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Committee D02 on Petroleum Products and Lubricants

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Instrumentation Task Force Report to the ASTM Technical Guidance Committee

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INSTRUMENTATION TASK FORCE REPORT

TO THE

ASTM TECHNICAL GUIDANCE COMMITTEE

(ASTM Committee D-2, Subcommittee B)

APRIL 22, 1987

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I. INTRODUCTION

There is a growing use of electronic process measuring instrumentation for supporting the operations of ASTM engine-dynamometer type lubricant tests, particularly those using automated data acquisition systems. This Task Force was formed to develop instrumentation guidelines that will provide uniformity in process measurements throughout this testing industry.

This Task Force was formed in January of 1986. (See Appendix A for membership list.) Meetings were held to discuss instrumentation used by this industry and to develop guidelines for their selection and use. This report is the summary of the findings of this group for implementation in new and existing test procedures.

II. SCOPE & OBJECTIVES

The objective of the Task Force was set to provide performance definitions for instrumentation in STP's 315H and 509A. This involves recommending replacement terminology based on such items as accuracy and frequency response rather than based on brand names or generic types. In order to more clearly define the objective, the following three goals were established.

A. Issue guidelines for instrumentation system specifications with performance definitions for accuracy and frequency response.

B. Issue calibration guidelines and procedures including record keeping.

C. Issue guidelines for showing equivalency.

III. RECOMMENDATIONS

A. PERFORMANCE SPECIFICATIONS

The Task Force agreed that independent of the hardware used, any instrumentation used for enhanced or automated systems must translate data into values of comparable accuracy and frequency response to those obtained with the accepted manual systems. The Task Force's efforts are aimed at defining instrumentation limits for specified operating conditions. The desire would be for the Operations and Hardware (O&H) subpanels to incorporate comparable limits on "record only" values.

1. ACCURACY

The desired accuracy of the measurement is important, but only as important as that parameter is to the test procedure. Based on current instrumentation technology and test procedures, the Task Force recommends the accuracy to be 20% of the test specification deviation, e.g., for $100^{\circ}F \pm 5^{\circ}F$, the accuracy is 20% of $\pm 5^{\circ}F$ which is $\pm 1^{\circ}F$. This limits the worst case actual deviation from test specification to 20% of the allowable deviation above the high or below the low limits. However, there are technical limitations for these values, e.g.:

Temperature:	$\pm 0.5^{\circ}F$
Pressure, low:	$\pm$ 0.05" H_2O
high:	$\pm$ 0.1" Hg.
Speed:	$\pm$ 1 count per gating period

III. RECOMMENDATIONS

A. PERFORMANCE SPECIFICATIONS (Cont'd)

2. FREQUENCY RESPONSE

The desired frequency response of the measured parameters must be established. There are examples of extreme frequency variations in the parameter value, however, only the average value is of interest. It is recommended that this known high frequency variation be attenuated to 20% of allowable test procedure deviation or its normal minimum as outlined in Performance Specification Accuracy section.

Example: Caterpillar Crankcase Vacuum 1 ± 0.5" H_2O (App. D7)

The crankcase vacuum variation, following the movement of the piston at 1800 RPM, has a frequency of 30 Hz. These pressure variations have been measured to be 30" H_2O peak to peak (15" H_2O baseline to peak). Based on the above guideline, it is desired to reduce that variation to 0.1" H_2O (20% of 0.5" H_2O). This requires -43.5 dB (20 log 0.1/15.0) of filtering, of a first order filter with a cutoff frequency of 0.2 Hz ($f_c = f_{noise}\ 10^{dB/20} = 30*10^{-43.5/20}$). The frequency response for a green fluid manometer is 0.64 Hz, hence, the reason for a variating manometer column. For this parameter, it would be desirable to have more filtering than is inherent in a water manometer.

In order to design a reliable instrument measuring system, it is necessary to understand the frequency response capabilities and limitations of the instrument devices that are commonly used. Electronic instruments with high frequency responses shall be allowed to be filtered (mechanically, electrically or digitally) to give equivalent readings to the historically more commonly used manual types of instrument systems with lower frequency responses. See Appendix B for definitions and Appendix C for a list of instrument devices' response characteristics.

B. CALIBRATION GUIDELINES

General guidelines were developed that will apply to all instrumentation systems. The Task Force considers the transmitter (manometer, transducer, etc.), the element (thermocouple, flowmeter, etc.) and the location of the element as parts of the system.

1. The Laboratory calibration standards will be traceable to a defined national standard, e.g., National Bureau of Standards, and be verified at least annually.

2. The time limit for verifying that laboratory equipment meets the laboratory standard is to be as defined in the test procedure. If no time interval is specified in the procedure, then it will be defined by the Operations and Hardware Groups.

3. Test measurement systems shall be calibrated at a frequency as prescribed by the individual test procedures. It is the Task Force's recommendation that all systems be calibrated a minimum of once every six months, or at any time the readout data indicates the need.

III. RECOMMENDATIONS

B. CALIBRATION GUIDELINES (Cont'd)

4. When calibrating a system, it is desirable to check the entire system as a complete unit, but if necessary, a summation of the individual system components calibration would be considered acceptable.

5. All measurement systems shall be checked at a minimum of three points along their operating range where feasible.

6. All calibrations shall be fully documented with complete indication of calibration prior to any adjustments, and what adjustments were made to achieve final calibration. This calibration documentation shall be retained by the laboratory as a permanent record for a minimum of 2 years.

7. Special instrumentation (such as an exhaust gas analyzer) which require zeroing and spanning as a part of the instrument set-up procedures do not have to comply with the above guidelines, but rather the manufacturer's recommendations are to be the guidelines or as prescribed by the test procedure.

C. EQUIVALENCY GUIDELINES

The Task Force realizes that equivalency of measurement systems is extremely important, especially when it comes to maintaining test severity while changing from gages to pressure transducers or from thermocouples to resistance thermal devices (RTDs). The following guidelines are to be used for establishing equivalency of complete systems or any part thereof.

1. The Test Monitoring Center (TMC) is the focal point for presentation of proposed instrumentation technology.

2. The TMC shall approve any proposed instrumentation system after being satisfied that such a system meets all calibration and performance guidelines, which may include concurrent operation with an accepted system.

3. The TMC should decide whether the proposed instrumentation needs more documentation via the following sources:

   a. Operation & Hardware Subpanel
   b. Test Developer
   c. Test Surveillance Panel

4. All documentation obtained during such an equivalency study shall be retained as part of the laboratory's permanent records.

D. OTHER RECOMMENDATIONS

1. The Task Force recommends that each O & H subpanel establish an ad hoc committee to review instrumentation practices for new and existing procedures.

D. OTHER RECOMMENDATIONS (Cont'd)

Pertinent examples are:

a. Pressure measurement specifications should include:

Port size
Port location

Drawings should be provided with exact dimensions.

b. Temperature measurement specifications should include:

Element size
Element location
Element immersion depth

Drawings should be provided with exact dimensions.

c. Flow measurements should be specified in mass units for critical flow applications.

2. In general, it is desirable that allowable parameter deviations be established such that they not exceed the accuracies of measuring devices. However, for a critical measurement which requires an accuracy better than the measuring device, procedures shall be provided detailing the specific techniques to be used to achieve the desired accuracies.

3. Because of the time responses required for certain measurements as discussed in this report, the Instrumentation Task Force has redefined the term DATA POINT from the original definition by the Data Acquisition Task Force.

DATA POINT: The value of a parameter after appropriate digital/analog filtering with due consideration for the time constants of the system. (Many greater than one second).

APPENDIX A

INSTRUMENTATION TASK FORCE MEMBERSHIP

NAME	COMPANY
Trevor A. Brettell, Chairman	Paramins, Exxon Chemical Technology Centre
Herbert E. Harpster, Secretary	The Lubrizol Corporation
Robert J. Belling	General Motors Research Laboratories
Samuel H. Crites	Ethyl Petroleum Additives Division
Robert P. Gauss, Jr.	Southwest Research Institute
John Glaser	EG&G Automotive Research, Inc.
Greg H. Guinther	ASTM Test Monitoring Center
Richard F. Irwin	Chevron Research Company
Herbert H. Kube	Shell Canada, Ltd.
William M. Nahumck	The Lubrizol Corporation
Robert A. Ratliff	EG&G Automotive Research, Inc.
John J. Skuzinski, Jr.	AutoResearch Laboratories, Inc.

APPENDIX B

DEFINITIONS

In order to establish common terminology for discussion of the various aspects in process measurement instrumentation, the following definitions were established.

PRECISION: The degree of mutual agreement between individual measurements from the process (App. E-1).

ACCURACY: The degree of agreement of an individual measurement with an accepted reference level of the property in the material measured (App. E-1).

ORDER: The number of energy storage devices in the system. (Most process systems can be reduced to first order, i.e. one dominant energy storage device.)

FILTER: A means of attenuating signals in a given frequency range. They can be mechanical (volume tank, spring, mass) and/or electrical (capacitance, inductance) and/or digital (mathematical formulas). Typically, a low-pass filter attenuates the unwanted high frequency noise.

DECIBEL (dB): A unit for measuring the ratio of the magnitude of two quantities (normally ouput voltage to input voltage). Calculated as follows:

$$dB = 20*\log(Output/Input)$$

TIME CONSTANT (τ): A value which represents a measure of the time response of a system. For a first order system responding to a step change in input, it is the time required for the output to reach 63.2% of its final value.

CUTOFF FREQUENCY (f_c): The frequency point that divides the frequencies that pass through the system almost unattenuated and the frequencies that pass through the system but are greatly attenuated. For a first order system, this value is calculated as follows:

$$f_c = 1/(2\pi\tau)$$

Where τ is the time constant

DEFINITIONS

SAMPLE FREQUENCY (f_s): The frequency at which a value is obtained for processing. This is normally considered for computer data acquisition, but is also true of a manual reading, i.e. once per hour.

INPUT FREQUENCY (f_{in}): The frequency of the input signal. This is most certainly changing and includes real but unwanted noise. (Normally the noise is a higher frequency than the frequency of the expected signal.)

ALIASING: Sampling-induced low frequency noise. This occurs when the sampling frequency is very close to the input frequency thus creating a beat frequency.

DATA POINT: The value of a parameter after appropriate digital/analog filtering with due consideration for the time constants of the system (many greater than one second).

The following symbols are used in the remaining definitions:

i,j	:	Indices for data parameter or point values
OUT ( )	:	Filtered data point
IN ( )	:	Unfiltered parameter value
EXP ( )	:	Value of e raised to a power
SUM ( )	:	A summation of values

FIRST ORDER DIGITAL FILTER: The digital equivalent to a first order analog filter (electrical or mechanical). The formula is as follows:

$$OUT(i) = EXP(-1/(f_s \tau))*OUT(i-1) + [1-EXP(-1/(f_s \tau))]*IN(i)$$

ROLLING AVERAGE DIGITAL FILTER: A digital filter that continually calculates the average of the most recent values over the rolling time period, T_{RA}. The formula is as follows:

$$OUT(i) = SUM\ [IN(j), j= i-f_s T_{RA}+1 \text{ to } i]/f_s T_{RA}$$

BLOCK AVERAGE DIGITAL FILTER A digital filter that calculates the average of the values over the block time period, T_{BA} and maintains that result until the next block of values has been collected and calculated. The formula is as follows:

$$OUT(i) \text{ thru } OUT(i+T_{BA}f_s-1) = SUM\ [IN(j), j= i-f_s T_{BA}+1 \text{ to } i]/f_s T_{BA}$$

APPENDIX C

INSTRUMENT DEVICES' RESPONSE CHARACTERISTICS

Manometers (App. D2):

Green Fluid, SG = 1	f_c = 0.64 Hz	τ = 0.25 s
Mercury	f_c = 0.83 Hz	τ = 0.19 s
100% Glycol	f_c = 0.22 Hz	τ = 0.72 s

Bourdon Tube (App. D6):	f_c = 0.03 Hz	τ = 5.31 s
Strain Gage (App. D6):	f_c = 1500 Hz	τ = 0.11 ms

Thermocouples (App E-2):

For grounded devices in air

1/8"	f_c = 0.012 Hz	τ = 13 s
3/16"	f_c = 0.006 Hz	τ = 24 s
1/4"	f_c = 0.004 Hz	τ = 44 s

Resistance Thermal Device (RTD) (App E-3):

For 1000-Ω device in water

1/8"	f_c = 0.080 Hz	τ = 2 s
3/16"	f_c = 0.053 Hz	τ = 3 s
1/4"	f_c = 0.040 Hz	τ = 4 s

Thermocouples (App. D3):

For Type J grounded in oil (32°F to 300°F)

1/8"	f_c = 0.028 Hz	τ = 5.67 s
3/16"	f_c = 0.017 Hz	τ = 9.45 s
1/4"	f_c = 0.009 Hz	τ = 17.27 s

Resistance Thermal Device (RTD) (App. D3)

For 1000-Ω closed ungrounded device in oil (32°F to 300°F)

3/16"	f_c = 0.011 Hz	τ = 14.28 s

APPENDIX C (Cont'd)

INSTRUMENT DEVICES' RESPONSE CHARACTERISTICS

Liquid Rotameter, IIID Test (App D6)	f_c = 0.035 Hz	τ = 4.54 s
Liquid Mass Flow by Weight	f_c = 0.0016 Hz	T_{BA} = 100 s
Gas Volume Flow by Natural Gas Meter	f_c = 0.0005 Hz	T_{BA} = 300 s
Speed by Gated Counter	f_c = 0.16 Hz	T_{BA} = 1 s

APPENDIX D

DATA INDEX

FOR REFERENCE DATA GENERATED

BY INSTRUMENTATION TASK FORCE MEMBERS

D1. Static and Dynamic Parameter Limits for Sequence Tests, by Data Acquisition Task Force, 1985. p. 11

D2. Manometer Responses for Different Fluids, by Bob Ratliff, EG&G, 1986. p. 17

D3. RTD and T/C Response Times, by Bob Ratliff, EG&G, 1986. p. 21

D4. Caterpillar Fuel Pressure Responses, by Trevor Brettell, Exxon, 1986. p. 23

D5. Buick IIIE Responses for Controlled Parameters, from an Automated Stand, by Bob Belling, GMR, 1986. p. 26

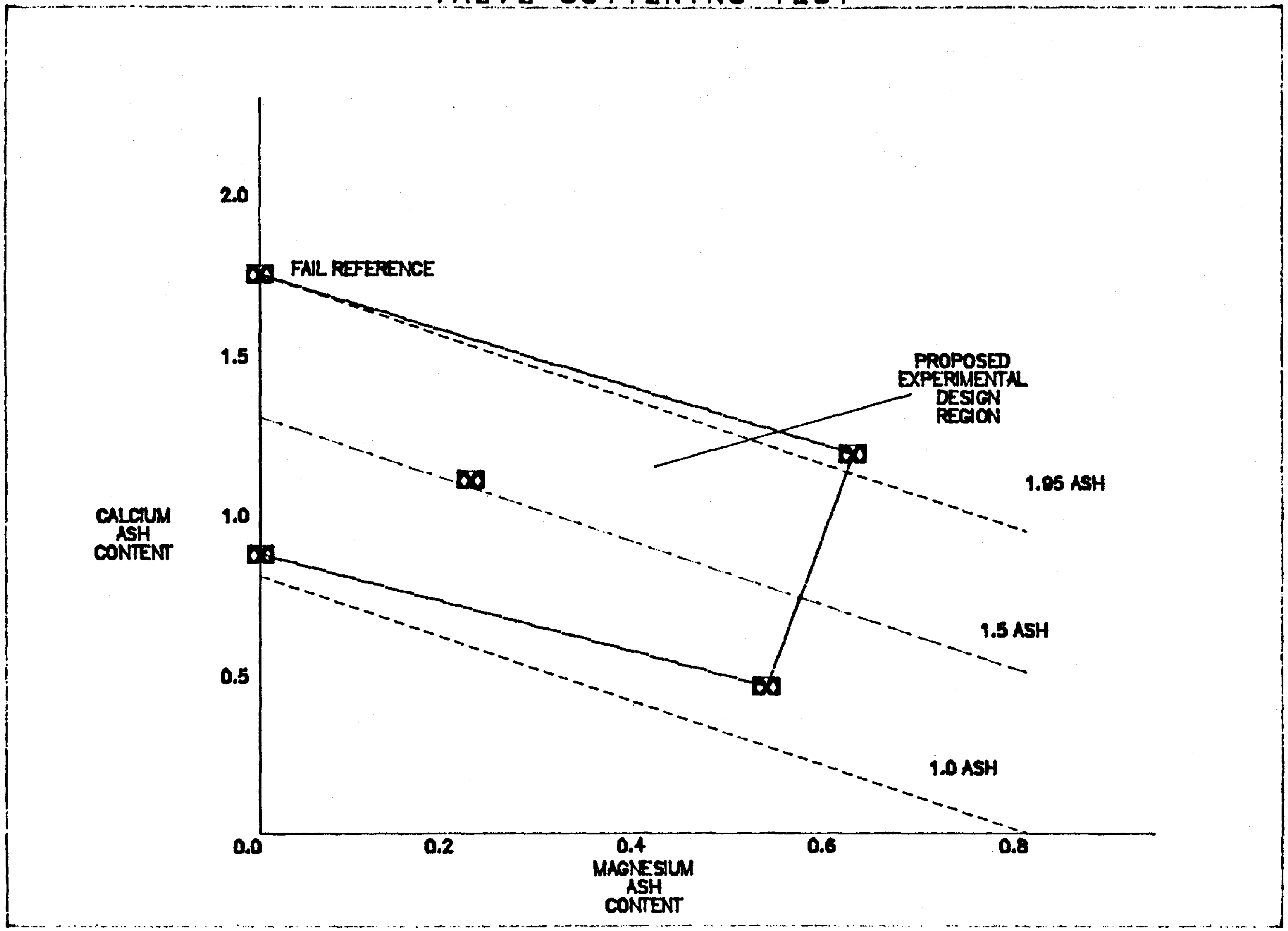
D6. Buick IIIE Responses for Controlled Parameters from a Manual Stand, by Bob Belling, GMR, 1986. p. 43

D7. Pressure Responses (Ford V-D Exhaust, Caterpillar Boost and Crankcase), by Bob Gauss, SWRI, 1986 & 1987. p. 49

D8. Relationship Between Types of Filters, by Herb Harpster, Lubrizol, 1986. p. 53

DETROIT DIESEL 8V-71

VALVE GUTTERING TEST



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APPENDIX D1

"Suggested Static and Dynamic Limits for Rejecting Bad Quality Data"

SEQUENCE IIID TEST

PARAMETER			STATIC LIMITS MINIMUM	MAXIMUM	RATE OF CHANGE LIMITS	
Average speed	RPM		0	4000	Up:	88 RPM/sec
					Down:	165 RPM/sec
Brake Load	Lb-ft	Hot	0	200		
		Cold	0	100		
B.H.P.			0	150		
Oil at filter block	Deg F	Hot	32	400	Up:	20 Deg F/min
		Cold		150	Down:	60 Deg F/min
Oil pan temperature	Deg F	Hot	32	400	Up:	20 Deg F/min
		Cold		150	Down:	60 Deg F/min
Oil pump outlet press	psi	Hot	0	120		30 psi/sec
Oil, engine pressure	psi	Hot	0	120		30 psi/sec
Coolant, jacket out	Deg F	Hot	32	300	Up:	12 Deg F/min
		Cold	32	150	Down:	28 Deg F/min
Coolant, jacket in	Deg F	Hot	32	300	Up:	12 Deg F/min
		Cold	32	150	Down:	28 Deg F/min
Coolant, jacket flow	GPM		0	100		5 GPM/min
Coolant, Breather out	Deg F	Hot	32	300	Up:	12 Deg F/min
		Cold	32	150	Down:	28 Deg F/min
Coolant, left cover out	Deg F	Hot	32	300	Up:	12 Deg F/min
		Cold	32	150	Down:	28 Deg F/min
Coolant, rt cover out	Deg F	Hot	32	300	Up:	12 Deg F/min
		Cold	32	150	Down:	28 Deg F/min
Coolant, crossover out	Deg F	Hot	32	300	Up:	12 Deg F/min
		Cold		150	Down:	28 Deg F/min
Coolant, cover-breather flow	GPM		0	10		
Coolant, Xover flow	GPM		0	10		
Coolant, jacket out	Deg F		32	300	Up:	12 Deg F/min
					Down:	28 Deg F/min
Coolant, jacket in	Deg F		32	300	Up:	12 Deg F/min
					Down:	28 Deg F/min
Coolant, Xover out	Deg F		32	300	Up:	12 Deg F/min
					Down:	28 Deg F/min

"Suggested Static and Dynamic Limits for Rejecting Bad Quality Data"

<u>SEQUENCE IID TEST</u> (continued)

PARAMETER		STATIC LIMITS MINIMUM	MAXIMUM	RATE OF CHANGE LIMIT
Air Fuel ratio		0	20	
Fuel inlet temp	Deg F	0	150	
Carb air temp	Deg F	32	100	10 Deg F/min
Humidity	Gr/lb	0	100	
Carb Air pressure	InH20	-200	1	
Ambient Air Temp	Deg F	0	150	
Blowby gas outlet temp	Deg F	32	350	
Blowby	CFM	0	3	
Right exhaust pressure	InH20	0	50	
Left exhaust pressure	InH20	0	50	
Diff. exhaust pressure	InH20	0	2	
Intake Vacuum	InHG	0	35	
Intake mixture temp	Deg F	32	150	
Crankcase pressure	InH20	0	5	Up: 1.6 In H_2O/sec Down: 5 In Hg/sec

"Suggested Static and Dynamic Limits for Rejecting Bad Quality Data"

SEQUENCE IIID TEST

PARAMETER		STATIC LIMITS MINIMUM	STATIC LIMITS MAXIMUM	RATE OF CHANGE LIMIT
Average speed	RPM	0	4000	Up: 88 RPM/sec Down: 165 RPM/sec
Brake Load	Lb-ft	0	200	
B.H.P.		0	150	
Oil at filter block	Deg F	32	400	Up: 20 Deg F/min Down: 60 Deg F/min
Oil pan temperature	Deg F	32	400	Up: 20 Deg F/min Down: 60 Deg F/min
Oil pump outlet press	psi	0	100	30 psi/sec
Oil, engine pressure	psi	0	100	30 psi/sec
Coolant, jacket out	Deg F	32	300	Up: 12 Deg F/min Down: 28 Deg F/min
Coolant, jacket in	Deg F	32	300	Up: 12 Deg F/min Down: 28 Deg F/min
Coolant, jacket flow	GPM	0	100	
Coolant, Breather out	Deg F	32	300	Up: 12 Deg F/min Down: 28 Deg F/min
Coolant, left cover out	Deg F	32	300	Up: 12 Deg F/min Down: 28 Deg F/min
Coolant, rt cover out	Deg F	32	300	Up: 12 Deg F/min Down: 28 Deg F/min
Coolant, cover flow	GPM	0	10	
Coolant, breather tube flow	GPM	0	10	
Air Fuel ratio		0	20	
Fuel inlet temp	Deg F	0	150	
Carb air temp	Deg F	32	100	10 Deg F/min
Humidity	Gr/lb	0	100	
Carb Air pressure	InH2O	-200	1	
Ambient Air Temp	Deg F	0	150	
Blowby gas outlet temp	Deg F	32	350	
Blowby	CFM	0	3	
Right exhaust pressure	InH2O	0	50	
Left exhaust pressure	InH2O	0	50	
Diff. exhaust pressure	InH2O	0	2	
Intake Vacuum	InHG	0	35	
Intake mixture temp	Deg F	32	150	
Crankcase pressure	InH2O	0	5	Up: 1.6 InH2O/sec Down: 5 InHg/sec
Spark timing	BTDC	0	60	

"Suggested Static and Dynamic Limits for Rejecting Bad Quality Data"

SEQUENCE V-0 OPERATING REGIME

		Phase I (Rate/Chg.)	Phase II (Rate/Chg.)	Phase III (Rate/Chg.)
Speed, RPM	Max.	7000	7000	7000
	Min.	0	0	0
Torque, ft-lbs	Max.	130	130	130
	Min.	0	0	0
Oil In, °F	Max.	350 (5.0 °F/min.)	350 (3.5 °F/min.)	350 (1.7 °F/min)
	Min.	50 (1.0 °F/min.)	50 (2.0 °F/min.)	50 (1.7 °F/min)
Coolant Out, °F	Max.	240 (15.0 °F/min)	240 (14.4 °F/min)	240 (3.6 °F/min)
	Min.	32 (2.2 °F/min)	32 (10.0 °F/min)	32 (2.0 °F/min)
Carb. Air, °F	Max.	250 (3.2 °F/min)	250 (3.2 °F/min)	250 (3.2 °F/min)
	Min.	32 (3.3 °F/min)	32 (3.3 °F/min)	32 (5.0 °F/min)
Carb. Air Press., In. H_2O	Max.	20	20	20
	Min.	-200.0	-200.0	-200.0
Cooldown Time, Minutes	Max.	---	---	---
	Min.	---	---	5 (9.0 °F/min)
DewPoint, °F	Max.	110	110	110
	Min.	32	32	32
Exhaust Back Press., In. H_2O	Max.	400	400	400
	Min.	0	0	0
Blowby Coolant, °F	Max.	240 (15.0 °F/min)	240 (14.4 °F/min)	240 (3.6 °F/min)
	Min.	32 (2.2 °F/min)	32 (10.0 °F/min)	32 (20.0 °F/min)
Blowby Gas, °F	Max.	350	350	350
	Min.	32	32	32
Marine Manifold, °F	Max.	240	240	240
	Min.	32	32	32
Int. Vacuum, In. Hg.	Max.	33	33	33
	Min.	0	0	0
Timing	Max.	76°BTDC	76°BTDC	50°BTDC
	Min.	7°ATC	7°ATC	7°ATC
Barom. Press., In. Hg.	Max.	---	33	---
	Min.	---	20	---
Crank. Press., In. H_2O	Max.	20	20	20
	Min.	-10	-10	-10
Fuel Flow, lb/hr	Max.	25.0	25.0	10.0
	Min.	0	0	0

"Suggested Static and Dynamic Limits for Rejecting Bad Quality Data"

L-38 TEST

PARAMETER		STATIC LIMITS MINIMUM	MAXIMUM	RATE OF CHANGE LIMIT	
Average speed	RPM	0	6000	Up: Down:	88 RPM/sec 165 RPM/sec
Brake Load	Lb-ft	0	32.6		
B.H.P.		0	13.5		
Intake air to engine	Deg F	32	160		10 Deg F/min
Dynamometer water	Deg F	32	212		
Water In	Deg F	32	212	Up: Down:	12 Deg F/min 28 Deg F/min
Water Out	Deg F	32	212	Up: Down:	12 Deg F/min 28 Deg F/min
Oil Gallery	Deg F	32	400	Up: Down:	10 Deg F/min 22 Deg F/min
Oil Sump	Deg F	32	400	Up: Down:	10 Deg F/min 14 Deg F/min
Heater	Watts	0	3000		
Intake Pressure or vac.	InHg	-0.5	-15		
Crankcase vacuum	InH2O	-15	15	Up: Down:	1.6 InH2O/se 5 · InHg/sec
Exhaust Back press.	InHg	-2	10		1.2 InHg/sec
Oil Gallery Press.	psi	0	100		30 psi/sec
Fuel time	sec/lb	0	400		
Intake air	lb/hr	0	185		
Rocker Air flow	CFH	0	40		
Off gas flow	CFH	0	40		

"Suggested Static and Dynamic Limits for Rejecting Bad Quality Data"

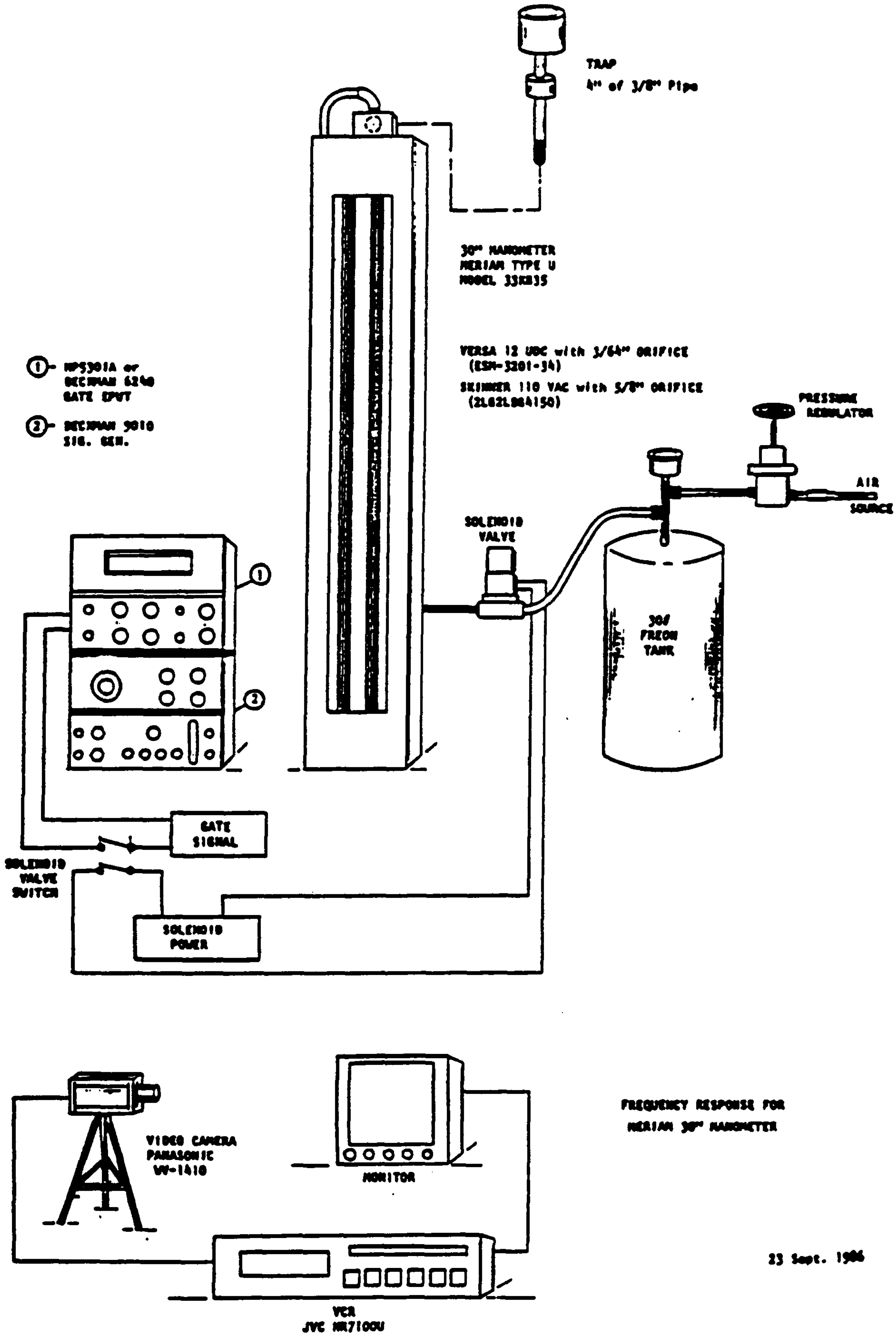
CATERPILLAR 1H AND 1G TESTS

PARAMETER		STATIC LIMITS MINIMUM	STATIC LIMITS MAXIMUM	RATE OF CHANGE LIMIT
Average Speed	R.P.M.	0	2600	100 RPM/sec
B.H.P.		0	55	
Humidity	Grains/LB	0	300	10 Gr/LB/min
Intake Air to Engine	Deg F	40	350	4 Deg F/min
Water In	Deg F	40	220	14 Deg F/min
Water Out	Deg F	40	220	14 Deg F/min
Coolant Delta	Deg F	0	20	
Oil Gallery	Deg F	40	220	18 Deg F/min
Oil Cooler Inlet	Deg F	40	220	18 Deg F/min
Exhaust Temperature	Deg F	60	1300	
Boost pressure	In Hg	27	60	1 In Hg/sec
Crankcase vacuum	In H2O	-5	5	
Exhaust back pressure	In Hg	0	20	
Fuel pressure	psi	0	100	
Oil Gallery pressure	psi	0	100	16 psi/min
Cooling jet pressure	psi	0	100	16 psi/min
B.T.U. / Minute		0	6500	
Blowby	C.F.H.	0	80	

MANOMETER STEP RESPONSE DATA SYNOPSIS

Fluid	Orifice	Time (Seconds) To % F.S. (30")			Frequency Response (Hz)	
		10%	63%	90%	.4/(90%-10%)	.159/63%
Hg	5/8"	.10	.35	.58	.83	.45
	3/64"	.20	.46	.70	.80	.35
#4 Green S.G.=1.000	5/8"	.10	.43	.72	.64	.37
	3/64"	.15	.45	.79	.63	.35
100% Glycol 1 Tube	5/8"	.12	.76	1.93	.22	.21
	3/64"	.20	.94	2.96	.14	.17
100% Glycol 2 Tubes	5/8"	.15	.93	2.55	.17	.17
	3/64"	.20	1.36	3.60	.12	.12

9/23/86


TRAP
30" MANOMETER
MERIAN TYPE U
VERSA 12 UDC with 3/64" ORIFICE
SKINNER 110 VAC with 5/8" ORIFICE
PRESSURE REGULATOR
AIR SOURCE
SOLENOID VALVE
FREON TANK
GATE SIGNAL
SOLENOID VALVE SWITCH
SOLENOID POWER
VIDEO CAMERA
PANASONIC
MONITOR
VCR
JVC HR7100U
FREQUENCY RESPONSE FOR
MERIAN 30" MANOMETER
23 Sept. 1986

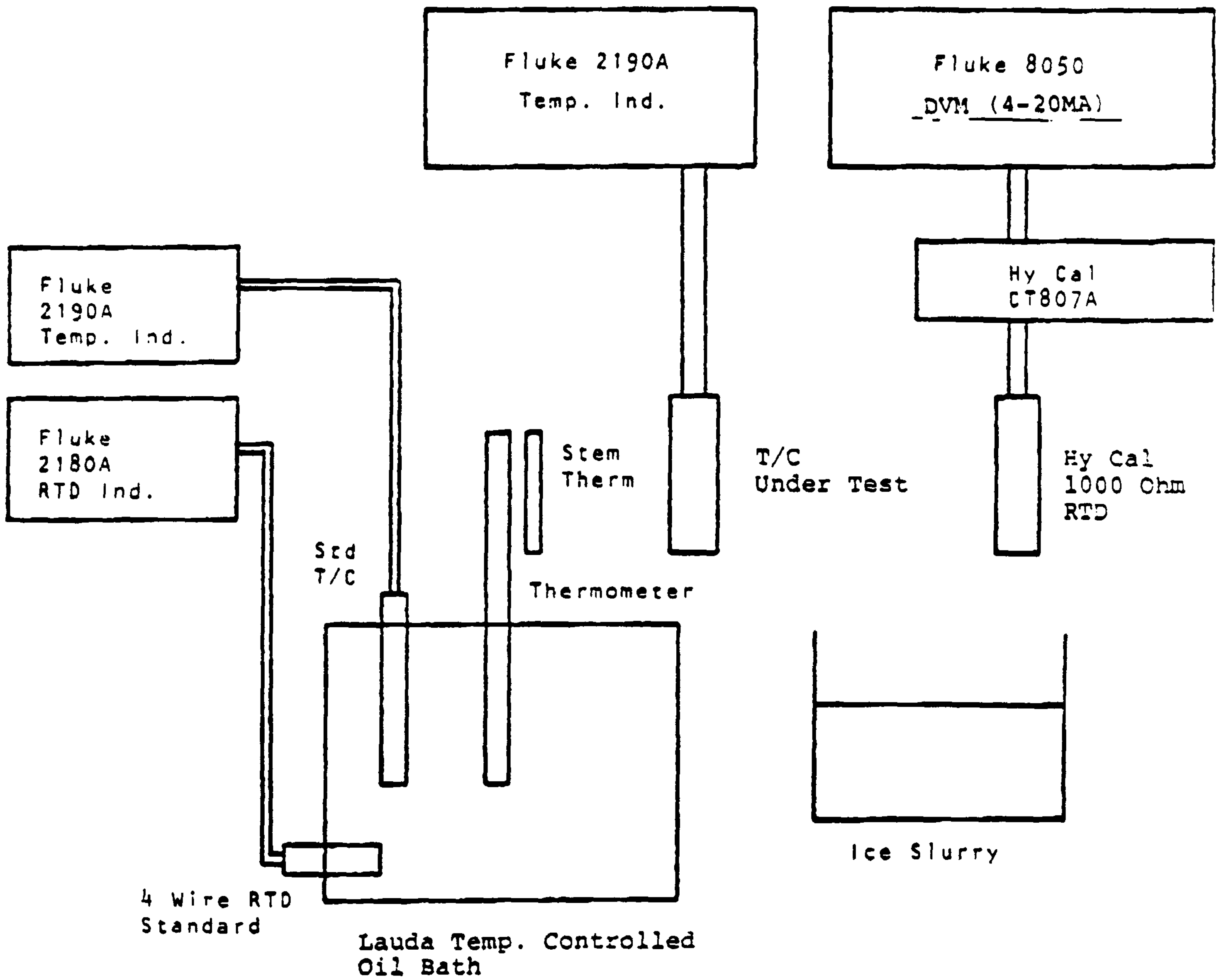
RTD AND T/C RESPONSE TIMES

Probe Type	Length In.	Depth In.	Oil Temp °F	99% Sec	63% Sec	$f = \frac{2\pi}{63\%}$ Hz
3/16 RTD Closed	6	1.87	200	50.16	15.83	.010
			300	44.89	14.28	.011
3/16J T/C Closed	6	1.87	200	37.35	11.07	.014
			300	28.39	9.45	.017
3/16J T/C Closed	3	1.87	200	42.67	12.01	.013
			300	32.11	9.81	.016
1/8J T/C Closed	6	1.25	200	22.70	6.47	.025
			300	17.63	5.67	.028
1/4J T/C Flex Closed	6	2.50	200	70.70	21.04	.008
			300	54.00	16.77	.009
1/4J T/C Closed	4	2.50	200	78.18	21.53	.007
			300	60.28	17.27	.009
1/4J T/C Open	3	2.50	200	30.24	3.82	.042
			300	17.81	2.59	.061

Times are averaged for 4-5 repeats per point.

Robert Ratliff
EG&G-AR
10/27/86

EQUIPMENT SKETCH

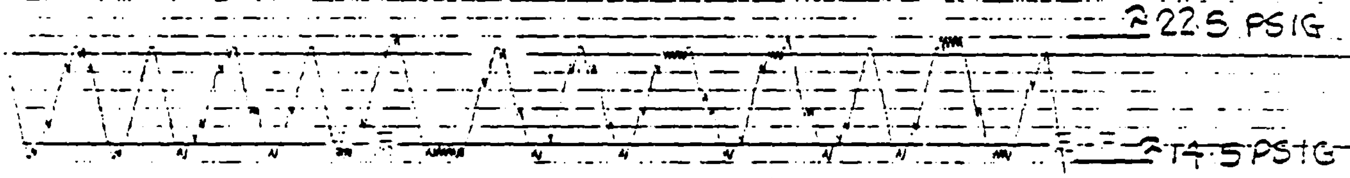


Notes:

1. Immersion depth quite critical for repeatable readings. Fixtures in both mediums were required.
2. Ice bath measured with standards prior to readings. Range was 31.5°F to 32.0°F.
3. Oil bath was set to 200.0°F and 300.0°F.

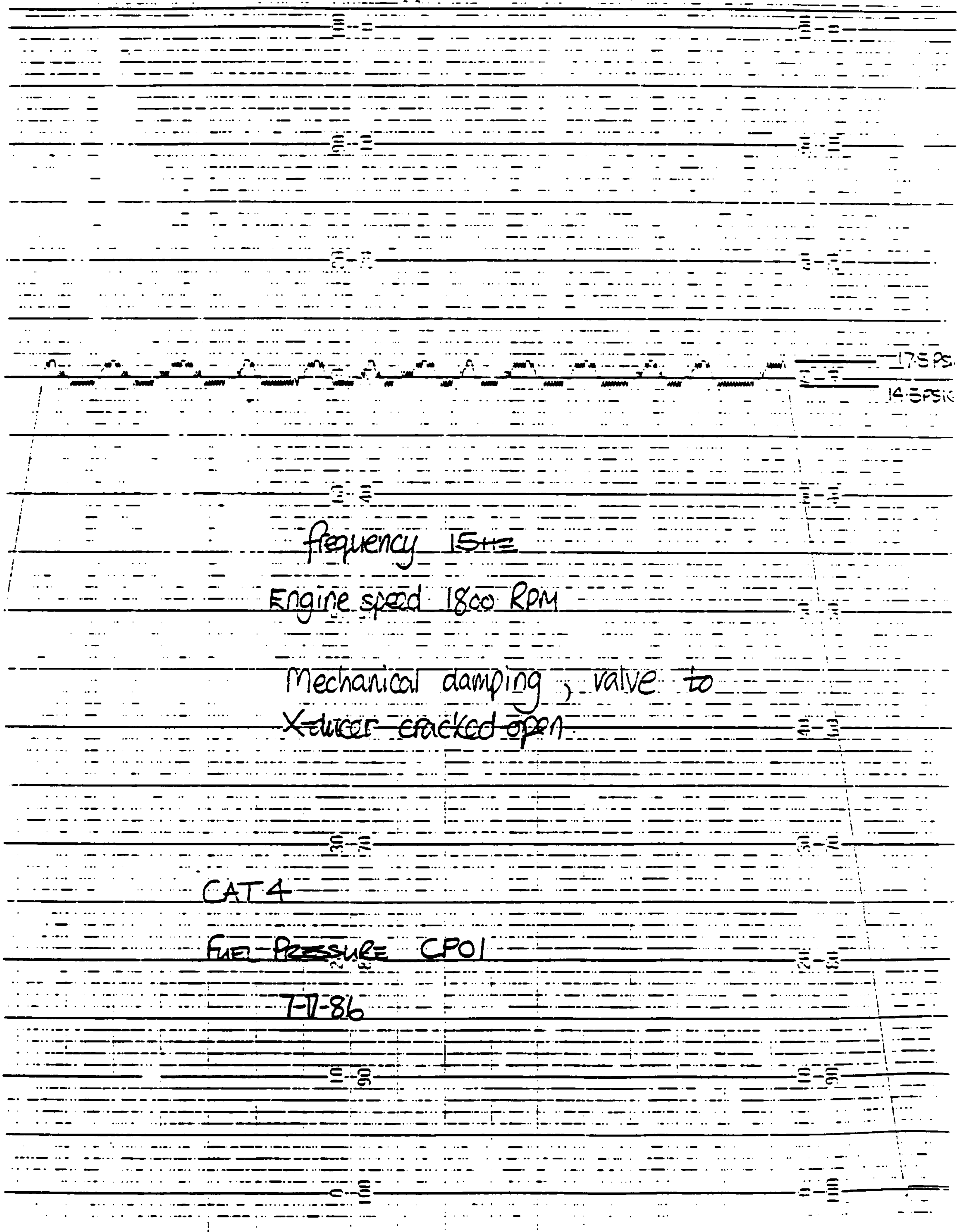
EG&G-AR
Robert Ratliff
10-27-86

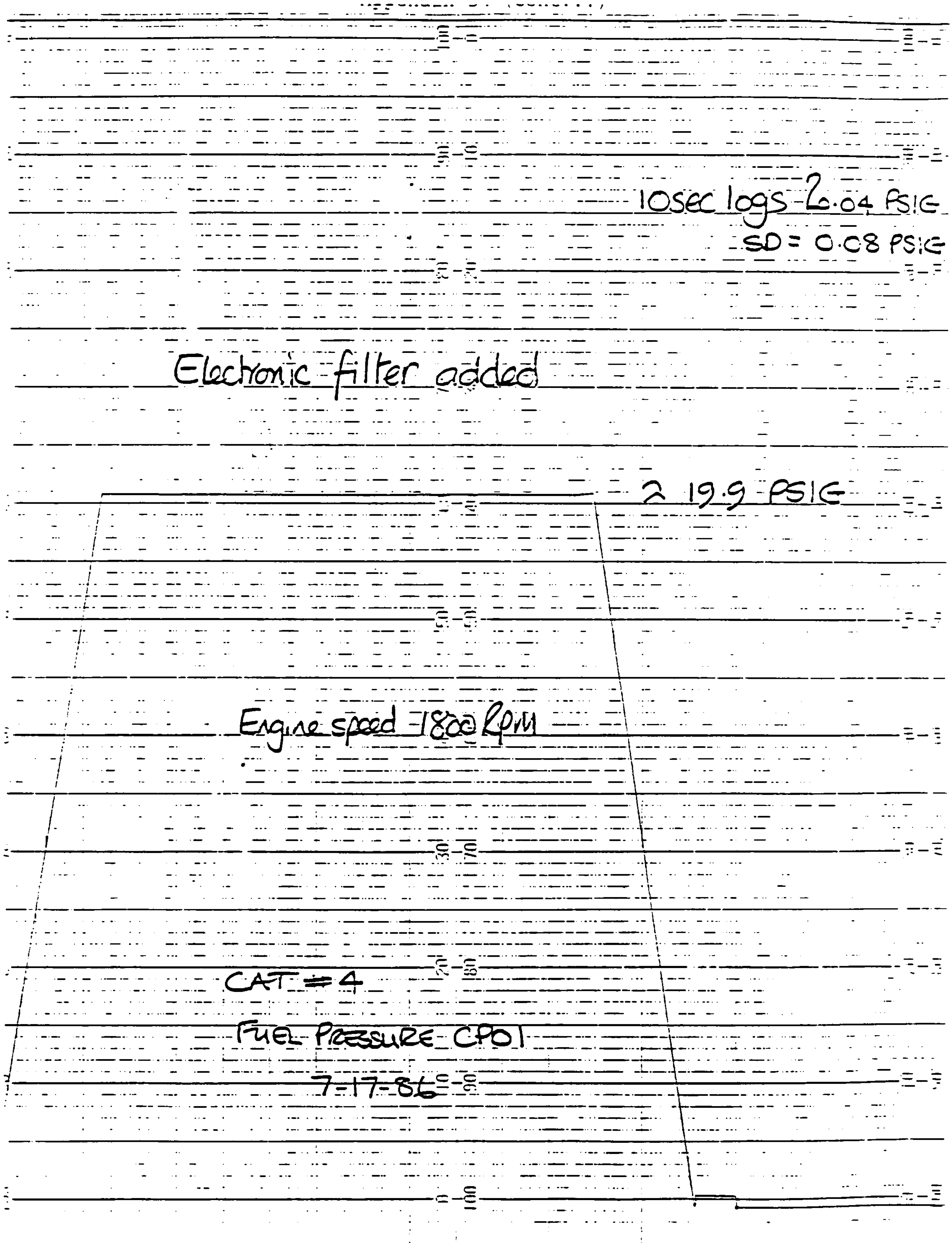
10sec logs 18.34 psig mean
SD = 2.46 psig



frequency 15Hz
Engine speed 1800 RPM
No damping

CAT #4
FUEL PRESSURE CP01
7-17-86


17.5 PSI
14.5 PSIG
frequency 15Hz
Engine speed 1800 RPM
Mechanical damping, valve to
X-ducer cracked open
CAT 4
FUEL PRESSURE CP01
7-11-86


10sec logs 2.04 PSIG
SD = 0.08 PSIG
Electronic filter added
2 19.9 PSIG
Engine speed 1800 RPM
CAT = 4
FUEL PRESSURE CP01
7-17-86

8-1-86

filename: tcel\TC14resp.S86

R.Belling (FL)
D.Smolenski (FL)

J.Howes
R.Tidrow

Users Request:

We have been asked to indicate the frequency response of the control systems in TC-14. We understand the interest is to determine the system response using the automatic technique versus previously used manual processes.

A series of curves were provided to help develop a statement of the system response for each of several parameters. The curves are the output signal to some step input change. Two curves for each output were provided, one an expanded section of the first.

General Statements of the system:

In general the response of a system is based on the change in the output for some change on the input. Ideally the input command is a step change. There might be some latency or delay time before the output reacts to the input change, this should be considered in the statement of response. We did review the files on the TC-14 disk and find the particular recordings. The command step is not documented. We had neglected to ask Belling for this info.

Our statement of response is based only on the curves provided.

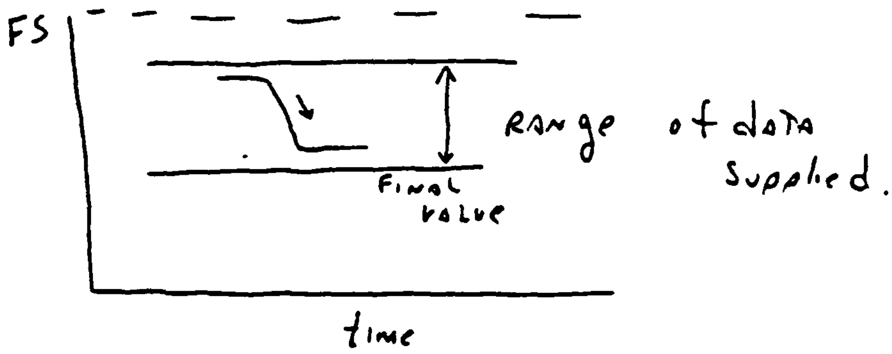
Several of the output curves have characteristics which display some of the forcing functions we would expect from the control algorithms, such as a large fast change and then a tapering off as it nears the final value, rather than a purely underdamped or overdamped response curve. While this varies from the text book variety the general features suggest our use of the standard formula should be acceptable.

We understand R.Belling tried not to incorporate any additional pre-analog filtering nor any special digital filtering to better simulate what the other users might have with their manual systems. The CATS system does have 1.5 Hz anti aliasing passive filters on the Computer Products Inc analog input channels. The PID control loop constants assigned (gain, integral and differenial factors) in the CATS software act as system filters. We don't have numbers that we can pre-assign to these effects, so presently rely on test output characteristics. The control can be speeded up or slowed down by changing these factors. R.Belling has them operating at the speed he feels is right.

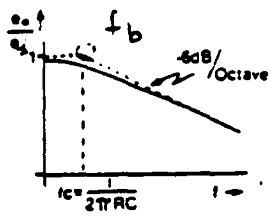
Users Test Data:

The analog plots supplied by the user show a control step of some finite value.

This step change may only be a small portion of the full range. In developing a statement of the time it takes for the output circuit to reach the final level we are considering the final value shown on the plots to be the full scale range. This could be intapreted as a small signal change and may not accurately describe the time to reach the final level over a large command change.



The frequency vs amplitude ratio plot (Bode plot) is frequently used when describing signal circuits and is used by the designer when developing the separate blocks of the control system. The Bode plot shows at what frequency the circuit will begin to attenuate signals. We've include the breakpoint frequency (point where the signal is attenuated 3 db) of such a plot in specifying each circuit.



Bode Plot

Based on the above discussion we've made a statement of the response time, that describes the output curve in a general sense. We have guessitimated the command start location in 'time' to have the calculated response better match the real input signal.

The response is stated in terms of the time to reach approximately 99% of the final value (usually considered 5 time constants, but in our curve interpretation the value is reached much sooner). The time period is listed in seconds and in time constants (which is based on the time for the first time constant). The frequency break point value used in the Bode plot is also shown.

Based on standard formulas one time constant is 63.8% of final value and 5 time constants is 99% of final value. We will consider the final value as the average final level as shown in the plots.

In the case of TC-14;

1. Flow:

a. Breather Tube Coolant Flow:

Time for final value (~ 99%), 1.34 seconds.
, 1.62 Time Constants.

The break point frequency from the formula

F(break) = 1/(2*PI*time constant)
, 0.194 or ~ 0.2 Hz

These values would be different if a delay time were added. The final value time would be longer and the frequency would be slower.

b. Right Rocker Cover Coolant Flow;

Time for final value (~99%), ~30 seconds.
, eql or 20 TC's.

F(break) = 1.0 Hz

The higher freq appears in error but its calculated on one time constant where the output slews rapidly then the output slows down as it nears the final value.

c. Rocker Flow;

Time for final value (99%), 1.7 seconds.
, 5.17 TC's

F(break) = 0.9 Hz

d. Water Flow Through the Cooling Jacket;

Time for final value (99%), 7.9 seconds,
, 1.6 TC's.

F(break) = 0.03 Hz

2. Pressure;

a. Carburetor Air Pressure;

Time for final value (99%), 10 seconds,
, 4 TC's.
(Really need trailing edge of control curve)

F(break) = 0.06 Hz

b. Engine Oil Pressure:

Time for final value (99%), 8.3 seconds,
, 2.25 TC's.

F(break) = 0.04 Hz

c. Left Exhaust Pressure;

Time for final value (99%), 16 seconds,
, 2 TC's.

F(break) = 0.01 Hz

3. Engine Torque;

Time for final value (99%), 5.8 seconds,
, 2.4 TC's.

F(break) = 0.06 Hz.

4. Dyno Speed:

Time for final value (99%), 5.8 seconds.
, 2 TC's.

F(break) = 0.05 Hz.

The user may determine the above analysis is sufficient. We'll leave it to your descretion. We plan to use the TC-14 site as an example of our systems and will document the operation in more detail.

R.Spain

References:

Plot reproduced from;

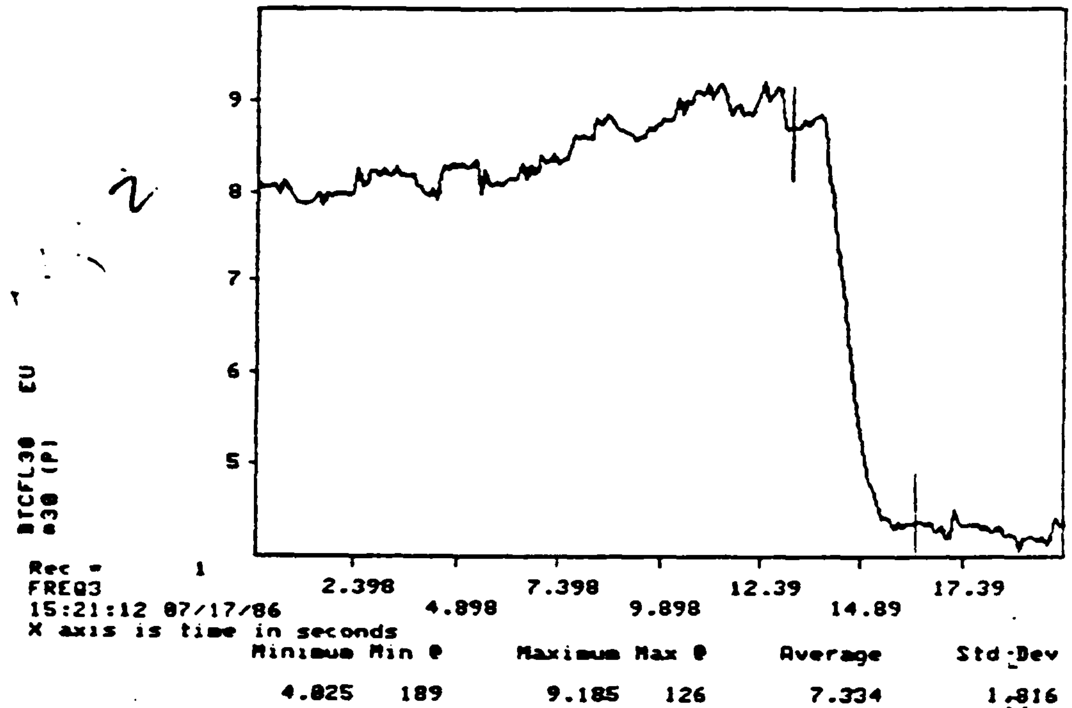
"Active Filter Products: Design and Selection" manual, by
Frequency Devices Inc,
25 Locust Str,
Haverhill, Mass, 01830

Articles:

"Frequency Response of The Process",
Instruments and Control Systems", Vol 36, Pg 136, Sept 1963.

"Frequency Response Analysis", ISA Journal,Feb 1962, Vol 9,
No. 2, Pg 25.

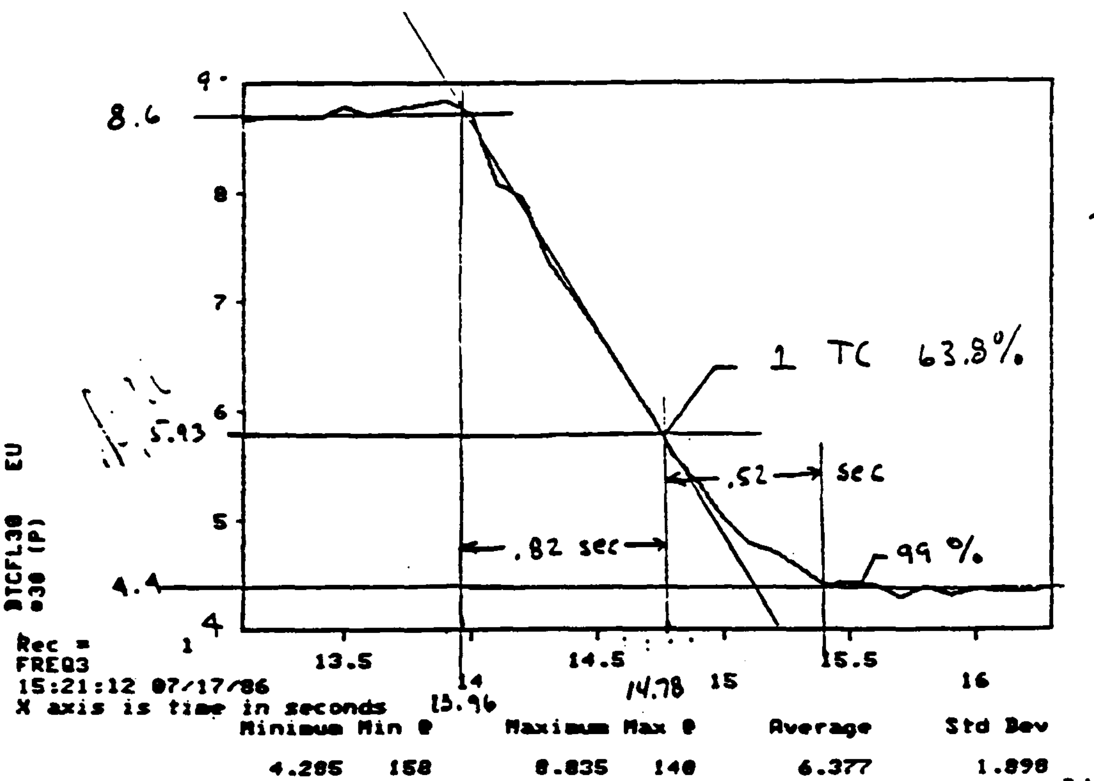
BTCFL30 Breather Tube Coolant Flow



Breather Tube coolant flow

(4)

BTC FL 30



$TC = \frac{1}{2\pi f_{break}}$

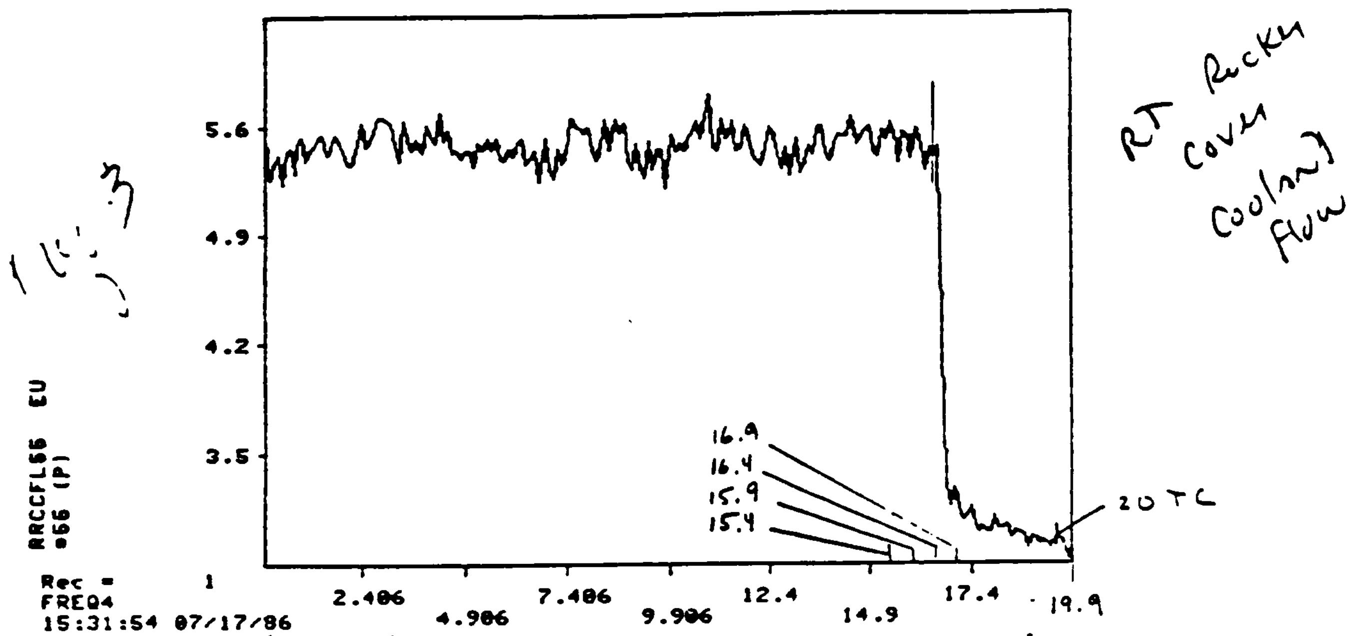
f_b = 3 db pt

$f_b \simeq 0.2$ Hz

(6)

RRCCFL55 Right Rocker Cover CoolantFlow

12

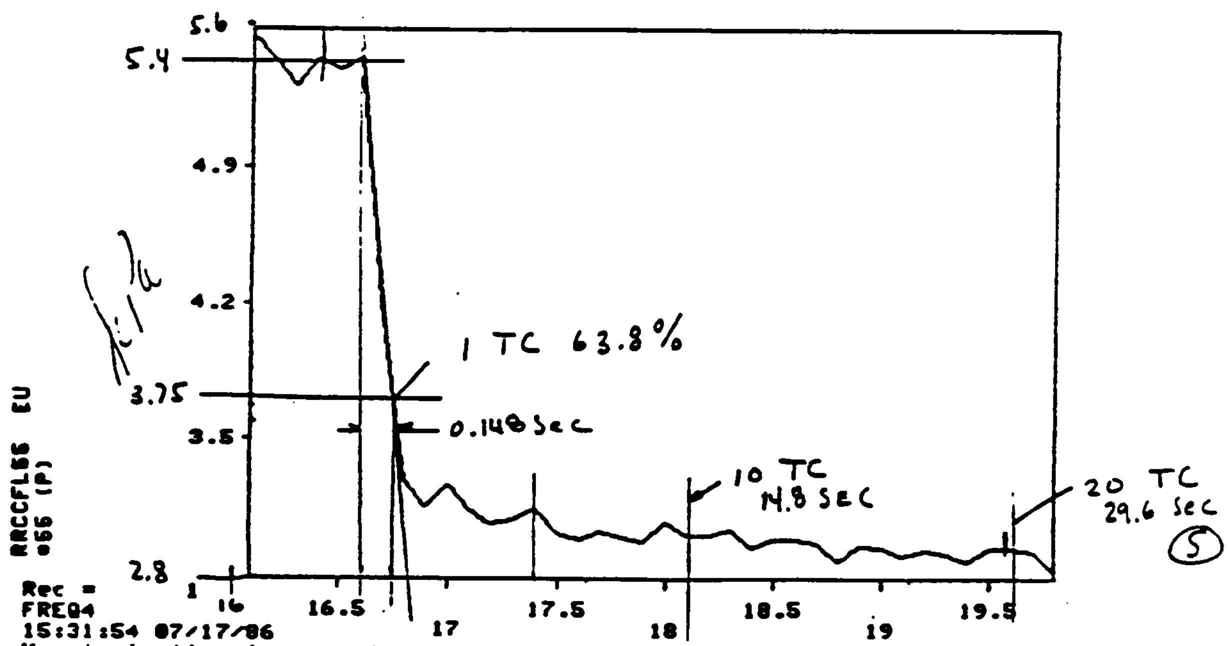


Rec = 1
FREQ4
15:31:54 07/17/86
X axis is time in seconds

Minimum	Min @	Maximum	Max @	Average	Std Dev
2.822	199	5.786	118	5.07	.9114
3.396	161	4.929	144	3.991	.5818

6

RRCCFL55



Rec = 1
FREQ4
15:31:54 07/17/86
X axis is time in seconds

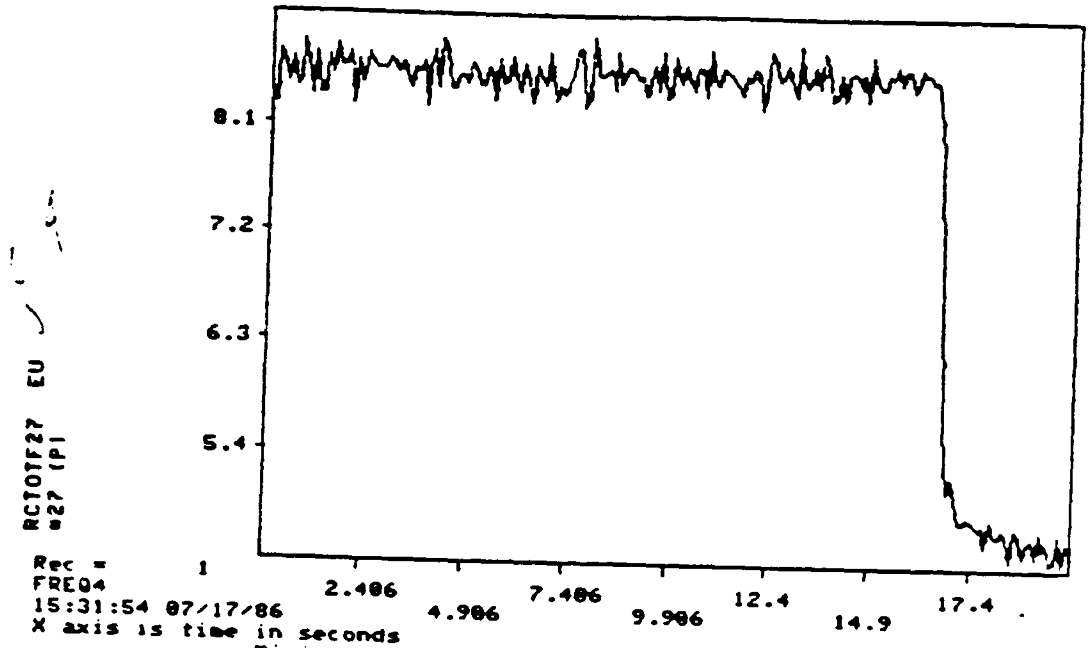
Minimum	Min @	Maximum	Max @	Average	Std Dev
2.822	199	5.554	162	3.427	.9053

5

RCTOTF27

Rocker Cover flow

3

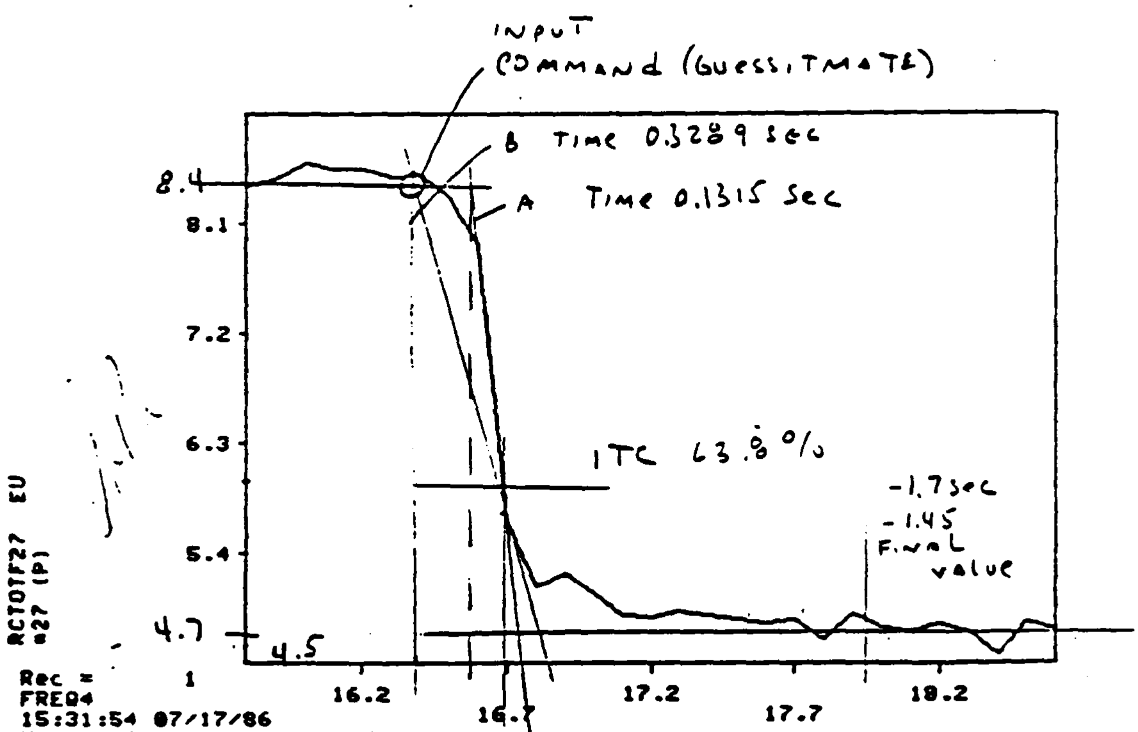


Rec = 1
FREQ4
15:31:54 07/17/86
X axis is time in seconds

Minimum	Min @	Maximum	Max @	Average	Std Dev
4.519	198	8.816	80	7.894	1.386

5

RCTOTF27



Rec = 1
FREQ4
15:31:54 07/17/86
X axis is time in seconds

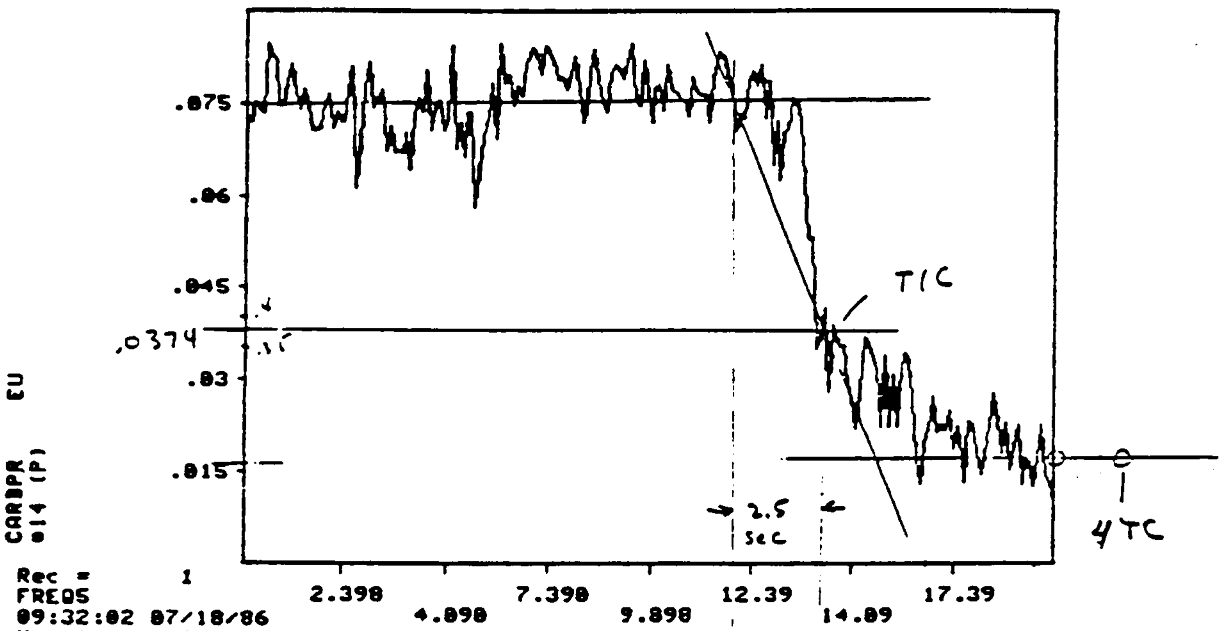
Minimum	Min @	Maximum	Max @	Average	Std Dev
4.563	185	8.595	161	5.988	1.674

7

4

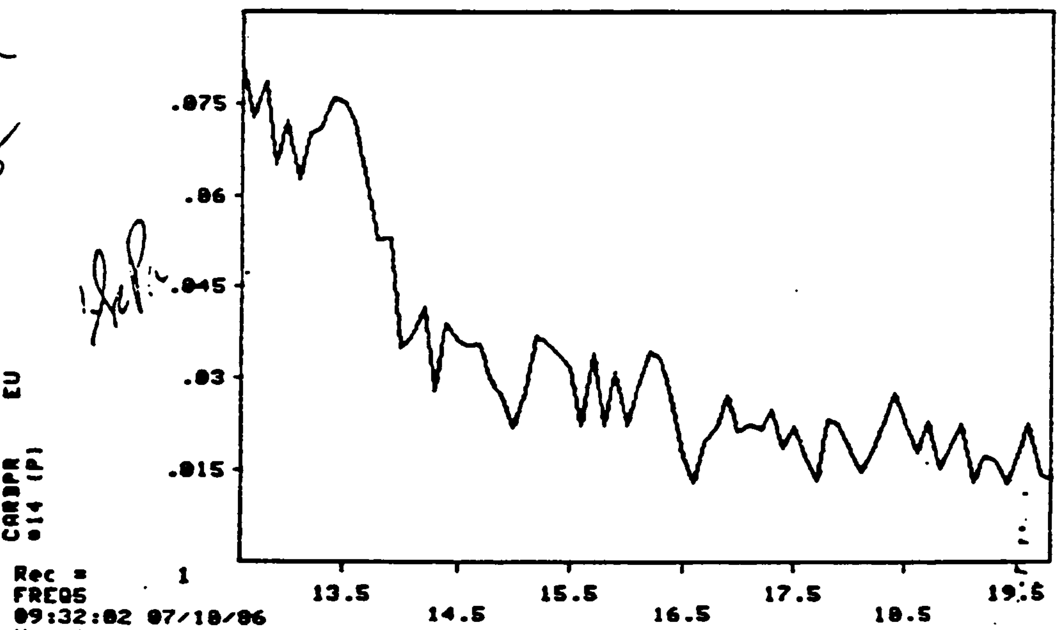
CARBPR

Carburetor Air Pressure



Rec = 1
FREQS
09:32:02 07/18/86
X axis is time in seconds

Minimum	Min @	Maximum	Max @	Average	Std Dev
.01	200	.08476	95	.05991	.02433



Rec = 1
FREQS
09:32:02 07/18/86
X axis is time in seconds

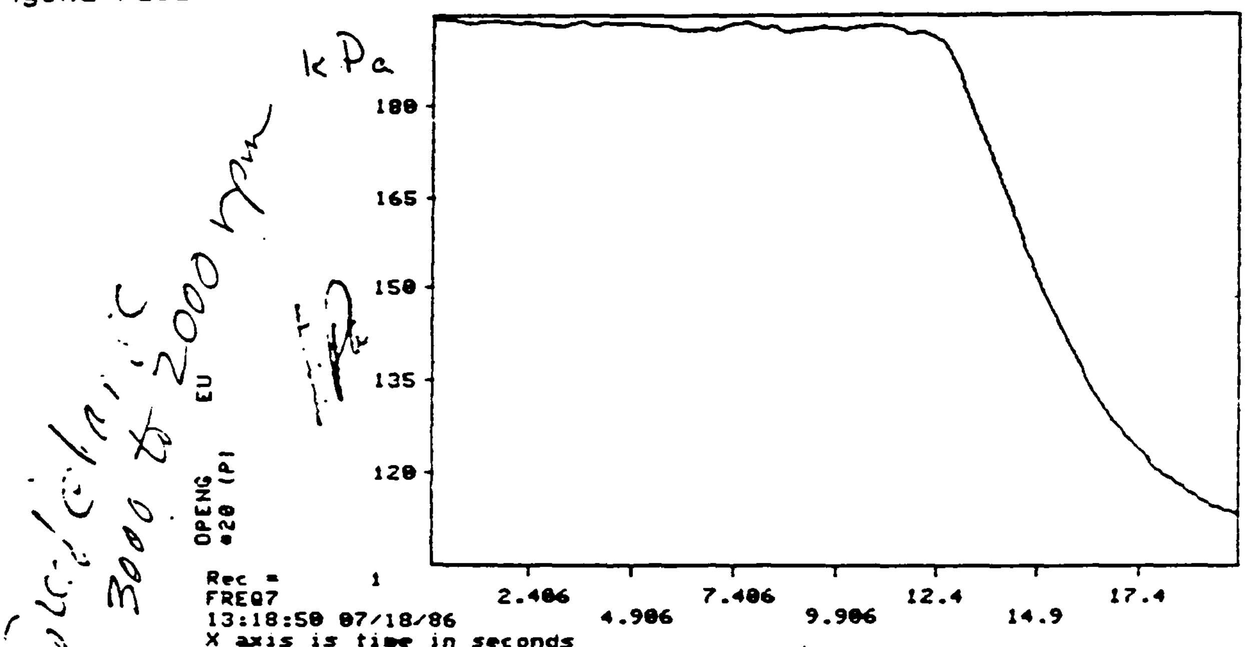
Minimum	Min @	Maximum	Max @	Average	Std Dev
.01264	195	.08128	127	.03298	.01929

ENGINE OIL PRESSURE

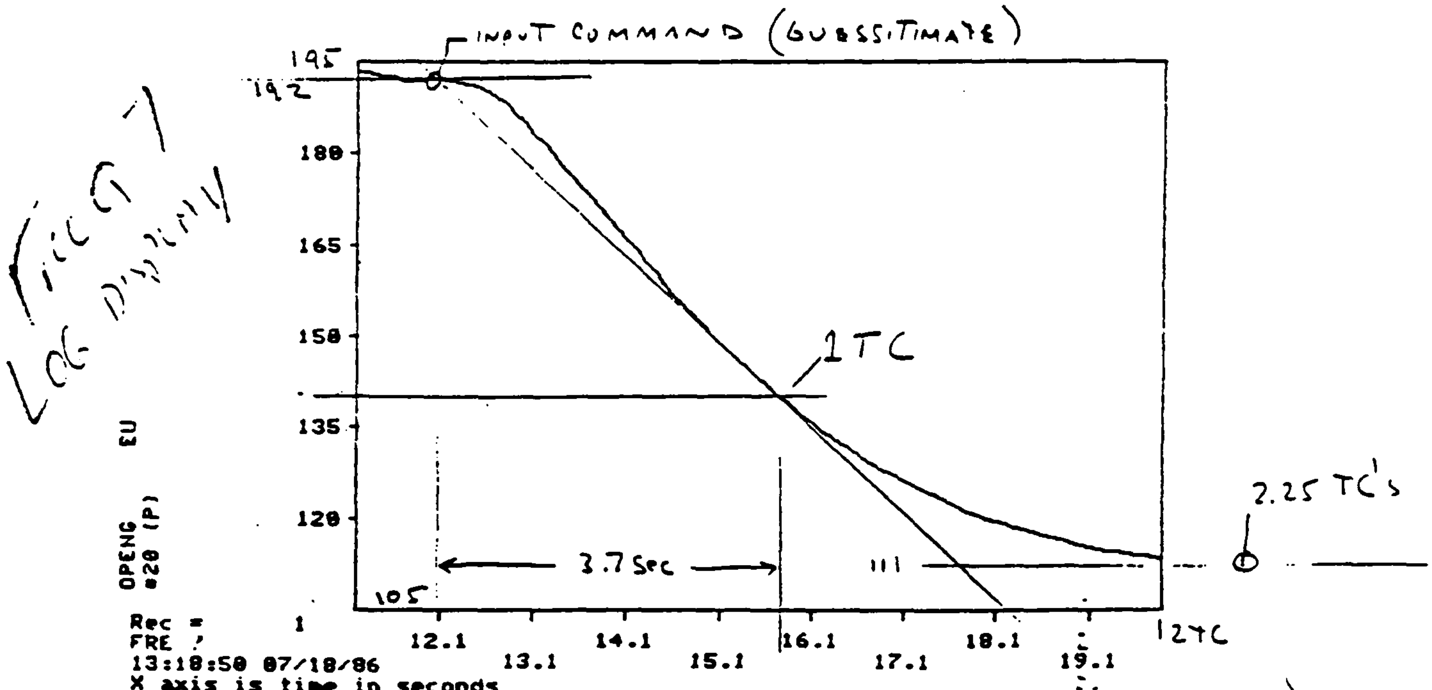
5

OPENG

igine reset



Minimum	Min @	Maximum	Max @	Average	Std Dev
113.2	200	194.6	1	173.8	29.11

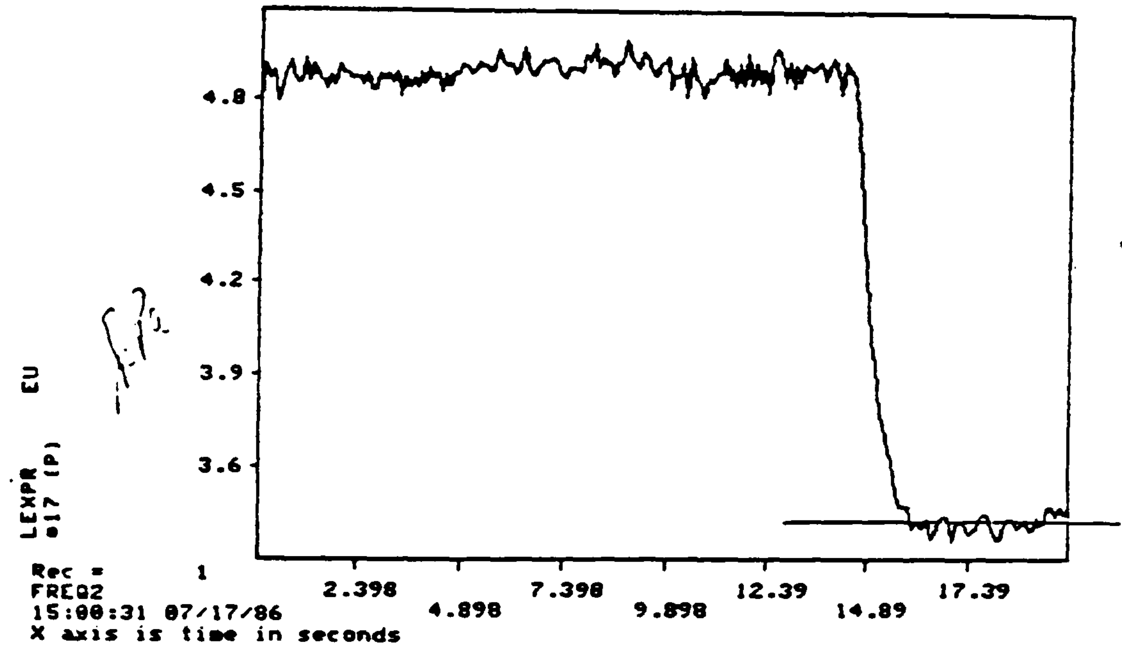


Minimum	Min @	Maximum	Max @	Average	Std Dev
113.2	200	193	113	149.2	28.99

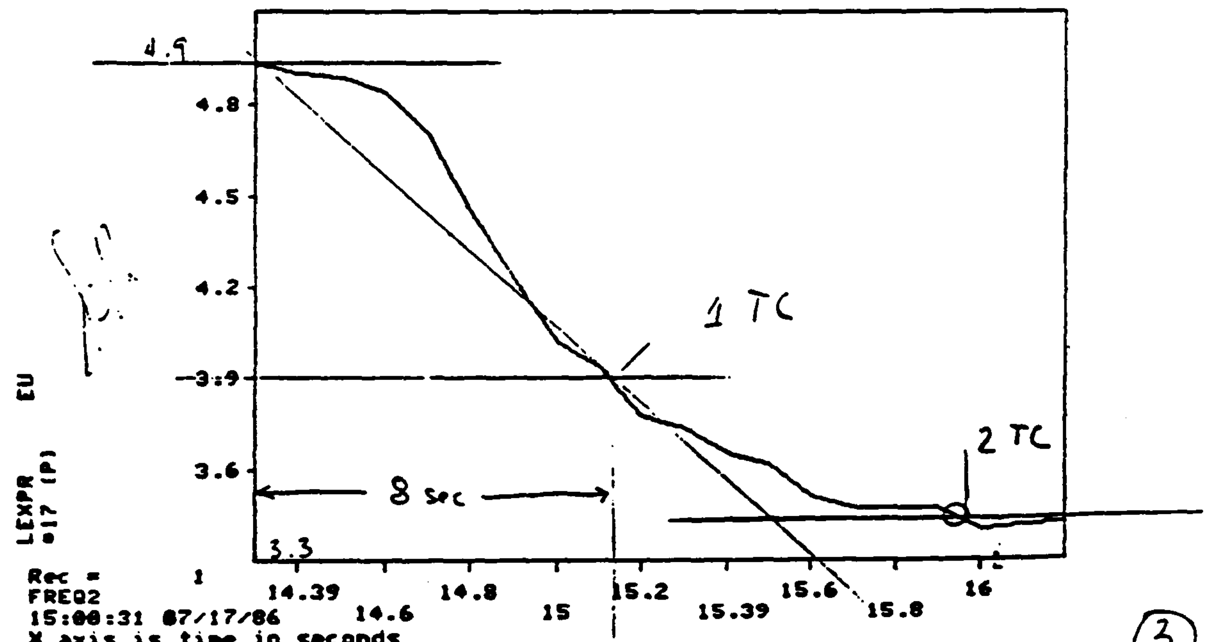
10

LEXPR LEFT EXHAUST PRESSURE

16



Minimum	Min @	Maximum	Max @	Average	Std Dev
3.354	171	4.996	98	4.529	.6234



Minimum	Min @	Maximum	Max @	Average	Std Dev
3.396	161	4.929	144	3.991	.5818

(3)

17

ETORQ 4

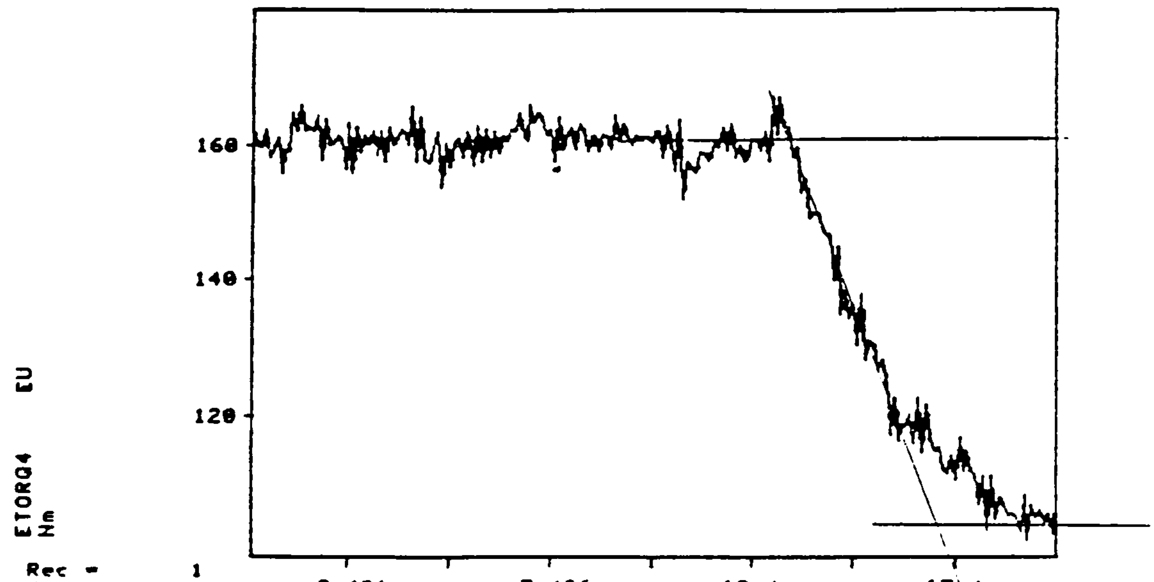
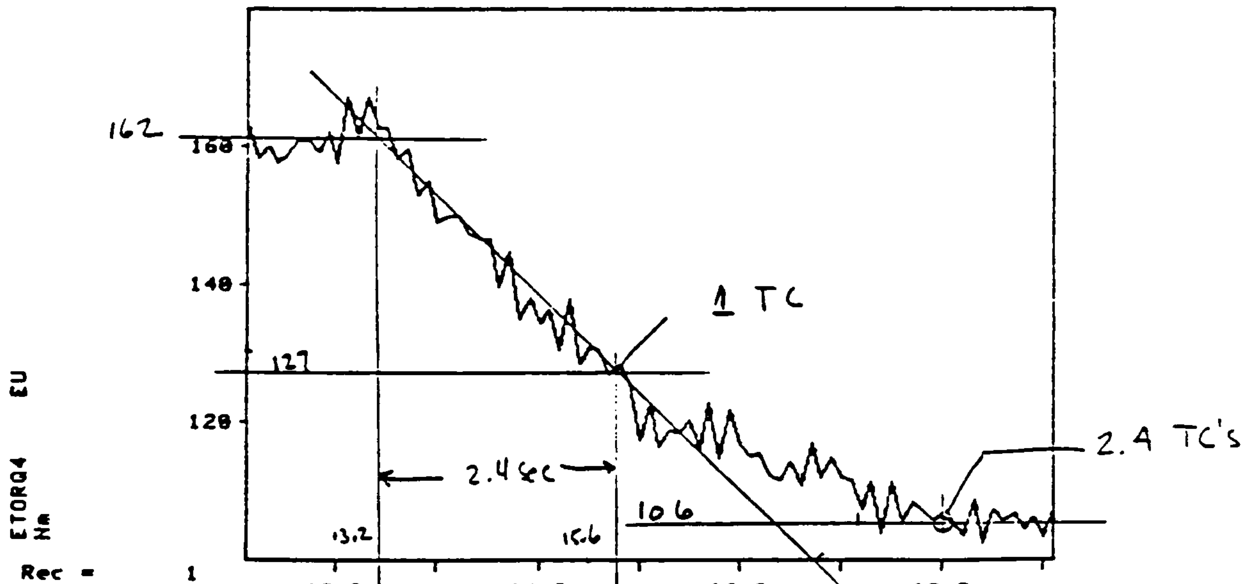


Fig 8

Rec = 1
FREQ8
13:29:12 07/18/86
X axis is time in seconds

Minimum	Min @	Maximum	Max @	Average	Std Dev
102.1	193	167.1	130	148	20.5



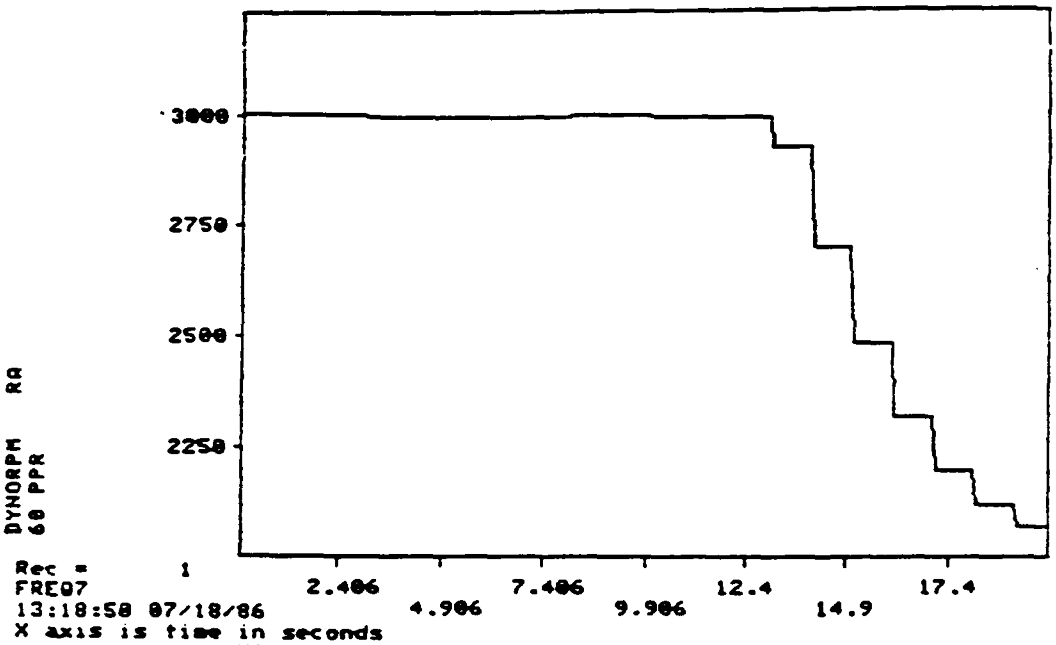
Rec = 1
FREQ8
13:29:12 07/18/86
X axis is time in seconds

Minimum	Min @	Maximum	Max @	Average	Std Dev
102.1	193	167.1	130	129.4	21.22

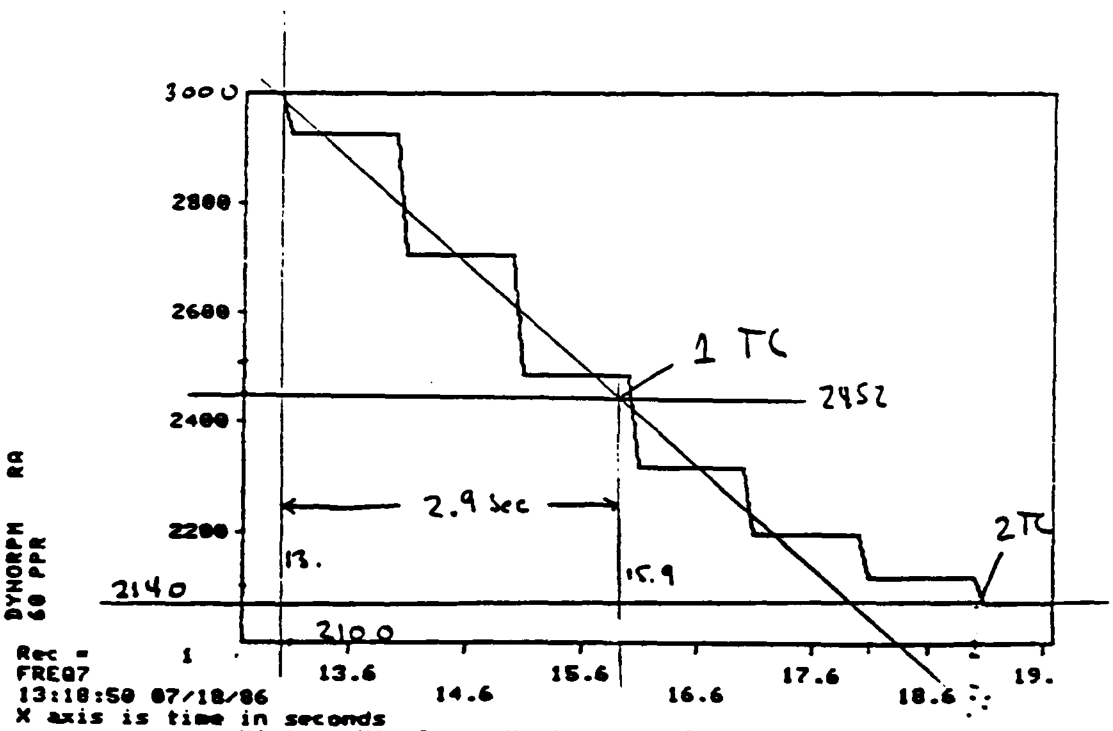
9

8

DYNORPM



Minimum	Min @	Maximum	Max @	Average	Std Dev
2068	192	3001	1	2795	331.8

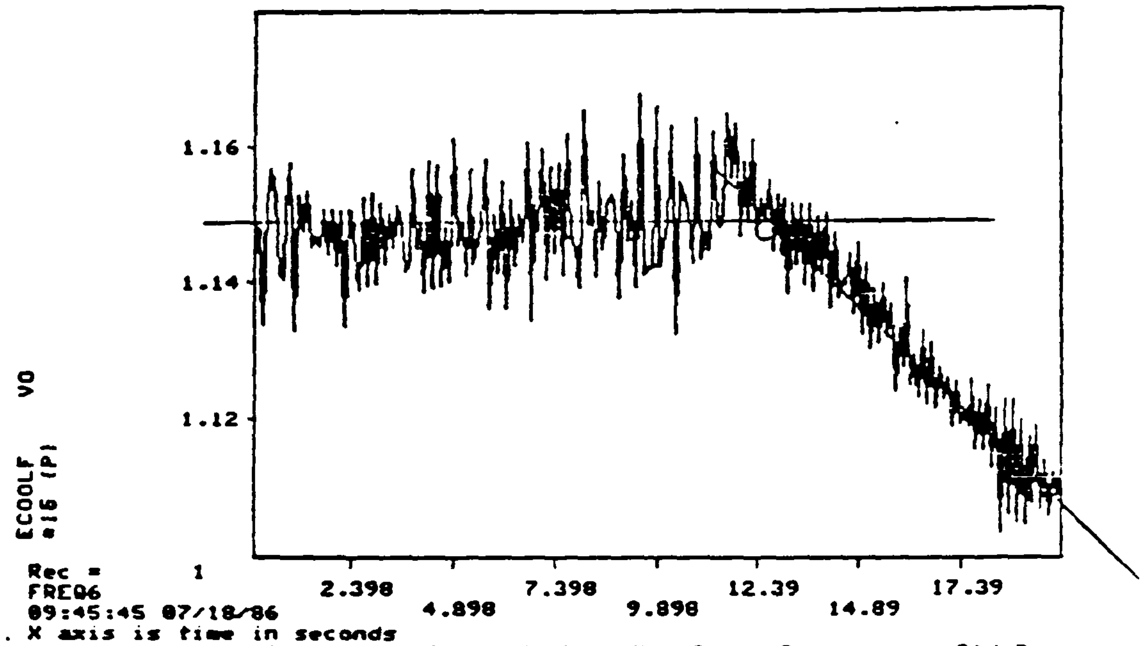


Minimum	Min @	Maximum	Max @	Average	Std Dev
2068	192	2999	128	~2458	317.9

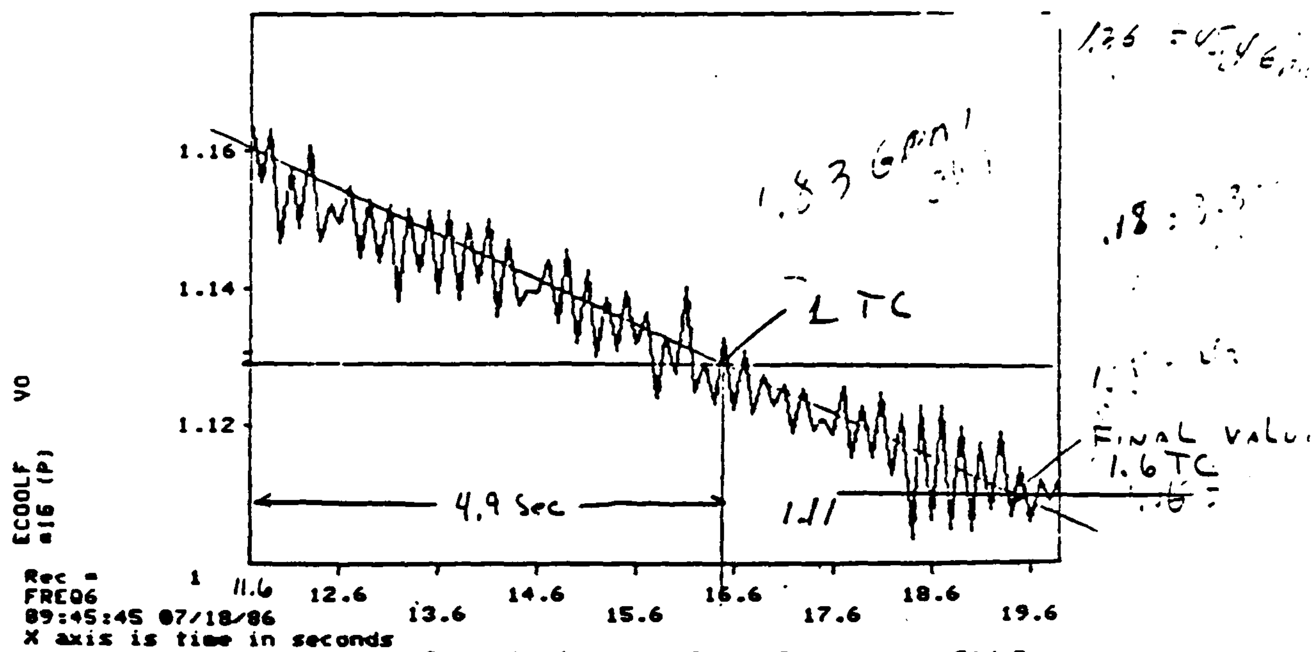
8

ECO OLF 9

WATER FLOW THROUGH THE COOLING JACKET



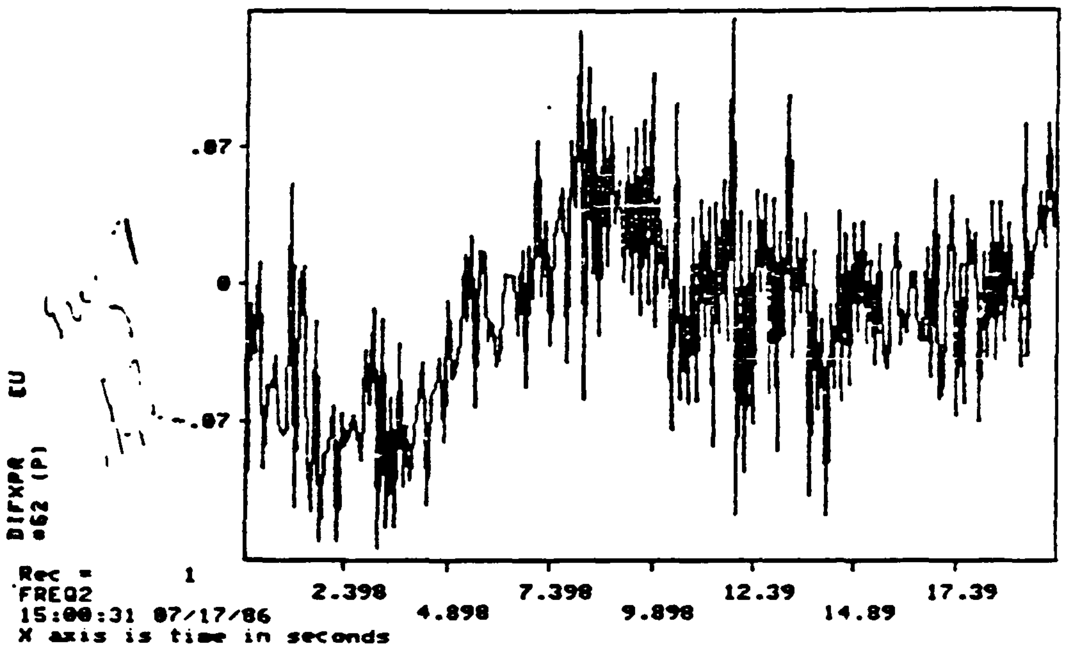
Minimum	Min @	Maximum	Max @	Average	Std Dev
1.103	185	1.167	96	1.141	.01481



Minimum	Min @	Maximum	Max @	Average	Std Dev
1.103	185	1.164	118	1.132	.01564

2

DIFXPR DIFFERENTIAL Exh PRESS 10



Minimum	Min @	Maximum	Max @	Average	Std Dev
-.1345	33	.1354	120	-.01421	.05592

(4)

NOT evaluated

WET/WET DIFFERENTIAL [illegible] TRANSDUCERS

This catalog describes Sensotec's complete range of strain gage wet/wet (will accept fluid into both pressure po[illegible] welded, stainless steel diaphragm) differential pressure transducers. There are three BASIC ACCURACIES, [illegible] (0.5%), available for wet/wet models. The accuracy is the combined effect of linearity, hysteresis, and repeatability [illegible] subminiature wet/wet differential unit.

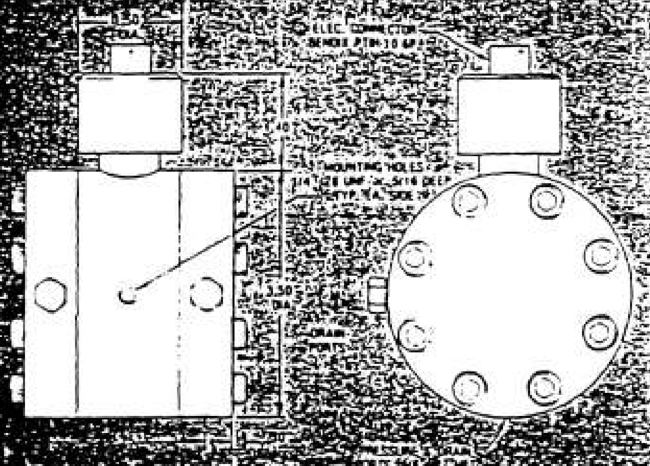
LOW RANGE WET/WET

0.5 to 30 psid

Range	Output	Accuracies	Line Pressure	Maximum Overload One Side
0.5 psid	1.0 mV/V	A - 5	4500 psi	1500 psi
1.0	1.5	A - 5		
2.0	1.5	A - 5		
5.0	2.0	A - 5 or Z		
10.0	2.0	A - 5 or Z		
15.0	2.0	A - 5 or Z		
30.0	2.0	A - 5 or Z		

SPECIFICATIONS

Input: 10 Vdc
Bridge: 350 ohms
Operating Temperature Range: 30°F to 190°F
Special Option: [illegible]
Compensated Range: 30°F to 130°F
Wetted Material: [illegible] welded
Pressure Chamber Volume: approx. 0.1 in³
Weight: [illegible] pounds
Drain Ports: Standard
[illegible]
[illegible]
[illegible]



[illegible]

All low range (0.5 to 30 psid) units are filled with [illegible]

SUBMINIATURE P30P WET/WET

Range	Linearity & Hysteresis (BFSL)	Line Pressure*	Output	Input
5, 10, 15, 30 psid	0.5%	250 psi	100 mv	10v

AL PRESSURE

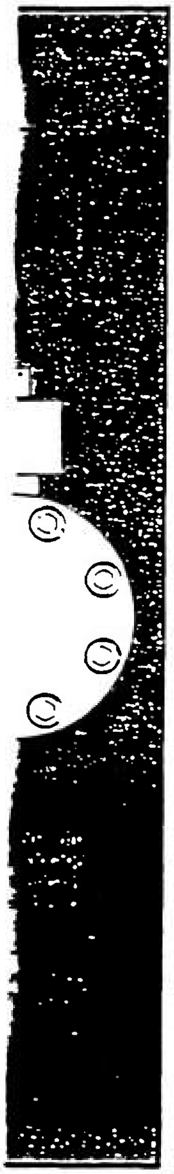
0.5 psid to 10

3 STANDAF
3 BASIC AC
0.1%, 0.25%

'h pressure ports because each port has a
IACIES. TJE (0 1%), Z (0 25%), and A 5
d repeatability Also presented is the P30P

MID RANGE WET/ WET

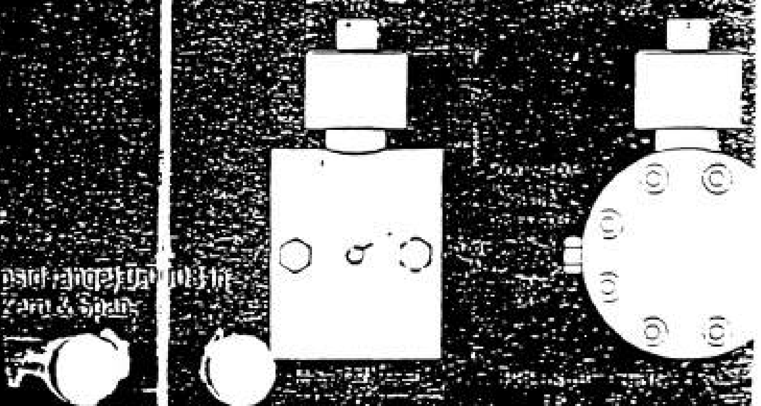
50 psid to 750 psid



Range	Accuracies TJE = 0.1%, Z = 0.25%, A-5 = 1.0%	Line Pressure	Overload One Side
50 psid	TJE or Z or A-5	1500 psi	1500 psi
100	"		
150	"		
200	"		
300	"		
500	"		
750	"		

SPECIFICATIONS

- Input: 10vdc
- Output: 2 mv/v
- Bridge: 350 ohms
- Weight: 4.5 pounds
- Compensated Range: 30 to 160°F
- Wetted Material: 17-4 ph stainless
- O-Ring Seals: Buna-N (other materials)
- Pressure Port Volume: 0.25 oz
- Operating Temperature Range: [illegible] to 250°F
- Natural Frequency: 7500 hertz for 200 psid
- Volume Change on Full Scale Pressure: (200 psid range) [illegible]
- Temperature Compensation Specification for Zero & Span:
  - TJE — 0.25% over compensated range
  - Z — 0.5%
  - A-5 — 1.0%



SPECIAL RANGES ... For A-5 Series Accuracy

Ranges	Overrange	One Side
[illegible]	[illegible]	[illegible]

Line Pressure

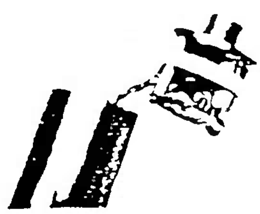
[illegible]	[illegible]	FS Output
[illegible]	[illegible]	[illegible]

OPTIONS

Internal Transducer Electronics Amplifier

0 - 5 Volt or 4 to 20MA

TJE, Z, A 5 and A 10 Series Pressure Transducers are available for all pressure ranges with integral built in electronic amplifiers



9-24-86

filename: tcel\TC8resp.986

R.Belling (FL)
D.Smolenski (FL)

J.Howes
R.Tidrow

Users Request;

R.Belling asked that we make a comparative analysis of the test system response performed in TC-8 as was done for the test data from TC-14. R.Belling will supply the test data to the ASTM sub committee.

General Statements of the Test Set Up;

In this case a group of time response statements were provided as were documented from TC-8 when running a similar test to that in TC-14. In this installation all controls are manually positioned for the next desired setting. The change in process may be done by simple valve change or be accomplished by manually re-positioning the command dial on a pneumatic controller (Moore).

The ranges are as previously documented, that is only a comparative incremental change has been made and the time recorded (manually).

Manually Response Data;

The information is stated in direct comaprison to the automatically controlled information previously supplied.

1. Flow:

a. Breather Tube System (coolant flow);

Flow change from 3 gal to 2 gal/min (by manual valve change):

Time to approach the or strike the maximum value was 6 seconds.

Time to stablize to the final value, 15 seconds.

The break point frequency from the formula

F(break) = 1/(2*PI*time constant)

One time constant (TC) = 63.8% X 6 = 3.8 sec

F(break) = 0.04 Hz

(This compares to 0.2 Hz for the auto process)

b. Rocker Cover Coolant Flow;

Flow change from 3 gal to 2 gal/min (by manual valve change):

Time to approach the or strike the maximum value was 7 seconds.

Time to stablize to the final value, 14 seconds.

The break point frequency from the formula

One time constant (TC) = 63.8% X 7 = 4.47 sec

F(break) = 0.035 Hz

(This compares to 1.0 Hz for the auto process)

c. Engine Coolant Flow;

Flow change from 40 gal to 38 gal/min (by manually resetting a Moore pneumatic controller);

Time to approach the or strike the maximum value was 20 seconds.

Time to stablize to the final value, 97 seconds.

The break point frequency from the formula

One time constant (TC) = 63.8% X 20 = 12.8 sec

F(break) = 0.012 Hz

(This compares to 0.3 Hz for the auto process)

2. Pressure:

a. Carburetor Pressure;

Pressure change from 0.02" H2O to 0.01" H2O (by manually resetting a Moore pneumatic controller);

Time to approach the or strike the maximum value was 18 seconds.

Time to stablize to the final value, 33 seconds.

The break point frequency from the formula

One time constant (TC) = 63.8% X 18 = 11.5 sec

F(break) = 0.014 Hz

(This compares to 0.06 Hz for the auto process)

b. Engine Oil Pressure;

Pressure change from 40 psi to 33.5 psi (read as a gage pressure and changed by a speed change from 3000 rpm to 2000 rpm);

Time to stablize to the final value, 8 seconds.

The break point frequency from the formula

One time constant (TC) = 63.8% X 8 = 5.1 sec

F(break) = 0.03 Hz

(This compares to 0.04 Hz for the auto process)

c. Left Exhaust Pressure;

Pressure change from 4.9 kPa to 3.5 kPa (by manually resetting a Moore pneumatic controller);

Time to approach the or strike the maximum value was 5 seconds.

Time to stablize to the final value, 35 seconds.

The break point frequency from the formula

One time constant (TC) = 63.8% X 5 = 3.2 sec

F(break) = 0.05 Hz

(This compares to 0.01 Hz for the auto process)

2. Engine Torque:

Torque change from 160 N*m to 130 N*m (by adjusting an electrical servo for Throttle Position):

Time to approach the or strike the maximum value was 13 seconds.

Time to stablize to the final value, 35 seconds.

The break point frequency from the formula

One time constant (TC) = 63.8% X 13 = 8.3 sec

F(break) = 0.02 Hz

(This compares to 0.06 Hz for the auto process)

3. Dyno Speed;

Speed change from 3000 rpm to 2000 rpm (by adjusting the speed pot on the dyno control panel);

Time to approach the or strike the maximum value was 8 seconds.

Time to stablize to the final value, 15 seconds.

The break point frequency from the formula

One time constant (TC) = 63.8% X 8 = 5.1 sec

F(break) = 0.03 Hz

(This compares to 0.05 Hz for the auto process)

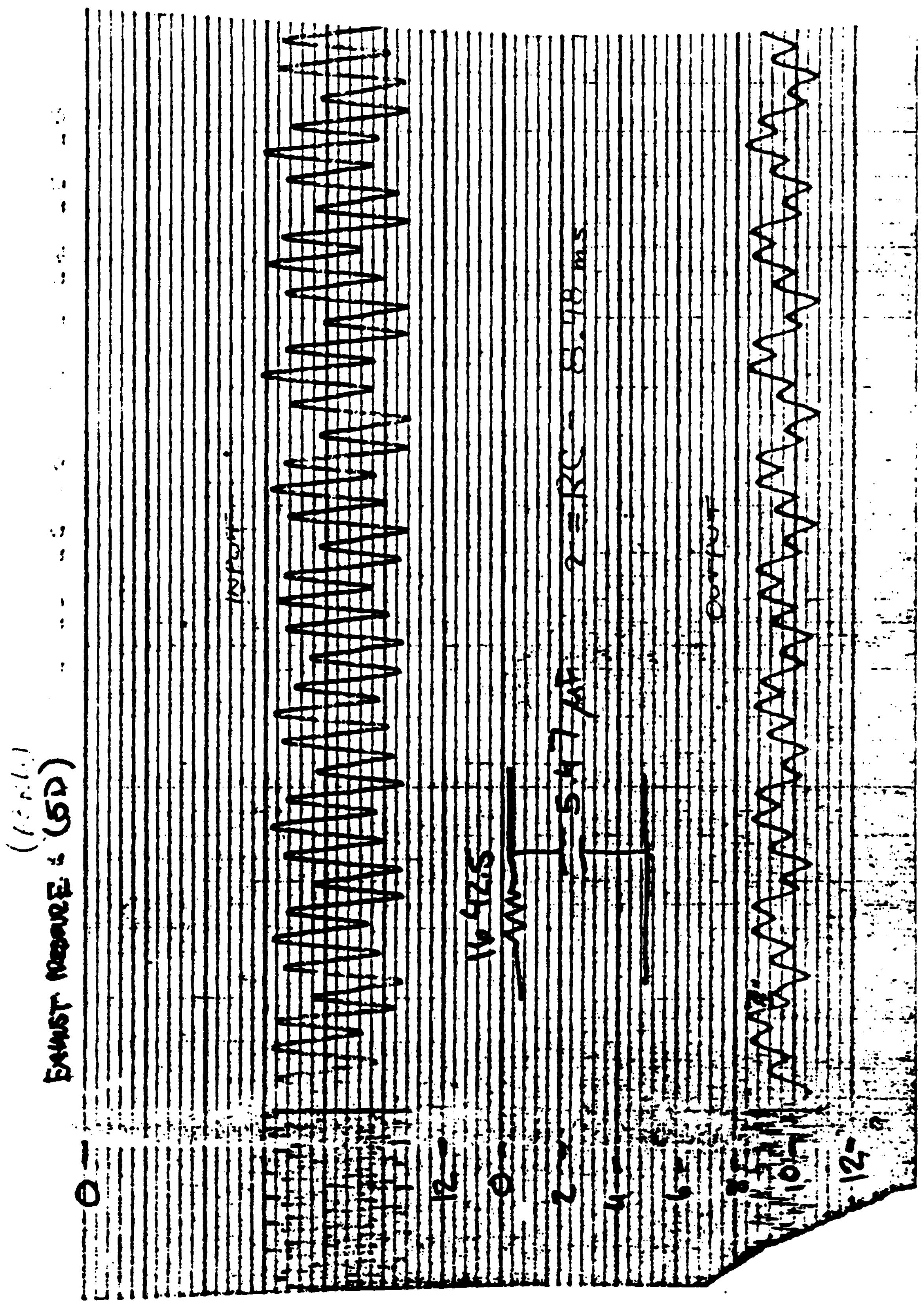
R.Spain
Instrumentation Dept

Attachment; Comparison Chart

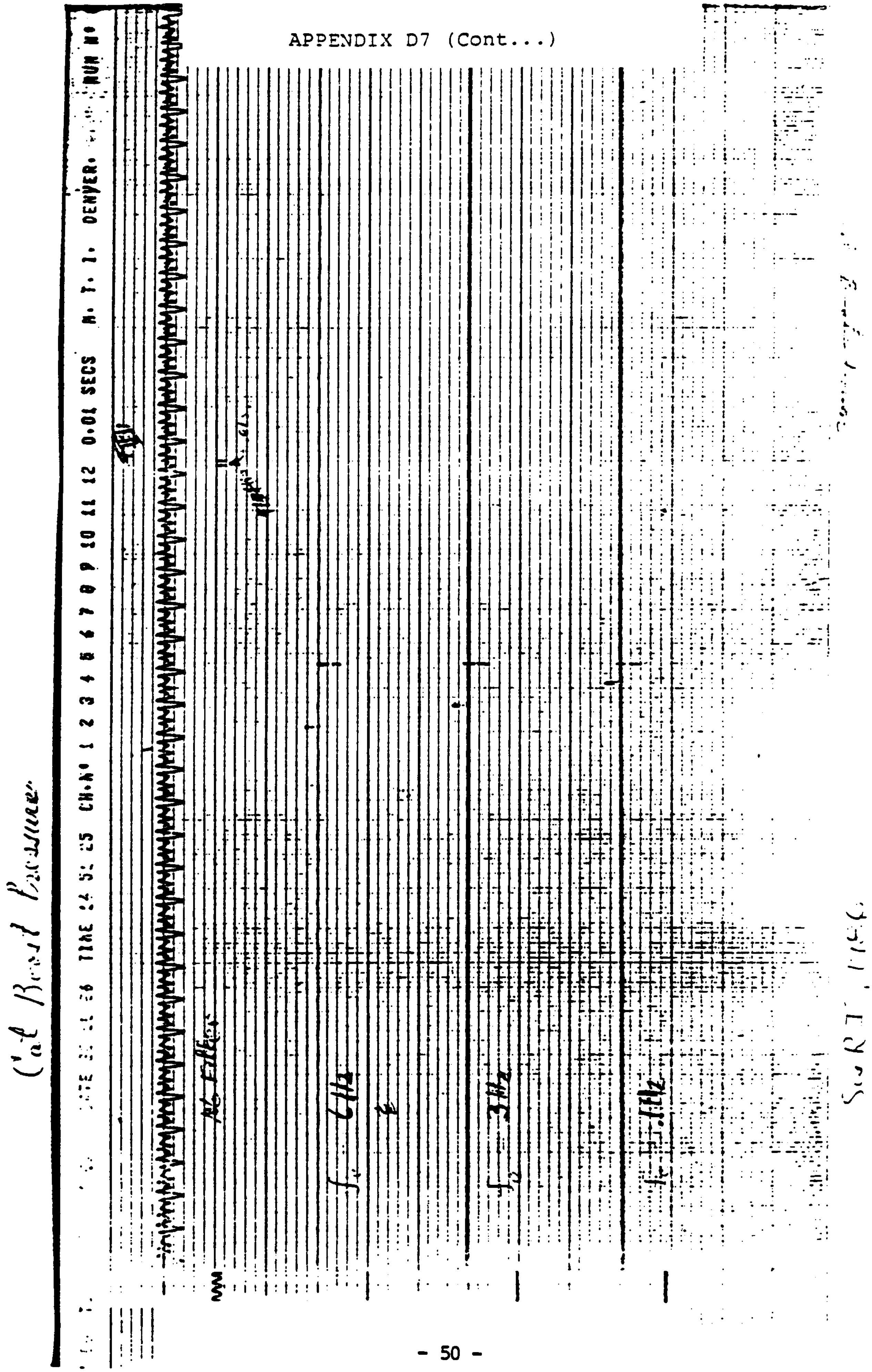
filename: tc14vstc8 (ALT U) Lotus

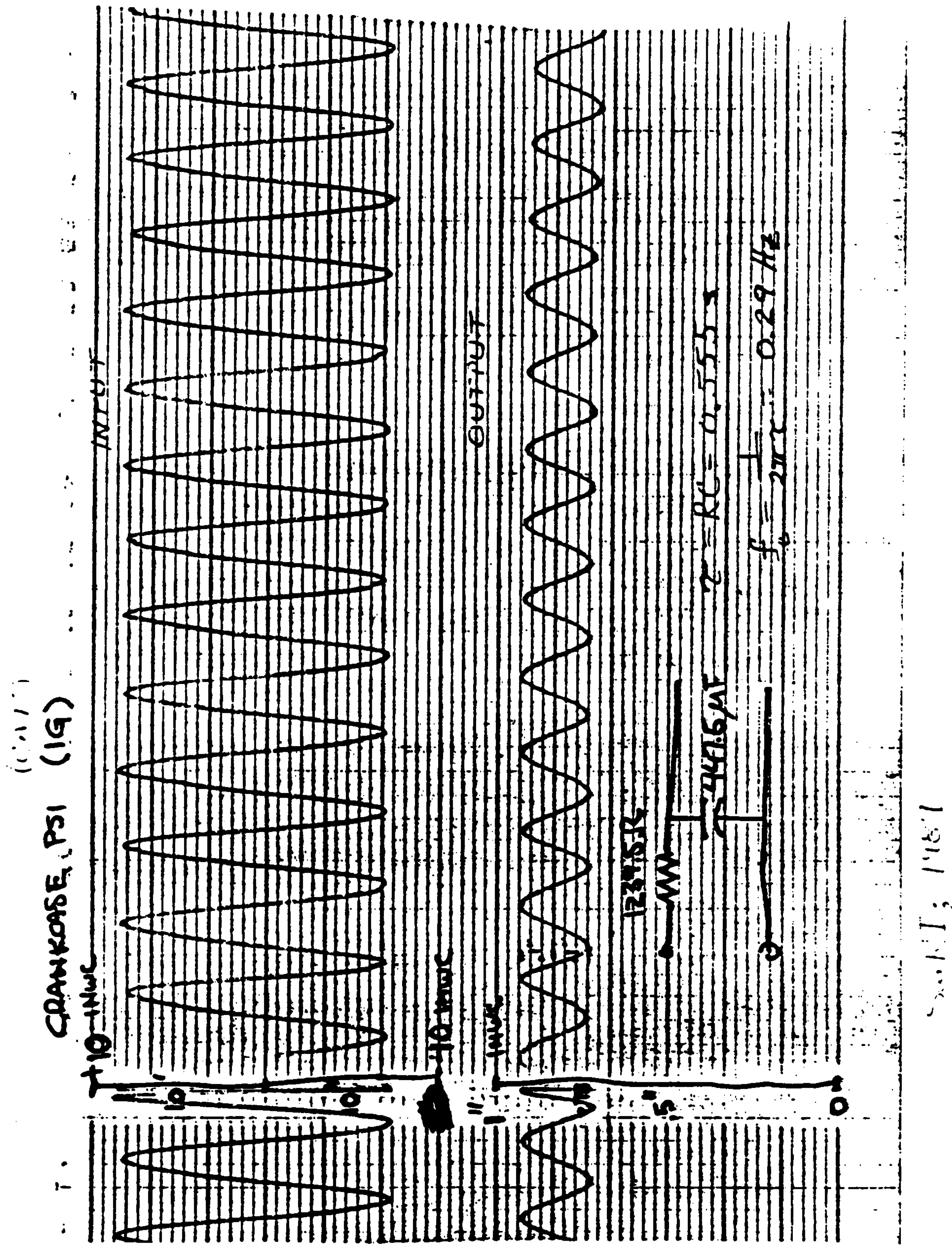
Comparison Chart for Response Data between the Test Cell 14 (computerized) and Test Cell 8 (Manual) control systems

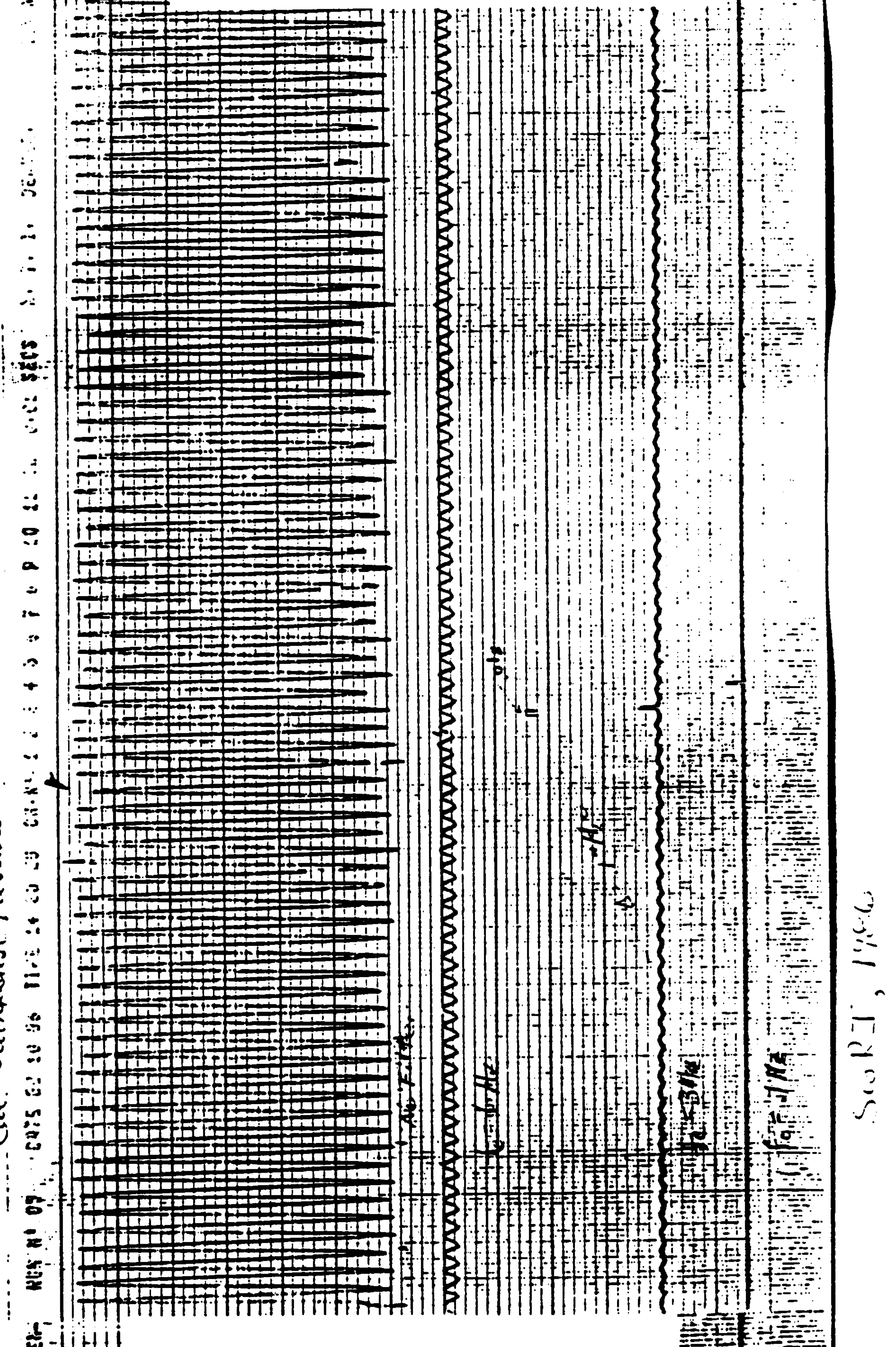
Control Parameter	Reach Max Value(Sec) TC-14/8	Final Value(Sec) TC-14/8	One Time Const TC-14/8	F(break) Hz TC-14/8
Breather Flow Cool	1.34/6	___/15	0.82/3.8	0.2/0.04
Rocker Cov Cool Flow	0.3/7	30/14	0.15/4.47	1.0/0.035
Engine Cool Flow	6/20	___/97	4.9/12.8	0.03/0.012
Carburetor Press	5/19	10/33	2.5/11.5	0.06/0.014
Engine Oil Press	7.4/8	---	3.7/5.1	0.04/0.03
Left Exh Press	16/5	20/35	8/3.2	0.01/0.05
Engine Torque	2/13	5.8/35	2.4/8.3	0.06/0.02
Dyno Speed	5.4/8	5.4/15	2.9/5.1	0.05/0.03


EXHAUST PRESSURE : (5D)
INPUT
OUTPUT

APPENDIX D7 (Cont...)




CRANKCASE PSI (1G)
INPUT
OUTPUT
0.29 Hz



HERB HARPSTEE
LUDRIZOL CORP.
10-13-86

RELATIONSHIP BETWEEN

a) DIGITAL 1ST ORDER FILTER

b) ROLLING AVERAGE FILTER

c) BLOCK AVERAGE FILTER

AND THE CLASSICAL ANALOG 1ST ORDER FILTER

DEFINITION OF SYMBOLS

f: FREQUENCY OF INPUT FUNCTION

T: PERIOD OF INPUT FUNCTION $(= 1/f)$ 200 sec for example:

f_s: SAMPLING FREQUENCY

T_s: SAMPLE TIME PERIOD $(= 1/f_s)$ 1 sec for examples

f_c: CLASSICAL ANALOG FILTER CUTOFF FREQUENCY X÷ for example

τ_c: CLASSICAL TIME CONSTANT $\left(= \frac{1}{2\pi f_c}\right)$

T_{RA}: ROLLING AVERAGE TIME PERIOD $\simeq 2\tau_c$ for best fit, see examp.

T_{BA}: BLOCK AVERAGE TIME PERIOD $\simeq \tau_c$ for best fit, see example:

FORMULAS

DIGITAL 1ST ORDER FILTER

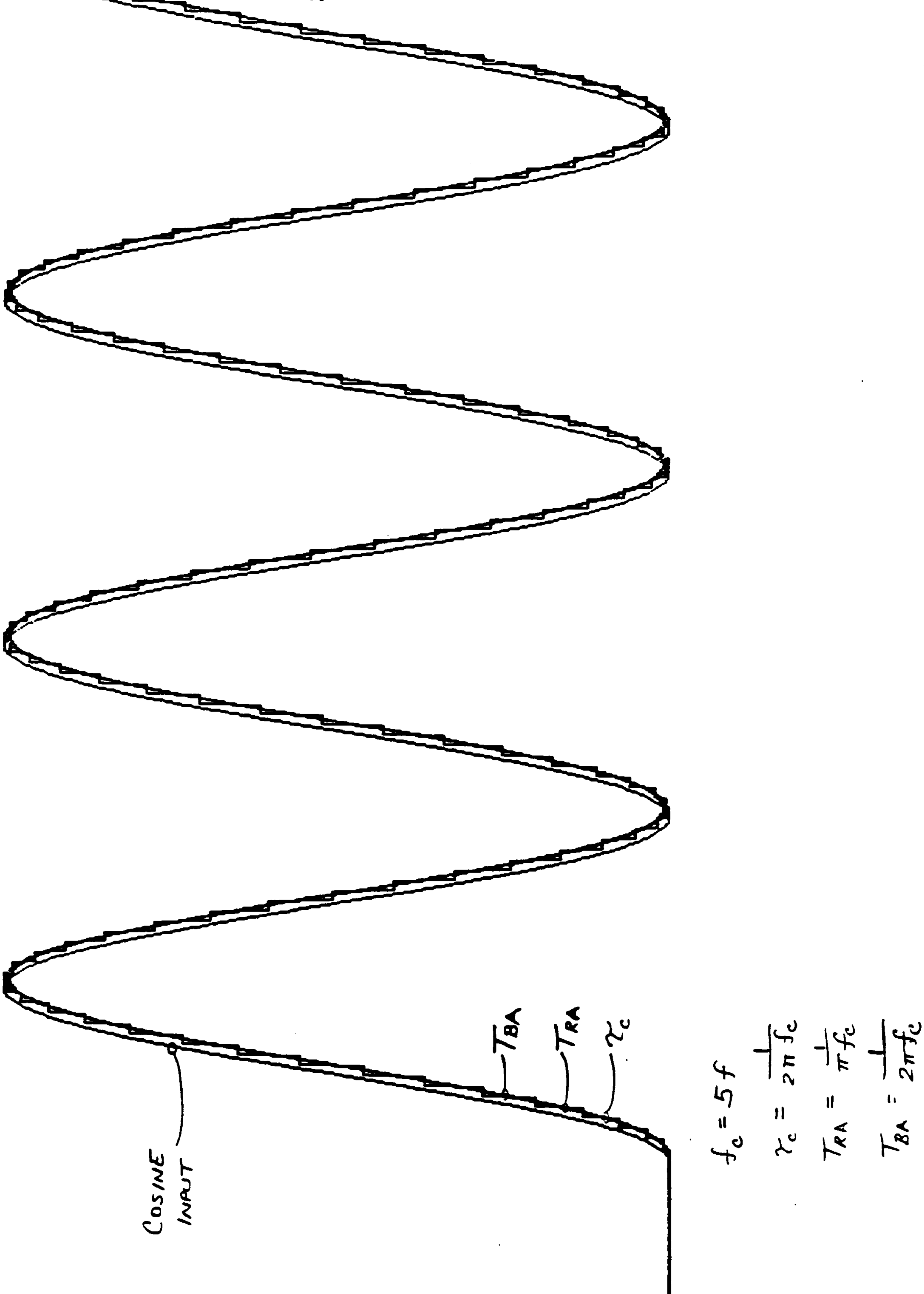
$$OUT(i) = \left[e^{-T_s/\tau_c}\right] OUT(i-1) + \left[1 - e^{-T_s/\tau_c}\right] IN(i)$$

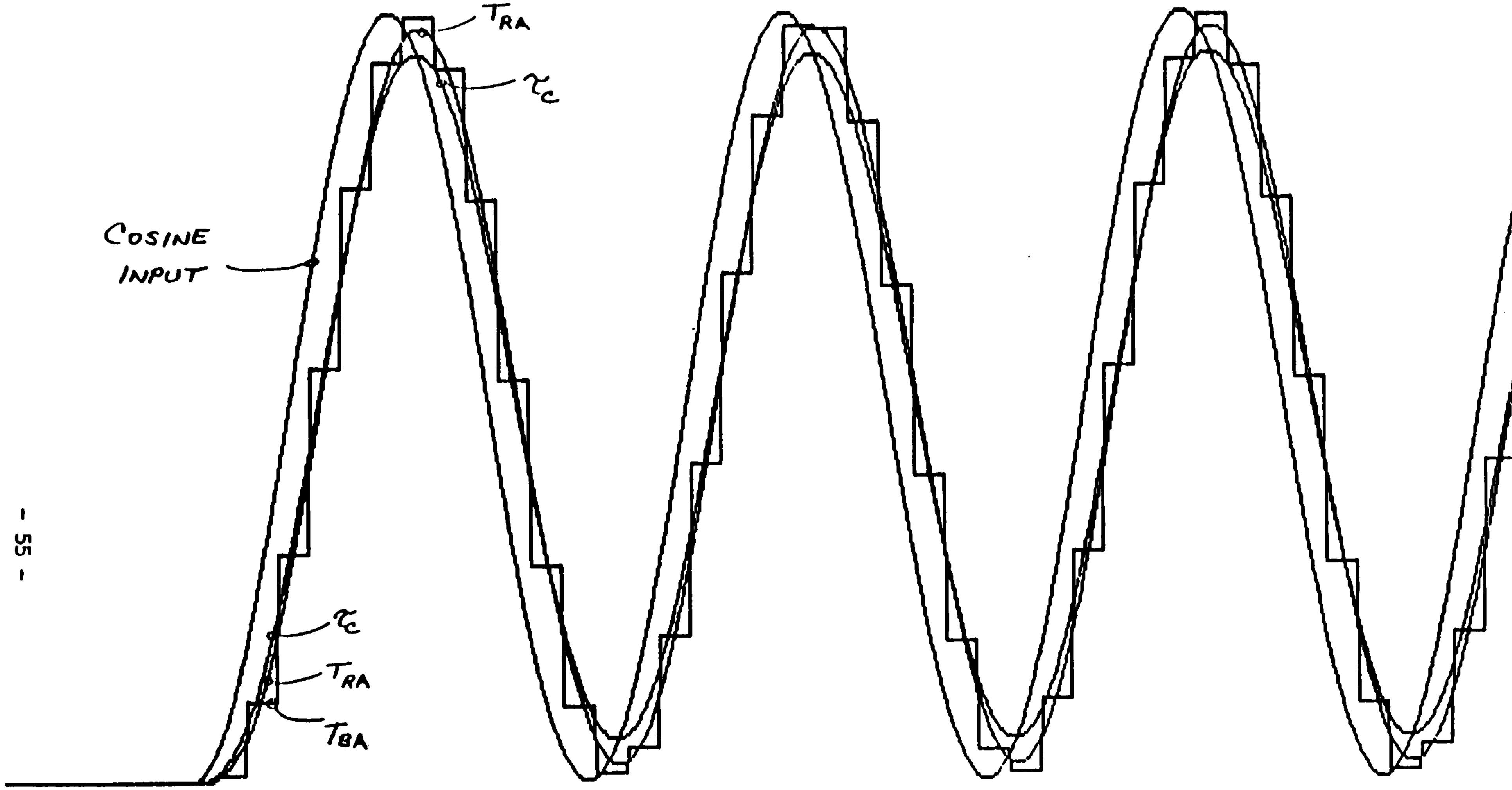
ROLLING AVERAGE FILTER

$$OUT(i) = \frac{T_s}{T_{RA}} \sum_{(i - T_{RA}/T_s + 1)}^{i} IN(j)$$

BLOCK AVERAGE FILTER

$$OUT(i) \text{ thru } OUT(i + T_{BA}/T_s - 1) = \frac{T_s}{T_{BA}} \sum_{(i - T_{BA}/T_s + 1)}^{i} IN(j)$$


Cosine Input
T_{BA}
T_{RA}
τ_c
$f_c = 5f$
$\tau_c = \frac{1}{2\pi f_c}$
$T_{RA} = \frac{1}{\pi f_c}$
$T_{BA} = \frac{1}{2\pi f_c}$

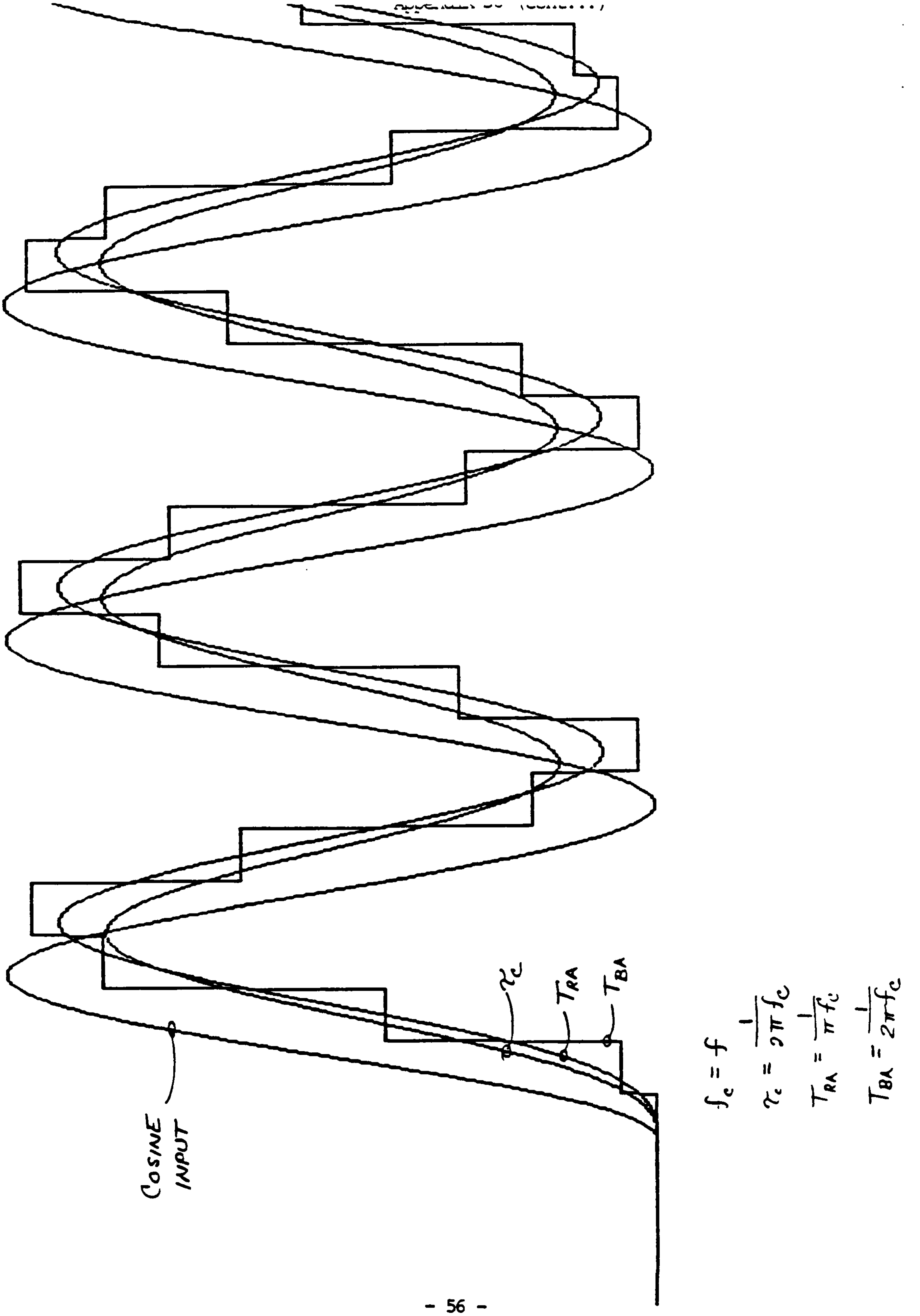


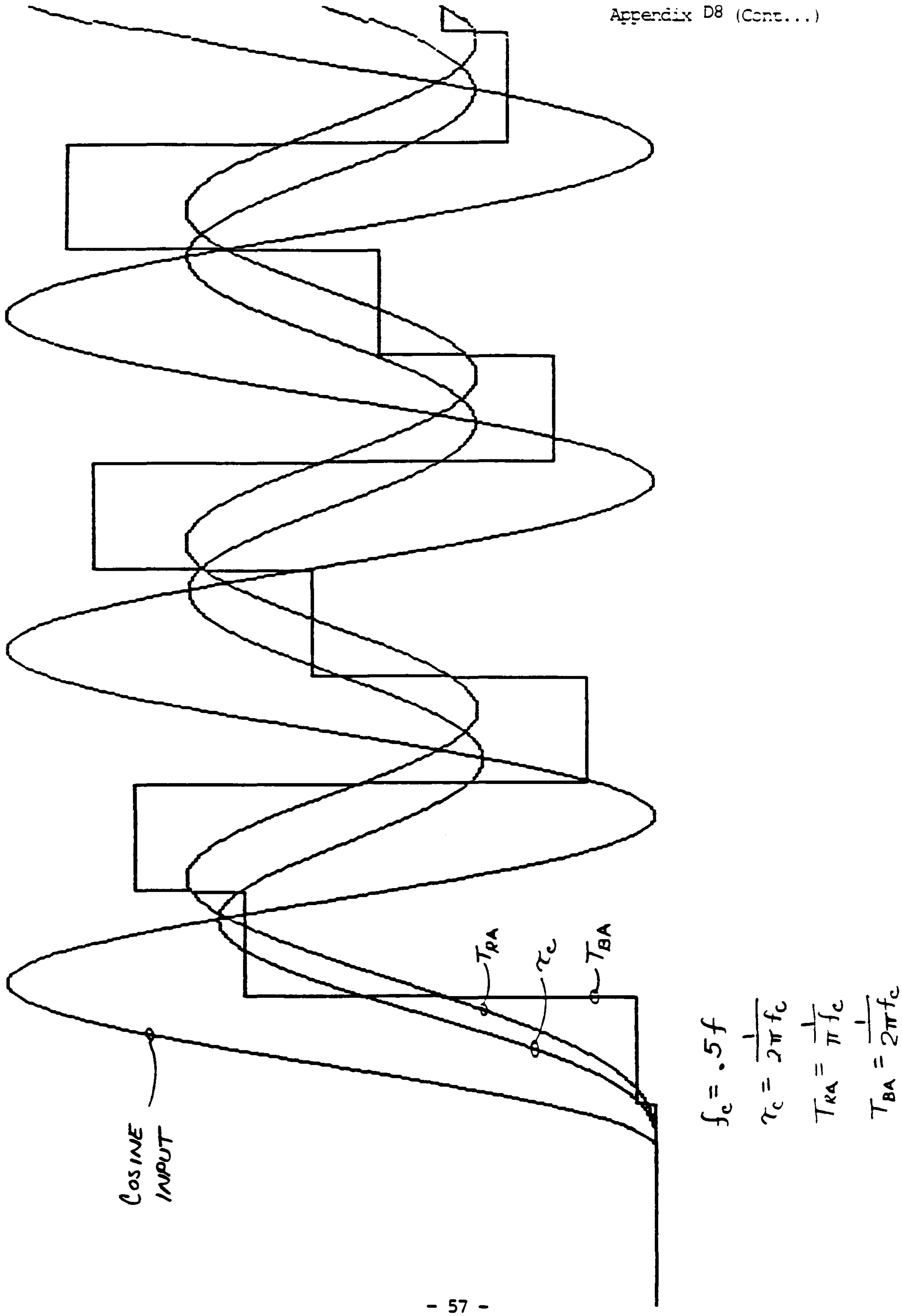
$f_c = 2f$

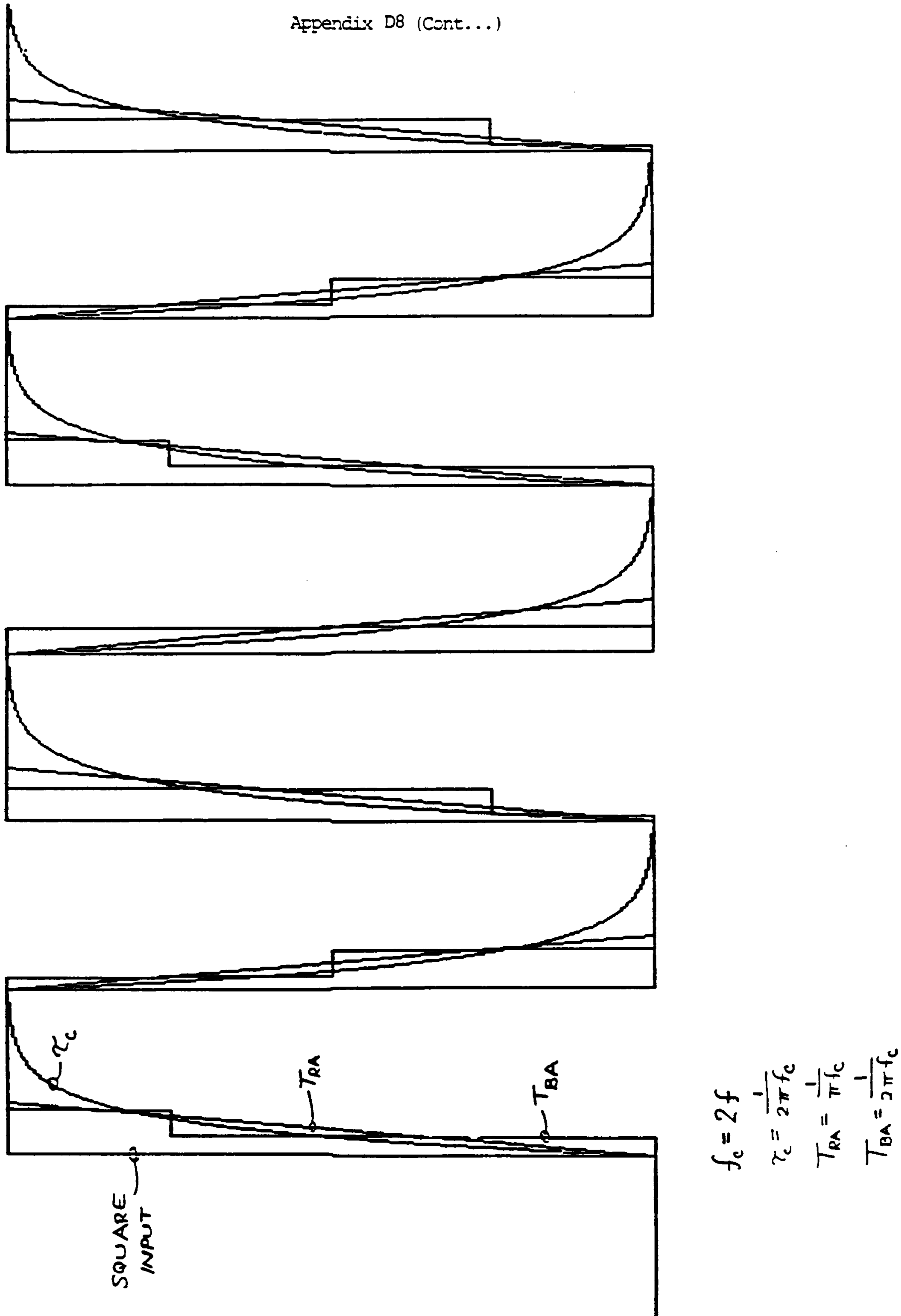
$\tau_c = \frac{1}{2\pi f_c}$

$T_{RA} = \frac{1}{\pi f_c}$

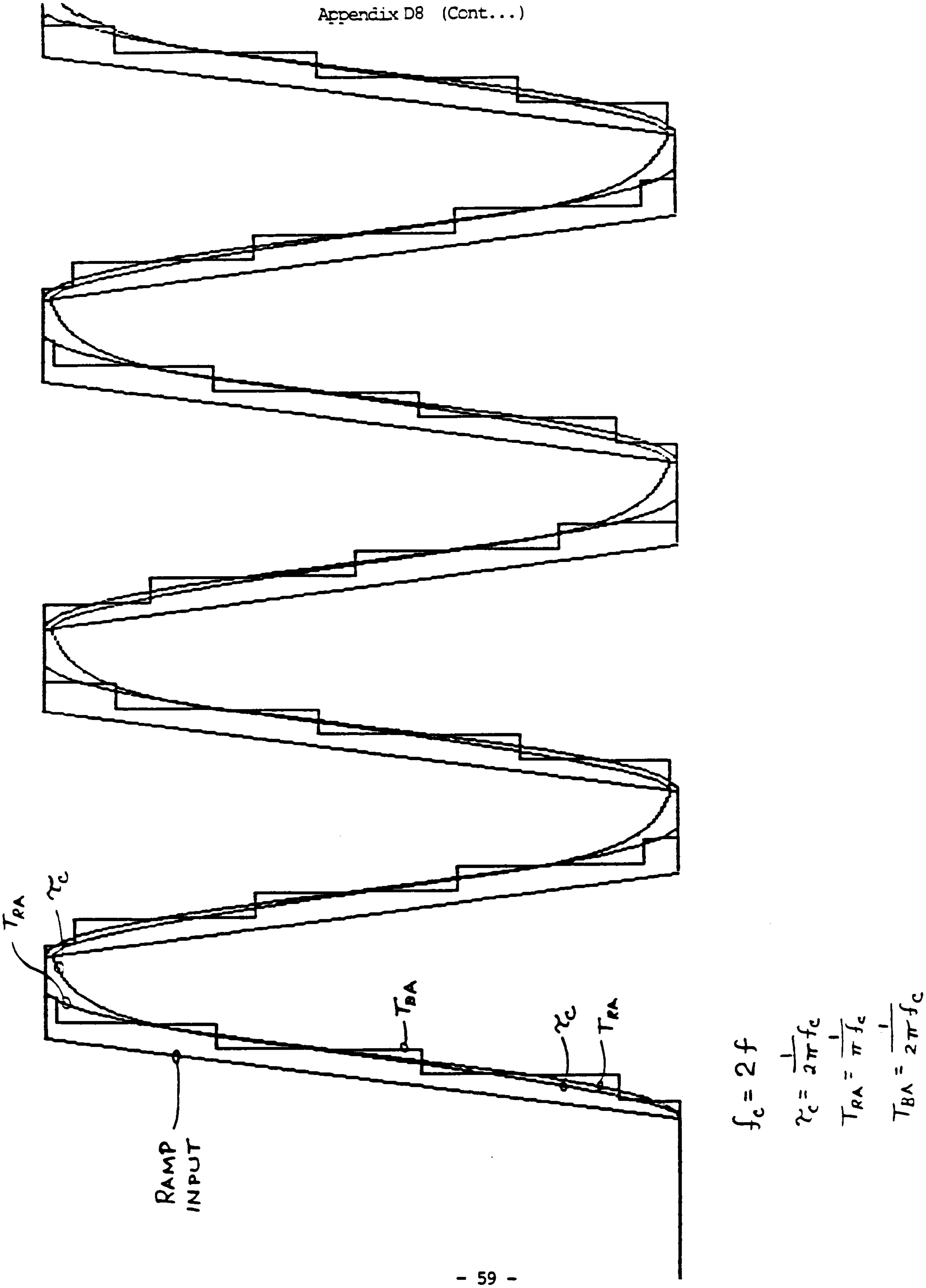
$T_{BA} = \frac{1}{2\pi f_c}$

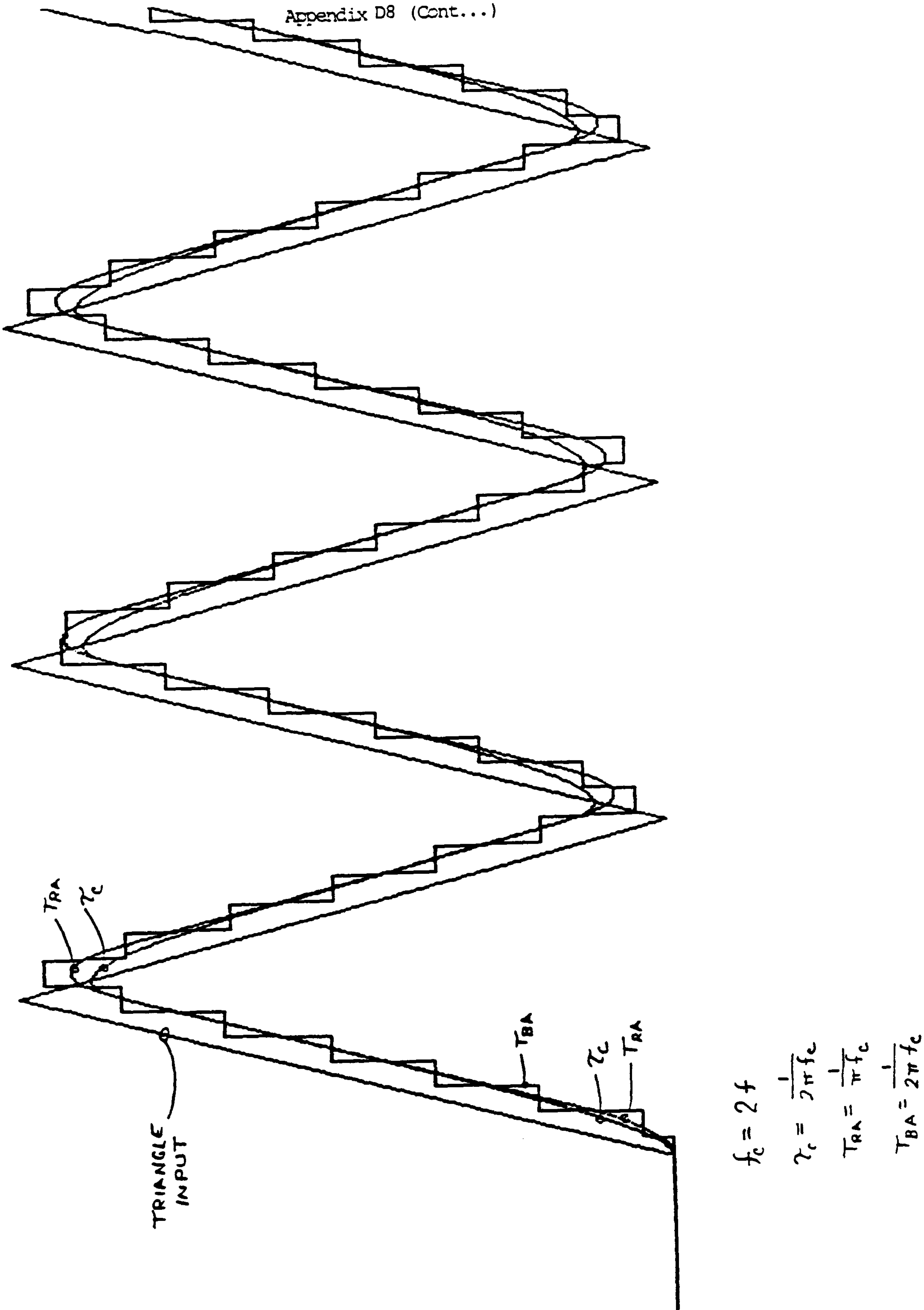

COSINE INPUT
τ_C
T_{RA}
T_{BA}
$f_c = f$
$\tau_c = \frac{1}{2\pi f_c}$
$T_{RA} = \frac{1}{\pi f_c}$
$T_{BA} = \frac{1}{2\pi f_c}$


COSINE INPUT
T_RA
τ_c
T_BA
f_c = .5f
τ_c = 1/(2π f_c)
T_RA = 1/(π f_c)
T_BA = 1/(2π f_c)



SQUARE INPUT
τ_c
T_{RA}
T_{BA}
$f_c = 2f$
$\tau_c = \frac{1}{2\pi f_c}$
$T_{RA} = \frac{1}{\pi f_c}$
$T_{BA} = \frac{1}{2\pi f_c}$


T_{RA}
τ_c
T_{BA}
τ_c
T_{RA}
RAMP INPUT
$f_c = 2f$
$\tau_c = \frac{1}{2\pi f_c}$
$T_{RA} = \frac{1}{\pi f_c}$
$T_{BA} = \frac{1}{2\pi f_c}$


TRIANGLE INPUT
T_{RA}
τ_c
T_{BA}
τ_c
T_{RA}
$f_c = 2f$
$\tau_c = \frac{1}{2\pi f_c}$
$T_{RA} = \frac{1}{\pi f_c}$
$T_{BA} = \frac{1}{2\pi f_c}$

APPENDIX E

REFERENCES

1. ASTM Standard E 177 "Use of the Terms Precision and Accuracy"
2. Omega Temperature Measurement Handbook, "Comparison of Time Constants", p. T39, 1986.
3. Hy Cal Engineering Co.