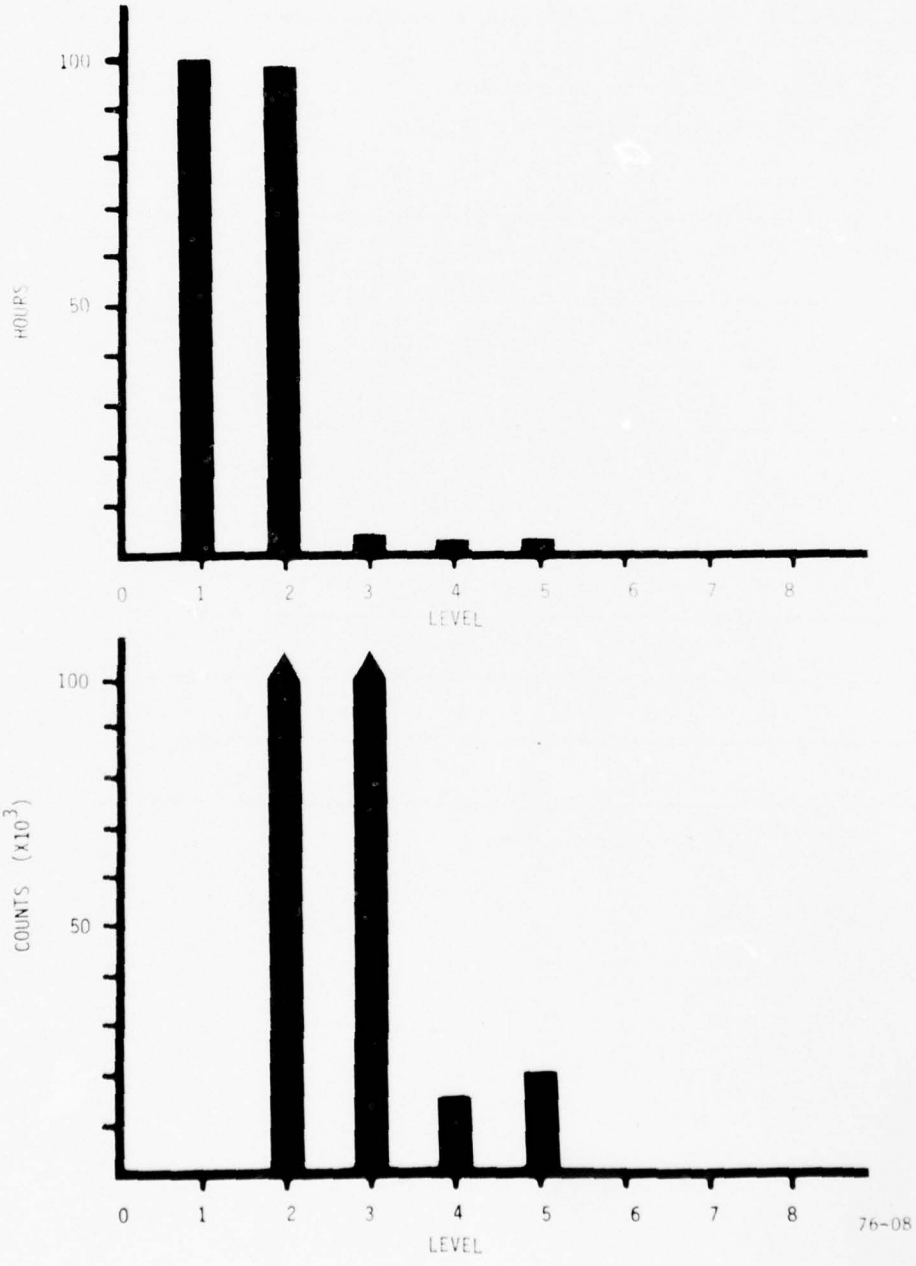
APPLICATION: *(Type of Vehicle and Location of Sensors)*

Ag Tractor – Steering and Clutch Pump

CHANNEL	LEVEL (PSI)	TIME (HRS.)	COUNTS
1	10	100	0
2	320	99	>210,000
3	680	3	181,000
4	1040	2	15,000
5	1400	2	2,000
6	1750	0	0
7	2110	0	0
8	2470	0	0

100 (Hrs.) Total Operation Time

REMARKS: Vehicle No. 1-B 76-8


100
50
HOUPS
0
1
2
3
4
5
6
7
8
LEVEL
100
50
COUNTS (X10^3)
0
1
2
3
4
5
6
7
8
LEVEL
76-08

DATA SHEET

DATE: Sept., 1976 UNIT NO.: 1038

COMPANY: D

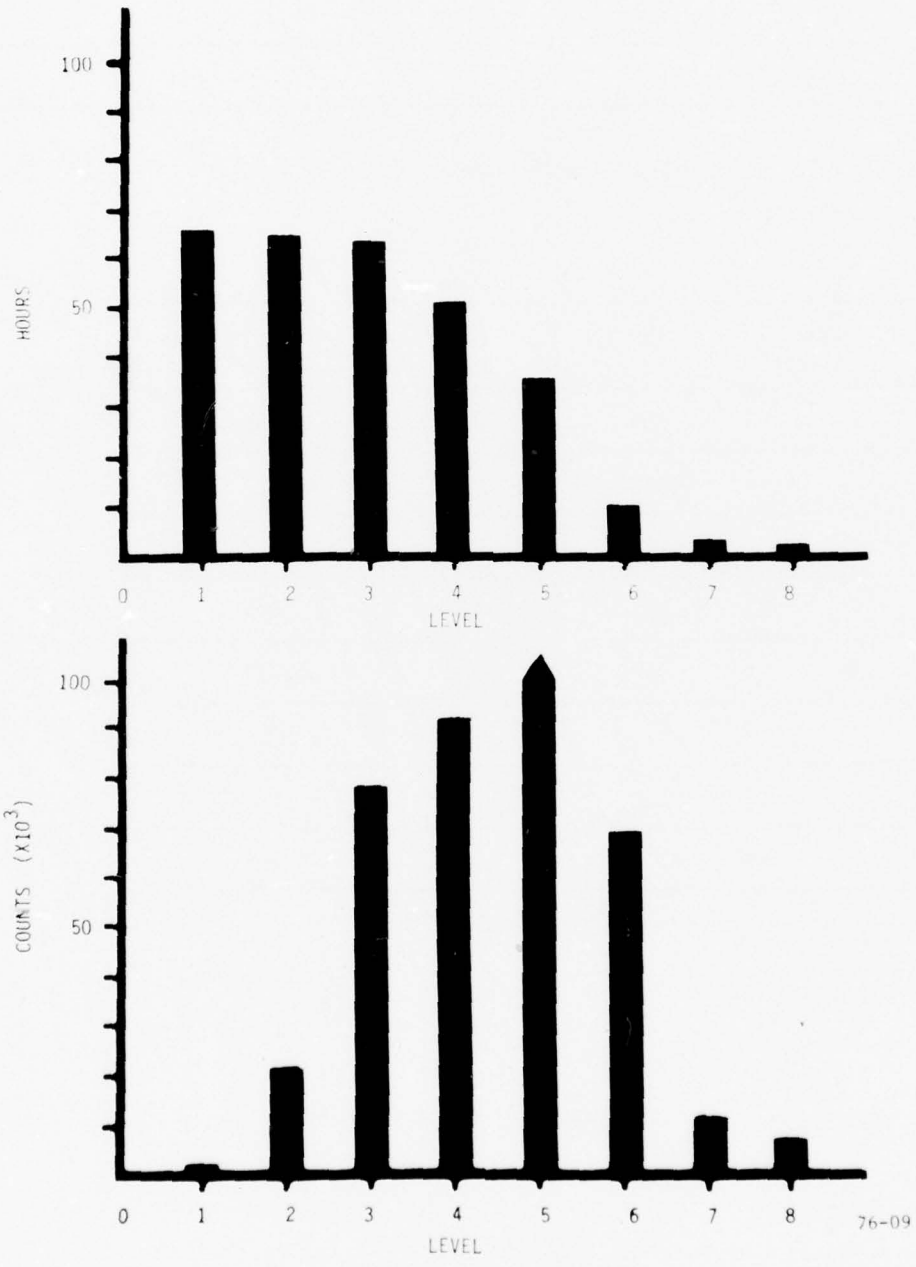
UNIT TYPE: Temperature

APPLICATION: *(Type of Vehicle and Location of Sensors)*
Ag Tractor

CHANNEL	LEVEL	TIME (HRS.)	COUNTS
1	82	66	1,000
2	104	65	22,000
3	125	63	78,000
4	146	52	91,000
5	167	36	196,000
6	189	10	69,000
7	210	2	12,000
8	231	1	7,000

66 (Hrs.) Total Operation Time

REMARKS: Vehicle No. 1-C 76-9


100
50
HOURS
0
1
2
3
4
5
6
7
8
LEVEL
100
50
COUNTS (X10^3)
0
1
2
3
4
5
6
7
8
LEVEL
76-09

DATA SHEET

DATE: Sept, 1976 UNIT NO.: 1038

COMPANY: D

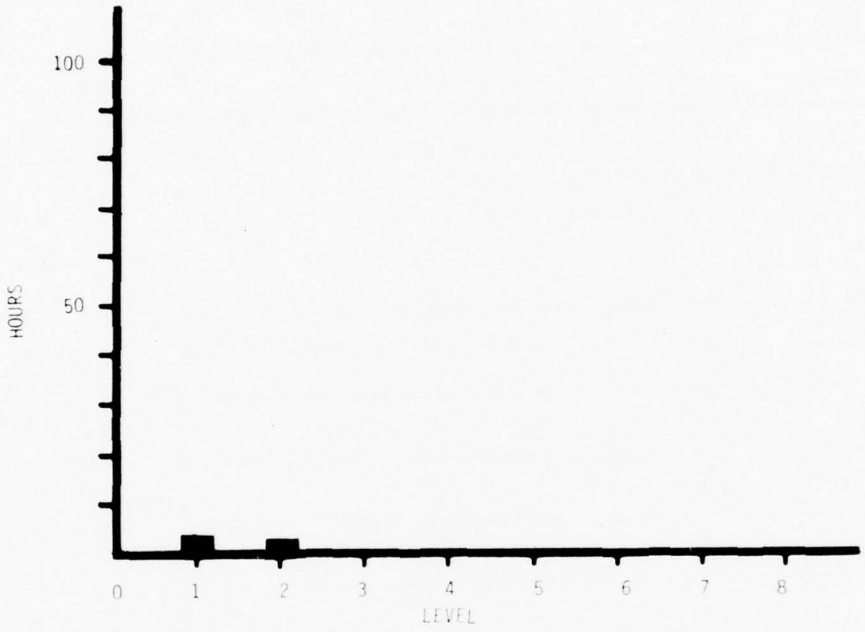
UNIT TYPE: Pressure

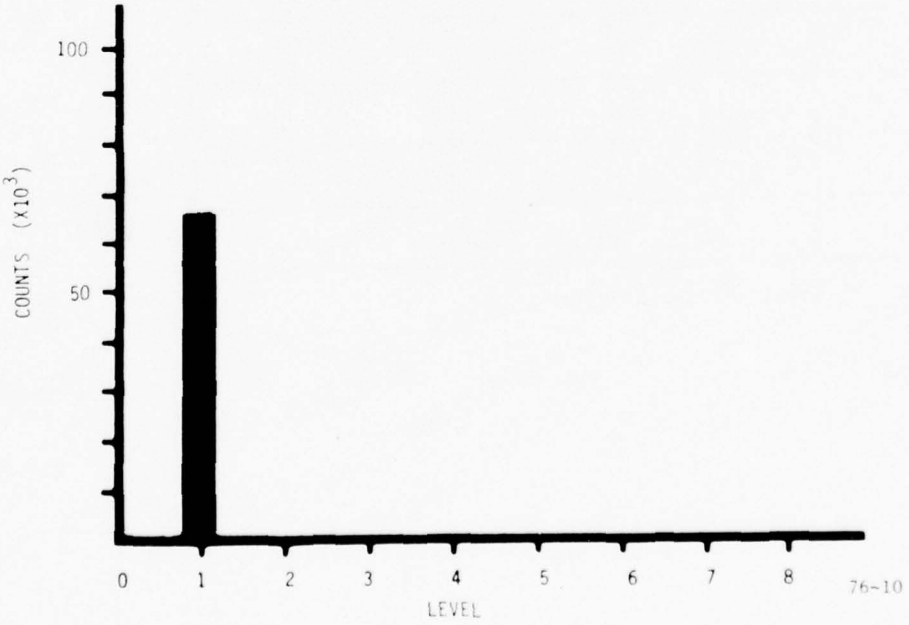
APPLICATION: *(Type of Vehicle and Location of Sensors)*
Ag Tractor – Hitch Cylinder Pressure

CHANNEL	LEVEL	TIME (HRS.)	COUNTS
1	430	2.0	66,000
2	900	1	0
3	1380	0	0
4	1850	0	0
5	2320	0	0
6	2790	0	0
7	3270	0	0
8	3740	0	0

66 (Hrs.) Total Operation Time

REMARKS: Vehicle No. 1-C 76-10


100
50
HOURS
0
1
2
3
4
5
6
7
8
LEVEL


100
50
COUNTS (X10^3)
0
1
2
3
4
5
6
7
8
LEVEL
76-10

DATA SHEET

DATE: Sept., 1977 UNIT NO.: 1066

COMPANY: D

UNIT TYPE: Pressure

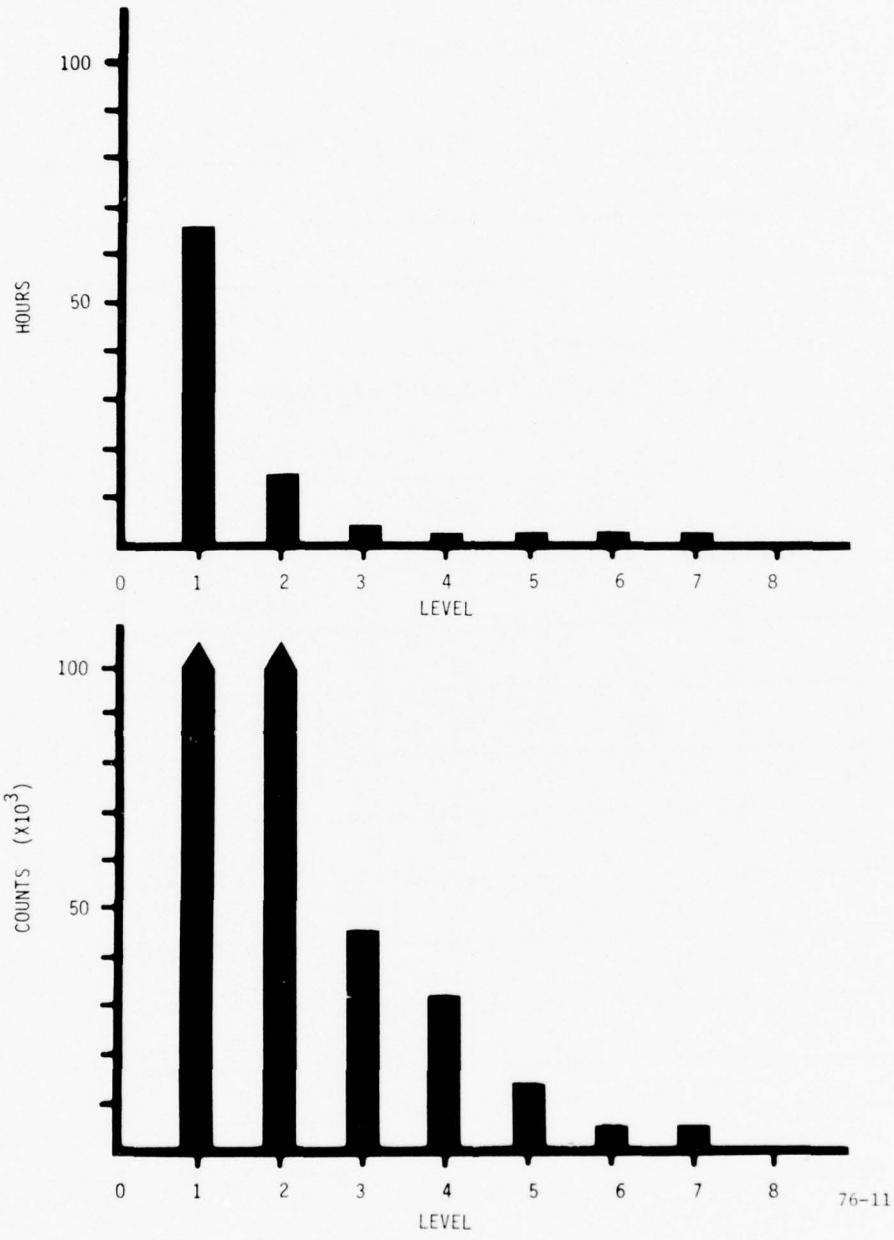
APPLICATION: *(Type of Vehicle and Location of Sensors)*

Ag Tractor – Steering and Clutch Pump Pressure

CHANNEL	LEVEL (PSI)	TIME (HRS.)	COUNTS
1	60	65	170,000
2	430	14	>374,000
3	790	2	45,000
4	1150	1	31,000
5	1510	1	13,000
6	1890	1	5,000
7	2240	1	5,000
8	2600	0	0

66 (Hrs.) Total Operation Time

REMARKS: Vehicle No. 1-C 76-11


100
50
HOURS
0
1
2
3
4
5
6
7
8
LEVEL
100
50
COUNTS (X10^3)
0
1
2
3
4
5
6
7
8
LEVEL
76-11

DATA SHEET

DATE: June, 1976 UNIT NO.: 1066

COMPANY: D

UNIT TYPE: Pressure

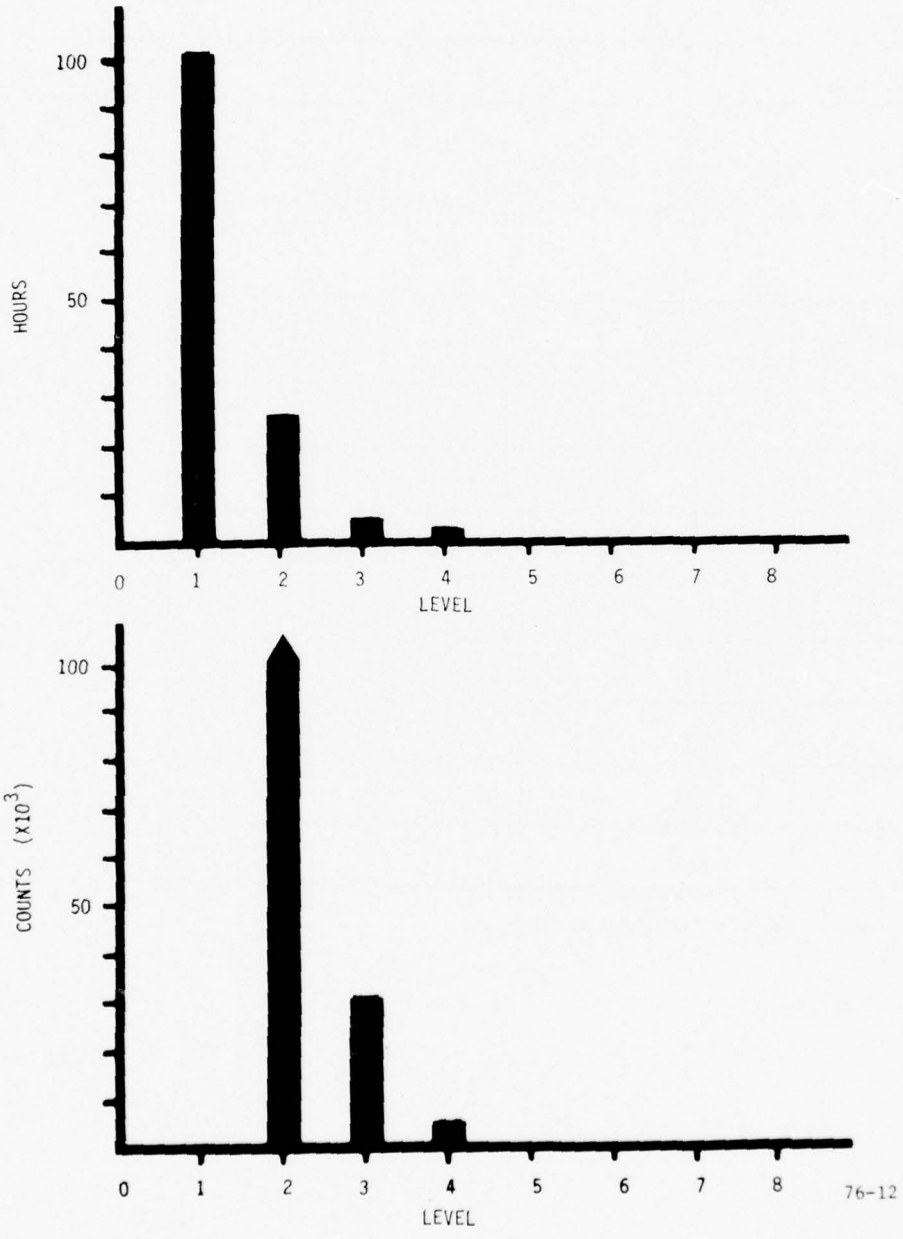
APPLICATION: *(Type of Vehicle and Location of Sensors)*

Ag Tractor – Steering and Clutch System Pump Pressure

CHANNEL	LEVEL	TIME (HRS.)	COUNTS
1	60	100	0
2	430	25	>210,000
3	790	3	30,000
4	1150	1	3,000
5	1510	0	0
6	1880	0	0
7	2240	0	0
8	2600	0	0

100 (Hrs.) Total Operation Time

REMARKS: Vehicle No. 2-A 76-12


100
50
HOURS
0
1
2
3
4
5
6
7
8
LEVEL
100
50
COUNTS (X10^3)
0
1
2
3
4
5
6
7
8
LEVEL
76-12

DATA SHEET

DATE: June, 1976 UNIT NO.: 1066

COMPANY: D

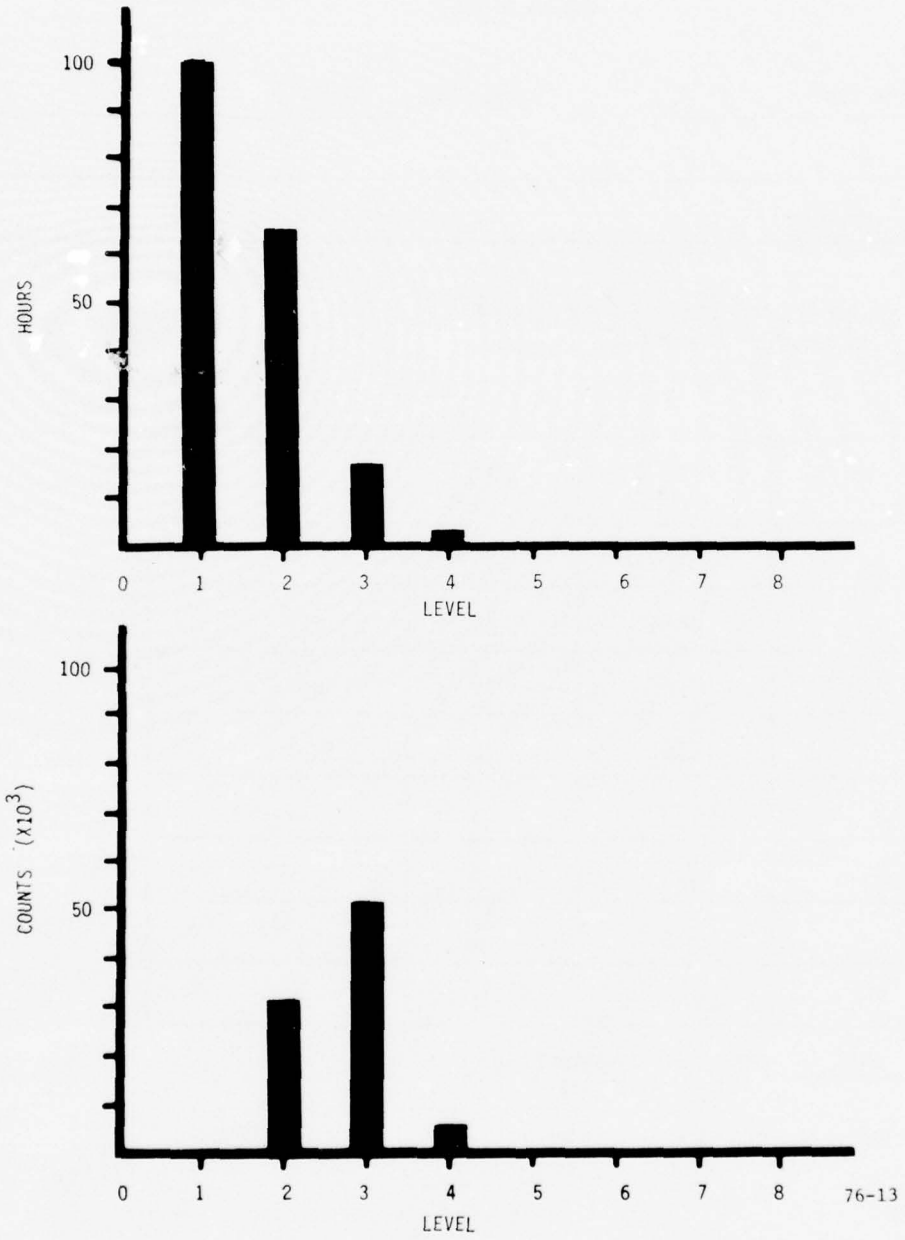
UNIT TYPE: Pressure

APPLICATION: *(Type of Vehicle and Location of Sensors)*
Ag Tractor – Draft Control Cylinder

CHANNEL	LEVEL (PSI)	TIME (HRS.)	COUNTS
1	50	100	0
2	400	65	31,000
3	760	17	51,000
4	1120	2	5,000
5	1470	0	0
6	1830	0	0
7	2200	0	0
8	2550	0	0

100 (Hrs.) Total Operation Time

REMARKS: Vehicle No. 2-A 76-13


100
50
HOURS
0
1
2
3
4
5
6
7
8
LEVEL
100
50
COUNTS (X10^3)
0
1
2
3
4
5
6
7
8
LEVEL
76-13

DATA SHEET

DATE: June, 1976 UNIT NO.: 1038

COMPANY: D

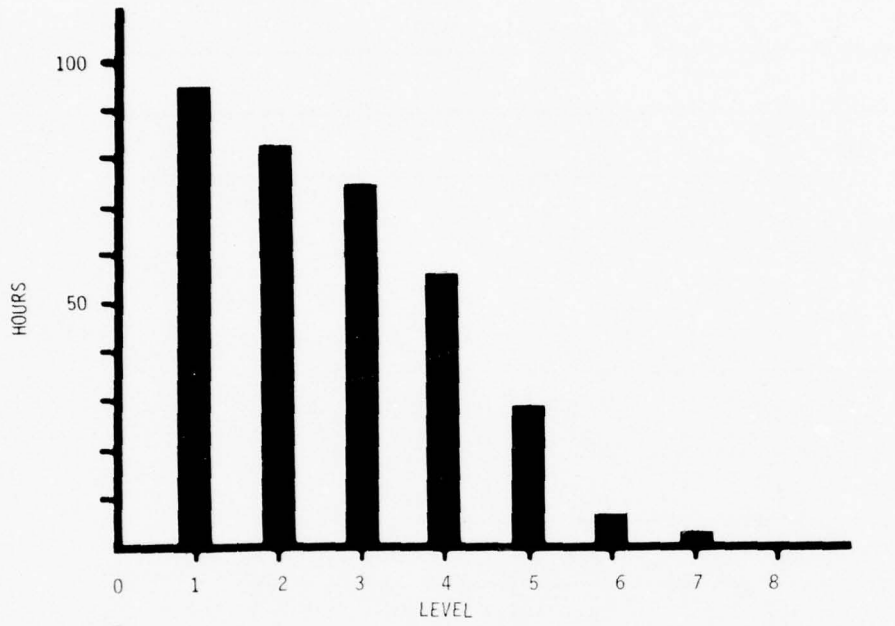
UNIT TYPE: Temperature

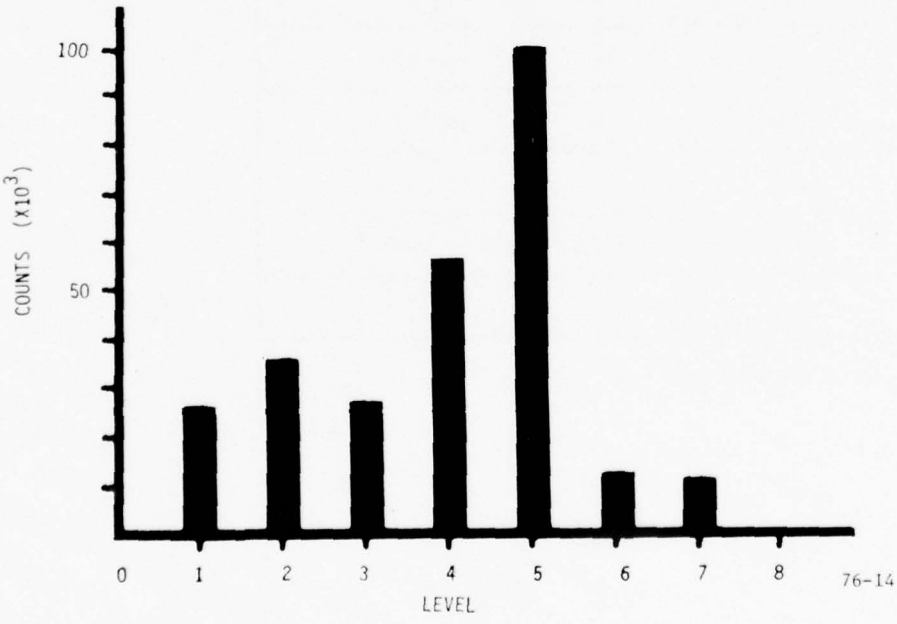
APPLICATION: *(Type of Vehicle and Location of Sensors)*

CHANNEL	LEVEL (°F)	TIME (HRS.)	COUNTS
1	82	94	26,000
2	104	83	34,000
3	125	74	27,000
4	146	56	64,000
5	167	29	100,000
6	189	6	12,000
7	210	2	11,000
8	231	0	0

100 (Hrs.) Total Operation Time

REMARKS: Vehicle No. 2-A 76-14


100
50
HOURS
0
1
2
3
4
5
6
7
8
LEVEL


100
50
COUNTS (X10^3)
0
1
2
3
4
5
6
7
8
LEVEL

76-14

DATA SHEET

DATE: June, 1976 UNIT NO.: 1038

COMPANY: D

UNIT TYPE: Pressure

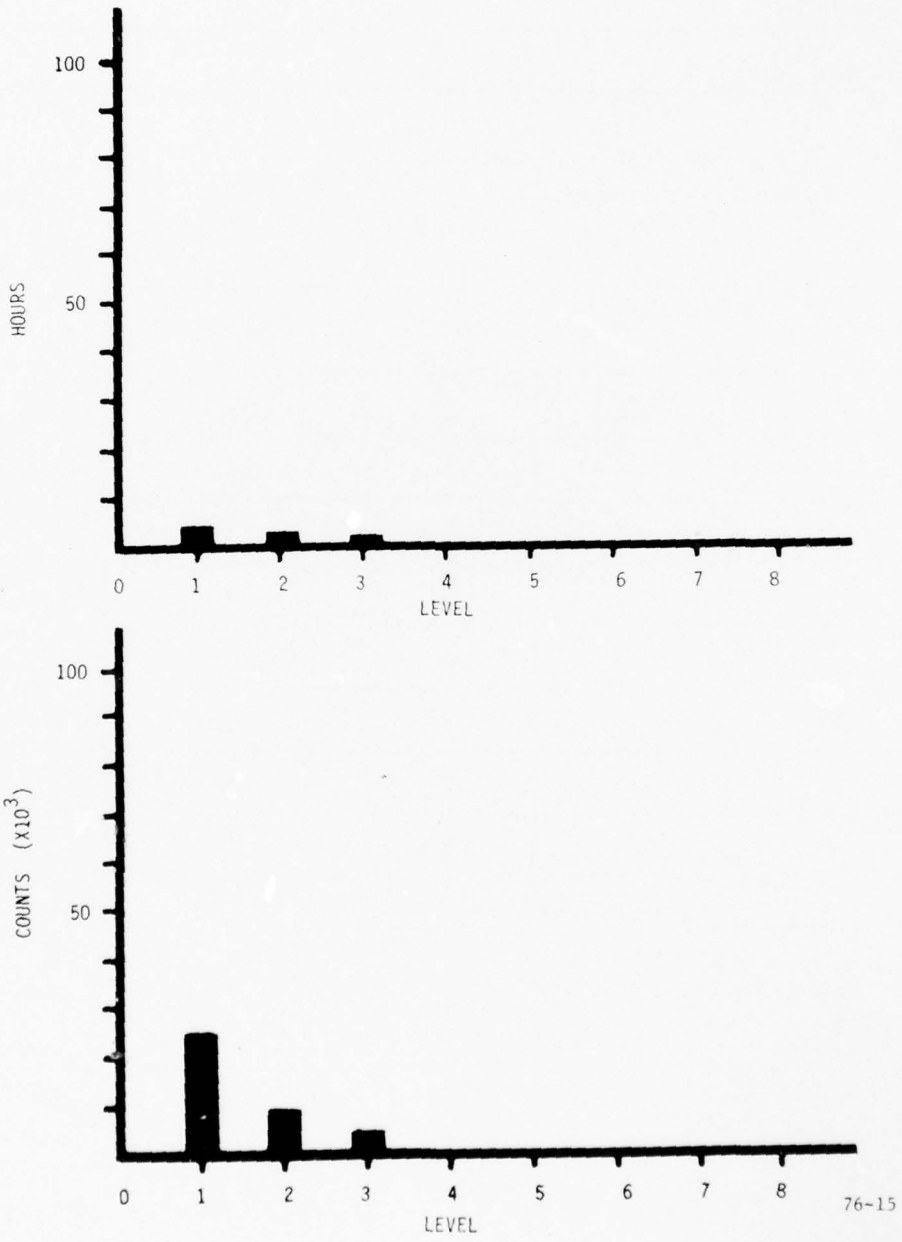
APPLICATION: *(Type of Vehicle and Location of Sensors)*

Ag Tractor – Hitch Pressure

CHANNEL	LEVEL	TIME (HRS.)	COUNTS
1	430	3	26,000
2	900	2	10,000
3	1380	1	4,000
4	1850	0	0
5	2320	0	0
6	2790	0	0
7	3270	0	0
8	3740	0	0

100 (Hrs.) Total Operation Time

REMARKS: Vehicle No. 2-A 76-15


100
50
HOURS
0
1
2
3
4
5
6
7
8
LEVEL
100
50
COUNTS (X10^3)
0
1
2
3
4
5
6
7
8
LEVEL
76-15

DATA SHEET

DATE: Feb., 1976 UNIT NO.: 1078

COMPANY: A

UNIT TYPE: Temperature

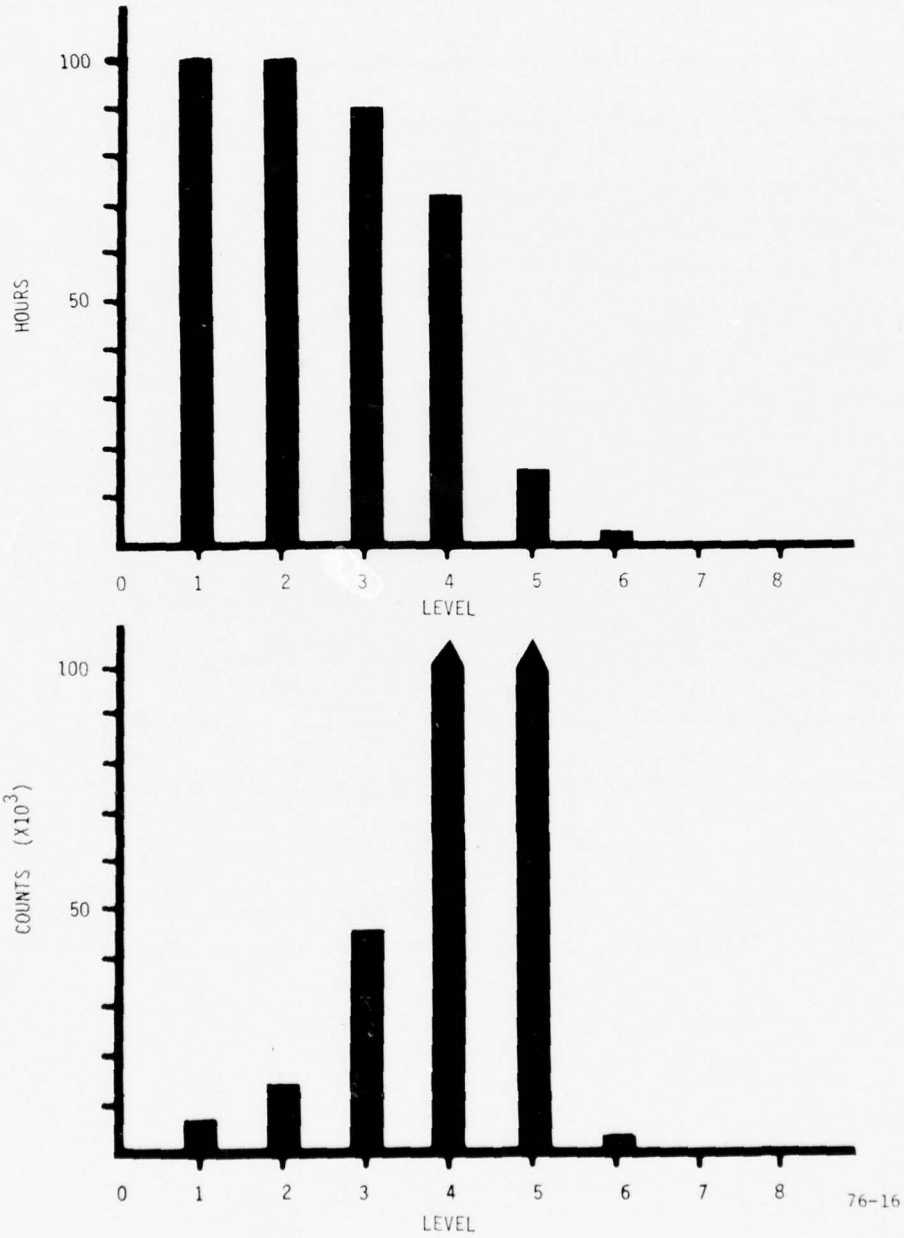
APPLICATION: *(Type of Vehicle and Location of Sensors)*

Ag Tractor – Auxiliary Hydraulic System
Load Sensing System

CHANNEL	LEVEL (^{O}F)	TIME (HRS.)	COUNTS
1	78	100	6,000
2	99	100	13,000
3	120	90	45,000
4	140	72	209,000
5	160	14	183,000
6	180	1	2,000
7	202	0	0
8	223	0	0

100 (Hrs.) Total Operation Time

REMARKS: 76-16


100
50
HOURS
0
1
2
3
4
5
6
7
8
LEVEL
100
50
COUNTS (X10^3)
0
1
2
3
4
5
6
7
8
LEVEL
76-16

DATA SHEET

DATE: Feb., 1976 UNIT NO.: 1078

COMPANY: A

UNIT TYPE: Pressure

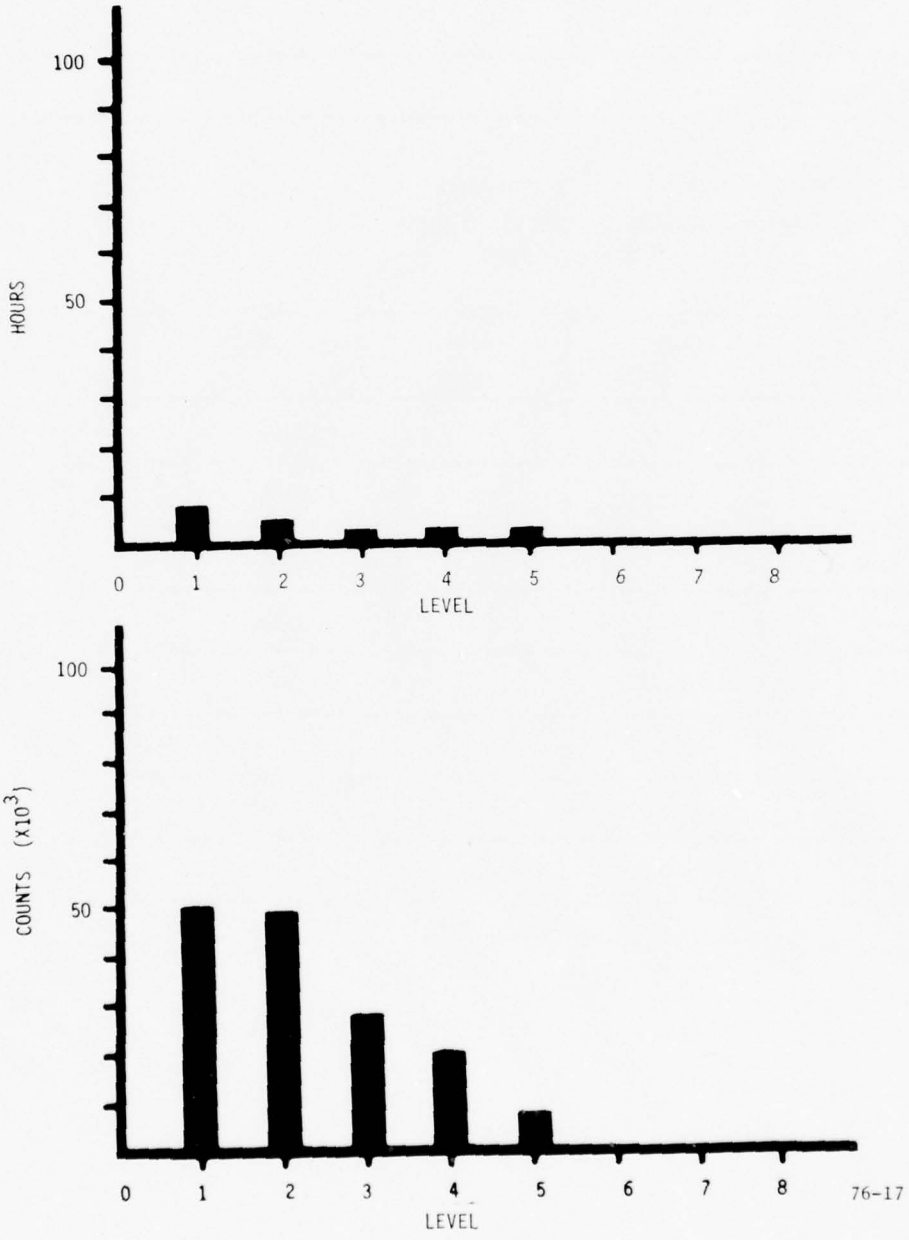
APPLICATION: *(Type of Vehicle and Location of Sensors)*

Ag Tractor – Auxiliary Hydraulic System
Load Sensing System

CHANNEL	LEVEL (PSI)	TIME (HRS.)	COUNTS
1	640	7	50,000
2	1070	3	49,000
3	1500	1	28,000
4	1920	1	20,000
5	2350	1	7,000
6	2770	0	0
7	3200	0	0
8	3630	0	0

100 (Hrs.) Total Operation Time

REMARKS: 76-17


100
50
HOURS
0
1
2
3
4
5
6
7
8
LEVEL
100
50
COUNTS (X10^3)
0
1
2
3
4
5
6
7
8
LEVEL
76-17

DATA SHEET

DATE: Aug., 1976 UNIT NO.: 1098

COMPANY: E

UNIT TYPE: Pressure

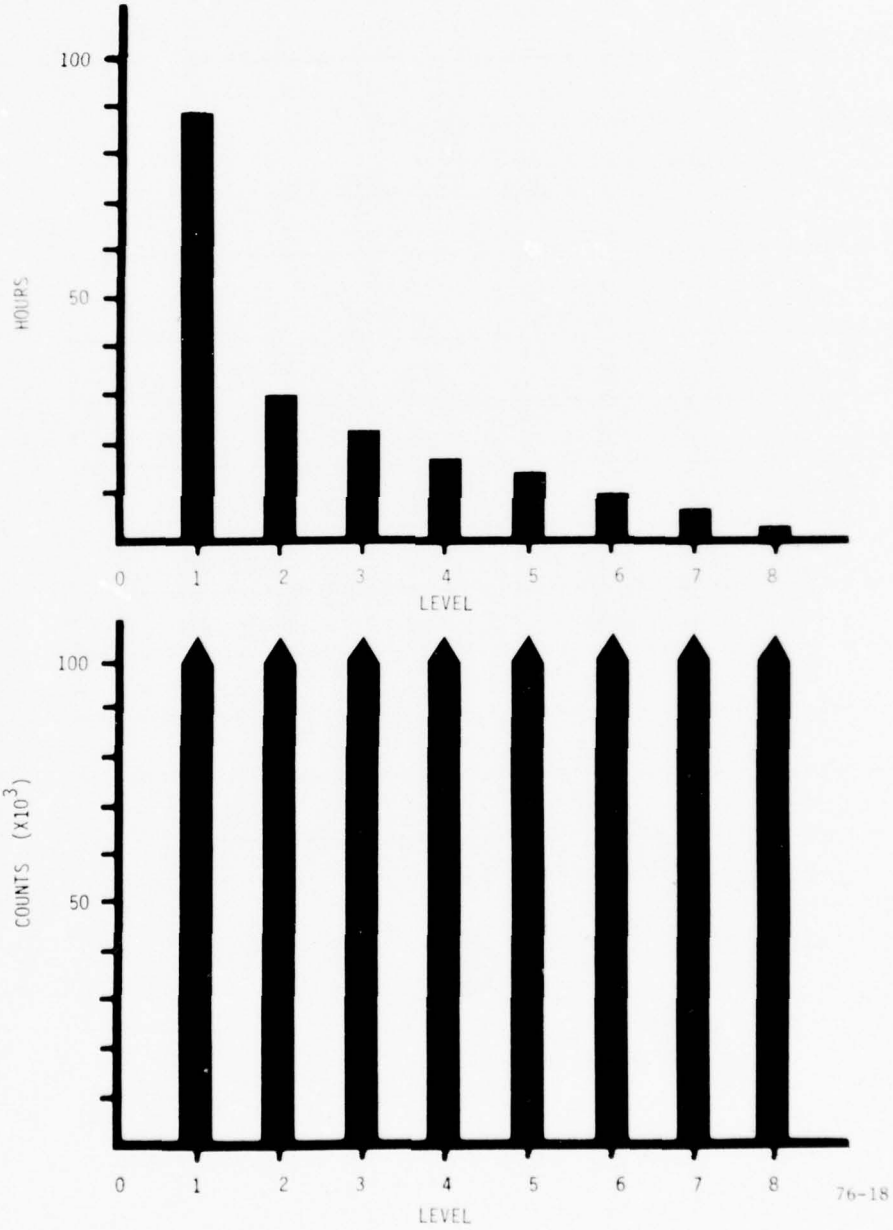
APPLICATION: *(Type of Vehicle and Location of Sensors)*

Loader/Backhoe – Pump Pressure
Pressure Compensated System

CHANNEL	LEVEL (PSI)	TIME (HRS.)	COUNTS
1	120	89	>412,000
2	510	30	>412,000
3	890	23	>412,000
4	1280	18	>412,000
5	1660	14	>412,000
6	2050	10	>412,000
7	2430	7	363,000
8	2820	3	286,000

100 (Hrs.) Total Operation Time

REMARKS: Vehicle No. 4-A 76-18


100
50
HOURS
0
1
2
3
4
5
6
7
8
LEVEL
100
50
COUNTS (X10^3)
0
1
2
3
4
5
6
7
8
LEVEL
76-18

DATA SHEET

DATE: Aug., 1976 UNIT NO.: 1098

COMPANY: D

UNIT TYPE: Temperature

APPLICATION: *(Type of Vehicle and Location of Sensors)*

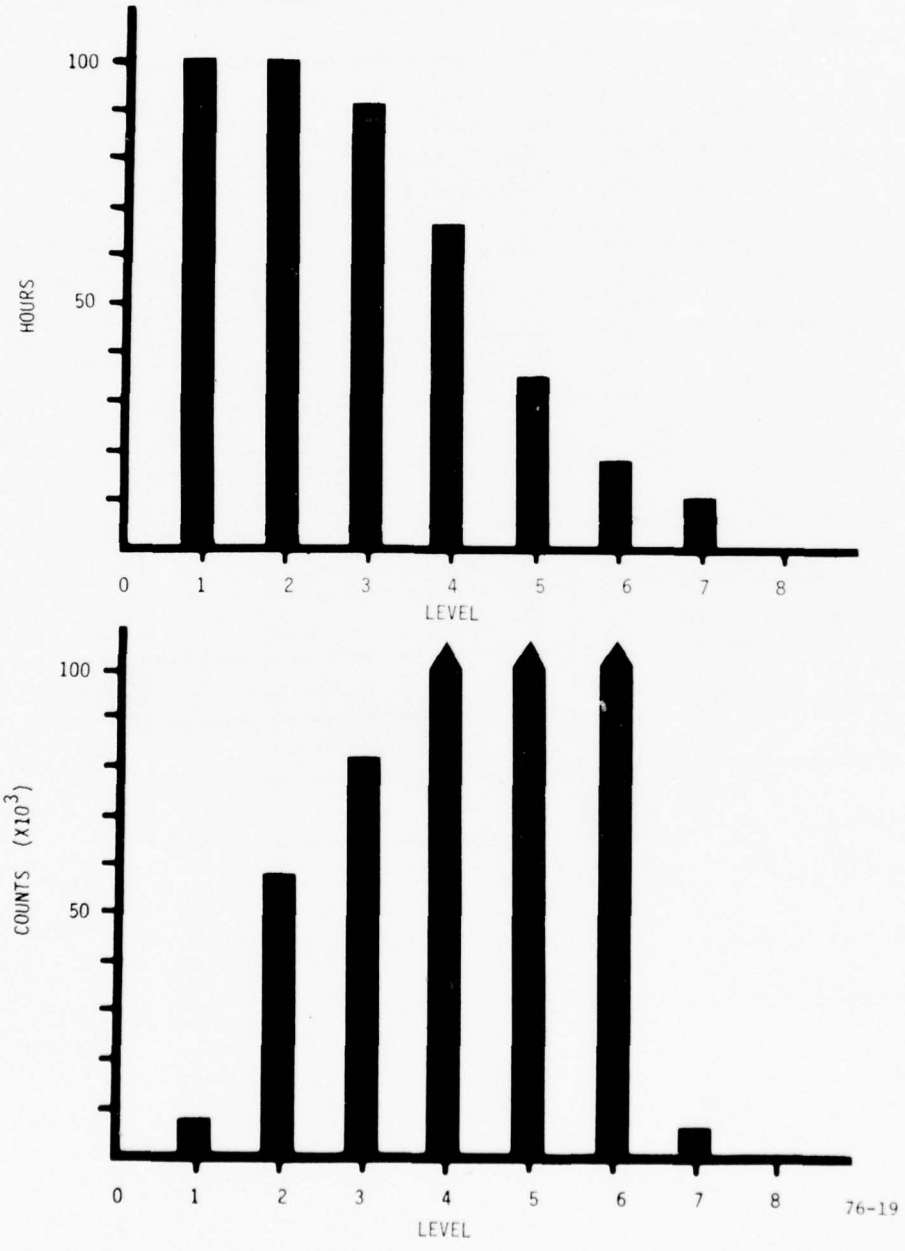
Loader/Backhoe – Pressure Line Temperature
Pressure Compensated System

CHANNEL	LEVEL (^{O}F)	TIME (HRS.)	COUNTS
1	75	100	8,000
2	96	100	57,000
3	117	91	81,000
4	138	66	>412,000
5	158	34	224,000
6	179	18	139,000
7	200	10	4,000
8	221	*	0

100 (Hrs.) Total Operation Time

REMARKS: Vehicle No. 4-A 76-19

* Defective


100
50
HOURS
0
1
2
3
4
5
6
7
8
LEVEL
100
50
COUNTS (X10^3)
0
1
2
3
4
5
6
7
8
LEVEL
76-19

DATA SHEET

DATE: Aug., 1976 UNIT NO.: 1006

COMPANY: E

UNIT TYPE: Rotational Angle

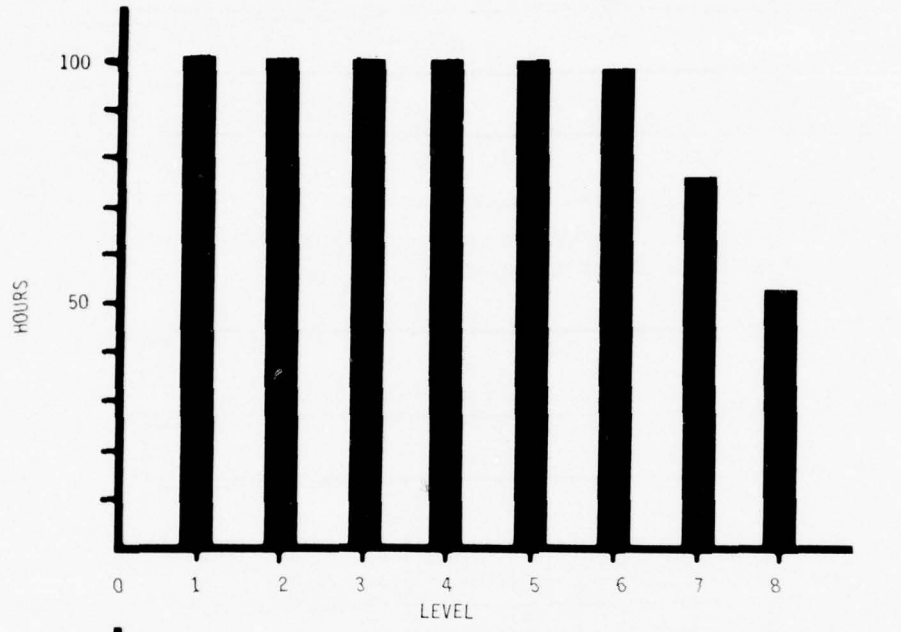
APPLICATION: *(Type of Vehicle and Location of Sensors)*

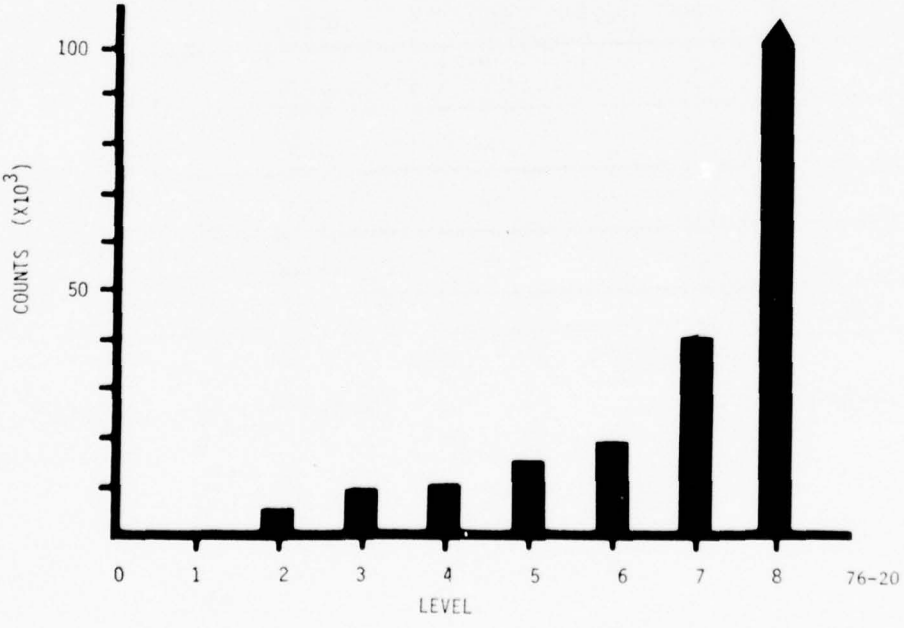
Loader/Backhoe – Swash Plate Angle
Pressure Compensated System

CHANNEL	LEVEL	TIME (HRS.)	COUNTS
1	1.5^{o}	100	0
2	3.3^{o}	100	3,000
3	5.2^{o}	100	9,000
4	7.1^{o}	100	10,000
5	9.0^{o}	100	14,000
6	10.9^{o}	98	18,000
7	12.8^{o}	75	40,000
8	14.7^{o}	52	228,000

100 (Hrs.) Total Operation Time

REMARKS: Vehicle No. 4-A 76-20


100
50
HOURS
0
1
2
3
4
5
6
7
8
LEVEL


100
50
COUNTS (X10^3)
0
1
2
3
4
5
6
7
8
LEVEL

76-20

DATA SHEET

DATE: August, 1976 UNIT NO.: 1092

COMPANY: E

UNIT TYPE: Pressure

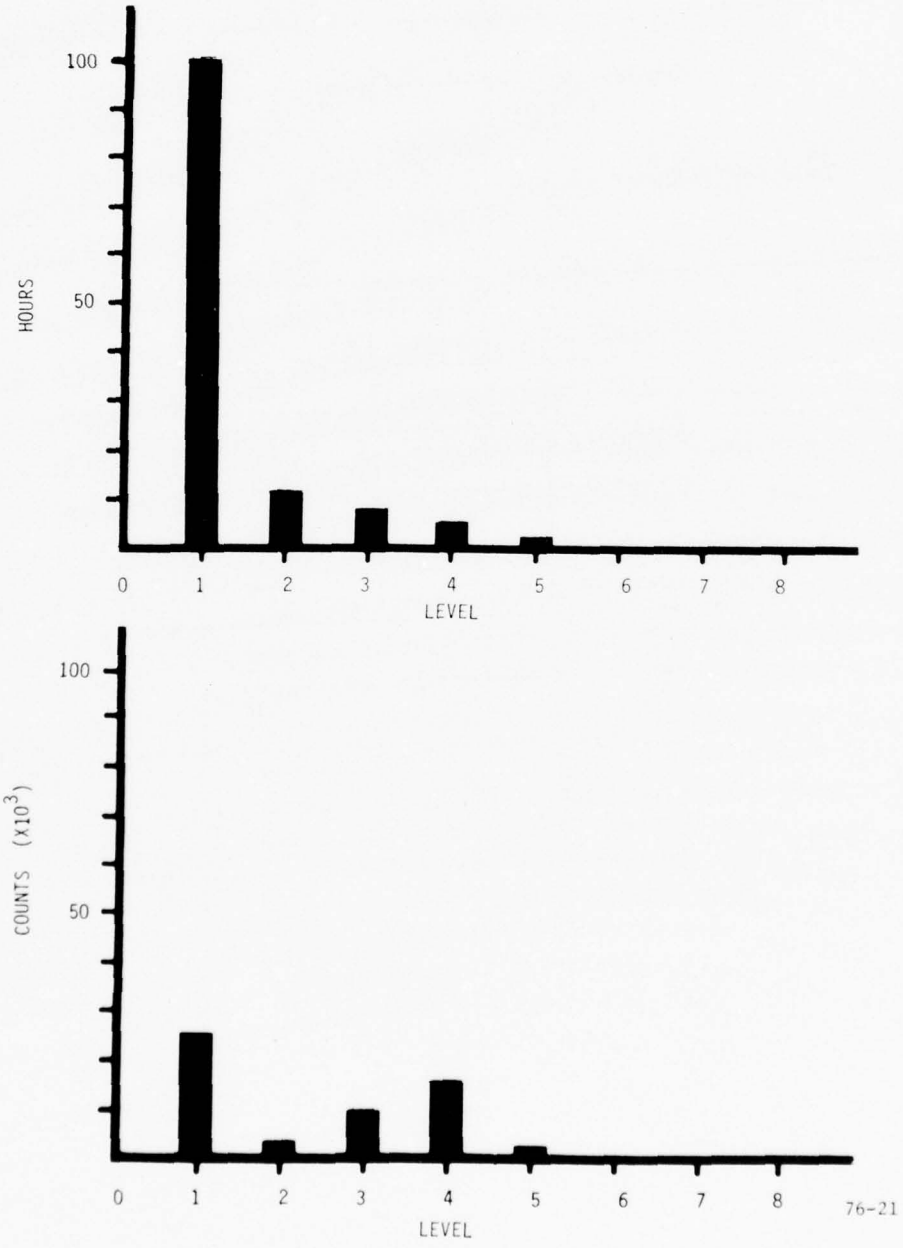
APPLICATION: *(Type of Vehicle and Location of Sensors)*

Industrial Tractor

CHANNEL	LEVEL (PSI)	TIME (HRS.)	COUNTS
1	60	100	25,000
2	450	11	2,000
3	830	8	10,000
4	1220	4	16,000
5	1600	2	1,000
6	1980	0	0
7	2350	0	0
8	2730	0	0

100 (Hrs.) Total Operation Time

REMARKS: 76-21


100
50
HOURS
0
1
2
3
4
5
6
7
8
LEVEL
100
50
COUNTS (X10^3)
0
1
2
3
4
5
6
7
8
LEVEL
76-21

DATA SHEET

DATE: Sept., 1976 UNIT NO.: 1216

COMPANY: E

UNIT TYPE: Pressure

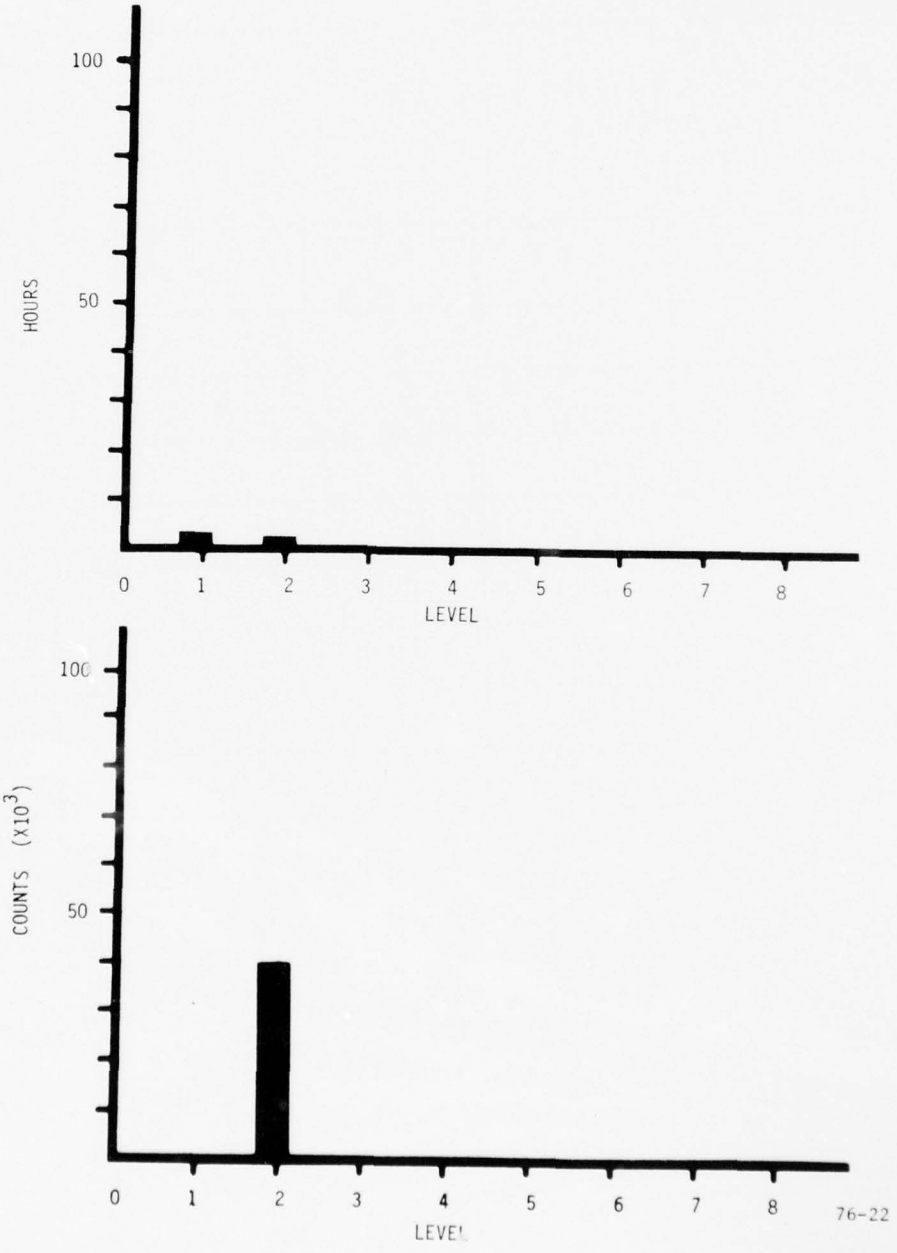
APPLICATION: *(Type of Vehicle and Location of Sensors)*

Industrial Tractor

CHANNEL	LEVEL	TIME (HRS.)	COUNTS
1	90	2	0
2	460	1	40,000
3	820	0	0
4	1190	0	0
5	1550	0	0
6	1920	0	0
7	2290	0	0
8	2650	0	0

5 (Hrs.) Total Operation Time

REMARKS: Vehicle No. 3-A 76-22


100
50
HOURS
0
1
2
3
4
5
6
7
8
LEVEL
100
50
COUNTS (X10^3)
0
1
2
3
4
5
6
7
8
LEVEL
76-22

DATA SHEET

DATE: Sept., 1976 UNIT NO.: 1036

COMPANY:

UNIT TYPE: Pressure

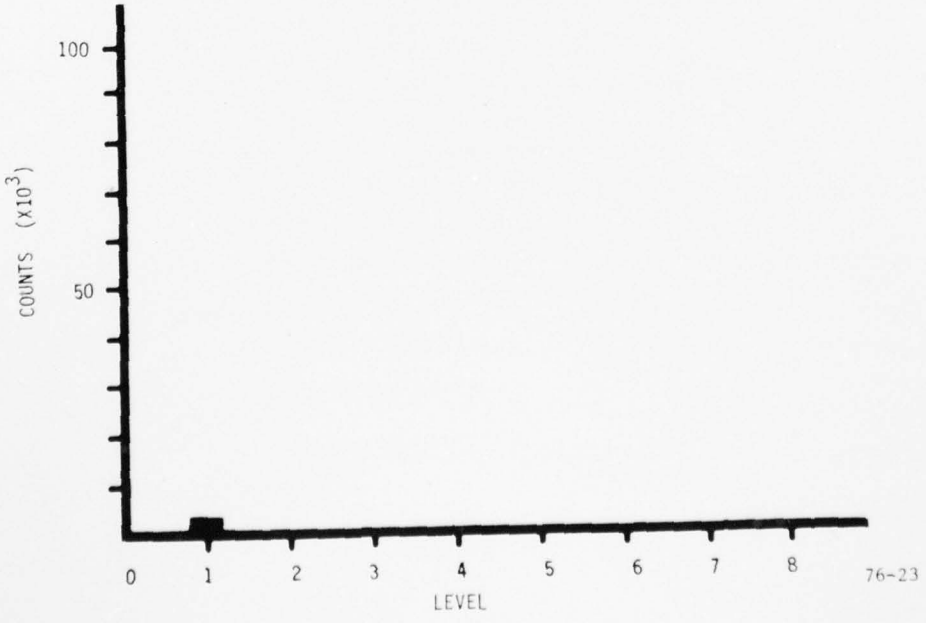
APPLICATION: *(Type of Vehicle and Location of Sensors)*
Industrial Tractor

CHANNEL	LEVEL (PSI)	TIME (HRS.)	COUNTS
1	440	1	1,000
2	930	0	0
3	1420	0	0
4	1900	0	0
5	2390	0	0
6	2870	0	0
7	3360	0	0
8	3840	0	0

5 (Hrs.) Total Operation Time

REMARKS: Vehicle No. 3-A 76-23


100
50
HOURS
0
1
2
3
4
5
6
7
8
LEVEL


100
50
COUNTS (X10^3)
0
1
2
3
4
5
6
7
8
LEVEL
76-23

DATA SHEET

DATE: Sept., 1976 UNIT NO.: 1036

COMPANY: E

UNIT TYPE: Temperature

APPLICATION: *(Type of Vehicle and Location of Sensors)*

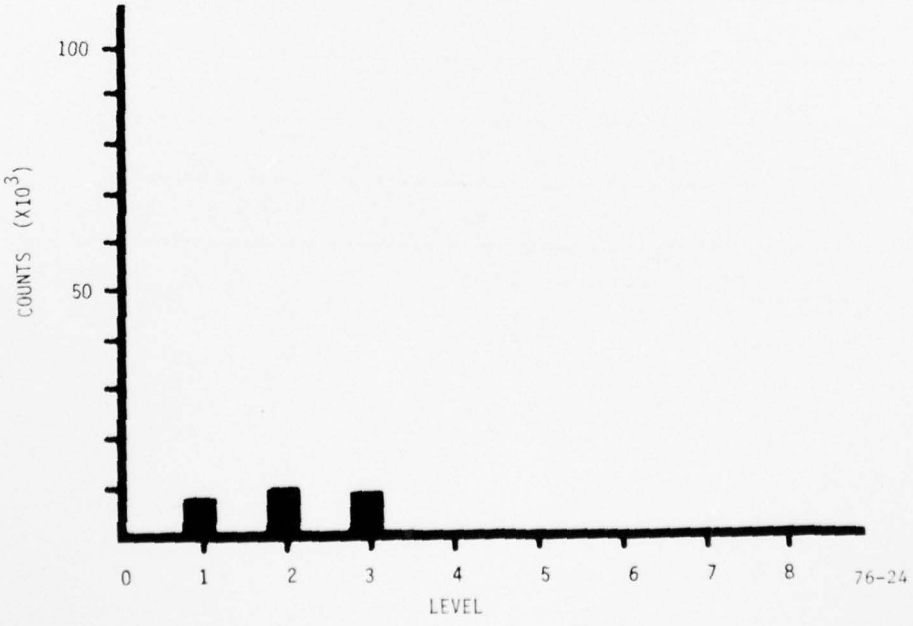
Industrial Tractor

CHANNEL	LEVEL (^{O}F)	TIME (HRS.)	COUNTS
1	81	2	8,000
2	102	1	10,000
3	123	1	9,000
4	144	0	0
5	165	0	0
6	185	0	0
7	206	0	0
8	227	0	0

5 (Hrs.) Total Operation Time

REMARKS: 76-24


100
50
HOURS
0
1
2
3
4
5
6
7
8
LEVEL


100
50
COUNTS (X10^3)
0
1
2
3
4
5
6
7
8
LEVEL
76-24

DATA SHEET

DATE: October, 1976 UNIT NO.: 1024

COMPANY: F

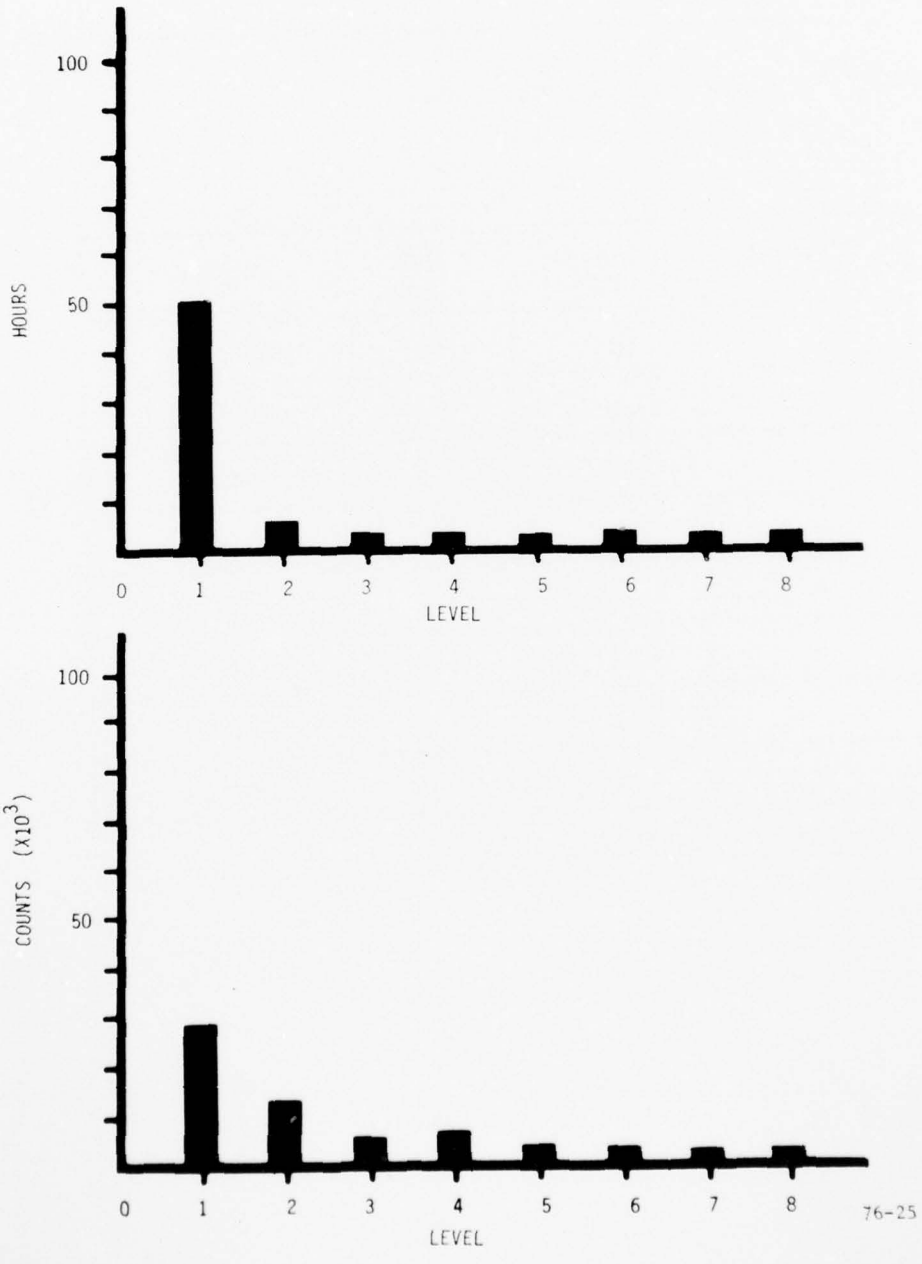
UNIT TYPE: Temperature

APPLICATION: *(Type of Vehicle and Location of Sensors)*
Lift Truck

CHANNEL	LEVEL (^{O}F)	TIME (HRS.)	COUNTS
1	83	50	28,000
2	104	4	13,000
3	123	2	4,000
4	144	2	6,000
5	164	2	3,000
6	184	2	3,000
7	204	2	1,000
8	225	2	1,000

122 (Hrs.) Total Operation Time

REMARKS: 76-25


100
50
HOURS
0
1
2
3
4
5
6
7
8
LEVEL
100
50
COUNTS (X10^3)
0
1
2
3
4
5
6
7
8
LEVEL
76-25

DATA SHEET

DATE: Oct., 1976 UNIT NO.: 1232

COMPANY: E

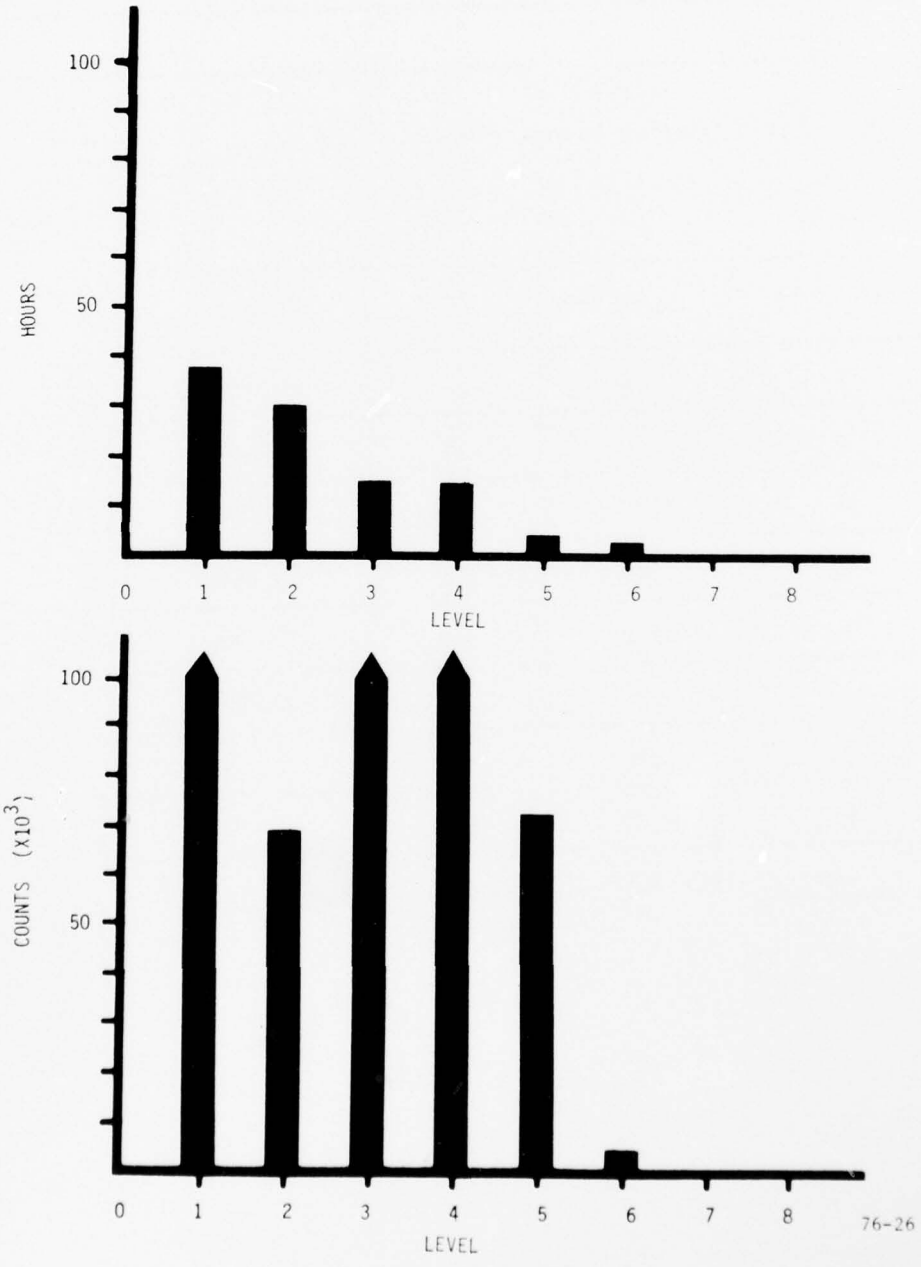
UNIT TYPE: Pressure

APPLICATION: *(Type of Vehicle and Location of Sensors)*

CHANNEL	LEVEL	TIME (HRS.)	COUNTS
1	680	37	102,000
2	1380	30	69,000
3	2100	14	>200,000
4	2820	14	>200,000
5	3530	3	72,000
6	4250	1	3,000
7	4970	0	0
8	5680	0	0

95 (Hrs.) Total Operation Time

REMARKS: 76-26


100
50
HOURS
0
1
2
3
4
5
6
7
8
LEVEL
100
50
COUNTS (X10^3)
0
1
2
3
4
5
6
7
8
LEVEL
76-26

DATA SHEET

DATE: November, 1976 UNIT NO.: 1038

COMPANY: D

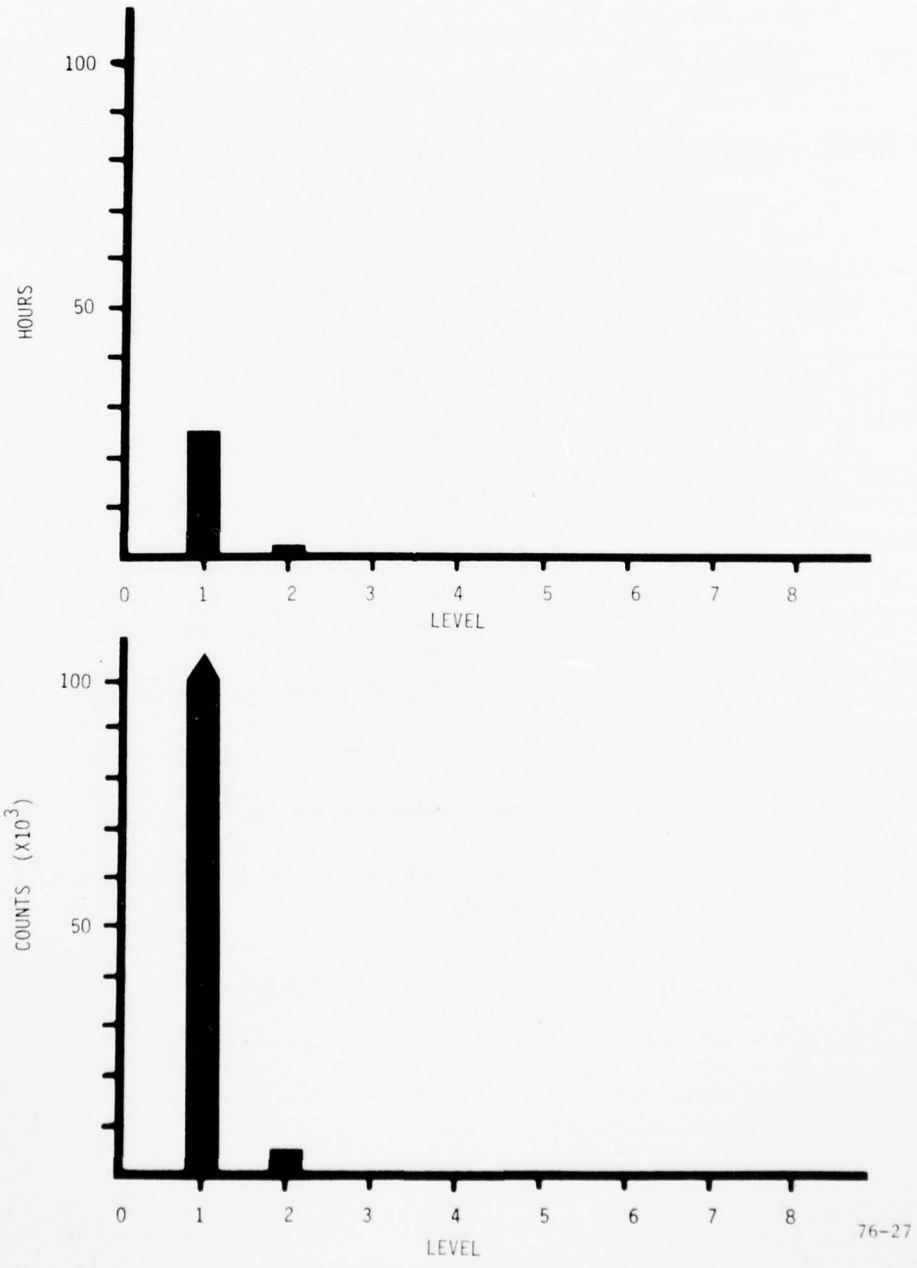
UNIT TYPE: Pressure

APPLICATION: *(Type of Vehicle and Location of Sensors)*

CHANNEL	LEVEL	TIME (HRS.)	COUNTS
1	430	26	181,000
2	900	2	4,000
3	1380	0	0
4	1850	0	0]
5	2320	0	0
6	2790	0	0
7	3270	0	0
8	3740	0	0

111 (Hrs.) Total Operation Time

REMARKS: 76-27


100
50
HOURS
0
1
2
3
4
5
6
7
8
LEVEL
100
50
COUNTS (X10^3)
0
1
2
3
4
5
6
7
8
LEVEL
76-27

DATA SHEET

DATE: November, 1976 UNIT NO.: 1066

COMPANY: D

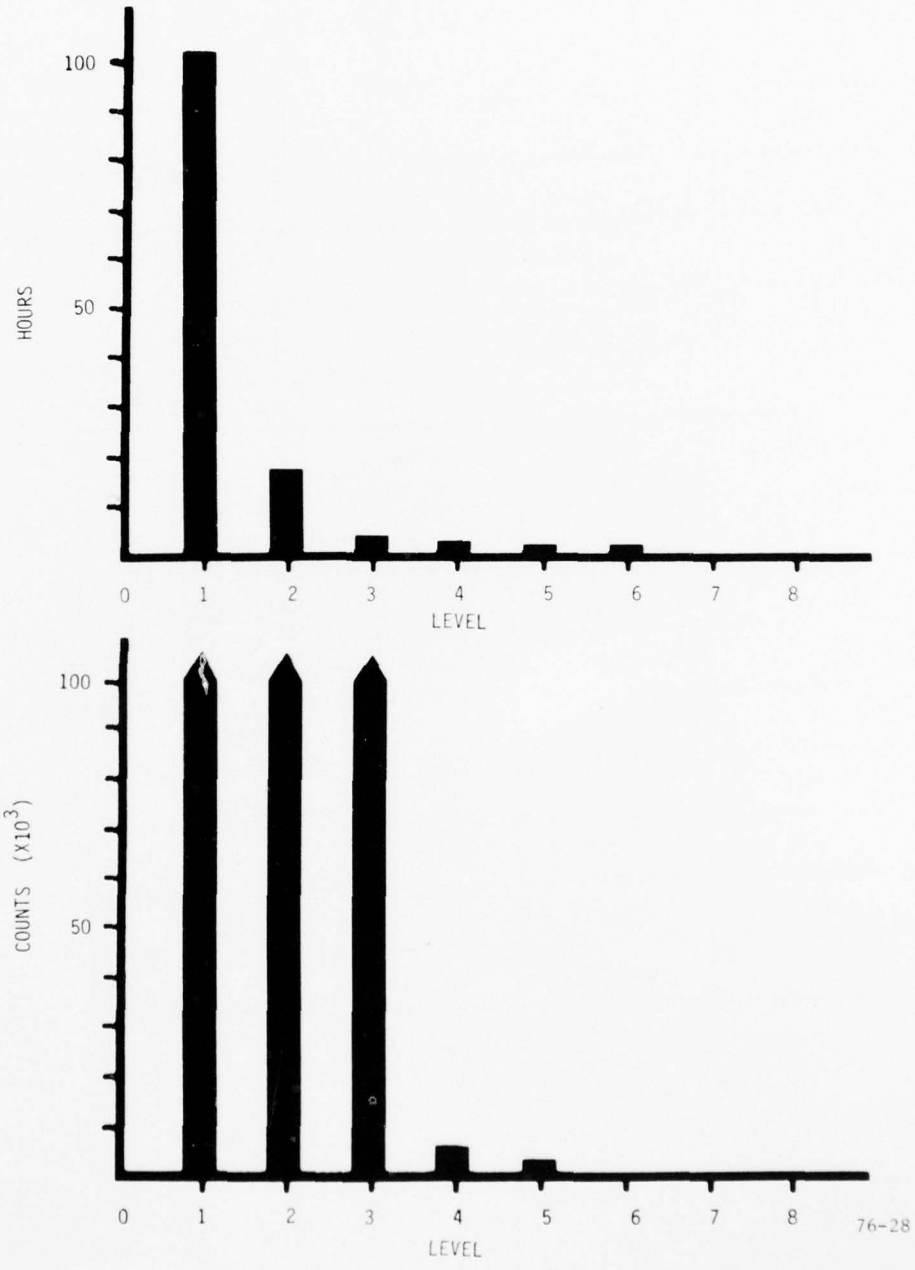
UNIT TYPE: Pressure

APPLICATION: *(Type of Vehicle and Location of Sensors)*

CHANNEL	LEVEL (PSI)	TIME (HRS.)	COUNTS
1	75	103	269,000
2	440	17	>923,000
3	806	3	108,000
4	1160	2	6,000
5	1520	1	3,000
6	1890	1	–
7	2250	0	0
8	2620	0	0

103 (Hrs.) Total Operation Time

REMARKS: 76-28


100
50
HOURS
0
1
2
3
4
5
6
7
8
LEVEL
100
50
COUNTS (X10^3)
0
1
2
3
4
5
6
7
8
LEVEL
76-28

DATA SHEET

DATE: November, 1976 UNIT NO.: 1082

COMPANY: E

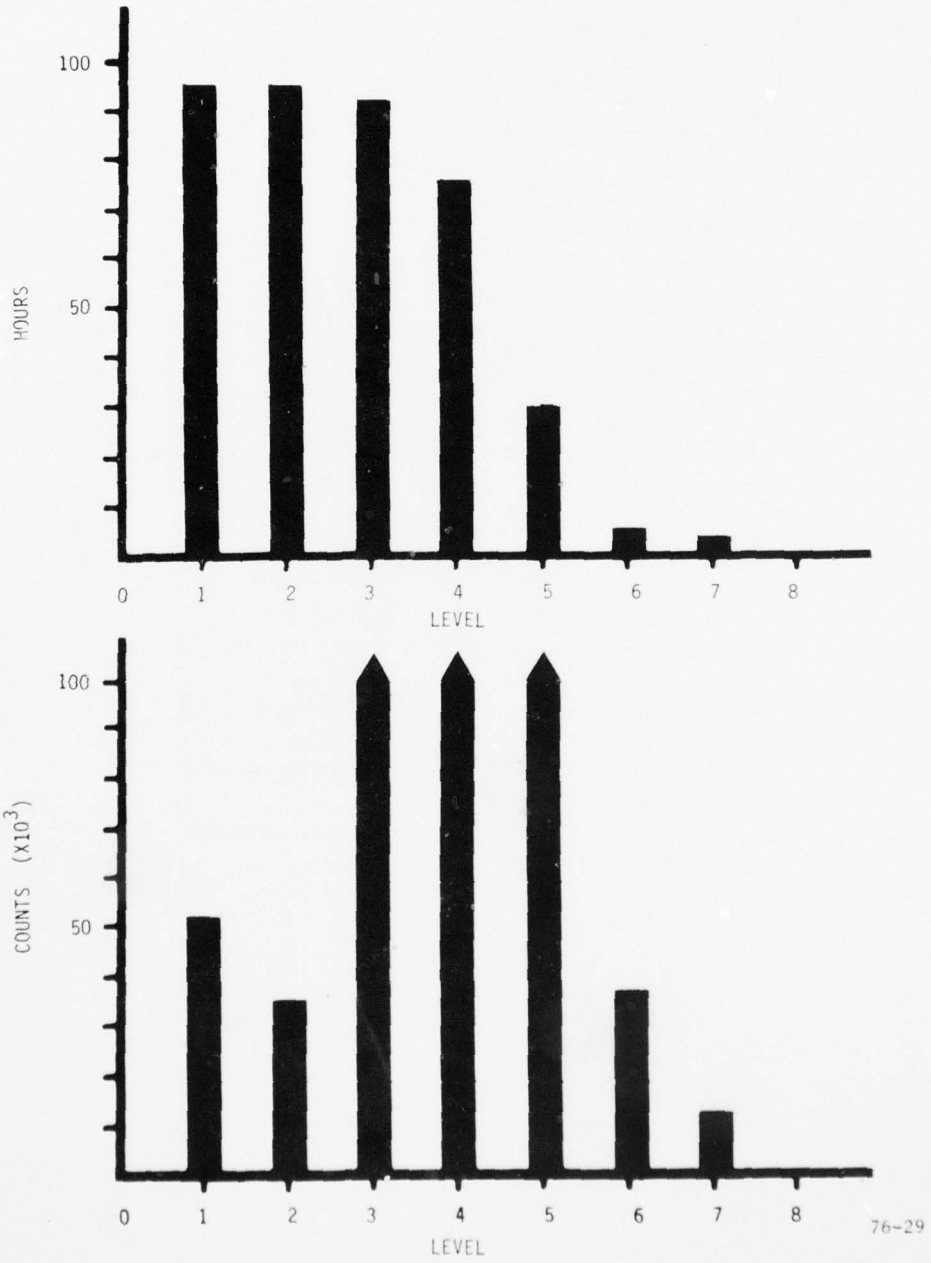
UNIT TYPE: Temperature

APPLICATION: *(Type of Vehicle and Location of Sensors)*
Loader/Backhoe – Pump Inlet Temperature

CHANNEL	LEVEL	TIME (HRS.)	COUNTS
1	84	96	52,000
2	107	96	35,000
3	128	92	156,000
4	150	76	>356,000
5	172	30	>356,000
6	193	4	36,000
7	215	3	12,000
8	237	0	0

102 (Hrs.) Total Operation Time

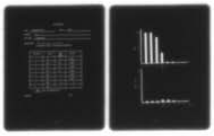
REMARKS: 76-29


100
50
HOURS
0
1
2
3
4
5
6
7
8
LEVEL
100
50
COUNTS (X10^3)
0
1
2
3
4
5
6
7
8
LEVEL
76-29

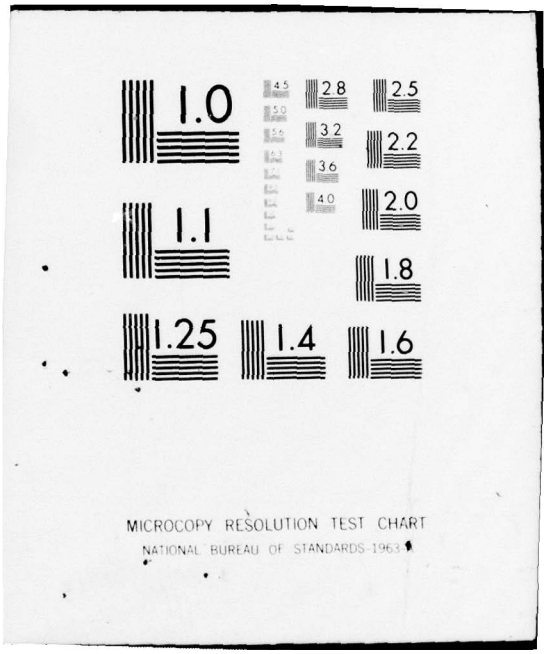
AD-A043 677 OKLAHOMA STATE UNIV STILLWATER FLUID POWER RESEARCH --ETC F/G 13/7
MERADCOM/OSU HYDRAULIC SYSTEM RELIABILITY PROGRAM. SECTION II. --ETC(U)
FEB 77 DAAK02-75-C-0137

UNCLASSIFIED OSU-FPRC-7M2 NL

3 OF 3
AD A043677



END
DATE FILMED
9-77
DDC


1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0
4.5
5.0
5.6
6.3
7.1
8.0
9.0
10.0
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

DATA SHEET

DATE: December, 1976 UNIT NO.: 1040

COMPANY: G

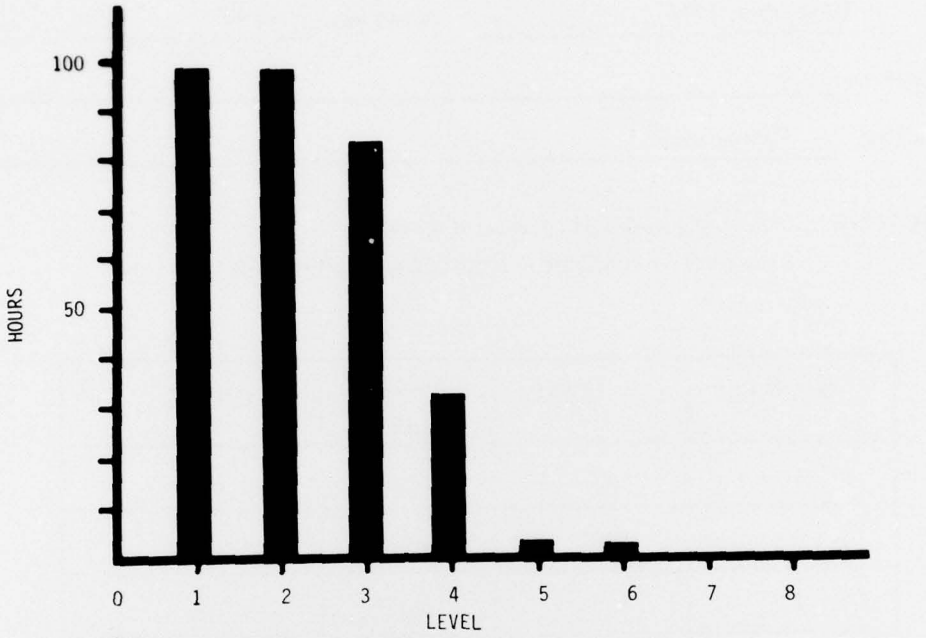
UNIT TYPE: Temperature

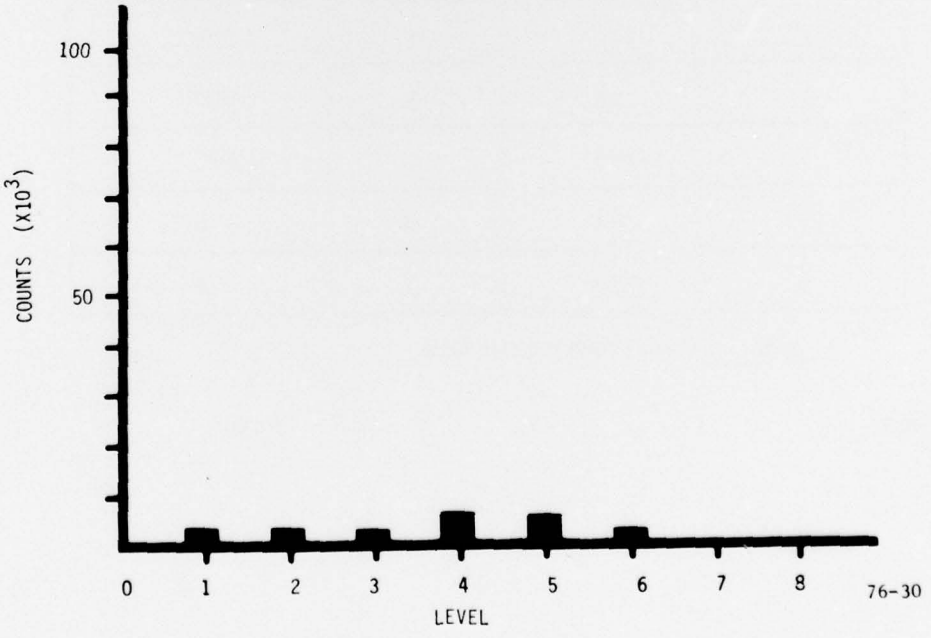
APPLICATION: *(Type of Vehicle and Location of Sensors)*
Construction Machine – Return Line Temperature

CHANNEL	LEVEL	TIME (HRS.)	COUNTS
1	85	98	1,400
2	106	98	1,000
3	127	83	1,000
4	147	31	4,000
5	168	1	4,000
6	189	1	1,000
7	209	0	0
8	230	0	0

100 (Hrs.) Total Operation Time

REMARKS: 76-30


100
50
HOURS
0
1
2
3
4
5
6
7
8
LEVEL


100
50
COUNTS (X10^3)
0
1
2
3
4
5
6
7
8
LEVEL
76-30