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NUCLEAR ROCKET SIMULATOR TESTS FLOW INITIATION WITH TURBINE ACCELERATED TANK PRESSURE 50 PSIA; RUN 11

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Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION · WASHINGTON, D.C. · 1964

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TECHNICAL MEMORANDUM

NUCLEAR ROCKET SIMULATOR TESTS
FLOW INITIATION WITH TURBINE ACCELERATED
TANK PRESSURE 50 PSIA; RUN 11

NASA-Lewis Research Center

Test Date: September 30, 1964

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David M. Straight

RESTRICTED DATA
Atomic Energy Act of 1954

GROUP 1
Excluded from Automatic Downgradings and Declassification

CLASSIFIED DOCUMENT - TITLE UNCLASSIFIED

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NATIONAL AERONATICS & SPACE ADMINISTRATION

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NUCLEAR ROCKET SIMULATOR TESTS
FLOW INITIATION WITH TURBINE ACCELERATED
TANK PRESSURE 50 PSIA; RUN 11

Lewis Research Center

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ABSTRACT

Preliminary data obtained from liquid hydrogen run 11 is presented. This run was conducted to determine if the turbine could achieve bootstrap acceleration during flow initiation of the nuclear rocket. The pressure rise versus weight flow and pump speed are presented to illustrate the degree of bootstrapping achieved. Pressure and temperature measurements are also presented as a function of time for selected stations and components throughout the system. The run was made by opening the turbine power control valve to maintain a speed ramp of 500 rpm/sec (2%/sec). The tank pressure was maintained at 50 psia throughout the run.

INTRODUCTION

The over-all objective of the nuclear rocket simulator tests is to study system dynamics and component phenomena during the nuclear rocket initial startup cycle.

Some pump performance data for an acceleration of 100 rpm/sec (0.4%/sec) obtained in run 10 are shown in figure 3 herein to indicate behavior at slower acceleration rates than run 11. No further reporting of run 10 is contemplated.

The primary objective of run 11 was to determine if the turbine could be bootstrapped during flow initiation of the simulated nuclear rocket. Secondary objectives were to obtain pressure and temperature oscillations during system chilldown, the chilldown history of various system components, and low speed turbopump characteristics.

RESEARCH APPARATUS

A detailed description of the B-1 Facility and test apparatus is given in reference 1. A schematic diagram of the complete nuclear rocket bootstrap startup experiment is shown in figure 1. For this experiment the turbine discharge line was reconnected to the ejector system. The turbopump package was modified to incorporate check valves in the balance piston bleed return lines.

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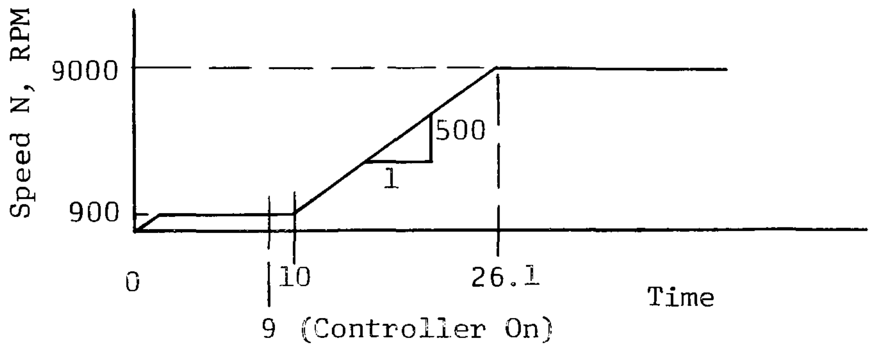
The turbine power control valve used in this experiment was close loop controlled on turbopump speed employing a proportional plus integral controller to condition the speed error signal. The speed demand input signal was as shown in the figure below:



The speed ramp demand was initiated 10 seconds after the pump discharge valve was opened. This delay time was determined from the cooldown data which indicated that the two phase oscillations at the nozzle inlet had dampened out by this time. It was also determined that at 10 seconds the turbopump windmill speed was approximately 1000 rpm. The initial speed reference was set below this value (at 900 rpm) so as not to step the turbine power control valve open when the valve was switched into automatic control at 9 seconds.

INSTRUMENTATION

A complete tabulation of all measurement item numbers and installation details of the nuclear rocket simulator instrumentation is given in reference 1. The measurements taken during run 11 are listed and described in Table I. The type of transducer used; e.g., resistance thermometers, thermocouples, etc., can be identified from their item numbers and the symbol descriptions given in reference 1.

The digital data recording systems used in run 11 were a 4000 cycle sampling rate digital system with 192 inputs and a 10,000 cycle sampling rate digital system with 100 inputs. High frequency data was recorded on FM tape and on various oscillographs.

An estimated over-all accuracy for each measurement is included in Table I. The accuracy estimates include possible errors in the transducer calibrations, data acquisition system and data processing system. A detailed discussion of the accuracy estimates of the copper constantan thermocouples is given in reference 3.

The data processing methods were the same as those outlined in reference 2.

TEST PROCEDURE

A complete description outlining the test procedure used is given in reference 3. The following is a description of the sequence of events that was used to obtain the desired test conditions for run 11.

The automatic sequence was initiated when the nozzle exit pressure reached 3 psia. The important events of the automatic sequencing used for run 11 are shown in Table II. At t = 25 seconds from the time the automatic sequence was initiated, the tank pressure was ramped to 35 psig. At t = 45 seconds, the pump main discharge valve was opened with a 1 second ramp. As the pump main discharge valve is initiated, a command signal is given to the various data recording devices to indicate zero time for flow initiation to the system. All figures in this report which have a time scale use this signal as a zero reference.

At t = 55 seconds from the time the automatic sequencer was initiated, the turbine power control valve was opened to maintain a programmed speed ramp of 500 rpm/sec. If during the test, the monitored pump weight flow would reach a predetermined maximum value of 25 lbs/sec, the speed demand ramp signal would be terminated; and the signal would be maintained at the last value it had attained. (The pump weight flow and pressure differential were also monitored on an X-Y plotter during the test. If this X-Y plot would indicate a deep pump stall, the research engineer could initiate shutdown.)

RESULTS AND DISCUSSION

System Performance

Although the data presented in this report is preliminary, the test verified the bootstrap capability of a nuclear rocket engine system. It is to be emphasized that the heated gas powering the turbine was obtained solely by heating the liquid hydrogen, using the latent heat of the major components of the system.

At approximately 20 seconds, the turbine power control valve was only open 34% of its maximum value, indicating ample power was still available at this time. In an actual startup, the reactor power could have been increased at any time between 5 lbs/sec and approximately 15 lbs/sec. flow.

At approximately 23 seconds, a pump weight flow of 25 lbs/sec was reached and the speed demand was held at 7600 rpm.

At approximately 24 seconds (26 lbs/sec LH_2 flow), the system was cooling down very rapidly and could not maintain the 7600 rpm speed demand. The turbine power control valve began to open to its maximum value, but it c[redacted]in bootstrap acceleration.

Pressures at major stations.- The time history of static pressures at major instrumentation stations throughout the system are shown in figures 6 through 16. These figures are reproductions of the 10 KC digital computer plots. These digital plots show the over-all level of the pressure and the magnitude of the low frequency oscillations during the run. High frequency oscillations in the static pressures, which occurred during the first 30 seconds, are shown in figure 4. These high frequency oscillation plots are recorded oscillograph traces of data from FM tapes. The noise on the nozzle inlet manifold static pressure on figure 4 is attributed to the data reduction system.

In general, all pressure oscillations of any consequency were damped out before turbine power was applied. Applying turbine power did not introduce any new severe pressure oscillations. The amplitudes of the oscillations seemed to be at a maximum at the nozzle inlet manifold and seem to be damped upstream and downstream from this station. All oscillations were negligible at the end of the run.

Temperature at major stations.- The time history of fluid temperatures at major instrumentation stations throughout the system are shown in figures 19 through 28. These figures are reproductions of the 10 KC digital computer plots. High frequency oscillations of fluid temperature recorded on FM tapes are shown in figure 17. The noise on the plot of reflector exit manifold fluid temperature is attributed to the data reduction system.

In general, the effect of bootstrapping is to lower the temperature of the downstream stations more rapidly. In chilldown run 6 (where the tank pressure is the same as run 11), the nozzle chamber station indicated liquid hydrogen temperature in about 50 seconds. In run 11, the nozzle chamber station recorded liquid hydrogen temperatures in about 25 seconds.

The oscillations in the fluid temperature at the pump discharge and nozzle inlet manifold stations are due to two-phase flow.

System pressure and temperature profiles.- A cross plot of the static pressure at various stations in the system at several selected times is shown in figure 5. A cross plot of the hydrogen fluid temperature at various stations at selected times is shown in figure 18.

Component Performance

Turbopump.- The startup and bootstrap history of run 11 is shown on the plot of pump differential pressure versus weight flow, figure 2.

The information for this plot was obtained from the 10 KC data system and was plotted at one second intervals. Figure 2 shows that the system load line followed by the turbopump was well out of the stall area. This load line can be compared with the load line obtained in run 10, figure 3. (Run 10 was similar to run 11 with the exception that in run 10 the speed ramp was 100 rpm/sec while in run 11 the speed ramp was 500 rpm/sec.) In each case, the estimated stall line plotted was based upon normalized test data obtained from the turbopump manufacturer. During run 11, the turbopump reached a maximum speed of 7570 rpm with no evidence of mechanical problems.

The pump performance during windmilling startup was similar to the data obtained in cooldown run 6 (reference 3). Figures 29 and 30 show plots of turbopump speed and weight flow versus time as obtained from the 10 KC digital recording systems. Figures 4 and 17 show high frequency data from FM tapes of turbopump speed and weight flow.

Included in this report are plots of the turbine parameters obtained from 10 KC digital recording systems. Figures 14 and 15 illustrate the turbine inlet and outlet static pressures versus time.

Figure 31 illustrates the 10 KC digital plot of the turbine inlet flowmeter versus time. Turbine mass flow is the product of the density of the turbine gas and the volumetric flow through the flowmeter. From the period t = 27.7 seconds to t = 28.4 seconds, the output from the flowmeter was limited. Thus, the plot in this range gives erroneous values of mass flow. Figure 32 shows turbine power control valve position versus time.

<u>Pump discharge pipe</u>.- The variation of pipe wall temperature with time at Station C is presented in Figure 33. Unlike previous runs, the temperature indicates a steady drop to liquid temperature instead of a leveling out for a period of time at a temperature about 100°R.

<u>Nozzle</u>.- Nozzle wall temperatures versus times are plotted in figures 34 and 35. A time history of static pressure inside the nozzle exit bell and the vibration load at the nozzle inlet manifold is plotted in figure 36.

<u>Reflector</u>.- Figures 37 and 38 are plots of the dynamic pressure versus time and fluid temperature versus time for various stations at the reflector outlet. The relative cooldown of the various components of the reflector are presented in figures 39 to 43. The temperatures presented are averages of the representative temperatures of each component plotted.

Core.- The relative cooldown of the core modulus and fuel elements is presented in figures 44 and 45. The temperatures presented are averages of material temperatures down the length of a module and a fuel element at the center of the reactor. A cross plot of material temperatures vs. length at selected times during the run for a fuel element is presented in figure 46. A cross plot of static pressure along the length of a fuel element is presented in figure 47.

Nozzle Chamber.- Figure 48 illustrates the fluid temperature at the nozzle chamber versus distance from the centerline of the chamber for various times during the run.

CONCLUDING REMARKS

From a review of the data presented in this report, it appears that:

1. The turbine maintained bootstrap operation during the flow initiation of the nuclear rocket.

2. No significant oscillations were introduced during the bootstrap operation.

3. The test verified the bootstrap capability of a nuclear rocket system.

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Coordinator: John N.B. Livingood
Contributors: Thomas J. Biesiadny, Robert E. Coltrin Albert G. Powers, Richard A. Rudey, David M. Straight.

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Coordinator: John N.B. Livingood
Contributors: Edward J. Petrik, John G. Pierce, Albert G. Powers, Richard A. Rudey, Roger W. Snyder, David M. Straight, George E. Turney.

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Coordinator: Richard A. Rudey
Contributors: John N.B. Livingood, Thomas C. Litzler, George W. Metger, John G. Pierce, Albert G. Powers, David J. Robinson, David M. Straight.

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LIST OF FIGURES

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TABLE I - INSTRUMENTATION

Item No.		Description	Recording Instrument 4 KC	10 KC	FM	Oscil.	Estimated Overall Accuracy	Remarks
TR-3	T_{fl},	Tank Adapter θ=90°	x	x			±.4° at 40°R	
TR-5	"	" " θ=270°		x			"	
TP-3	P_s ,	Run Tank Top		x		x	±0.6 psi	
TP-4	"	Run Tank Bottom		x			"	
TP-5	"	Tank Adapter	x				"	
TP-6	"	" "		x			"	
TT-7	T_{fl},	Tank Rake				x	See Text	
TT-8	"	" "				x	See Text	
TT-9	"	" "				x	See Text	
TL-1	Tank	Liquid Level	x					
TF-1	Tank	Exit Flowmeter	x	x	x	x		
TF-1B	Tank	Exit Flowmeter				x		
PR-1	T_{fl},	Pump Inlet Duct		x			±0.4°R at 40°R	
PR-2	"	" " "		x			"	
PR-4	"	Pump Outlet Duct	x	x	x		"	
PR-5	"	" " "		x			"	
PR-7	"	Turbine Inlet		x	x	x	±9.0°R at 40°R	
PR-8	"	Turbine Outlet		x	x	x	"	
PR-9	"	Balance Piston Bleed				x	See Text	
PR-23	"	Aft Bearing Bleed				x	See Text	
PP-3	P_s ,	Pump Inlet Duct		x		x	±0.6 psi	
PP-12	"	Venturi Inlet	x	x			±1.2 psi	
PP-14	"	Turbine Inlet		x		x	±0.6 psi	
PP-15	"	" "		x	x	x	"	
PP-16	"	Turbine Outlet		x		x	±0.15 psi	
PP-30	"	Turbine Lube Oil						Meter 18
PP-32	"	Interseal Bleed Pressure				x		
PP-33	"	Balance Piston Bleed				x	±0.6 psi	
PP-34	"	Pump Discharge Pressure		x	x	x	±1.2 psi	

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TABLE I (Cont.)

Item No.	Description	Recording Instrument 4 KC	10 KC	FM	Oscil.	Estimated Overall Accuracy	Remarks
PT-7	T_w, Turbine Inlet Wall, I/C	x				See Text	
PT-11	T_{fl}, Lube Oil Inboard I/C				x	See Text	
PT-12	" Lube Oil Outboard I/C				x	See Text	
PT-13	T_w, Torquemeter Inboard Bearing No. 1 I/C				x	See Text	
PT-14	" Torquemeter Outboard Bearing No. 2 I/C				x	See Text	
PT-15	" Turbine Inboard Bearing I/C				x	See Text	
PT-16	" Turbine Outboard Bearing I/C				x	See Text	
PT-28	" Pump Volute						Meter M-1
PS-1	Pump Speed		x	x	x	See Text	
PS-2	Pump Speed						Speed Controller
PS-3	Pump Overspeed						Overspeed Circuit
PDL-1	Pump Dynamic Torquemeter		x	x			
PA-2	Pump Inlet Radial θ=210°				x		
PA-3	Pump Torquemeter-Radial θ=210°				x		
PA-4	Pump Torquemeter-Radial θ=135°				x		
PA-6	Turbine Inlet Radial θ=135°				x		
PA-9	Turbine Exit Axial θ=135°				x		
PMF-1	Pump Bypass Flowmeter Mass		x				Coded Out
PP 11/2	ΔP Pump In/Out		x		x	±1.0 psi	
PP 6/1	ΔP Inlet Duct				x	±.05 psi	
PP 7/1	ΔP Inlet Duct				x	"	
PP 12/13	ΔP Venturi	x	x			±0.4 psi	
PR-10	T_{fl}, Turbine Flow Station		x			±9.0°R at 40°R	
PR-11	" Bypass Flow Station		x			±.4°R at 40°R	
PR-13	" 4" Feed Line Sta. A		x			±9.0°R at 40°R	
PR-15	" " " " " B	x		x		"	
PR-16	" " " " " C		x			"	
PR-17	" " " " " D	x				"	
PR-18	" " " " " "	x				"	
PR-19	" " " " " "	x				"	

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TABLE I (Cont.)

Item No.		Description	Recording Instrument 4 KC	10 KC	FM	Oscil.	Estimated Overall Accuracy	Remarks
PR-20	T_{fl},	4" Feed Line Sta. E		x			$\pm$9.0°R at 40°R	
PR-21	"	" " " " "	x				"	
PR-22	"	" " " " "	x				"	
PR-25	"	Main Valve Inlet	x	x	x		"	
PP-19A	P_s,	Turbine Flow Sta.		x		x	$\pm$0.8 psi	
PP-20	"	Bypass Flow Sta.		x				Coded Out
PP-21	"	4" Feed Line Sta. A	x	x		x	$\pm$1.2 psi	
PP-22	"	" " " " B	x				"	
PP-25	"	" " " " C	x				"	
PP-26	"	" " " " D	x				"	
PP-27	P_s,	4" Feed Line Sta. E	x	x		x	"	
PP-31	"	Hydraulic						Shutdown at 2000 psig
PP-36	"	Feed Line Sta. C		x			$\pm$1.5 psi	
PP-40	"	" " " B			x		$\pm$1.2 psi	
PP-41	"	Main Valve Inlet	x				"	
PP-42	"	" " "		x	x		"	
PP 23/22	ΔP	Sta. B				x	$\pm$0.1 psi	
PP 24/22	ΔP	Sta. B				x	$\pm$0.1 psi	
PP 28/43	ΔP	Sta. E				x	"	
PP 29/43	ΔP	Sta. E				x	"	
PP 46/44	ΔP	Sta. E.				x	"	
PP 47/45	ΔP	Sta. E				x	"	
PT-23	T_w,	Turbine Flow Sta.I/C	x				See Text	
PT-29	T_{fl},	Dump Line				x	See Text	
PT-33	T_m,	Main Valve Flange Neck	x				See Text	
PT-34	"	Gimbal Inlet Hinge Ring	x				See Text	
PT-35	"	Gimbal Exit Hinge Ring	x				See Text	
PT-36	"	Flange Near Sta. B (Neck)	x				See Text	
PT-37	"	Flange Near Sta. B (Neck)	x				See Text	

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TABLE I (Cont.)

Item No.		Description	Recording Instrument 4 KC	10 KC	FM	Oscil.	Estimated Overall Accuracy	Remarks
PT-38	T_m ,	Gimbal Inlet Hinge Ring	x				See Text	
PT-39	"	Gimbal Exit Hinge Ring	x				See Text	
PT-54	T_w ,	Elbow-Inside Radius	x				See Text	
PT-55	"	Elbow-Outside Radius	x				See Text	
PT-59	"	Pipe Wall Sta. A	x				See Text	
PT-60	"	Pipe Wall	x				See Text	
PT-61	"	Pipe Wall	x				See Text	
PT-66	"	Pipe Wall Sta. B	x				See Text	
PT-67	"	Pipe Wall	x				See Text	
PT-68	"	Pipe Wall	x				See Text	
PT-69	"	Pipe Wall	x				See Text	
PT-70	"	Pipe Wall Sta. C	x				See Text	
PT-73	"	Elbow-Inside Radius	x				See Text	
PT-74	"	Elbow-Outside Radius	x				See Text	
PT-75	"	Pipe Wall Sta. D	x				See Text	
PT-76	"	Pipe Wall Sta. D	x				See Text	
PT-77	"	Pipe Wall Sta. D	x				See Text	
PT-78	"	Pipe Wall Sta. E	x				See Text	
PF-1	$\dot{w}$,	Pump Bypass Line Flowmeter		x	x	x		
PF-2	"	Turbine Flowmeter		x				Coded Out
PQ-E	Quality Meter		x	x		x		
NP-39	P_s ,	Nozzle Throat	x				± 0.6 psi	
NP-40	"	Nozzle Exit Bell	x				± 0.4 psi	
NP-41	"	Nozzle Exit Bell	x				± 0.4 psi	
NP-42	"	Nozzle Exit Bell	x				± 0.4 psi	
NP-50	"	Nozzle Chamber	x				± 0.6 psi	
NP-51	"	Nozzle Chamber		x	x		"	

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TABLE I (Cont.)

Item No.	Description	Recording Instrument: 4 KC	10 KC	FM	Oscil.	Estimated Overall Accuracy	Remarks
NT-39	T_w, Support Skirt	x				See Text	
NT-40	" " "	x				See Text	
NT-56	T_m, Throat Ring	x				See Text	
NT-58	T_w, Nozzle Flange	x				See Text	
NA-0	Nozzle Inlet Manifold				x		
NA-270	" " "				x		
NR-1	T_{fl}, Nozzle Inlet Manifold		x	x		$\pm$9.0°R at 40°R	
NR-2	" " " "		x			$\pm$0.4°R at 40°R	
NR-4	" " " "		x			"	
NP-1	P_s, " " "	x				$\pm$1.5 psi	
NP-3	" " " "		x			"	
NP-52	" " " "		x	x		"	
NT-1	T_w, " " "	x				See Text	
NT-3	" " " "	x				See Text	
NT-72	" Siper Leg 82°	x				See Text	
NT-73	" " " 202°	x				See Text	
NT-74	" " " 322°	x				See Text	
NT-75	" " " 82°	x				See Text	
NT-76	" " " 202°	x				See Text	
NT-77	" " " 322°	x				See Text	
NP-7	P_s, Nozzle Wall Tube No. 93	x	x			$\pm$1.0 psi	
NP-8	" " " "		x		x	$\pm$1.5 psi	
NP-9	" " " "	x	x			"	
NP-10	" " " "		x		x	"	
NP-11	" " " "		x			"	
NP-12/8	ΔP Nozzle Tube #93				x	$\pm$0.05 psi	
NP-13/10	ΔP Nozzle Tube #93				x	$\pm$0.05 psi	

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TABLE I (Cont.)

Item No.	Description	Recording Instrument 4 KC	10 KC	FM	Oscil.	Estimated Overall Accuracy	Remarks
NT-7	T_w , Nozzle Tube #93	x	x			See Text	
NT-9	" " " "	x	x			See Text	
NT-10	" " " "	x	x			See Text	
NT-11	" " " "	x				See Text	
NT-12	" " " "	x	x			See Text	
NT-13	" " " "	x				See Text	
NT-14	" " " "	x				See Text	
NT-17	" " " #23	x				See Text	
NT-18	" " " "	x				See Text	
NT-19	" " " "	x				See Text	
NT-20	" " " "	x				See Text	
NT-23	" " " "	x				See Text	
NT-24	" " " "	x				See Text	
NT-26	" " " #178	x				See Text	
NT-27	" " " "	x				See Text	
NT-28	" " " "	x				See Text	
NT-29	" " " "	x				See Text	
NT-30	" " " "	x				See Text	
NT-31	" " " "	x				See Text	
NT-32	" " " "	x				See Text	
NT-79	" " " #23	x					
NT-80	" " " "	x					
NT-81	" " " "	x					
NT-82	" " " "	x					
IT-1	T-Insulation				x	See Text	
IT-2	"				x	See Text	
IT-3	"				x	See Text	
IT-4	"				x	See Text	
IT-5	"				x	See Text	
IT-6	"				x	See Text	

[redacted]

[redacted]

TABLE I (Cont.)

[redacted]

Item No.	Description	Recording Instrument 4 KC	10 KC	FM	Oscil.	Estimated Overall Accuracy	Remarks
NP-21	P_s , Nozzle Chamber	x				±0.6 psi	
NP-22	" " "					±1.2 psi	Meter M-9
NP-24	" Bleed Port		x	x		±0.8 psi	
NR-7	T_{fl}, Bleed Port		x	x		±9.0°R at 40°R	
NT-60	" Instrumentation Rake	x	x	x		See Text	
NT-61	" " "	x				See Text	
NT-62	" " "	x				See Text	
NT-63	" " "		x			See Text	
NT-64	" " "		x			See Text	
NT-78	T_w , Nozzle Bleed Port	x				See Text	
RR-601	T_{fl}, Reflector Inlet Plenum		x			±9.0°R at 40°R	
RR-610	" " " "		x			±0.4°R at 40°R	
RR-612	" " " "		x	x		±9.0°R at 40°R	
RP-140	P_s , Reflector Inlet Plenum		x	x		±1.5 psi	
RP-141	" " " "		x			"	
RP-603/66	ΔP Reflector Inlet/Reflector Pass		x			±0.09 psi	
RP-604/68	ΔP Reflector Inlet/Reflector Pass		x			±0.10 psi	
RT-98	T_m , Reflector Segment at 0°	x				See Text	
RT-99	" " " " "	x				See Text	
RT-100	" " " " "	x				See Text	
RT-101	" " " " "	x				See Text	
RT-104	" " " " "	x				See Text	

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[redacted]

TABLE I (Cont.)

Item No.	Description	Recording Instrument: 4 KC	10 KC	FM	Oscil.	Estimated Overall Accuracy	Remarks
RT-105	T_m, Reflector Segment at 0°	x				See Text	
RT-106	" " " " "	x				See Text	
RT-107	" " " " "	x				See Text	
RT-108	" " " " "	x				See Text	
RT-109	" " " " "	x				See Text	
RT-110	" " " " "	x				See Text	
RT-111	" " " " "	x				See Text	
RT-112	" " " " "	x				See Text	
RT-113	" " " " "	x				See Text	
RT-116	" " " " "	x				See Text	
RT-117	" " " " "	x				See Text	
RT-118	" " " " "	x				See Text	
RT-119	" " " " "	x				See Text	
RT-120	" " " " "	x				See Text	
RT-121	" " " " "	x				See Text	
RT-126	" " " "60°	x				See Text	
RT-194	" " " 240°		x			See Text	
RT-196	" " " "		x			See Text	
RT-199	" " " "		x			See Text	
RT-206	" " " "		x			See Text	
RT-208	" " " "		x			See Text	
RT-211	" " " "		x			See Text	
RT-223	" " " 300°	x				See Text	
RT-234	" " " "	x				See Text	
RT-235	" " " "	x				See Text	
RM-317	T_{fl}, Control Drum .06" Annulus		x				
RM-319	" " " "		x				
RM-321	" " " "		x				

[redacted]

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TABLE I (Cont.)

Item No.	Description	Recording Instrument 4 KC	10 KC	FM	Oscil.	Estimated Overall Accuracy	Remarks
RT-77	T_m, Graphite Cylinder θ=170°		x			See Text	
RT-78	" " " "		x			See Text	
RT-79	" " " "		x			See Text	
RT-94	" " " θ=350°	x				See Text	
RT-95	" " " "	x				See Text	
RT-96	" " " "	x				See Text	
RT-97	" " " "	x				See Text	
RT-263	" Control Rod θ=0°	x				See Text	
RT-264	" " " "	x				See Text	
RT-265	" " " "	x				See Text	
RT-266	" " " "	x				See Text	
RT-267	" " " "	x				See Text	
RT-268	" " " "	x				See Text	
RT-269	" " " "	x				See Text	
RT-270	" " " "	x				See Text	
RT-271	" " " "	x				See Text	
RT-274	" " " 60°	x				See Text	
RT-283	" " " 120°	x				See Text	
RT-290	" " " 180°		x			See Text	
RT-292	" " " "	x	x			See Text	
RT-293	" " " "		x			See Text	
RT-295	" " " "		x			See Text	
RT-301	" " " 240°	x				See Text	
RT-310	" " " 300°	x				See Text	
RT-380	T_m, Pressure Shell θ=180°	x				See Text	
RT-383	" " " 230°	x				See Text	
RT-386	" " " 290°	x				See Text	
RT-388	" " " 350°	x				See Text	
RT-389	" " " 350°	x				See Text	
RT-390	" " " 350°	x				See Text	
RA-0	g, Pressure Shell Radial				x		
RA-270	" " " "				x		
RA-A	g Pressure Shell Axial				x		

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TABLE I (Cont.)

Item No.		Description	Recording Instrument 4 KC	10 KC	FM	Oscil.	Estimated Overall Accuracy	Remarks
RR-619	T_{fl},	Reflector Outlet Plenum		x			$\pm$9.0°R at 40°R	
RR-622	"	" "	x	x	x		"	
RR-624	"	" "		x			"	
RP-82	P_t,	Reflector Segment, 0.188" Hole	x				$\pm$1.2 psi	
RP-85	"	Reflector 0.06" Annulus	x				$\pm$1.0 psi	
RP-88	"	Reflector Segment, 0.188" Hole	x				"	
RP-94	"	Control Drum, 0.188" Hole	x				"	
RP-97	"	Control Drum, 0.06" Annulus	x				"	
RP-100	"	Impedance Ring Passage	x				"	
RP-145	"	Reflector Outlet Plenum		x	x		$\pm$1.2 psi	
RP-146	"	Reflector Outlet Plenum	x				"	
RP-147	"	Reflector Outlet Plenum		x			$\pm$1.0 psi	
RT-242	T_{fl},	Reflector Segment, 0.188" Hole	x				See Text	
RT-245	"	Reflector 0.06" Annulus	x				See Text	
RT-248	"	Reflector Segment, 0.188" Hole	x				See Text	
RT-254	"	Control Drum 0.188" Hole	x				See Text	
RT-257	"	Control Drum 0.06" Annulus	x				See Text	
RT-260	"	Impedance Ring Passage	x				See Text	

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TABLE I (Cont.)

Item No.	Description	Recording Instrument: 4 KC	10 KC	FM	Oscil.	Estimated Overall Accuracy	Remarks
RP-82/58	ΔP Reflector Segment Passage	x				See Text	
RP-85/124	ΔP Reflector Shell Segment	x				$\pm$0.25 psi	
RP-88/58	ΔP Reflector Exit Passage	x				"	
RP-94/103	ΔP Control Rod Passage	x				"	
RP-97/70	ΔP Control Rod Hole	x				"	
RP-100/117	ΔP Imped. Ring Passage	x				$\pm$0.3 psi	
RP-121	P_s, Core Inlet Plenum	x	x			$\pm$1.0 psi	
RP-123	" " " "		x	x		"	
RT-342	T_{fl}, Core Support Plate Flow Passage	x	x	x		See Text	
RT-392	" Core Support Plate Flow Passage	x	x			See Text	
RT-403	T_m, Reactor Dome	x				See Text	
RT-409	" " "	x				See Text	
RT-415	" " "	x				See Text	
RP-31	P_s, Fuel Element Inlet Plenum		x			$\pm$1.0 psi	
RP-32	" " " "	x				"	
RP-33	" " " "		x			"	
RP-1/NP-50	ΔP Fuel Element #1 P_s/ Chamber P_s	x				$\pm$0.25 psi	
RP-2/NP-50	" "	x				"	
RP-3/NP-50	" "	x				$\pm$0.15 psi	
RP-4/NP-50	" "	x				"	
RP-5/NP-50	" "	x				$\pm$0.10 psi	
RP-6/NP-50	ΔP Fuel Element #7 P_s/ Chamber P_s	x				$\pm$0.25 psi	
RP-7/NP-50	" "	x				"	
RP-8/NP-50	" "					$\pm$0.15 psi	

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TABLE I (Cont.)

Item No.	Description	Recording Instrument 4 KC	10 KC	FM	Oscil.	Estimated Overall Accuracy	Remarks
RP-9/NP-50	ΔP Fuel Element #7 P_s/ Chamber P_s	x				±0.15 psi	
RP-10/NP-50	" "	x				±0.10 psi	
RP-28/29	ΔP Fuel Element Inlet/Exit Plenum	x				±0.4 psi	
RP-31/36	" "		x			±0.4 psi	
RP-33/38	" "		x			±0.6 psi	
RT-1	T_m, Fuel Element #1	x				See Text	
RT-2	" " " "	x				See Text	
RT-3	" " " "	x				See Text	
RT-4	" " " "	x				See Text	
RT-5	" " " "	x				See Text	
RT-31	T_m, Module R = 0.6"	x				See Text	
RT-32	" " " "	x				See Text	
RT-33	" " " "	x				See Text	
RT-34	" " " "	x				See Text	
RT-35	" " " "	x				See Text	
EP-1	P_s, Ejector Inlet		x		x	±0.15 psi	
ET-1	T_w, Exhaust Duct				x		
ET-2	" " "				x		
ET-3	" " "				x		
E_c	Main Valve Command Switch	x	x		x		E_c Marker
	Hermes Timer & Mail Valve Command			x	x		
BAR	Barometer	x	x				
PMDV	PMDV Position		x				
LHBV	LHVB Position		x				Coded Out
TPCV	TPCV Position		x		x		

[redacted]

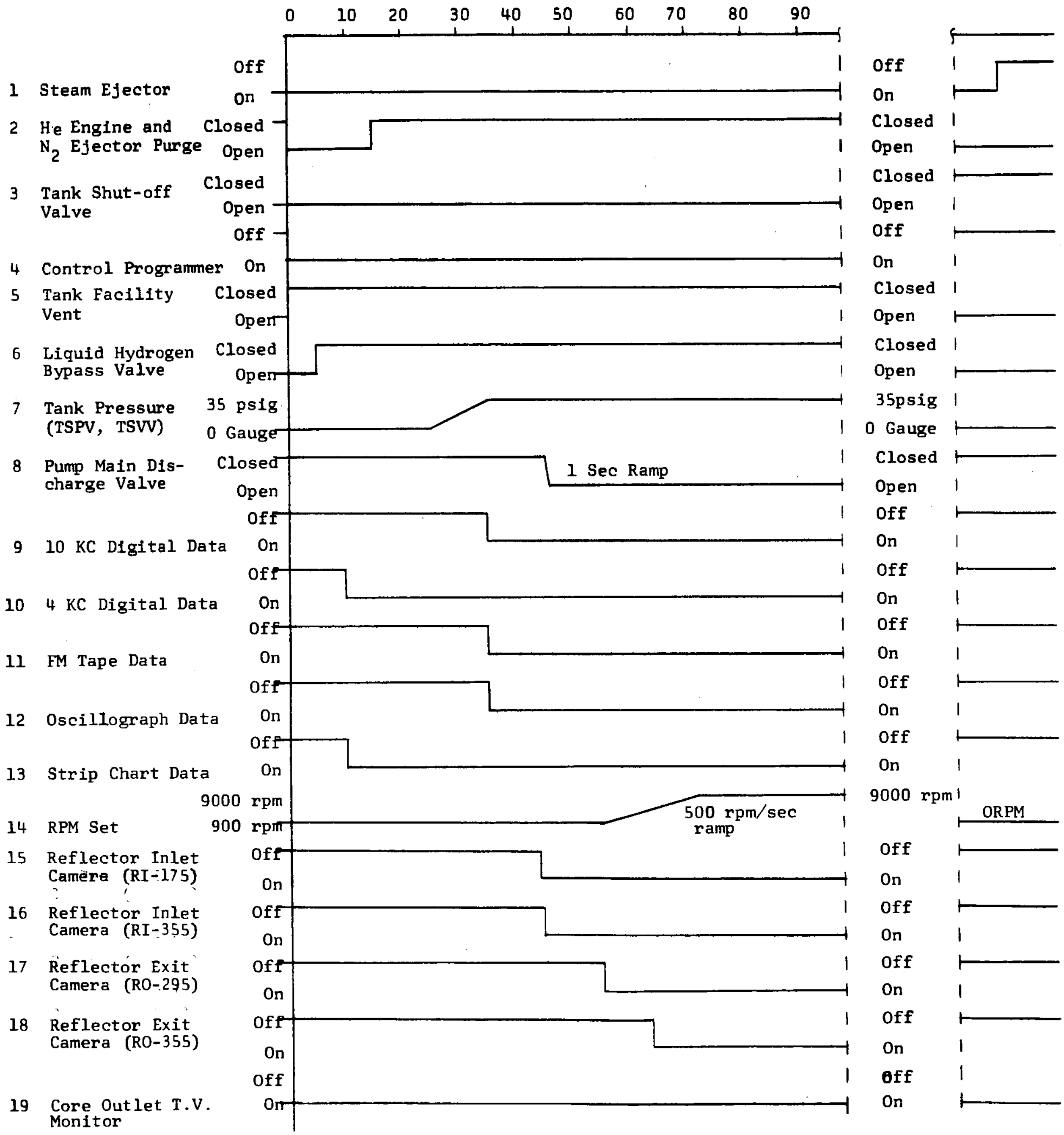
[redacted]

TABLE I (Cont.)

Item No.	Description	Recording Instrument: 4 KC	10 KC	FM	Oscil.	Estimated Overall Accuracy	Remarks
TPCV-L	TPCV Limit Switch				x		
SS	Speed Set				x		
TSPV	Pressure Valve Position				x		
TSVV	Vent Valve Position				x		
PM	Pressure Measured				x		
1	Fwd. Turbine Oil Flow				x		
2	Aft Turbine Oil Flow				x		

[redacted]

TABLE II - AUTOMATIC RUN SEQUENCE



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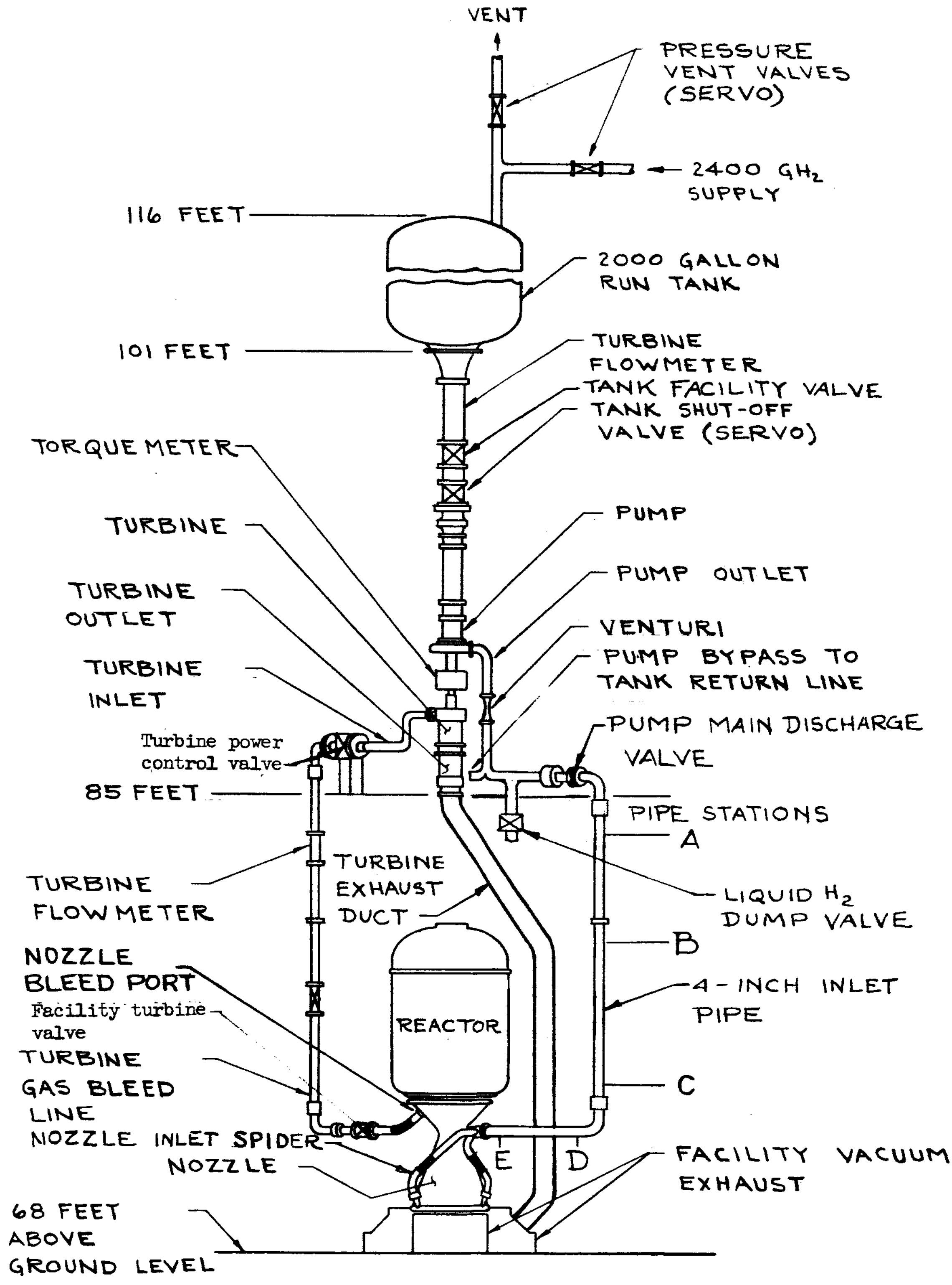

FIGURE 1 - Nuclear Rocket Cold Flow Experiment in B-1 Facility.

[redacted]

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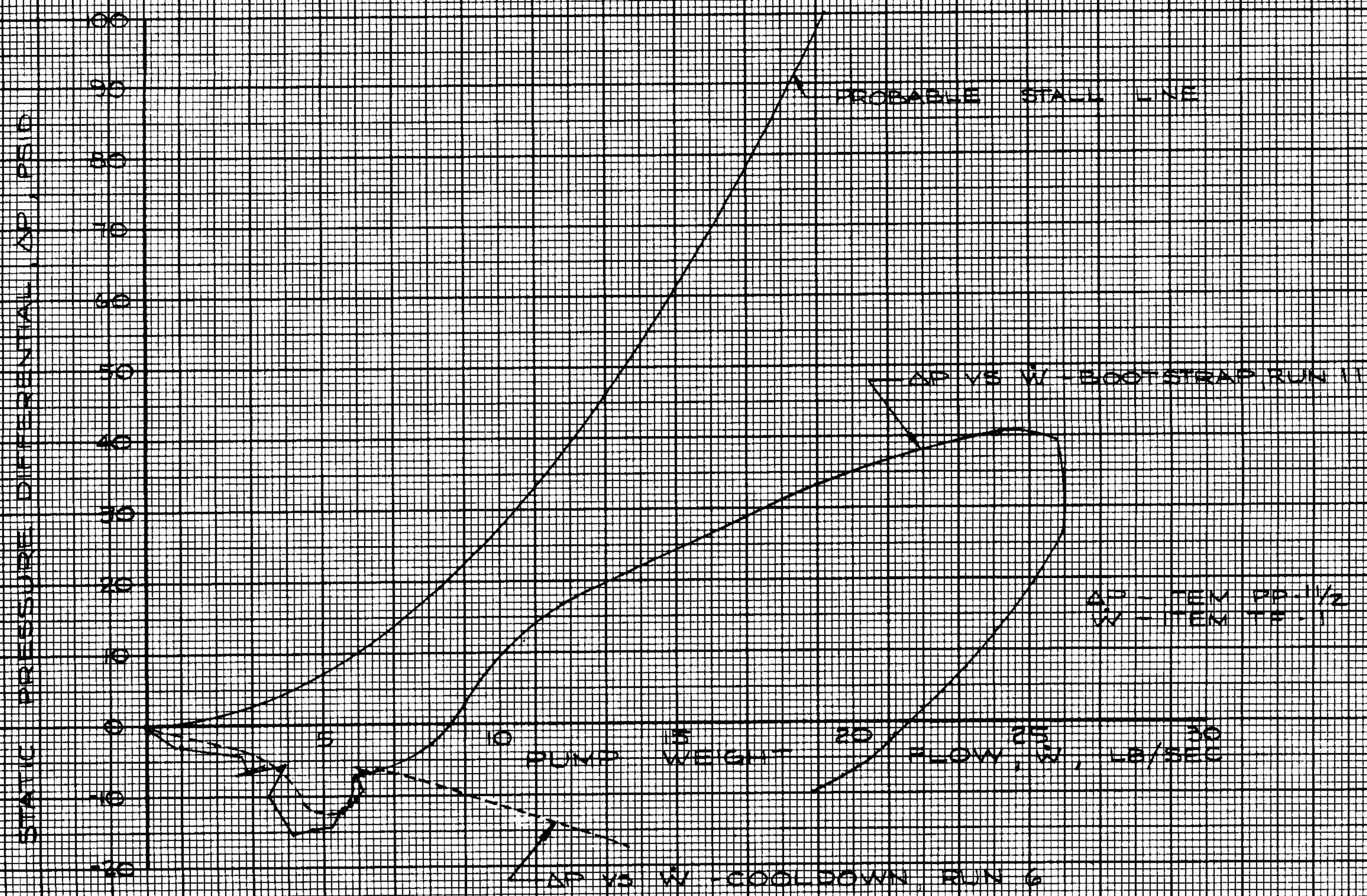

FIGURE 2 STATIC PRESSURE DIFFERENTIAL VS PUMP WEIGHT FLOW - RUN 1

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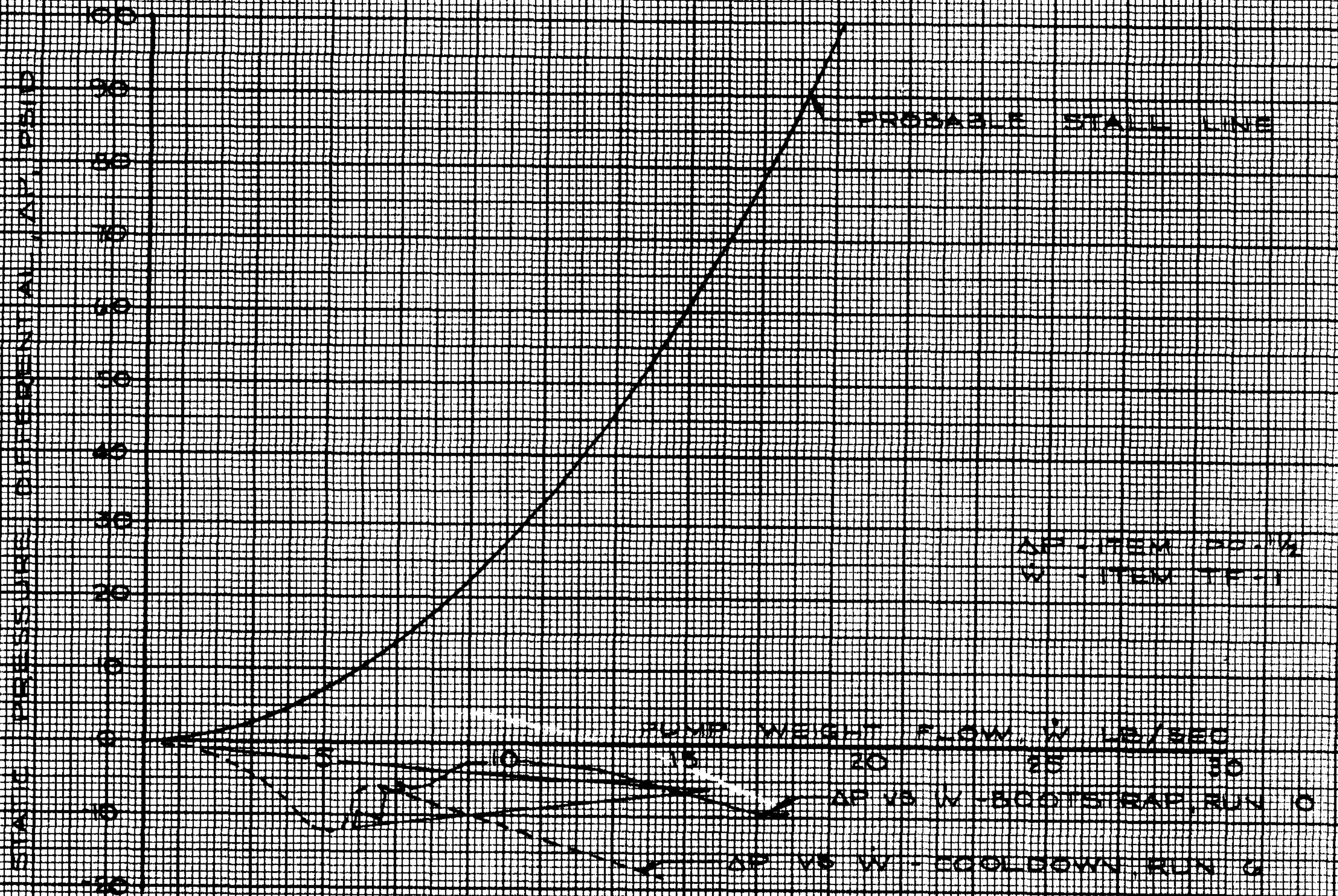

FIGURE 3 STATIC PRESSURE DIFFERENTIAL VS PUMP WEIGHT FLOW - RUN 10

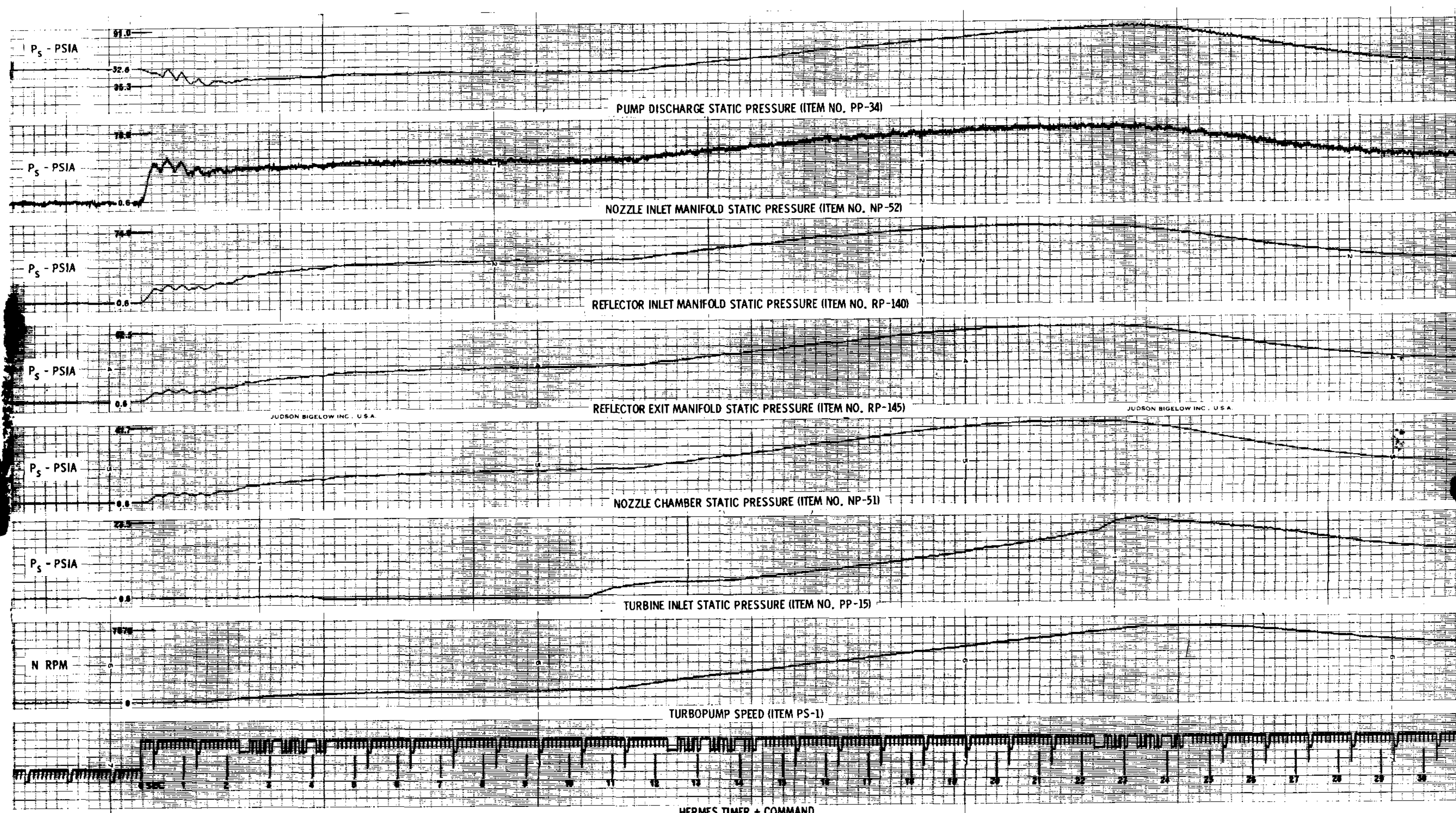

Figure 4. - FM high frequency pressure and speed data versus time.

[redacted]

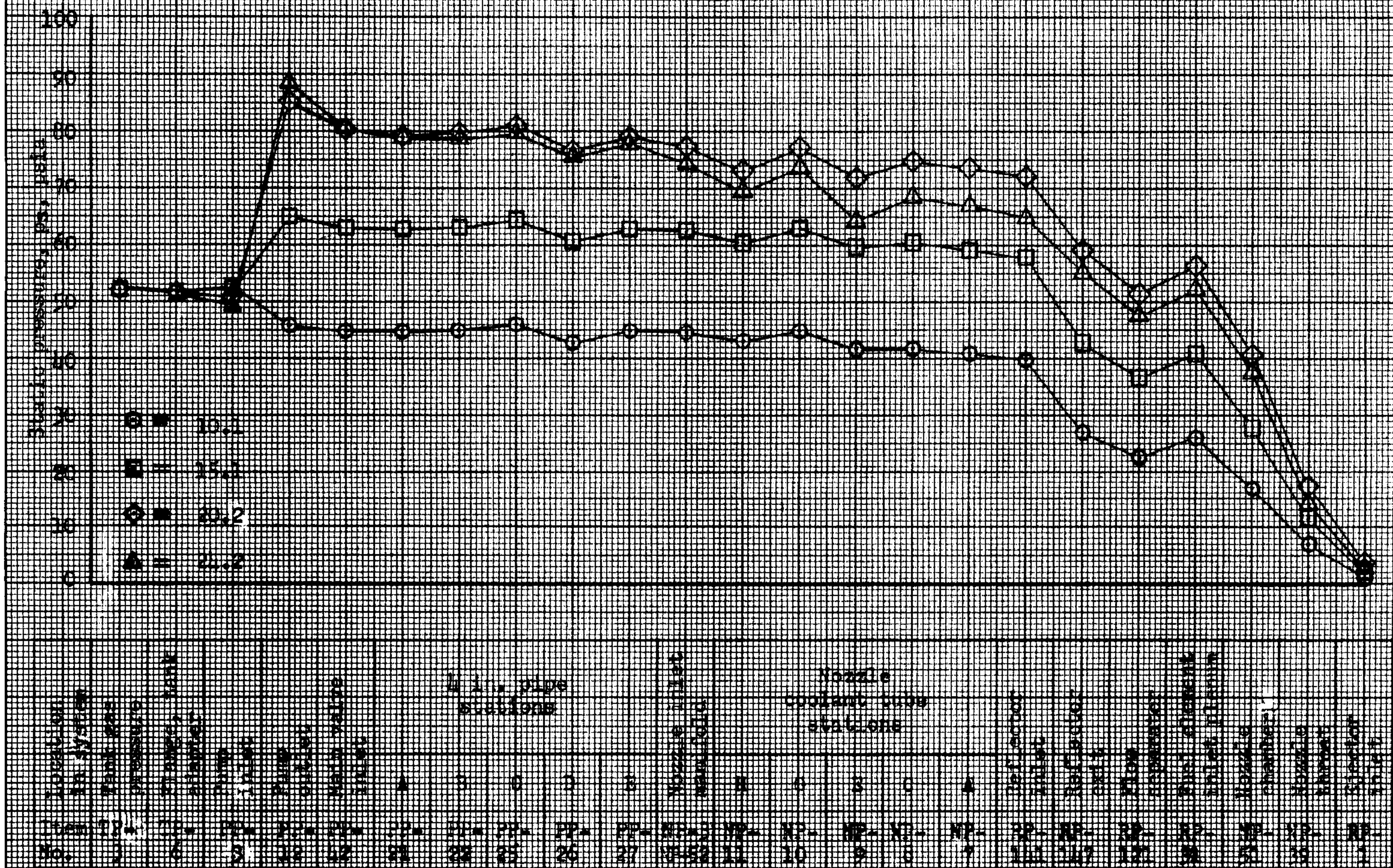

Figure 5.- Variation in Static Pressures through the System at Various Times

[redacted]

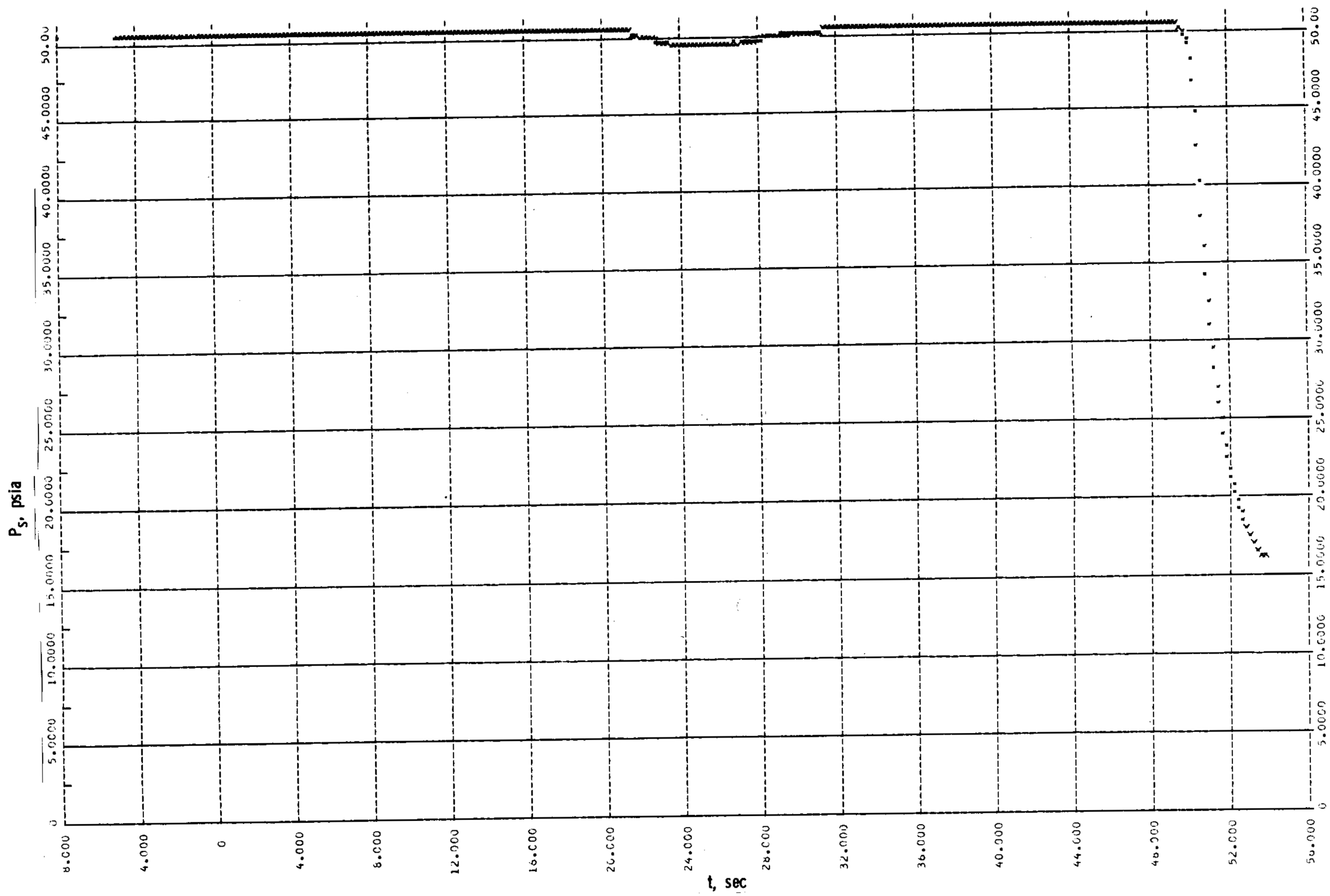

Figure 6. - Pump inlet static pressure versus time (item no. PP-3).

[redacted]

E-2673-5

[redacted]

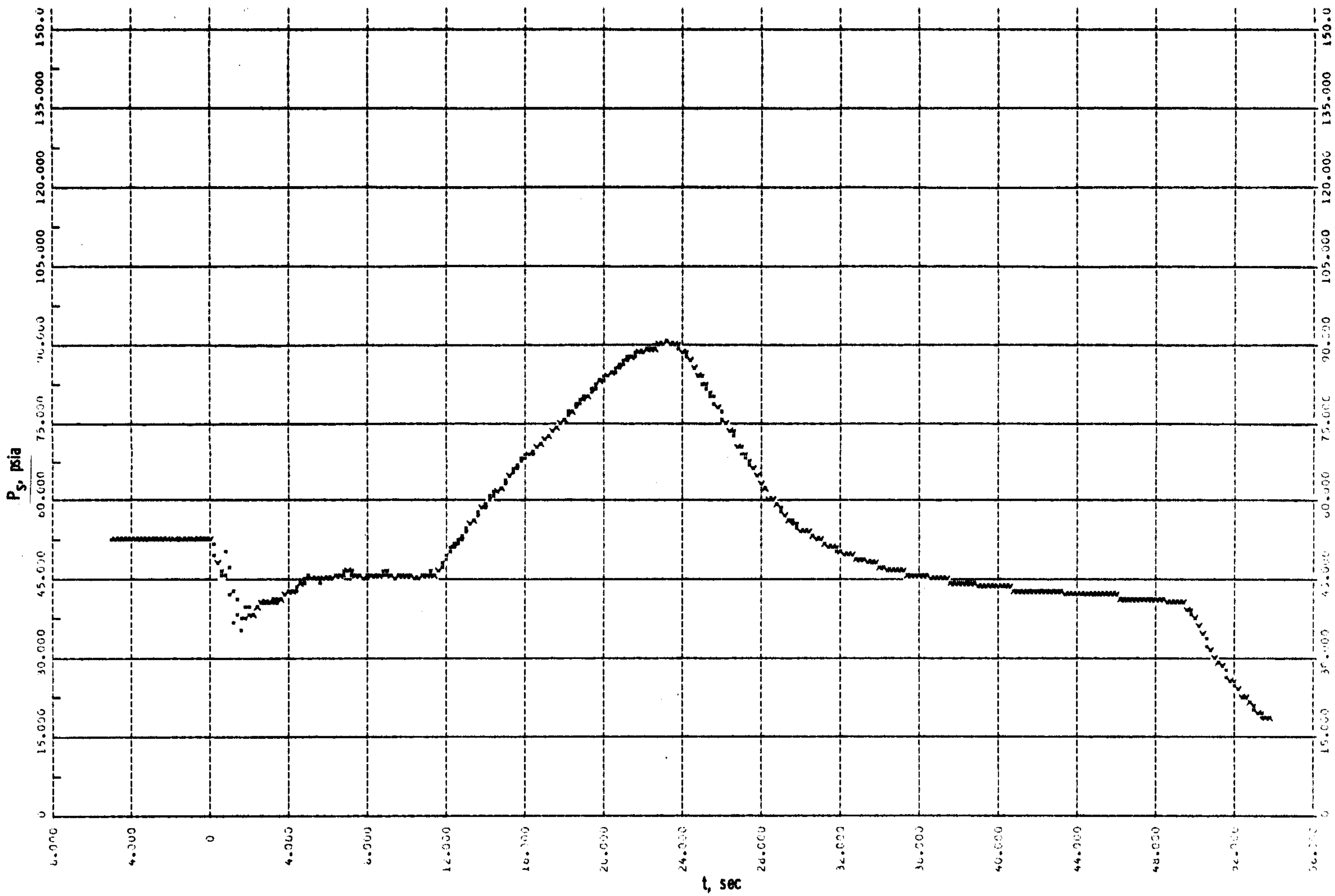

Figure 7. - Pump discharge static pressure versus time (item no. PP-34).

[redacted]

[redacted]

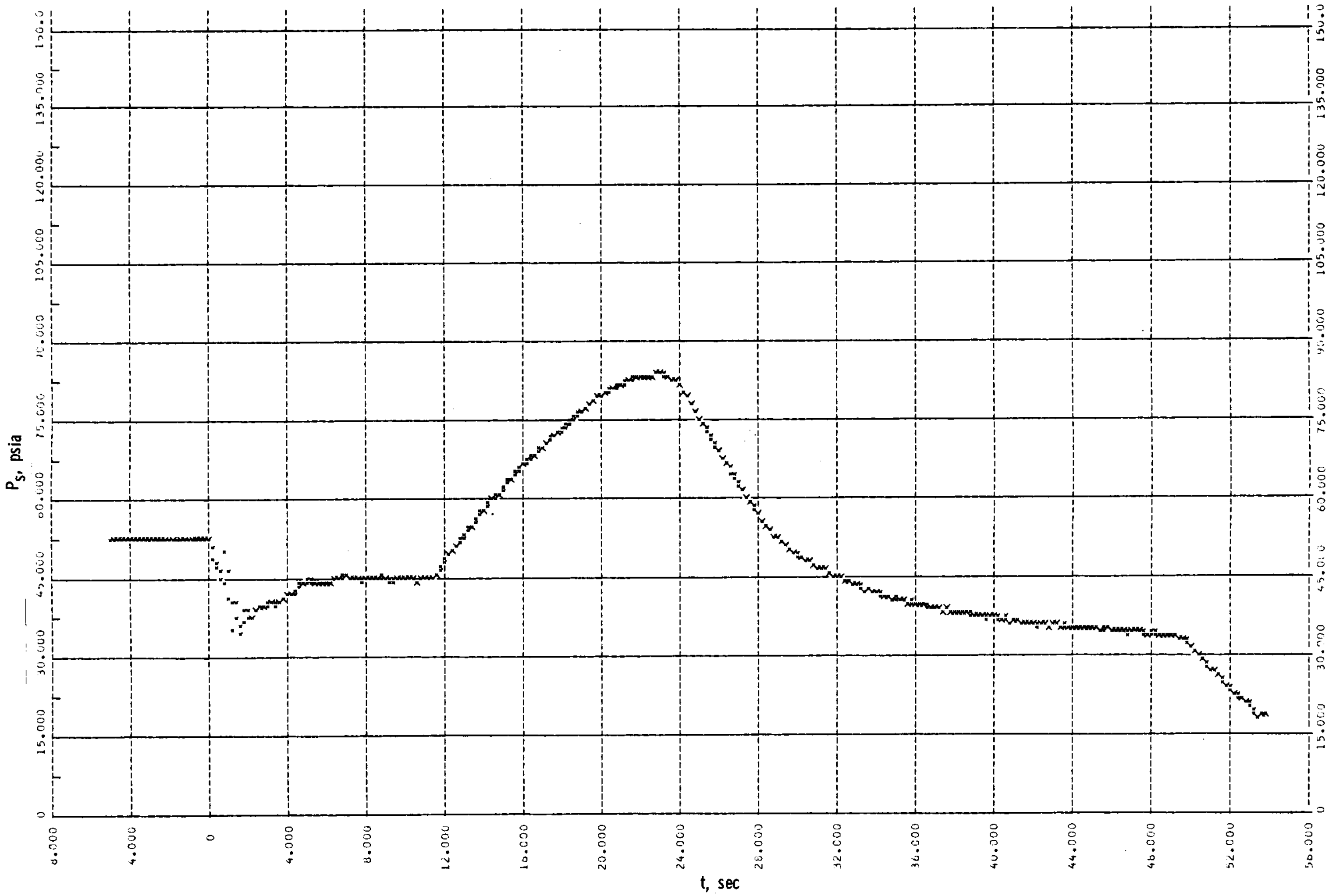

Figure 8. - Main valve inlet static pressure versus time (item no. PP-42).

[redacted]

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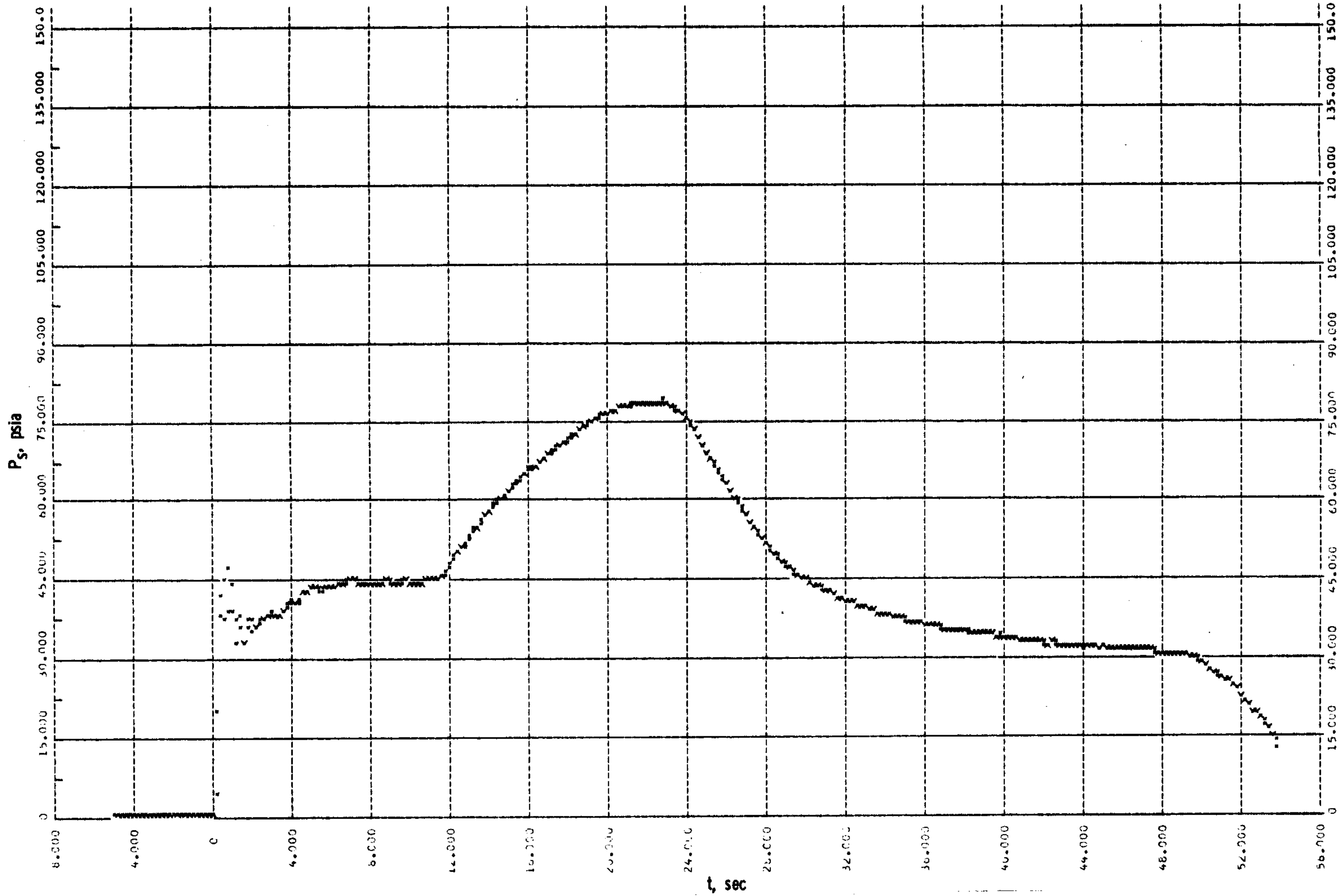

Figure 9. - Nozzle inlet manifold static pressure versus time (item no. NP-52).

[redacted]

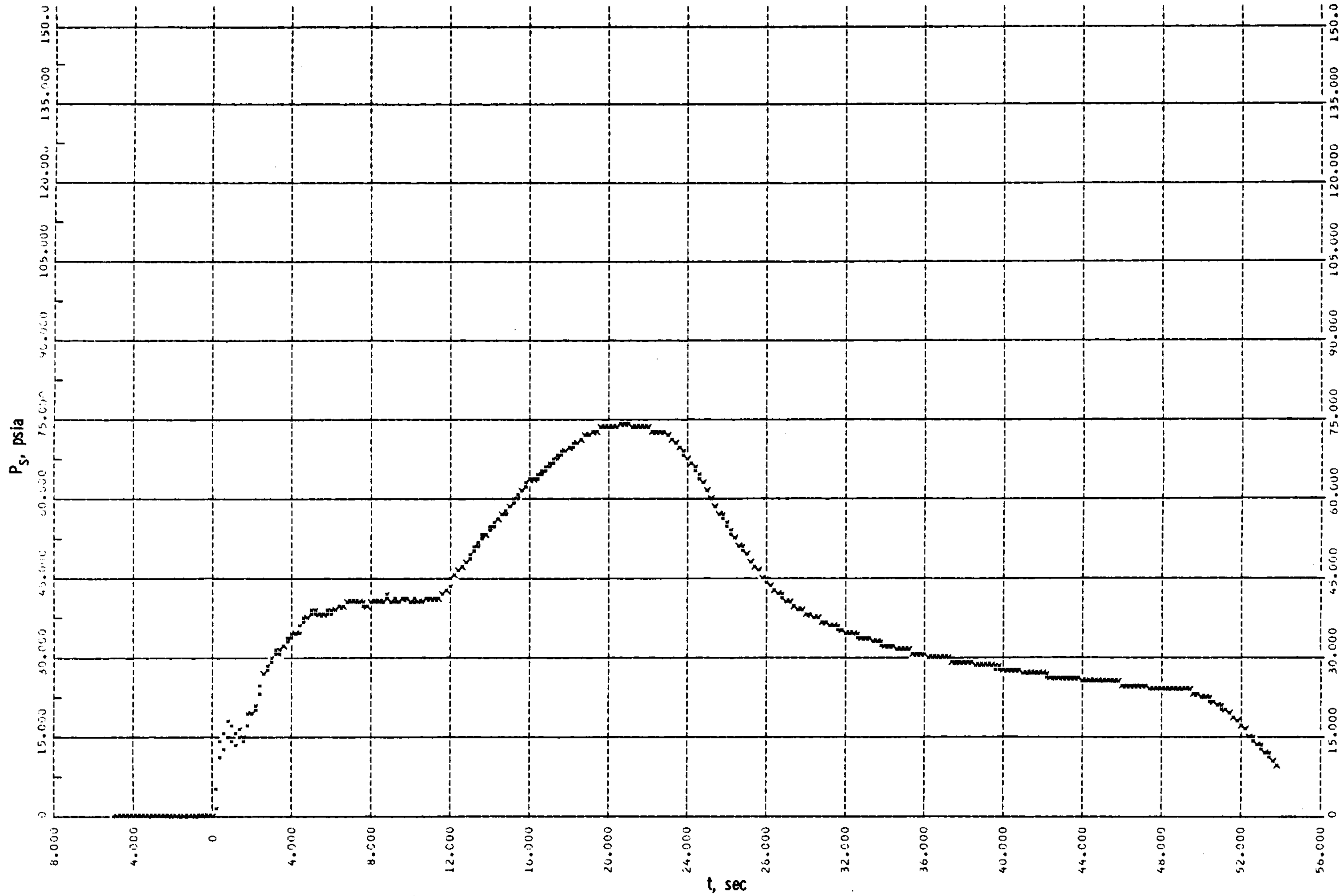

Figure 10. - Reflector inlet manifold static pressure versus time (item no. RP-140).

[redacted]

E-2673-5

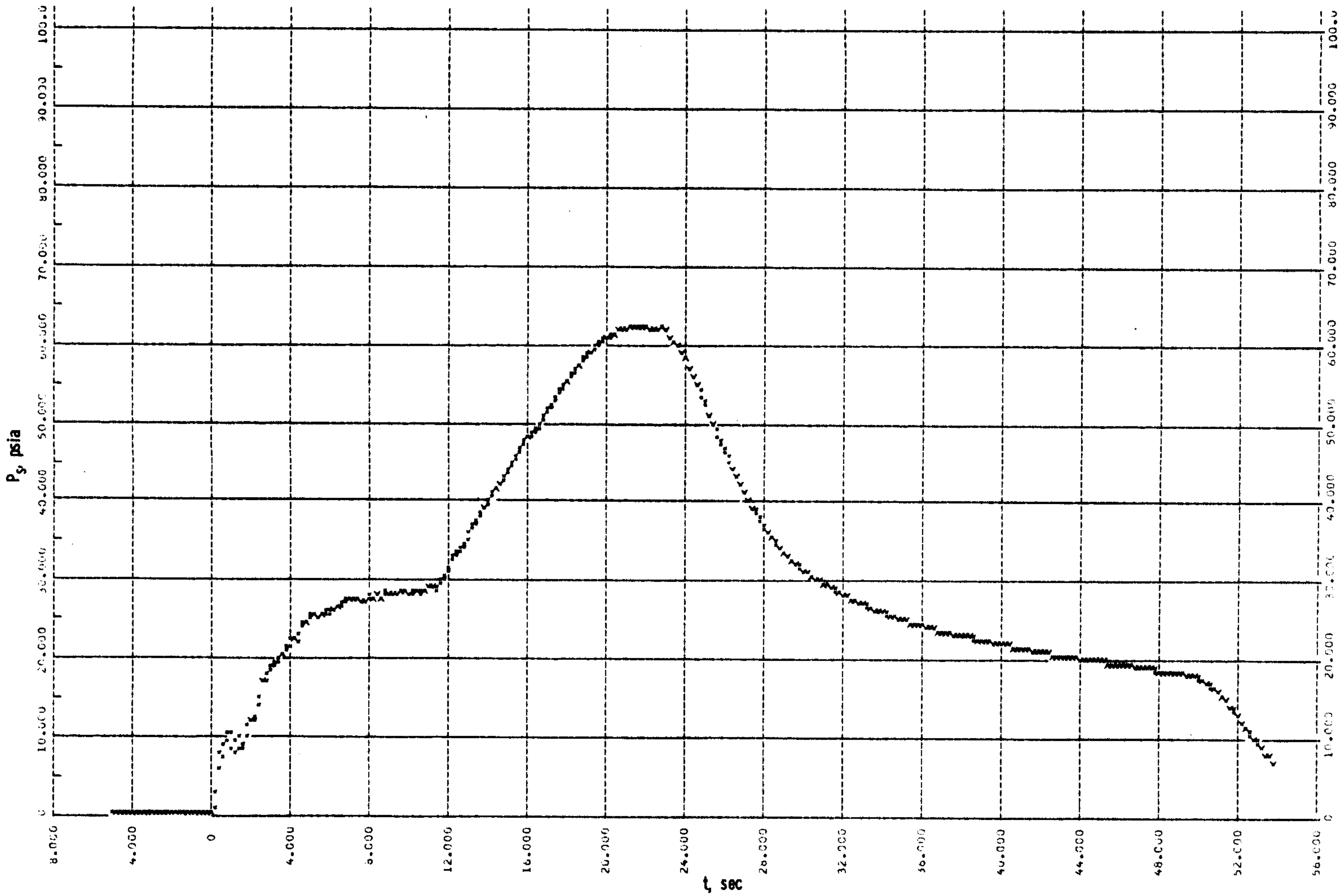

Figure 11. - Reflector exit manifold static pressure versus time (Item no. RP-145).

[redacted]

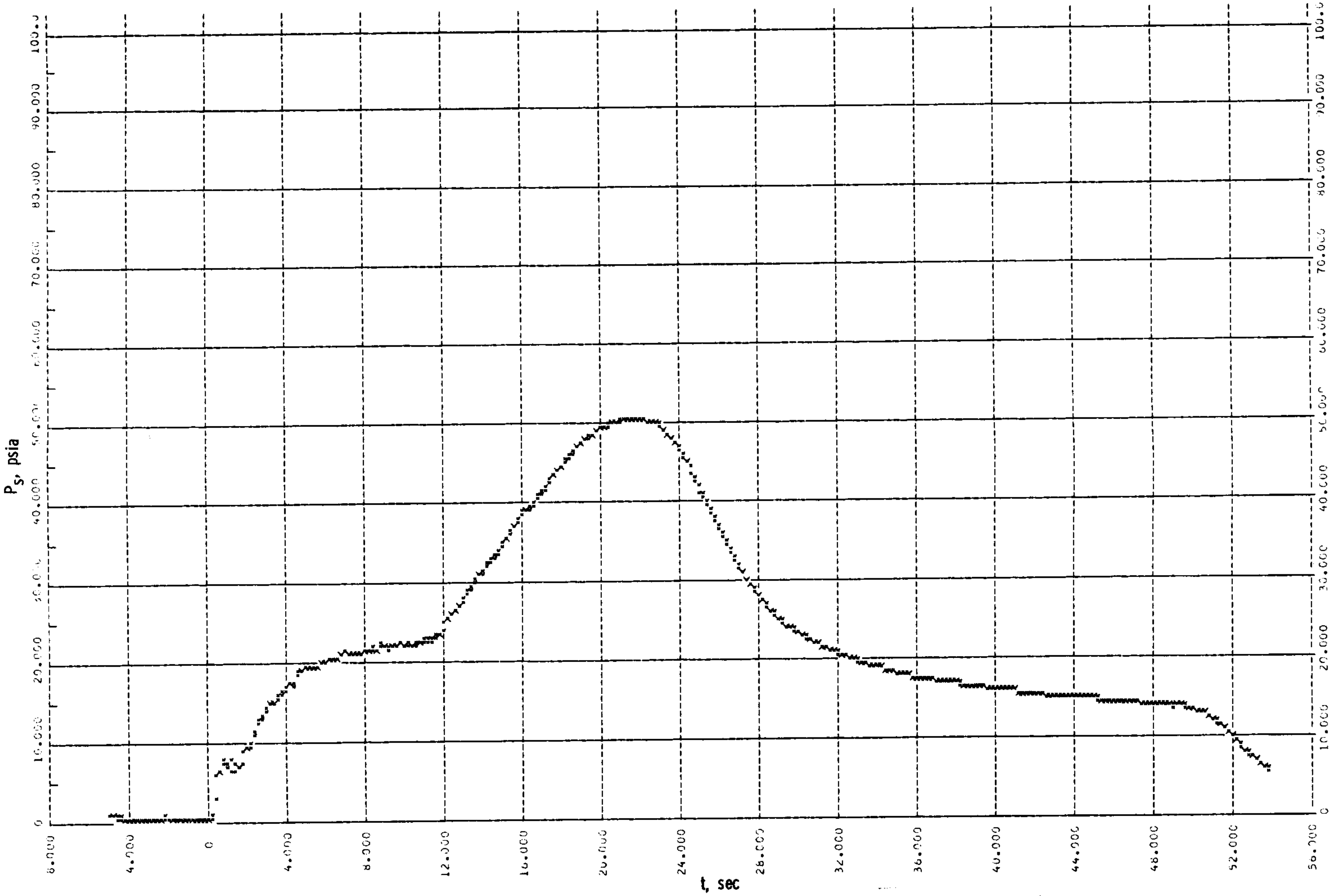

Figure 12. - Core inlet static pressure versus time (item no. RP-123).

E-2673-5

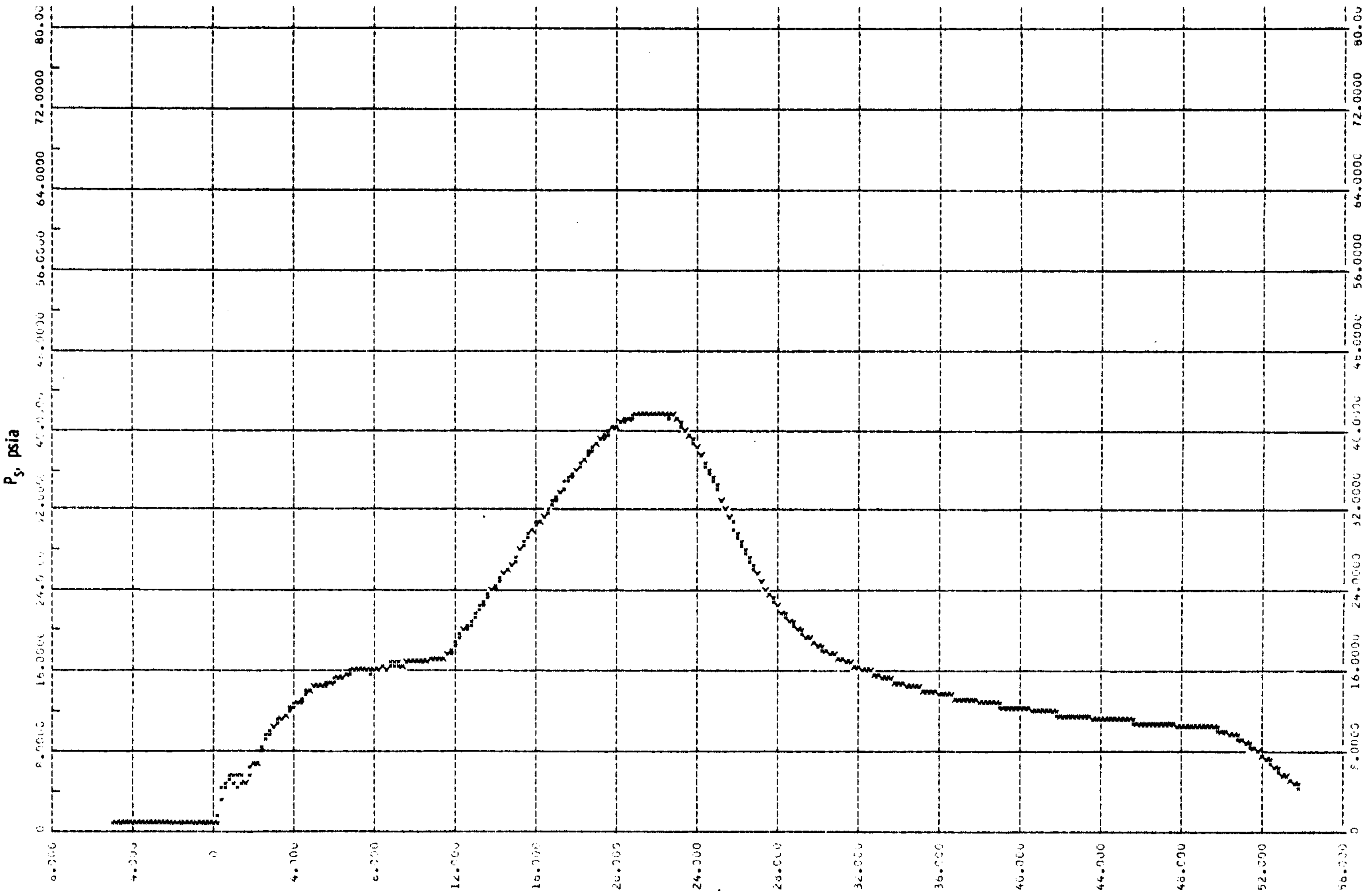

Figure 13. - Nozzle chamber static pressure versus time (item no. NP-51).

[redacted]

[redacted]

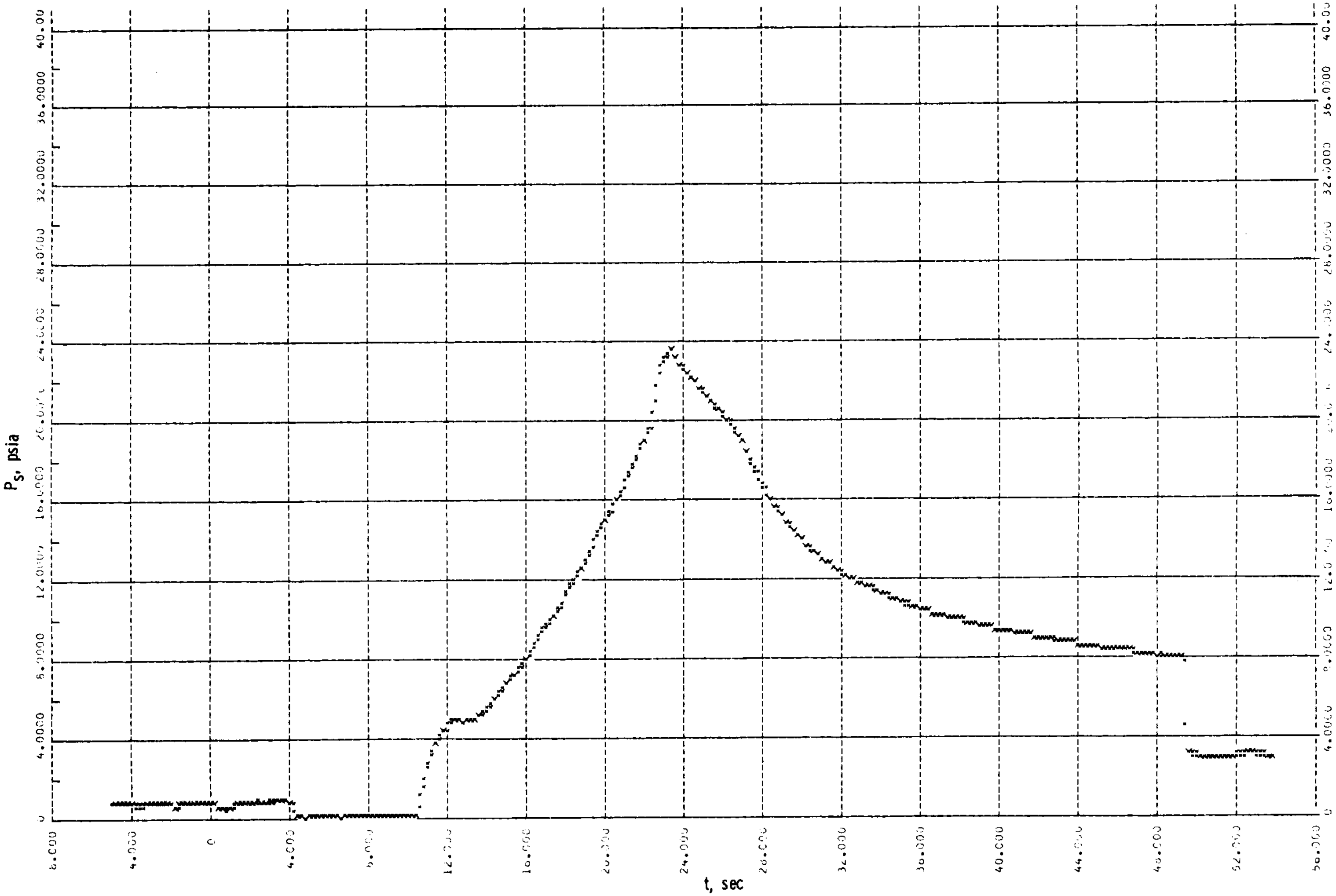

Figure 14. - Turbine inlet static pressure versus time (item no. PP-15).

[redacted]

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FIGURE 15 TURBINE OUTLET PRESSURE VS RUN TIME - RUN 11

[redacted]

[redacted]

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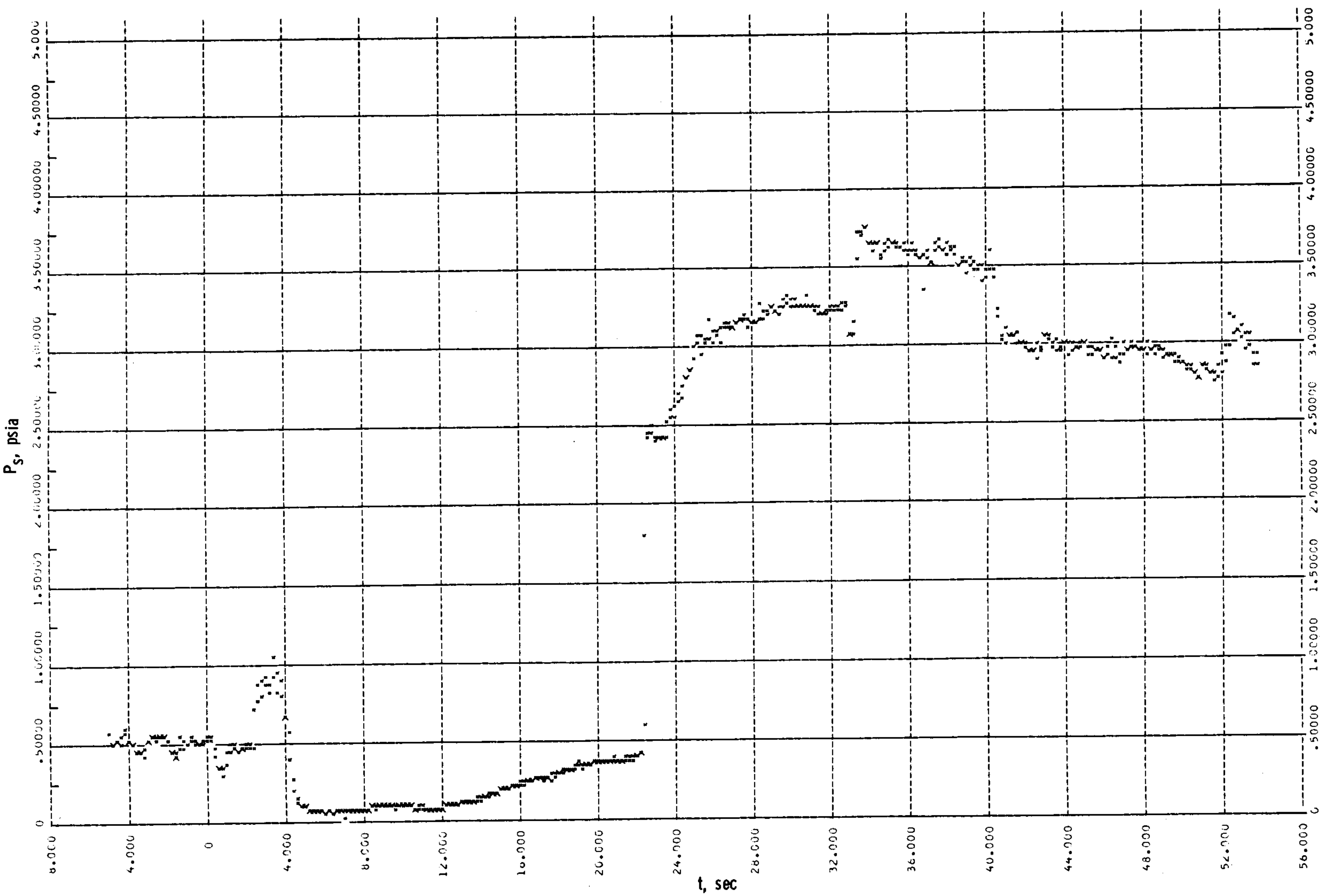

Figure 16. - Ejector inlet static pressure versus time (item no. EP-1).

E-2673-5

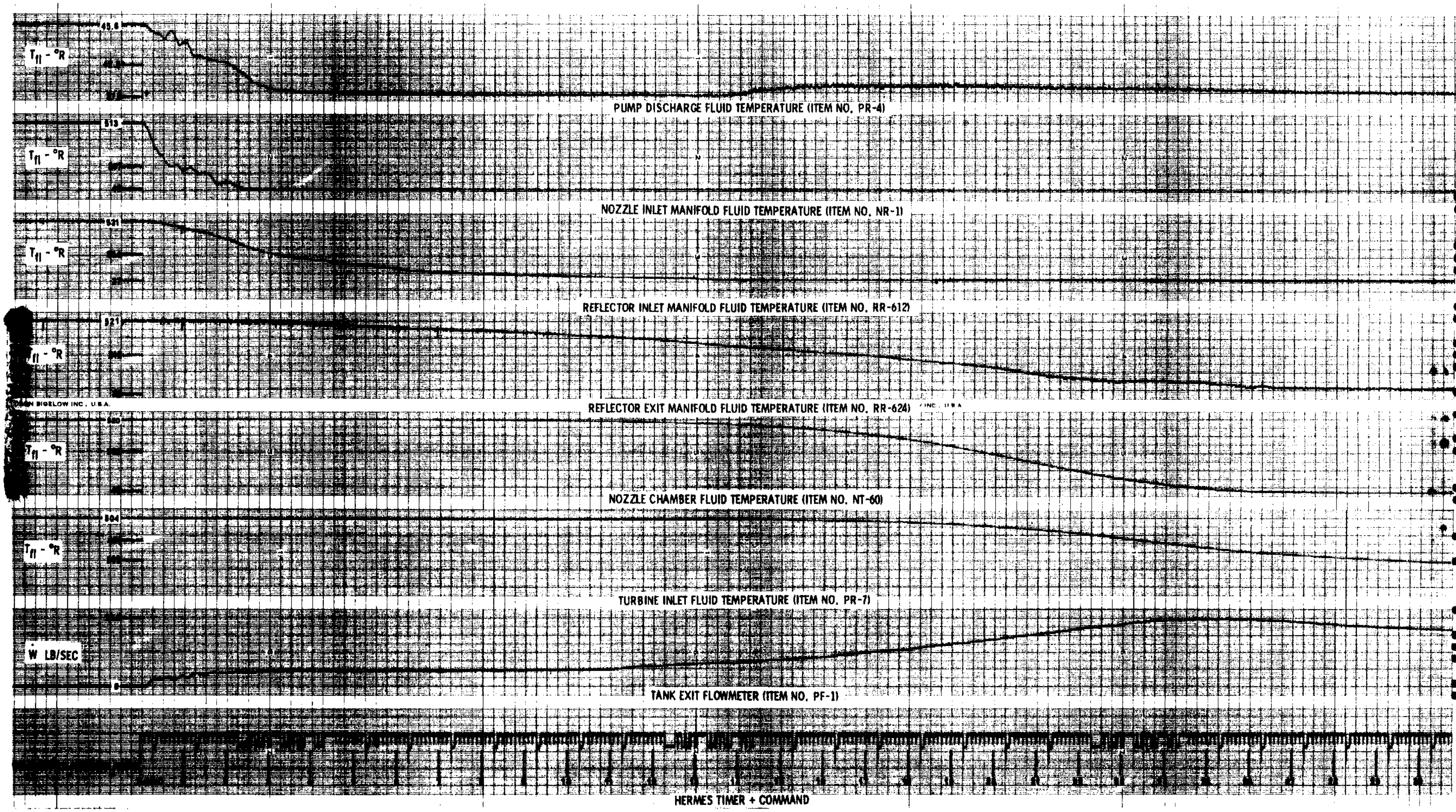

Figure 17. - High frequency temperature and weight flow data versus time.

[redacted]

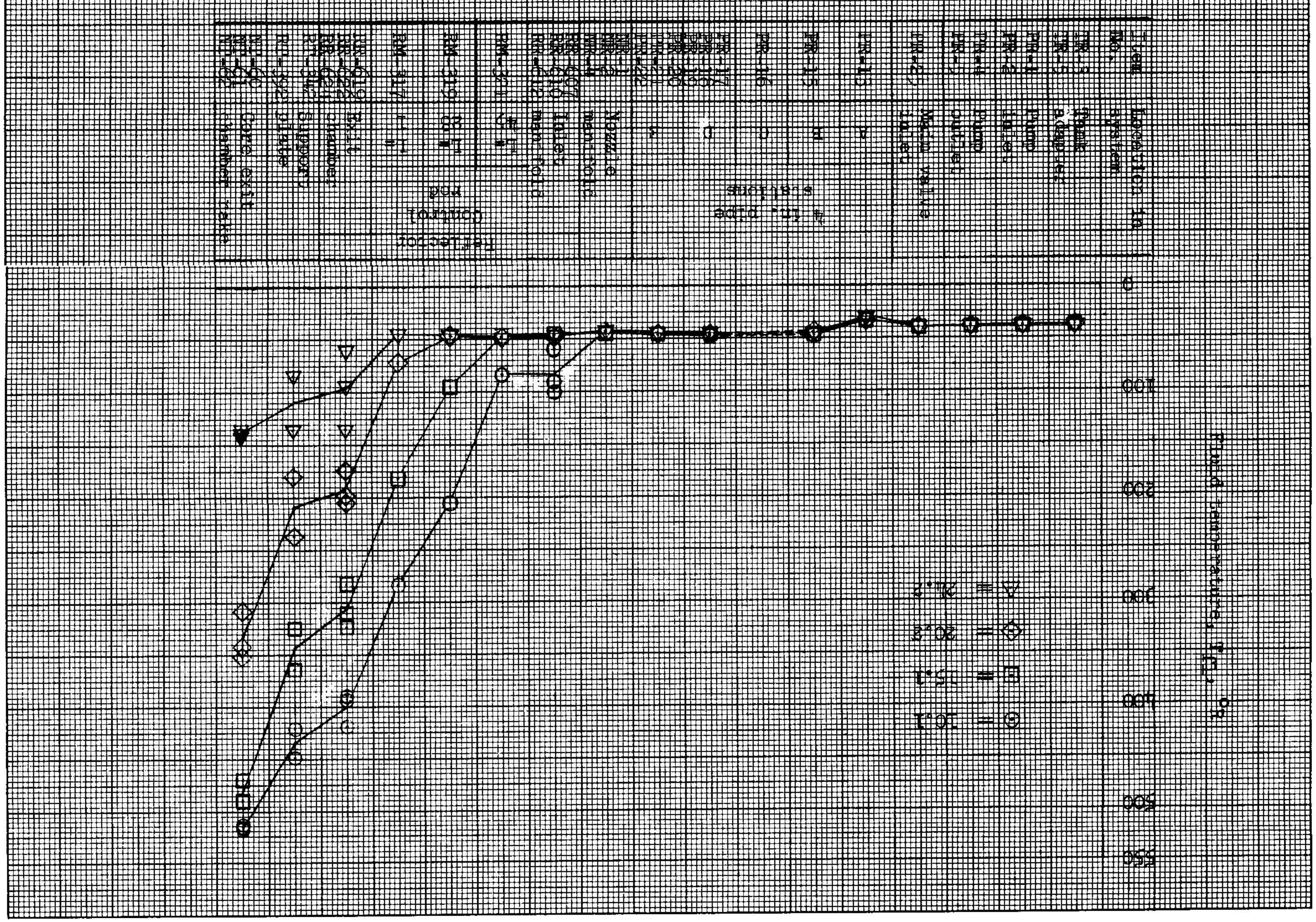

Figure 18. - Variation in fluid temperature throughout the system at various times

[redacted]

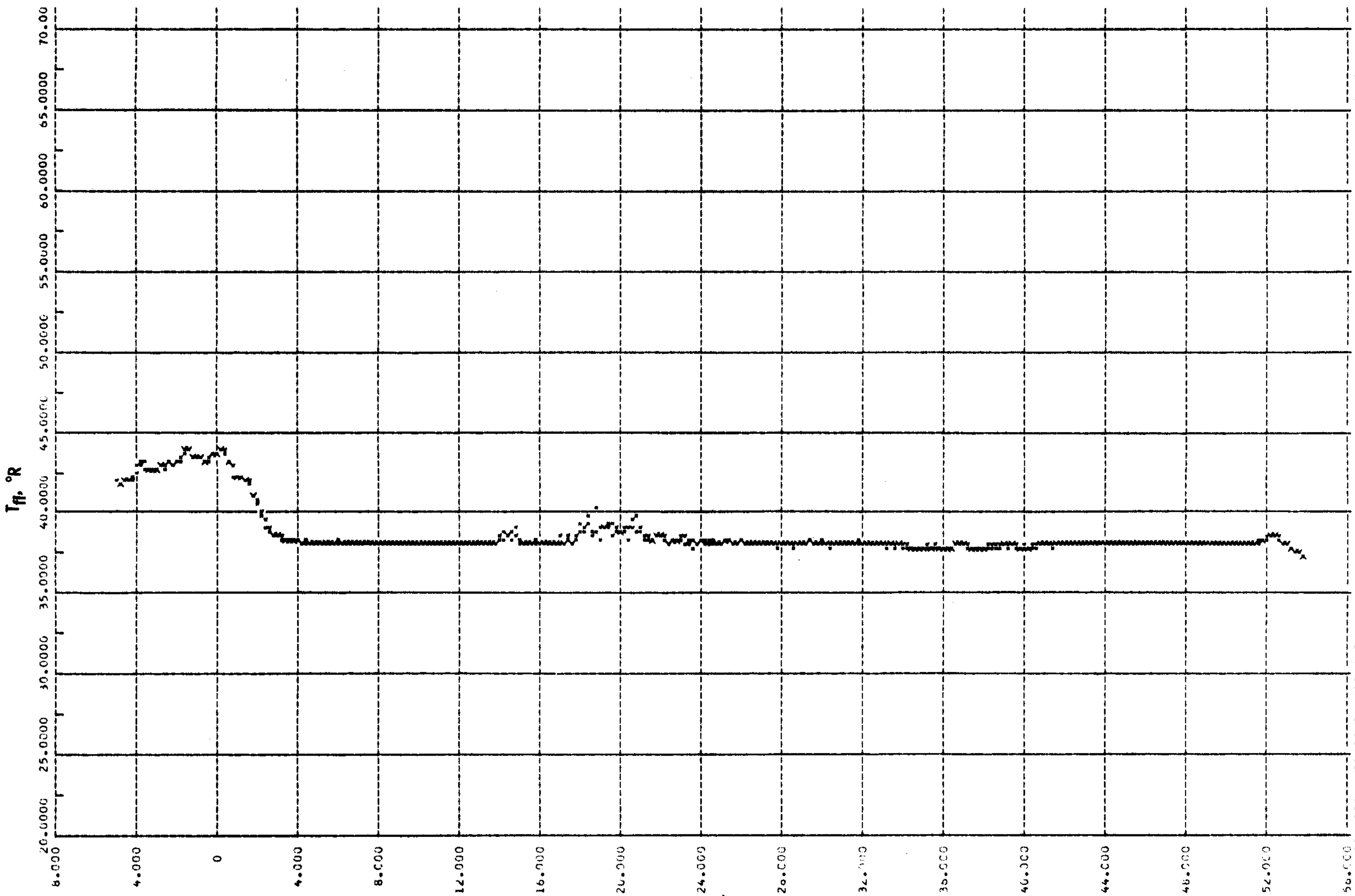

Figure 19. - Pump inlet fluid temperature versus time (item no. PR-1).

[redacted]

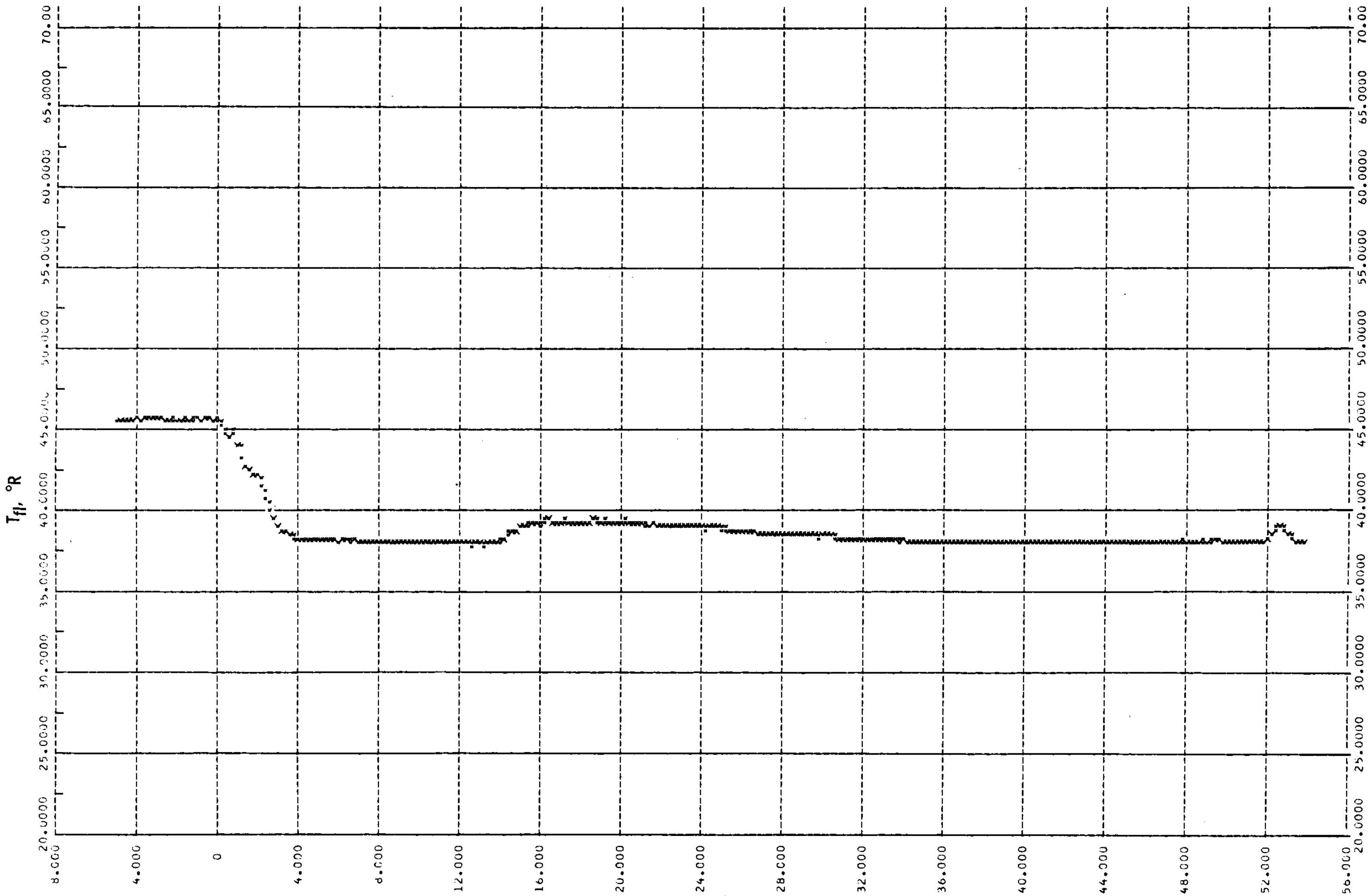

Figure 20. - Pump discharge fluid temperature versus time (item no. PR-4).

[redacted]

E-2673-5

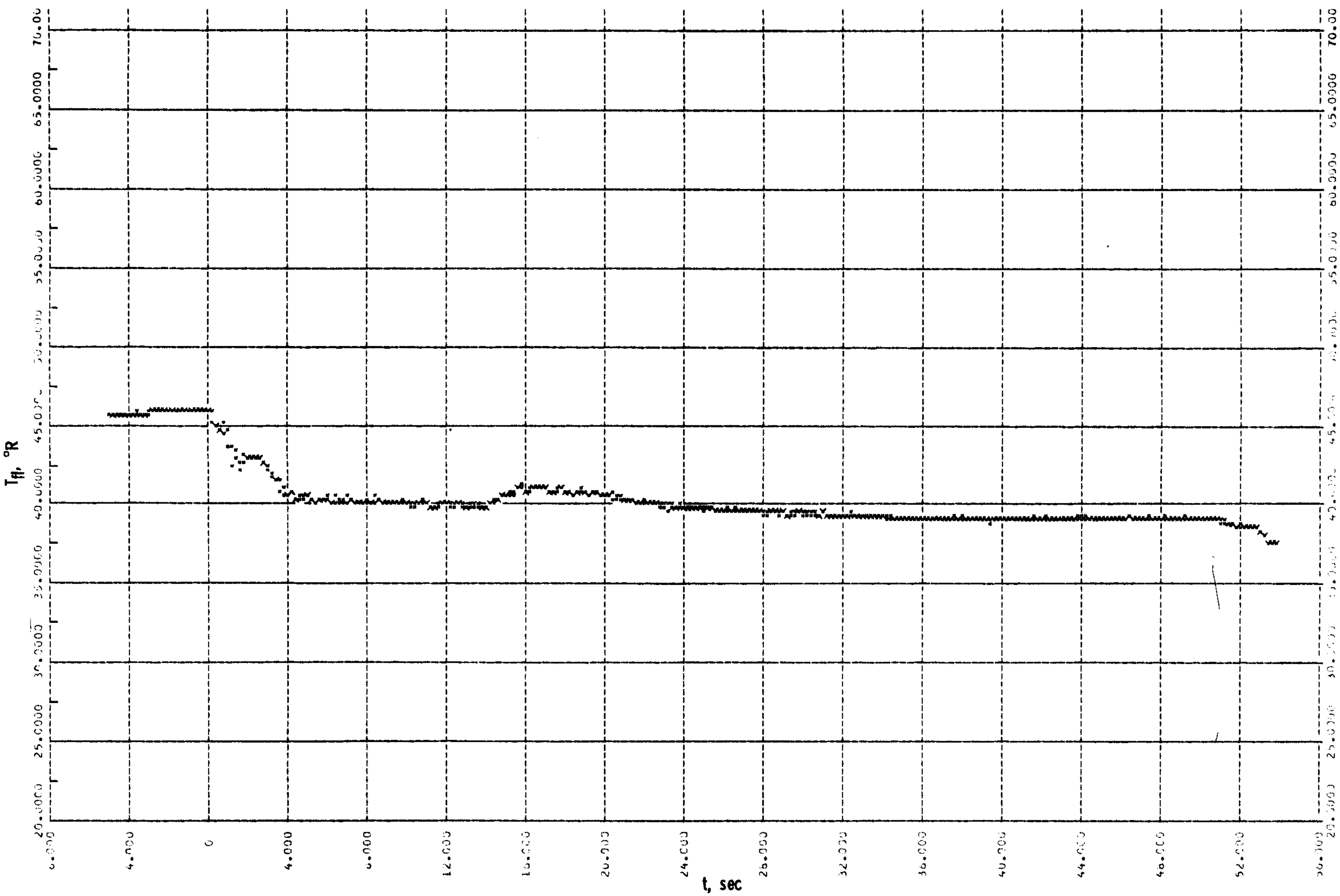

Figure 21. - Main valve inlet fluid temperature versus time (item no. PR-25).

[redacted]

[redacted]

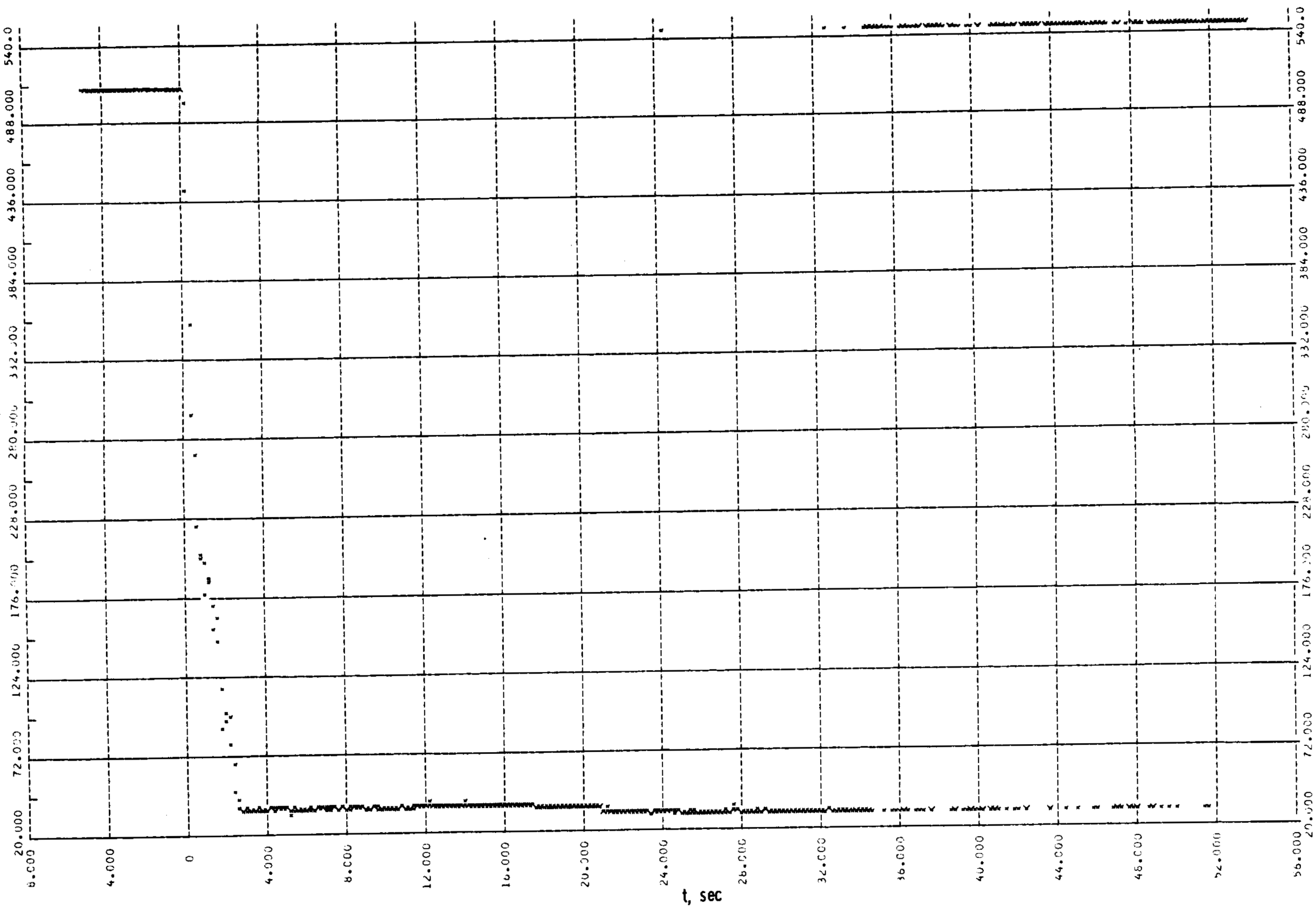

Figure 22. - Nozzle inlet manifold fluid temperature versus time (item no. NR-1).

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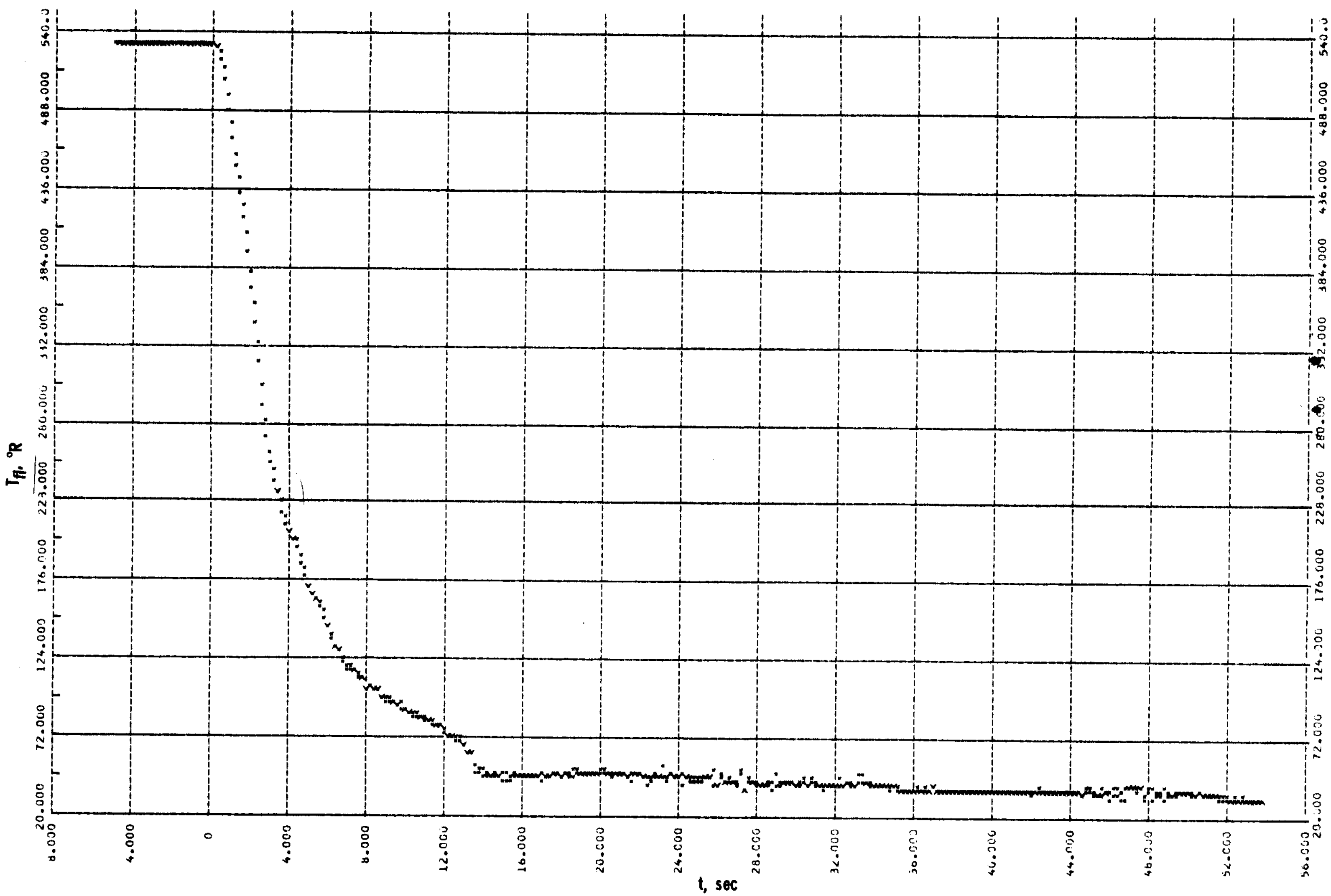

Figure 23. - Reflector inlet manifold fluid temperature versus time (item no. RR-612).

[redacted]

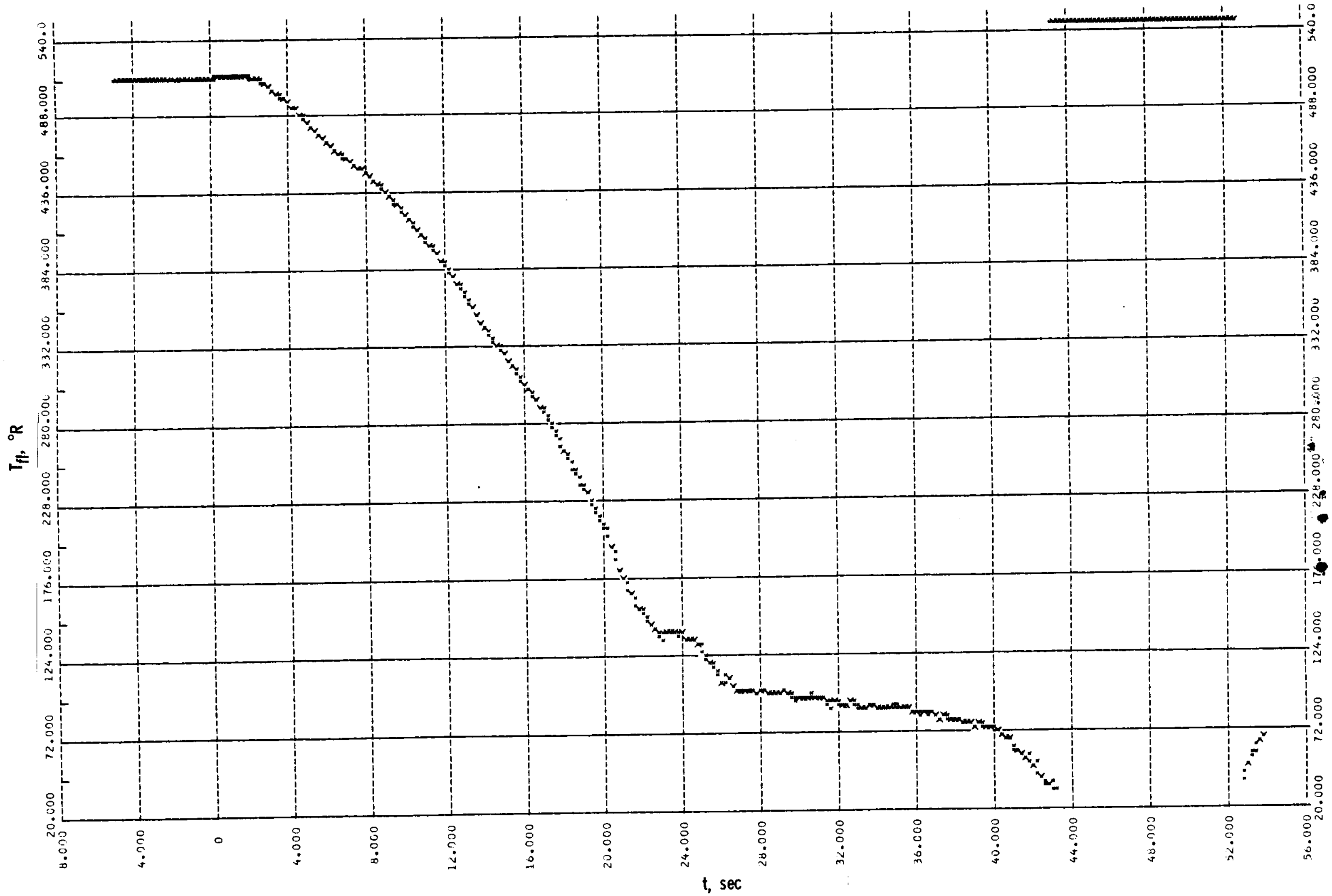

Figure 24. - Reflector exit manifold fluid temperature versus time (item no. RR-622).

[redacted]

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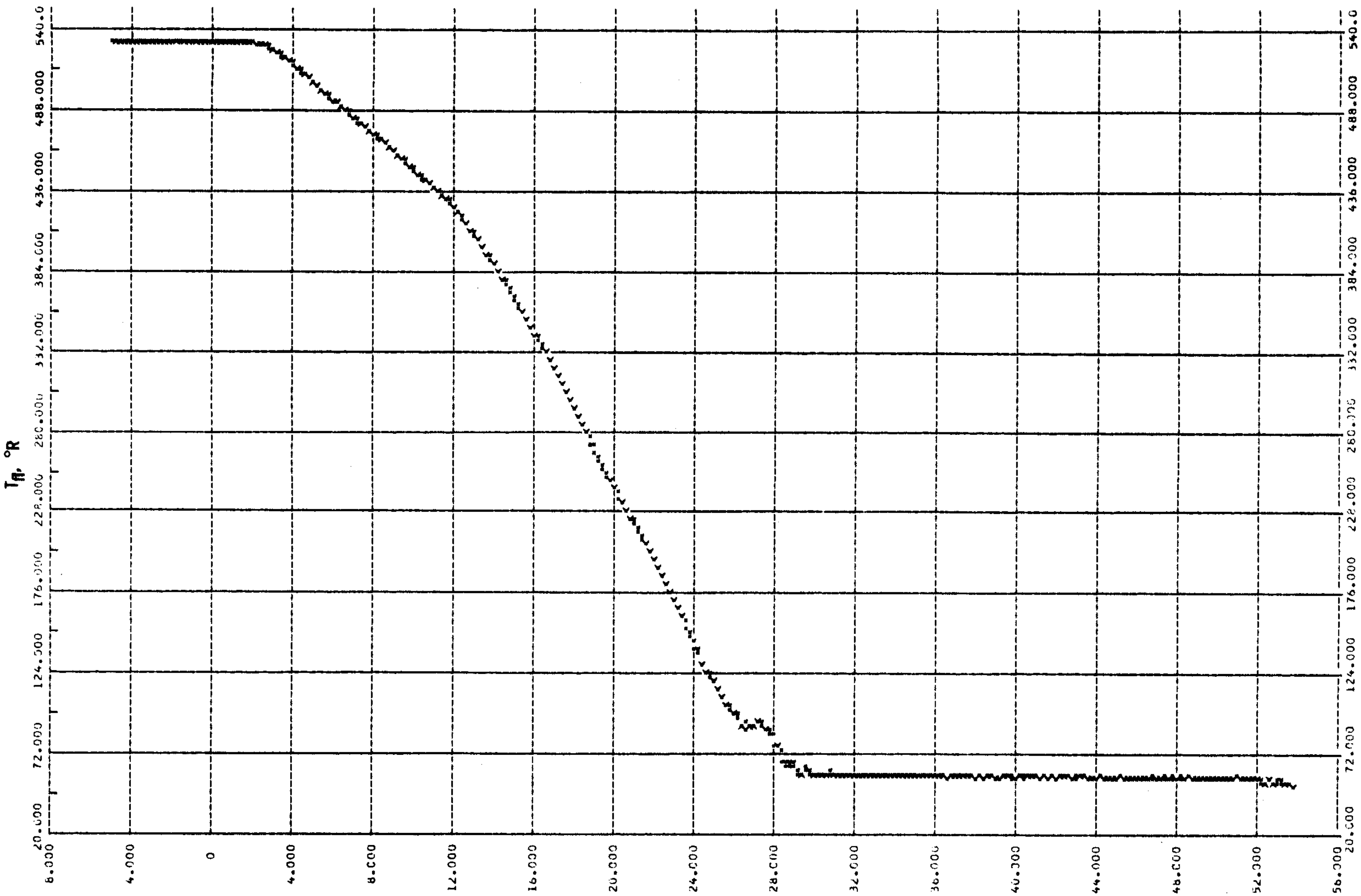

Figure 25. - Core inlet fluid temperature versus time (item no. RT-342).

[redacted]

[redacted]

Figure 26. - Nozzle chamber fluid temperature versus time (item no. NT-60).

[redacted]

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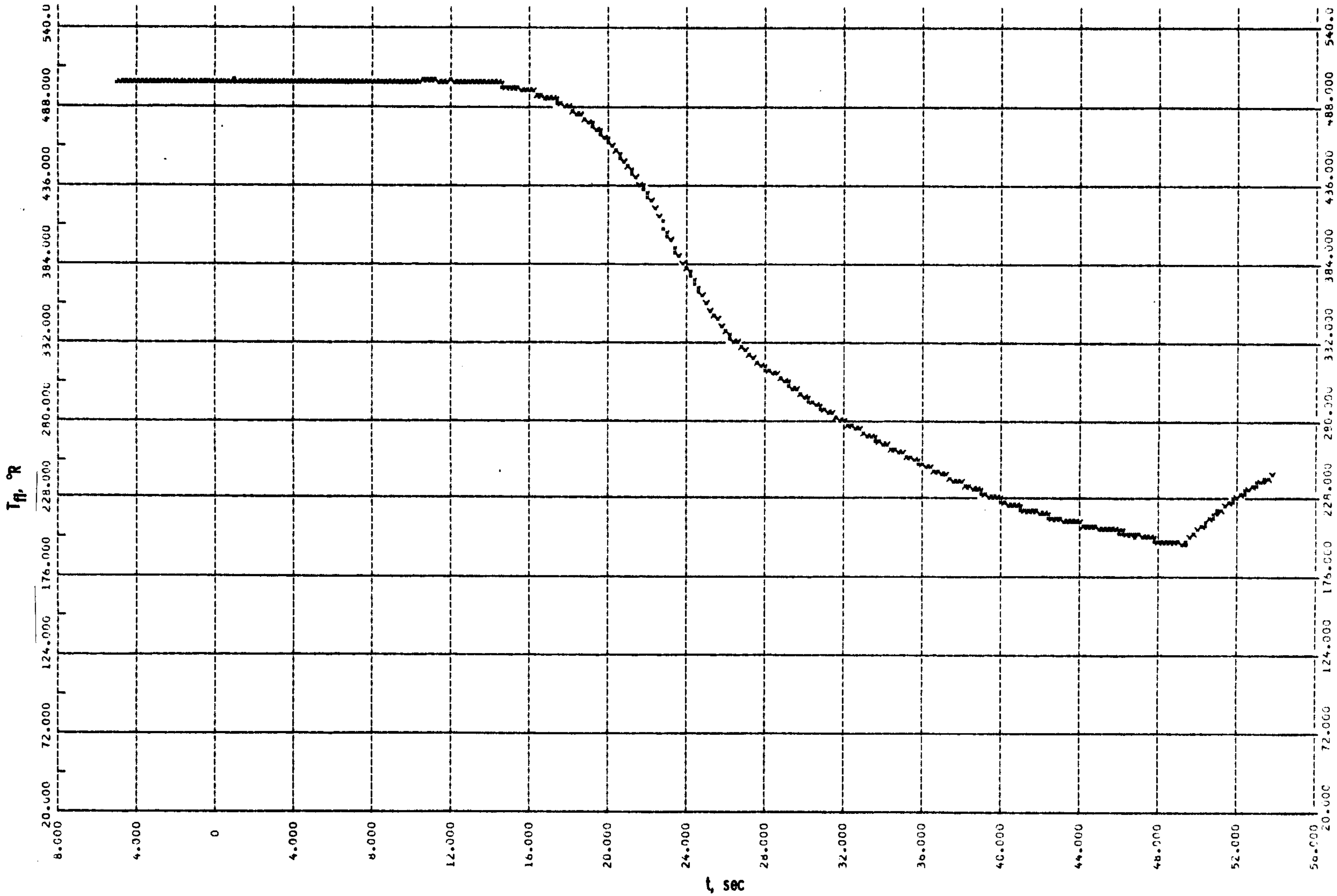

Figure 27. - Turbine inlet fluid temperature versus time (item no. PR-7).

[redacted]

[redacted]

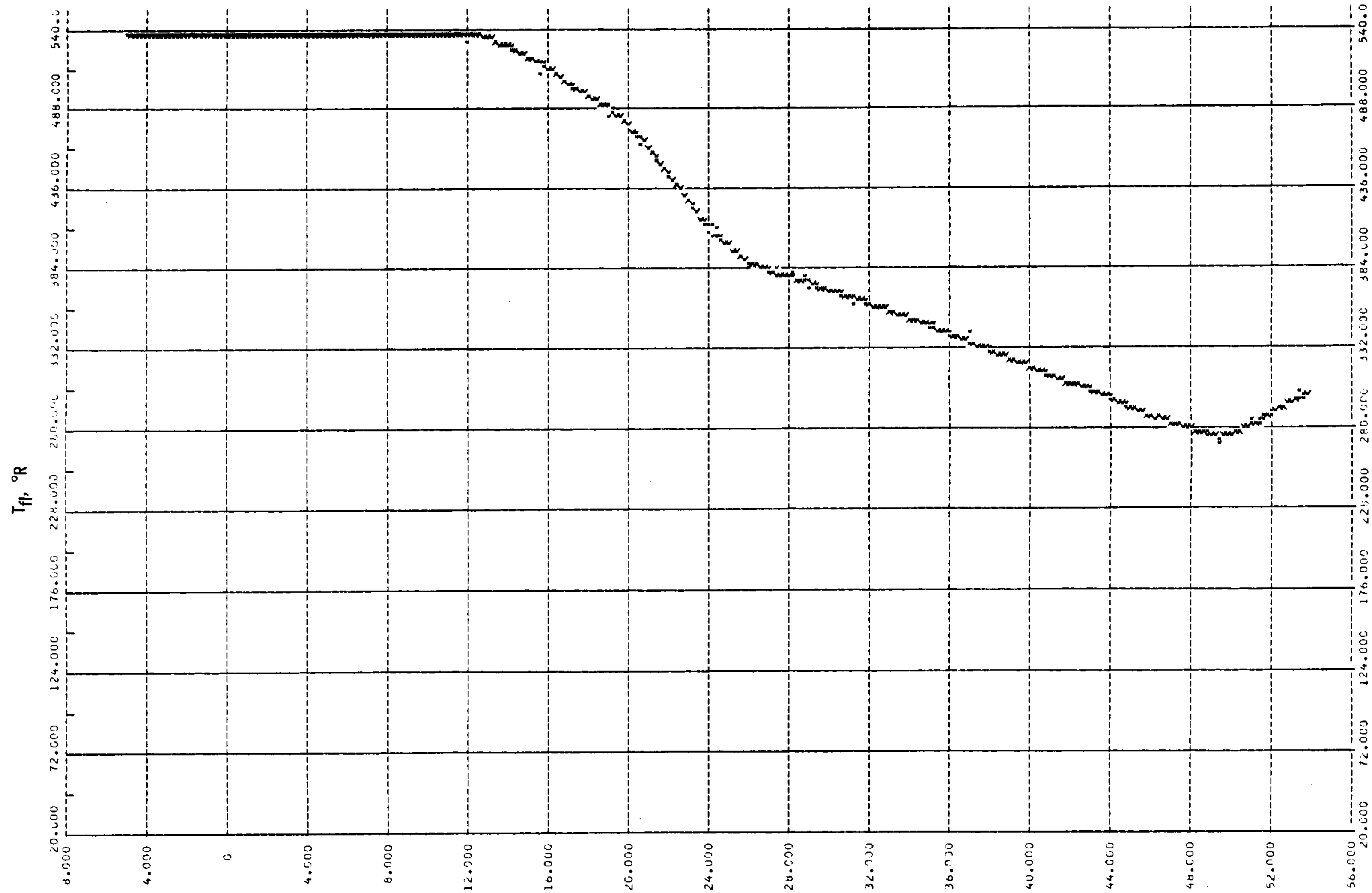

Figure 28. - Turbine outlet fluid temperature versus time (item no. PR-8).

[redacted]

E-2673-5

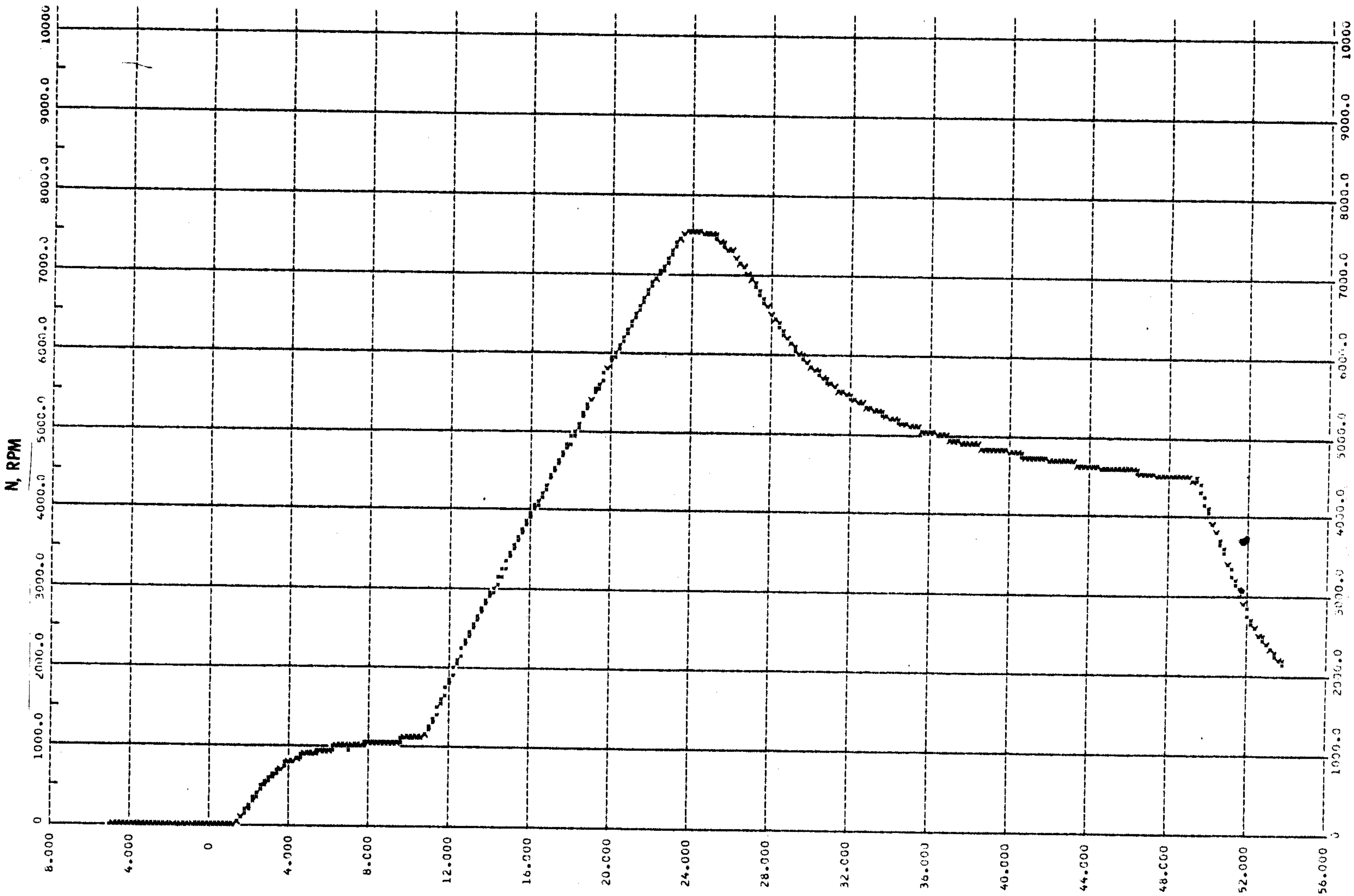

Figure 29. - Turbopump speed versus time (item no. PS-1).

[redacted]

[redacted]

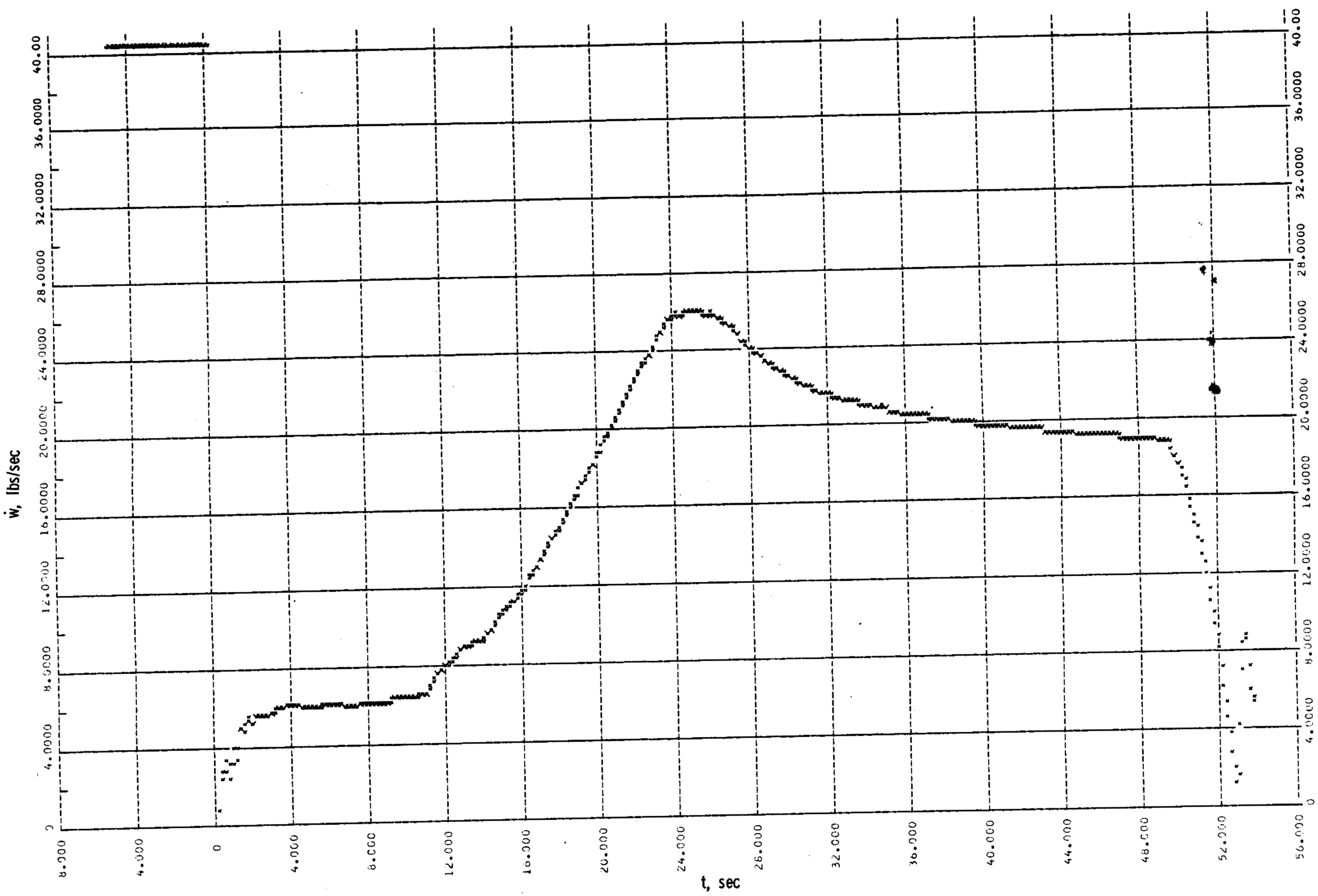

Figure 30. - Tank exit flowmeter versus time (item no. TF-1).

E-2673-5

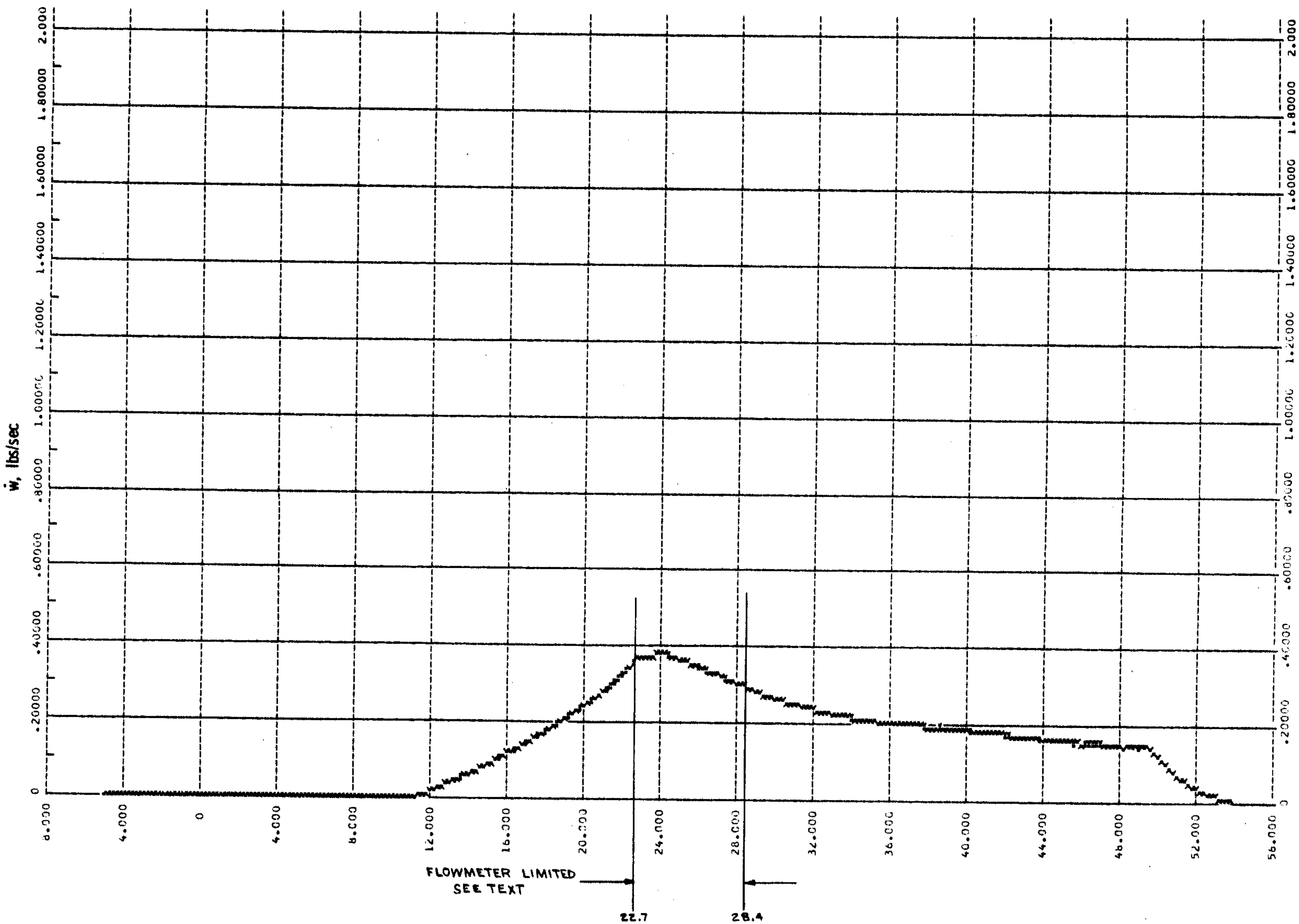

Figure 31. - Turbine inlet flowmeter versus time (item no. PF-1).

[redacted]

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[redacted]

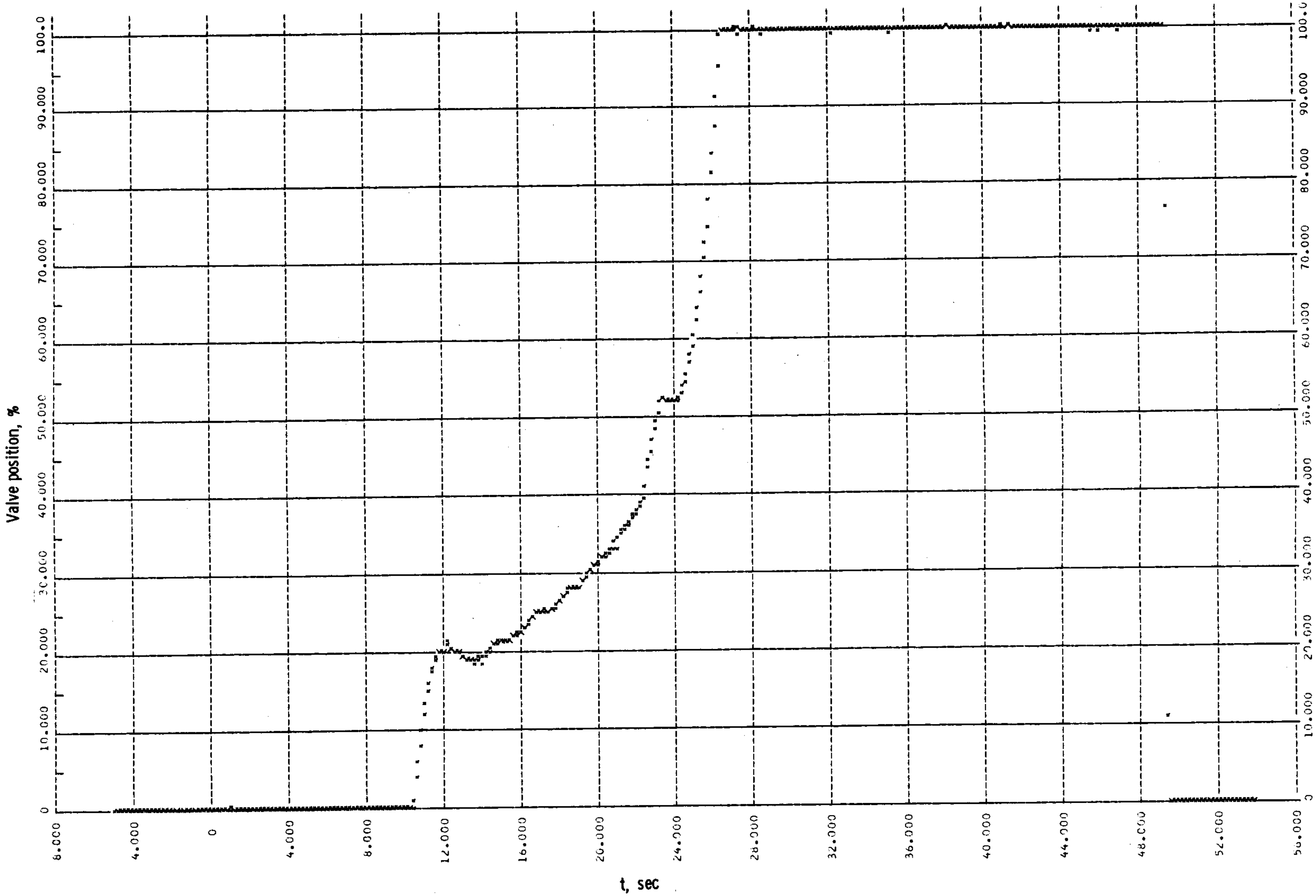

Figure 32. - Turbine power control valve position versus time (item no. TPCV).

[redacted]

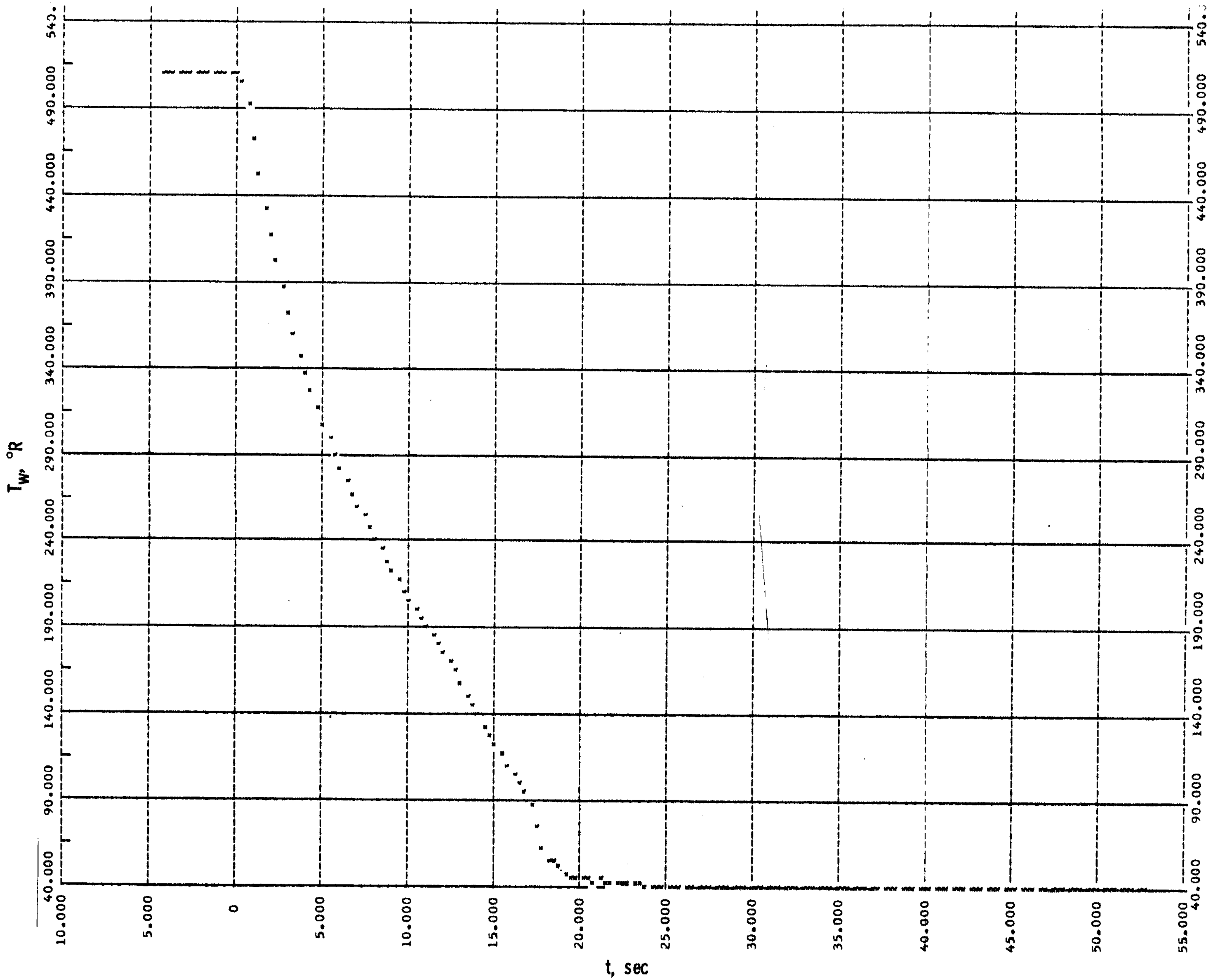

Figure 33. - Pump discharge pipe wall temperature at station C versus time (item PT-70).

[redacted]

[redacted]

[redacted]

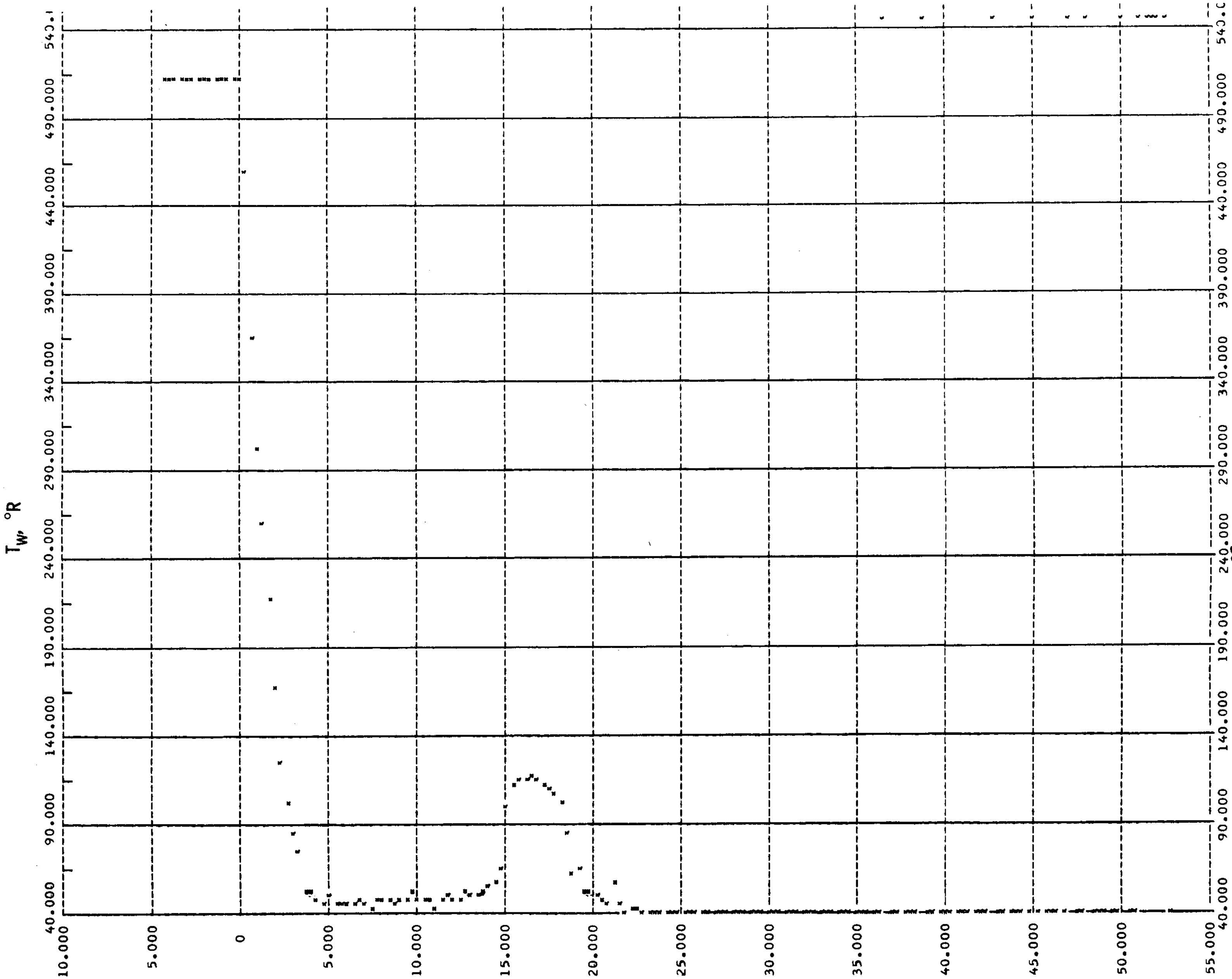

Figure 34. - Nozzle wall temperature at X = 25.7 versus time (item NT-10).

[redacted]

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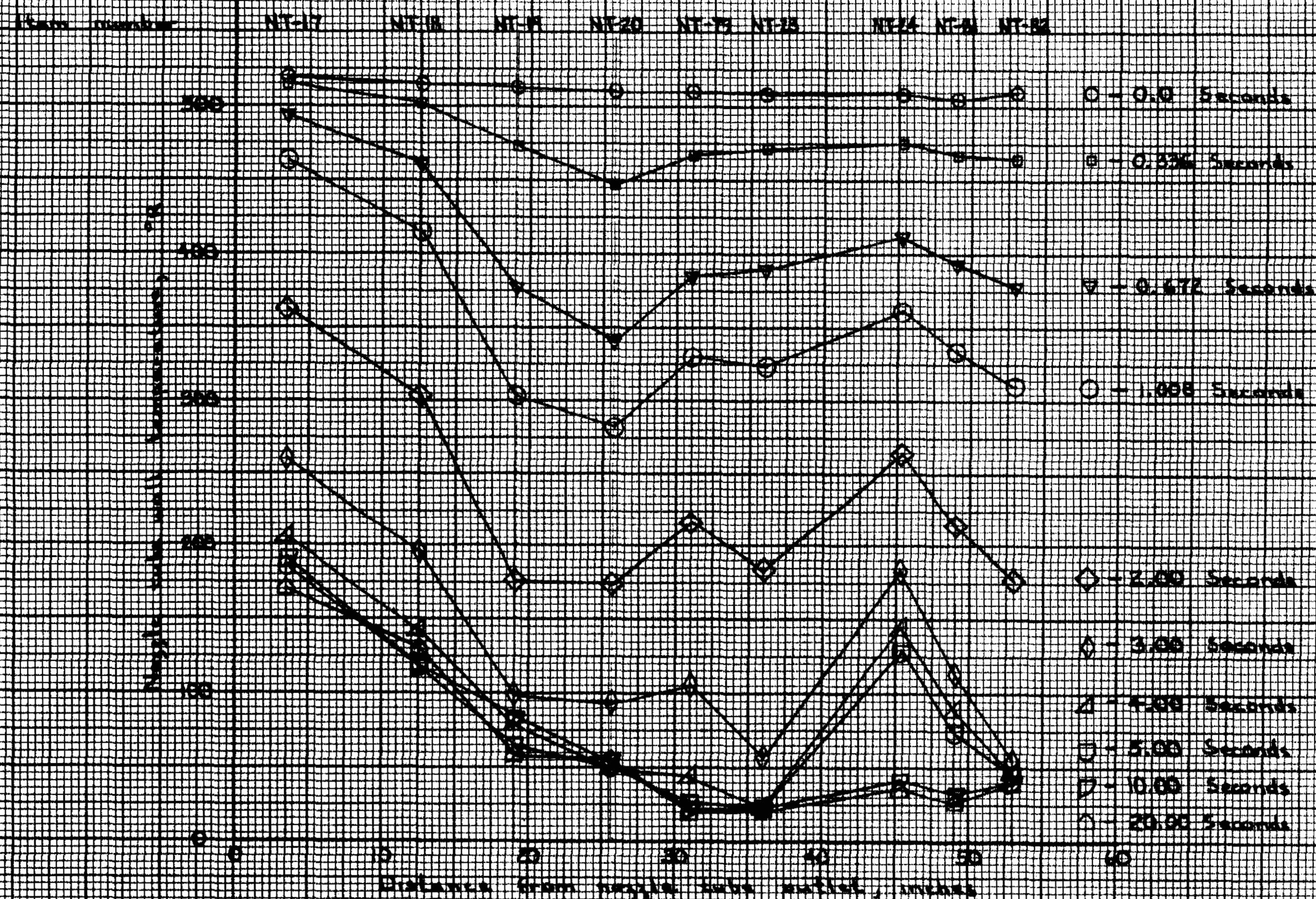

Figure 35 - Nozzle tube wall temperature versus length with time as parameter, tube number 23, Run number 11.

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[redacted]

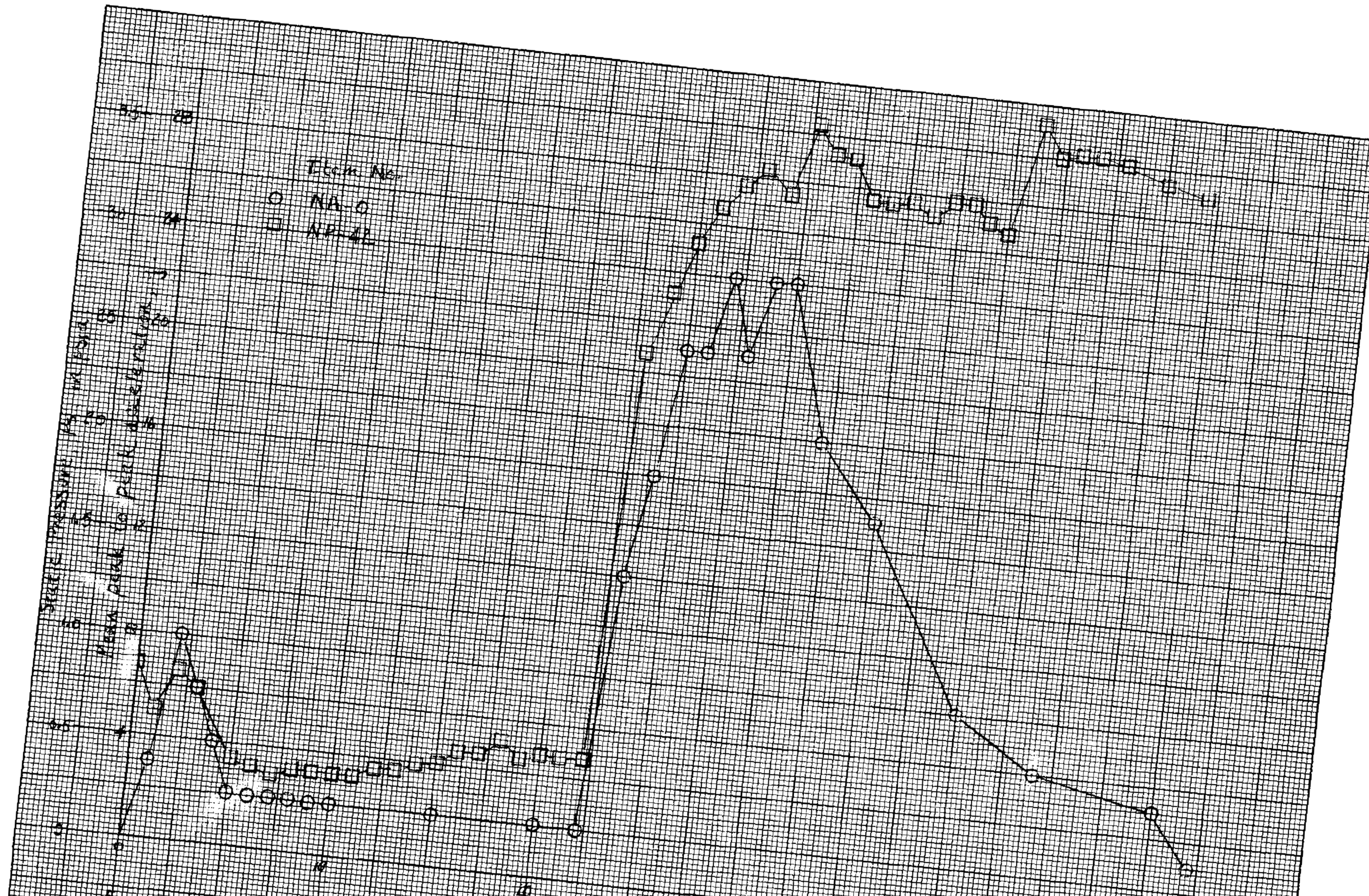

Figure 36. Time history of static pressure inside nozzle exit bell and vibration g load at nozzle inlet manifold for run 11.

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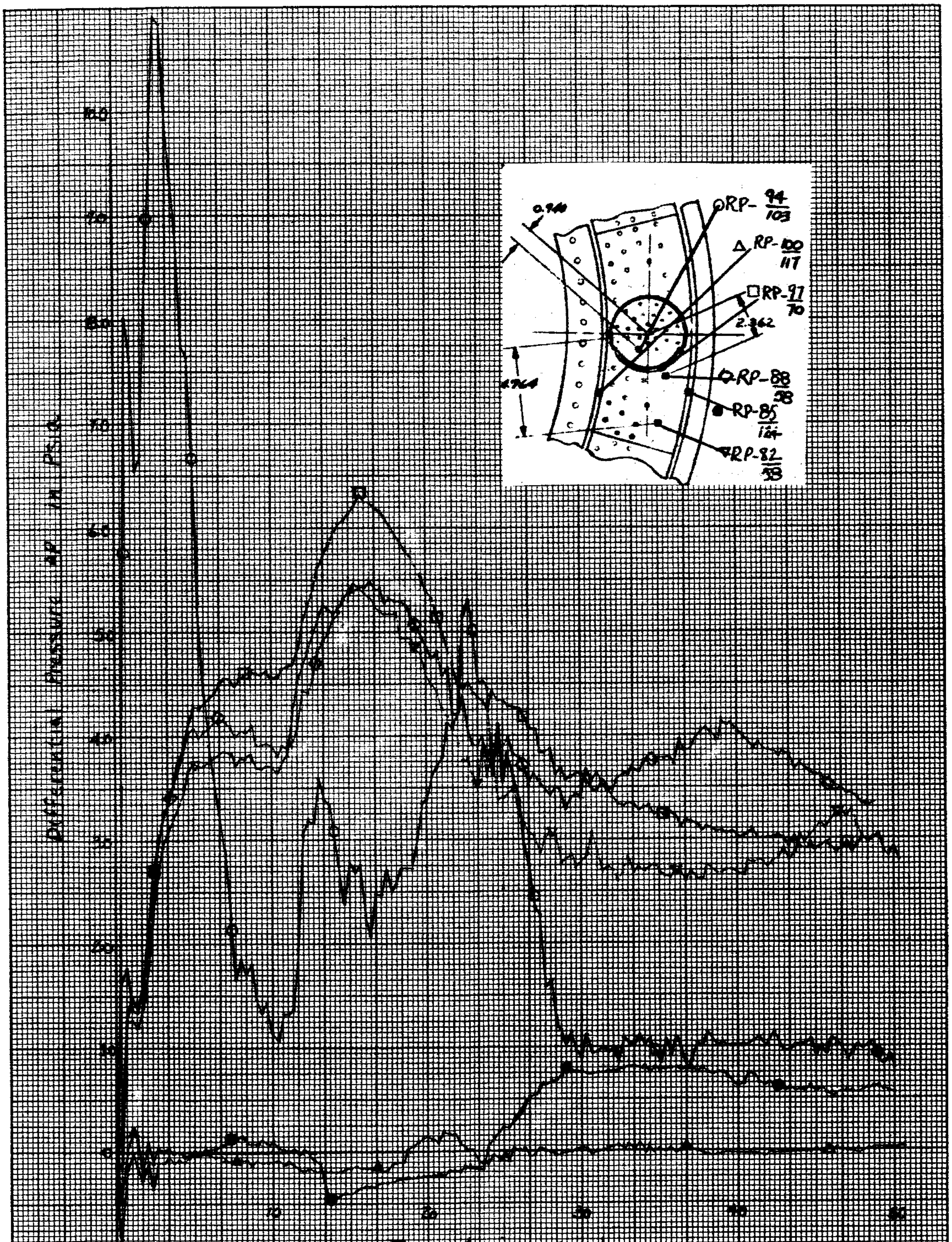

Figure 37. Total pressure minus static pressure for six stations at reflector outlet versus time for run K11.

[redacted]

[redacted]

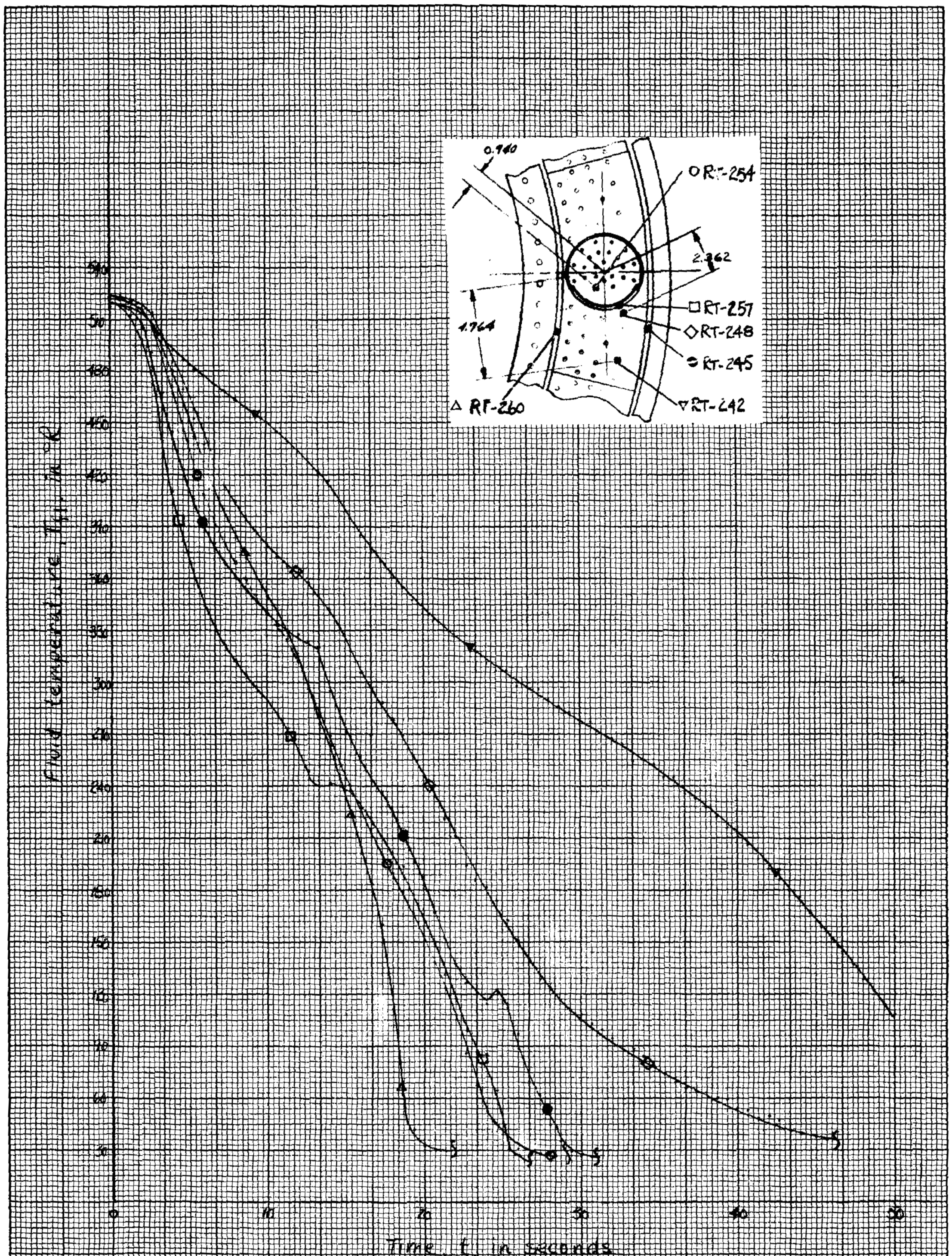

Figure 38. Fluid temperature vs time for six stations at reflector outlet for run # 11.

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 [redacted]

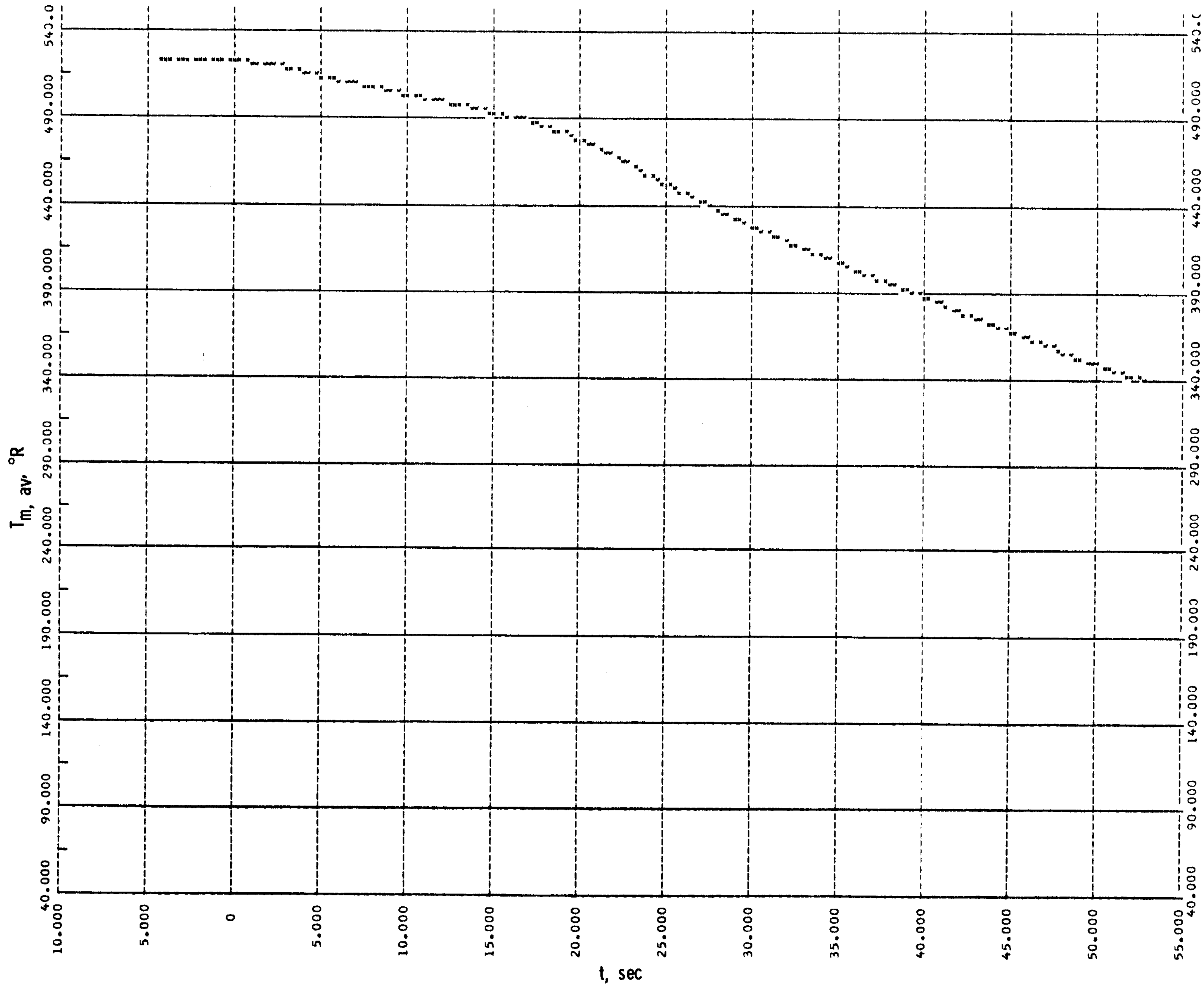

Figure 39. - Reactor pressure vessel average temperature versus time (item no's RT-388, RT-389, RT-390).

[redacted]

[redacted]

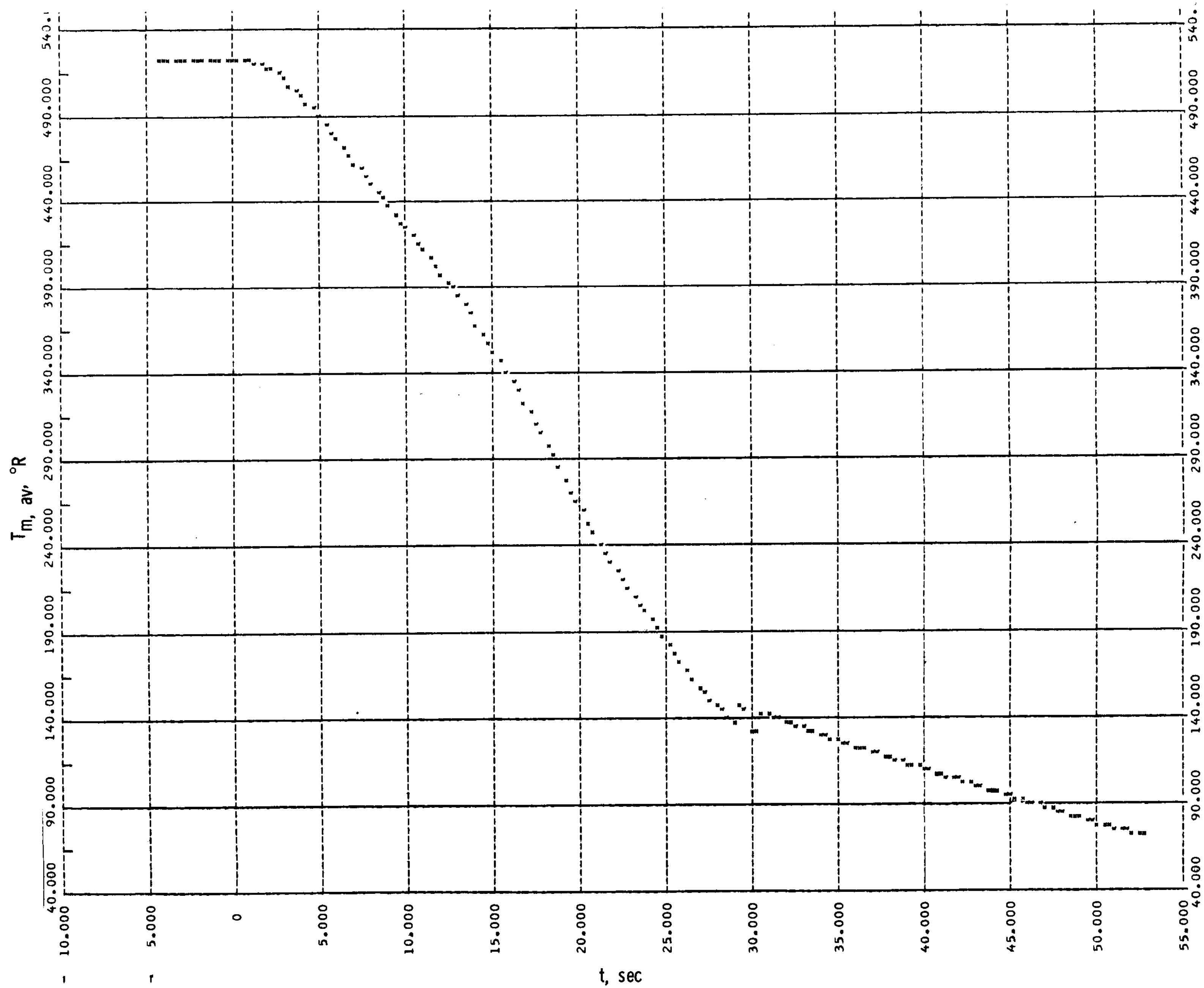

Figure 40. - Main aluminum reflector piece average temperature versus time (item no's: RT-98, 100, 104, 106, 109, 110, 112, 116, 118, 121, 223 and 235).

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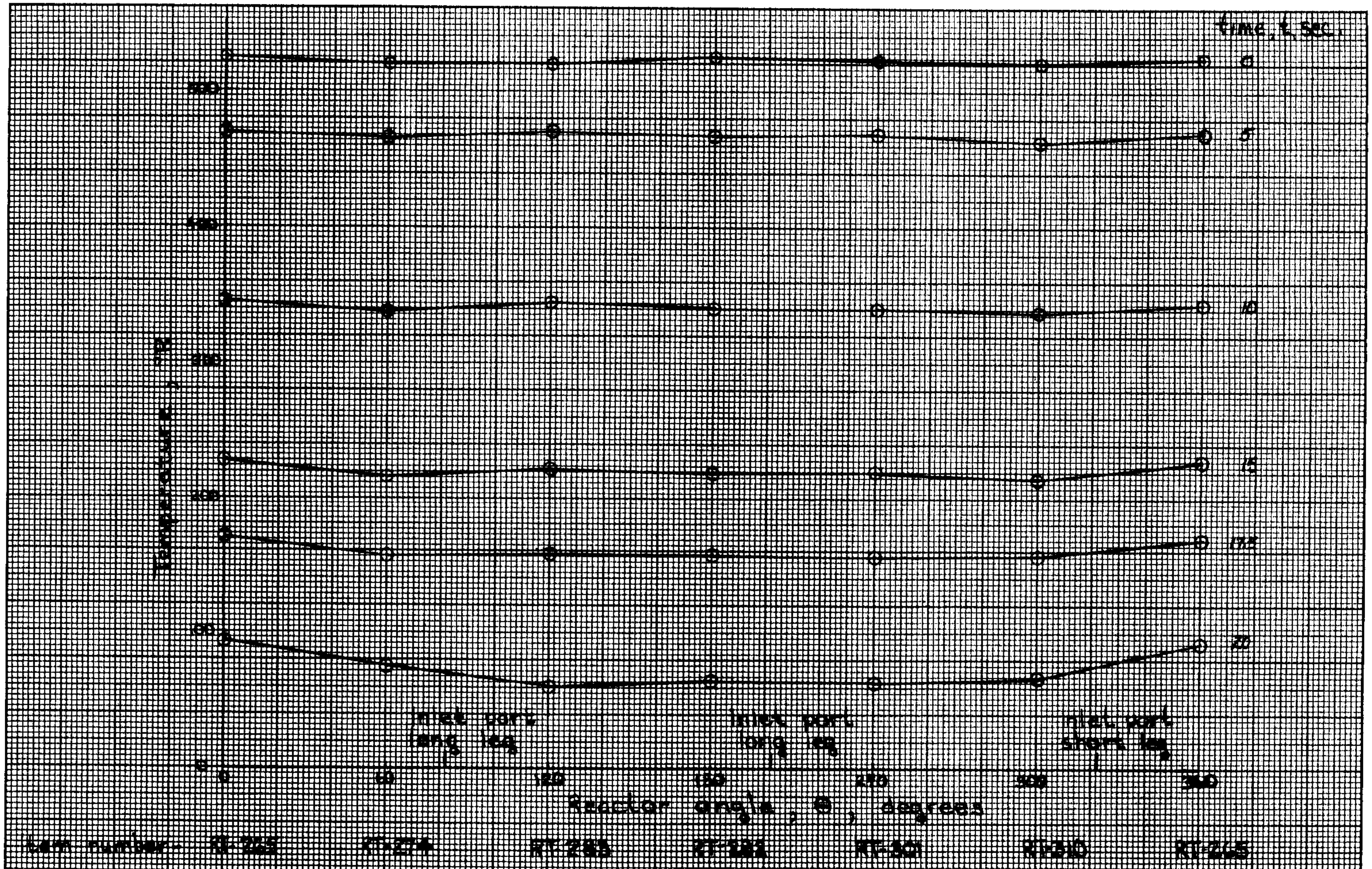

Figure 41 - Material temperature distribution in reflector near inlet ends of control drums, B1 LH$_2$ Run no. 11

[redacted]

[redacted]

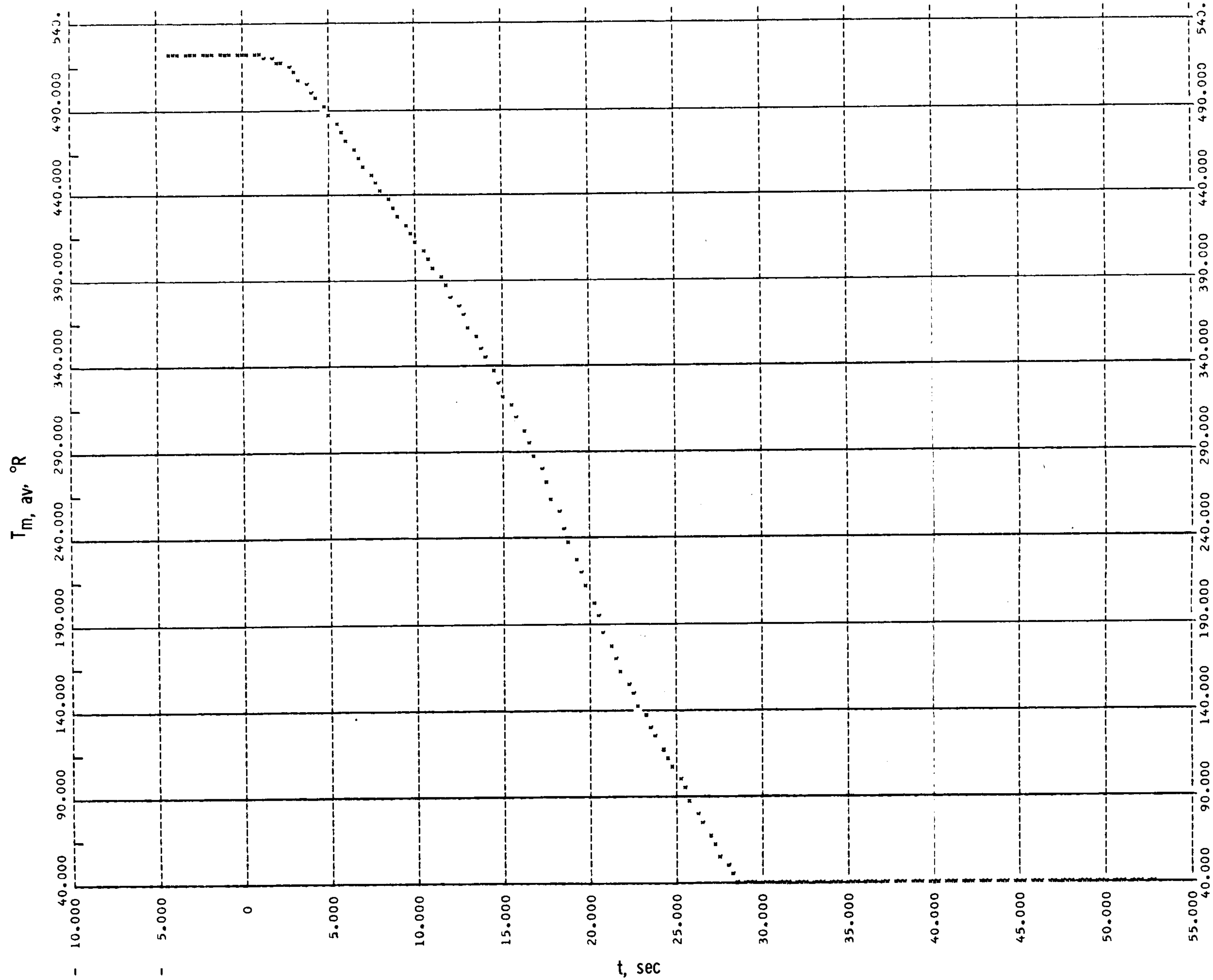

Figure 42. - Average aluminum control rod temperature versus time (item no's: RT-263, 264, 265, 266, 267, 268, 269, 270 and 271).

[redacted]

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DEC[redacted]FIED

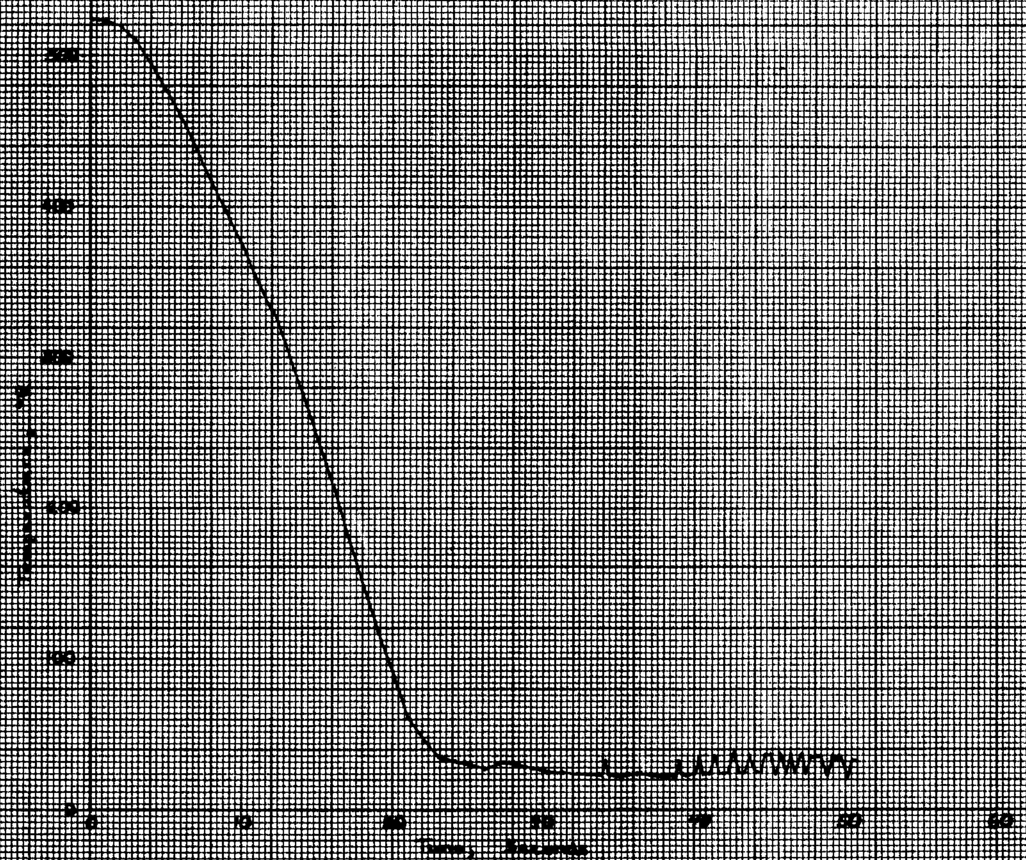

Figure 43- Average inner graphite reflector cylinder temperature versus time for run 11.
([illegible] RT-95, RT-96, RT-97).

[redacted]

[redacted]

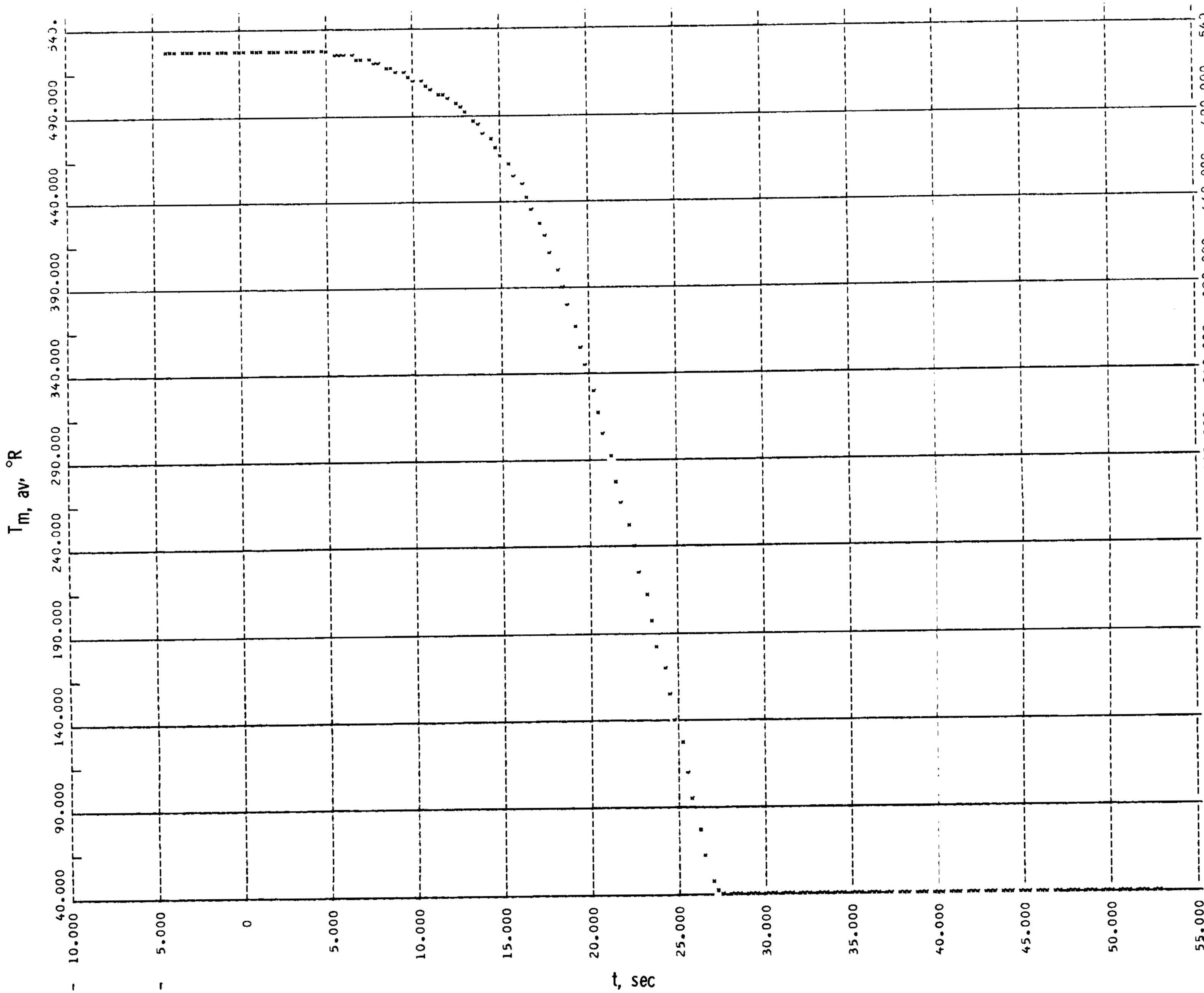

Figure 44. - Average graphite core module temperature, for a module at the center of the reactor, versus time (item no's RT-31, 32, 33, 34 and 35).

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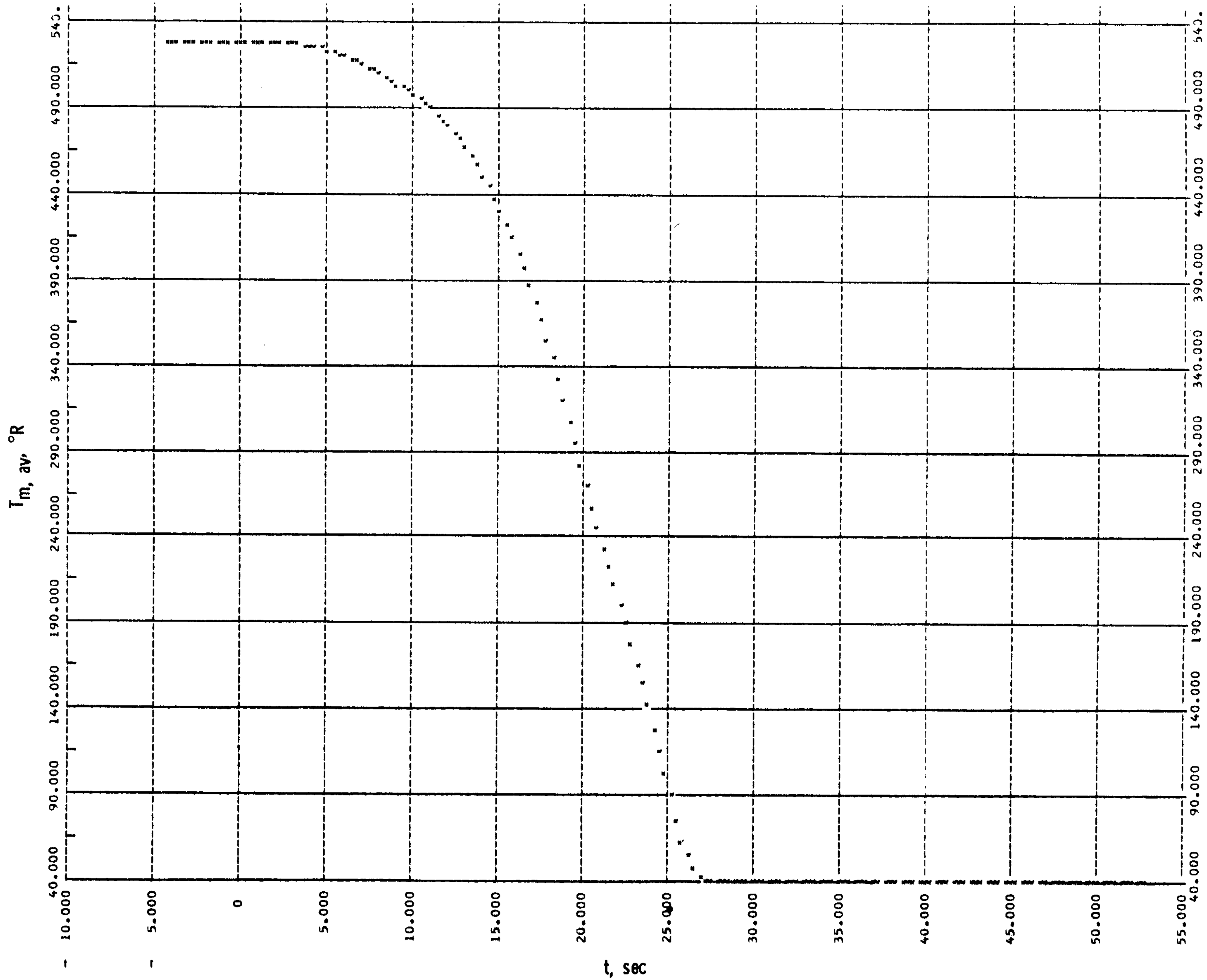

Figure 45. - Average graphite fuel element temperature, for a fuel element at the center of the reactor, versus time (item no's: RT-1, 2, 3, 4 and 5).

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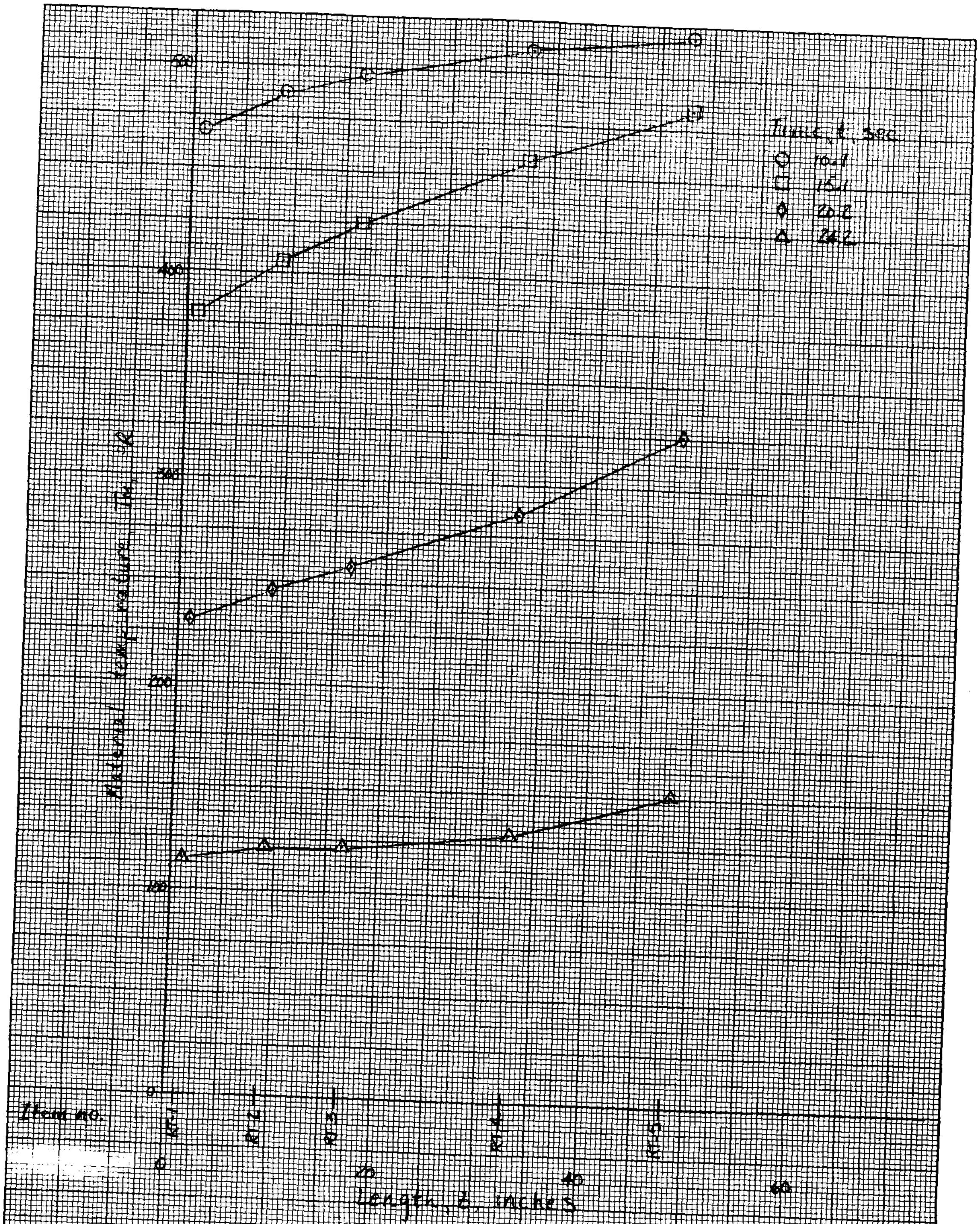

Figure 46. Material temperature vs length at various times for graphite core fuel element at center of reactor for run 14.

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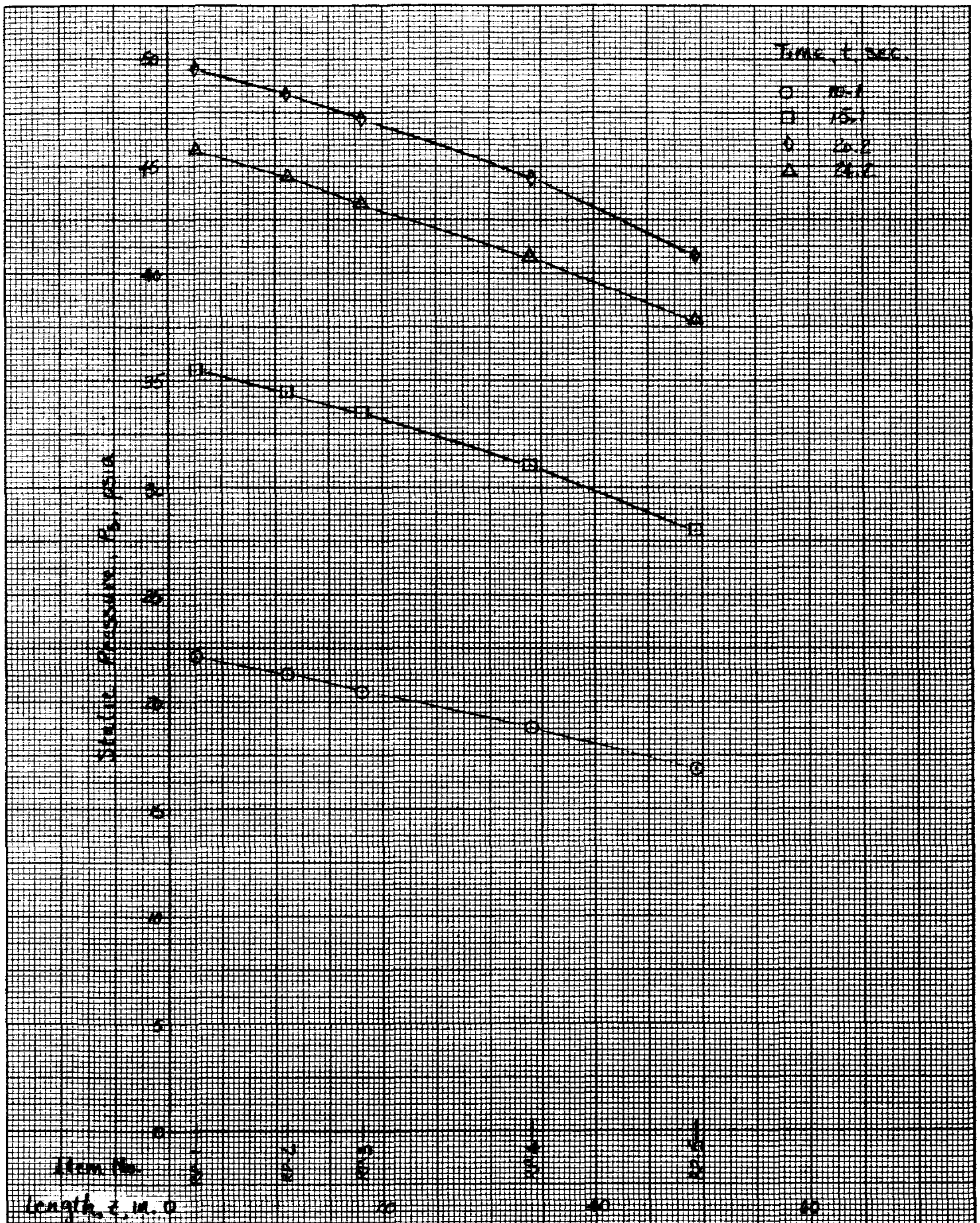

Figure 47. Static pressure vs length at various times for a graphite core fuel element at the center of the reactor for run 11.

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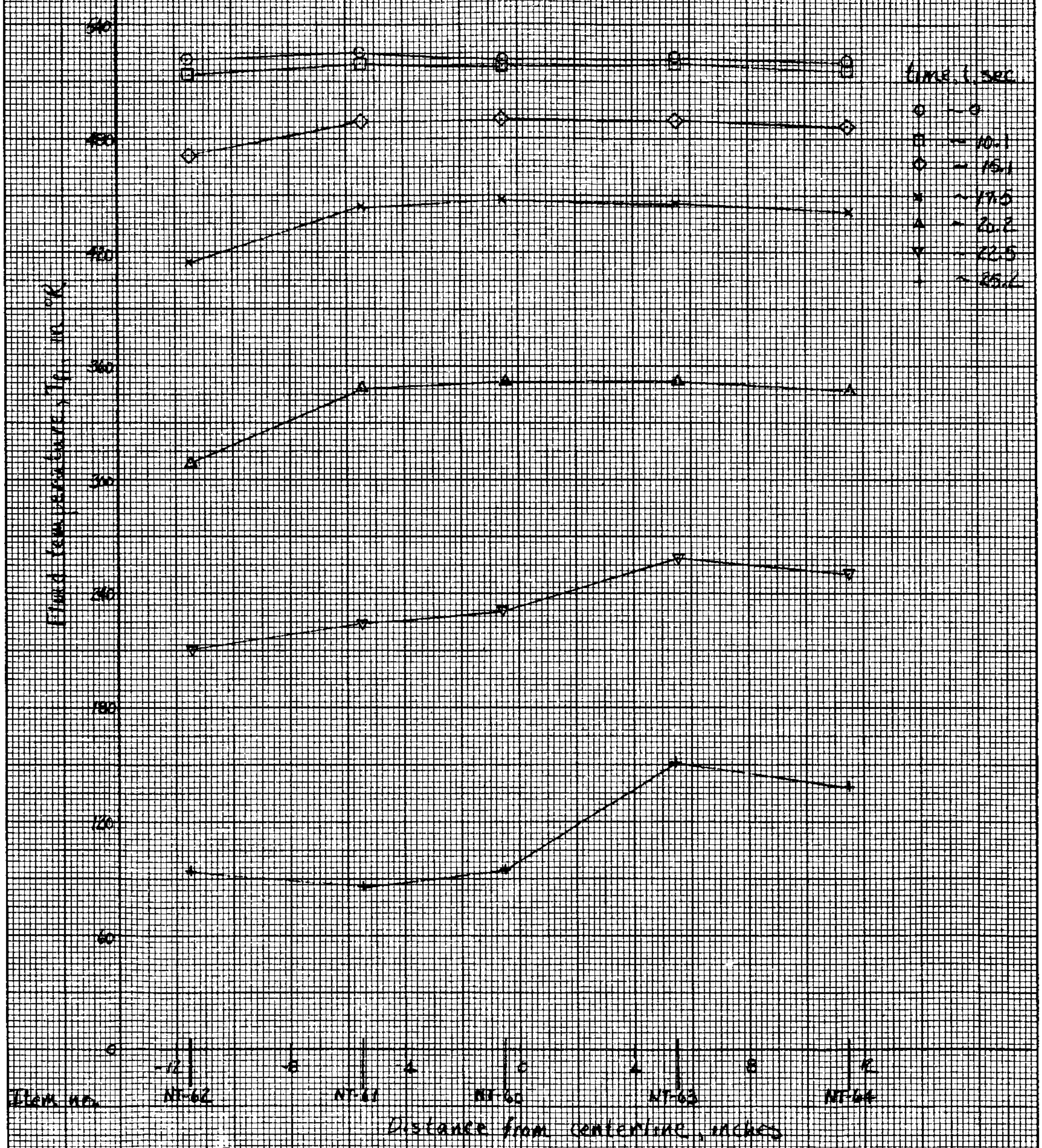

Figure 48. Fluid temperature at nozzle chamber vs distance from centerline at various times for run #11.

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