17618-H190-RO-00

PROJECT TECHNICAL REPORT

APOLLO MISSION J1
CSM 112
CRYOGENIC STORAGE SYSTEM
PREFLIGHT PERFORMANCE REPORT

NAS 9-8166

JULY 1971

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

Prepared by
R.K.M. Seto
Propulsion Systems Section
Chemical and Mechanical Systems Department

TRW
SYSTEMS GROUP

CR-115116

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SYSTEMS GROUP

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1. INTRODUCTION

PURPOSE

The purpose of this report is to provide a preflight prediction of the performance of the Mission J1/Apollo 15/CSM-112 Cryogenic Storage System and is submitted under MSC/Task 705-2, Contract NAS 9-8166. The general objectives of Task 705-2 are to develop an integrated mathematical model of the Apollo Cryogenic Storage System (CSS), provide support to the redesigned CSS oxygen tank development program, predict flight performance of the CSS to verify its adequacy to meet mission requirements, and perform postflight analysis of the CSS to confirm the adequacy of the mathematical model.

SCOPE

The scope of this report is to present the results of simulations to predict the nominal performance of the Cryogenic Storage System for the mission as delineated in Section 2 entitled "Mission Description." The CSS performance following certain system anomalies are also investigated. The Apollo Cryogenic Integrated Systems Program (Reference 1) developed under Subtask 3 of Task 705-2 was used for the analysis.

Section 3, "Simulated Conditions," describes the assumptions and input data used for simulating the system operation for both the nominal mission and the anomalies.

Section 4 entitled "Performance Prediction," discusses the results of the preflight analysis, while Section 5, "Conclusions," contain the conclusions and recommendations resulting from the analysis.

2. MISSION DESCRIPTION*

Launch of the Apollo J1 Mission is planned to occur from launch complex 39A of the Kennedy Space Center at 8:34 AM CDT on July 26, 1971. The launch vehicle will insert the spacecraft and the S-IVB stage into a 92.7 n. mile orbit at an inclination of 29.7 degrees approximately twelve minutes later. At approximately 2:50 (hr:min) after launch, the S-IVB stage will perform the Translunar Injection (TLI) Burn. The Command and Service Module (CSM) will be docked with the Lunar Module (LM) and the docked spacecrafts will be ejected from the S-IVB at approximately 4:16 Ground Elapsed Time (GET). During the Translunar Coast up to four midcourse corrections (MCC) may be performed. The times for these burns are presented in Table 1. Three periods of Passive Thermal Control (PTC) are planned during the coast. Table 2 presents the times for this mode of operation. The Lunar Orbit Insertion Maneuver will be performed by the Service Propulsion System (SPS) at approximately 78:30 GET placing the spacecraft in a 58.3 by 170.0 nautical mile lunar orbit. At 82:40 GET a Descent Orbit Insertion Burn will be conducted by the SPS, placing the spacecraft in a 9.6 by 58.4 nautical mile orbit.

The LM will separate from the CSM at 100:14 GET. The SPS will then be used to circularize the CSM orbit to 59.2 by 59.8 nautical miles at 165:13 GET. At 177:35 GET, the CSM will perform a 3.3 degree plane change. The Transearth Injection Burn will be performed by the SPS at 223:44 GET. During the ensuing coast, up to three midcourse corrections may be performed. Five periods of PTC are planned on the return trip. At 242:00 GET, a period of Extravehicular Activity (EVA) will begin. The EVA will require approximately

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*References 2 and 3

60 minutes to complete. CM/SM separation will occur at 294:48 GET with splashdown following at 295:12 GET.

3. SIMULATED CONDITIONS

The Cryogenic Storage System (CSS) of the CSM 112 is comprised of three oxygen tanks, three hydrogen tanks, and the related lines and components. Figures 1 and 2 present schematics of the oxygen and hydrogen systems, respectively. Two of the oxygen tanks and two of the hydrogen tanks are located in Bay 4 of the Service Module (SM) while the remaining hydrogen and oxygen tanks are located in Bay 1. The hydrogen tank in Bay 1 differs from the other hydrogen tanks since it does not have heaters although it does have destratification fans. In addition, a third flow restrictor has been added to the oxygen system for this and subsequent missions.

The physical and operating characteristics of the CSS tanks and major components obtained from End Item Acceptance Test Data (Reference 4) are presented in Table 3. These values were used in simulating the operation of the system using the Apollo Cryogenic Integrated Systems Program. Although the values in this table were based on tests conducted at 460, 530, and 630° R, the limits for the individual tank pressure switches may differ in flight from those shown due to temperature effects. Fluid temperatures in flight will be somewhat lower than those used for the tests and the test data was not of sufficient quality to permit a meaningful extrapolation to the lower inflight temperatures.

The storage tank heater and fan mode schedules have been arranged such that the tanks do not deplete equally since equal tank depletion could result in system venting in the minimum dq/dm region (at approximately 30 to 40% remaining). The oxygen tank heater mode schedule is given in Table 4. During the period between 74.3 and 222 hours GET, only two of the three heater elements will be active in oxygen tanks 1 and 2. The corresponding hydrogen tank heater and fan mode schedule is given in Table 5.

The oxygen and hydrogen demanded by the Electrical Power Subsystem (EPS) and the Environmental Control Subsystem (ECS) as a function of time were obtained from a pre-mission computer tape generated by MPAD/MSC and are presented in Figures 3 through 5. The spacecraft attitude was obtained from the Apollo 15 preflight trajectory and attitude sequence computer tape generated by MPAD/MSC.

Table 6 presents the planned fuel cell purge schedule obtained from Reference 2. In the simulation of the nominal mission, it was assumed that an oxygen fuel cell purge occurred every 24 hours while a hydrogen fuel cell purge occurred every 48 hours. The assumed amounts of oxygen and hydrogen consumed during each purge was .054 and .045 lbm, respectively. Although the simulated purge times do not completely agree with the planned purge schedule, its effect on the simulation is negligible.

The amounts of CSS hydrogen and oxygen loaded and remaining at launch are given in Table 7. The simulation began at approximately 2.9 GET, which was the first time point on the trajectory tape. The amounts of the cryogens assumed to be in the system at that time are also given in Table 7.

Three malfunction cases were considered for the preflight analysis report. These cases were: 1) a check valve failed open in the oxygen system, 2) an oxygen tank heater element failed during the EVA, and 3) degraded performance of an oxygen tank vacuum annulus.

The check valve immediately downstream of oxygen tank 2 was assumed to be failed open permitting oxygen to flow from tank 3 into tank 2. This malfunction is easily detected during the first period in which the tank 3 heaters are in the automatic mode with the tank 2 heaters in the off position. During the Apollo 15 Mission, this mode will occur at 15 hours GET. The purpose of this simulation was to determine if the failure would adversely effect the mission particularly during the EVA period.

During the EVA, it is planned that only two of the three heater elements in oxygen tank 3 be active. It was assumed that one of these two elements failed. This malfunction would result in longer tank 3 heater-on times than expected. The purpose of the simulation was to determine if the specified ECS flowrate of 11 lbm/hr could still be provided during the EVA.

It was assumed that the oxygen tank 2 bulk temperature transducer housing was ruptured during the boost phase of the mission. The air in the housing would then leak into the vacuum jacket thereby reducing the insulating ability of the annulus. The resulting heat leak to the tank is presented in Figure 3.14 of Reference 1. The pressure in the annulus was assumed to be 0.001 mm Hg at launch due to the malfunction. It was assumed that the high vacuum was eventually recovered after 48 hours due to the operation of the vac-ion pumps as well as cryo-pumping. Figure 6 shows the annulus pressure profile. The purpose of this simulation was to determine if venting of tank 2 would occur; and if so, whether or not the resulting loss of oxygen would impact the mission objectives.

In addition to the reductions of system operations for the malfunctions presented in this report, other malfunctions were simulated. The results of these simulations are reported under separate cover.

4. PERFORMANCE PREDICTIONS

The nominal performance predictions for the CSM 112 Cryogenic Storage System are presented in Figures 7 through 24. Of these figures, the remaining quantities as functions of time for the oxygen and hydrogen tanks are presented in Figures 7 and 8, respectively. Figures 9 and 10 show the oxygen and hydrogen bulk temperature as functions of time. Figures 11 through 13 present the expected pressure cycling in the oxygen and hydrogen tanks as well as the predicted oxygen tank heater temperature at the hottest spot on the heater column for the first 75 hours of the mission. Figures 14 through 16 present similar information from 75 to 150 hours GET, while Figures 17 through 19 and 20 through 22 cover the periods from 150 to 225 hours and 225 to 300 hours, respectively. Figures 23 and 24 present the oxygen tank pressure cycling and heater temperatures during the EVA with an expanded time scale.

All significant considerations which effect system performance, including the effects of thermal stratification in the oxygen tanks, have been accounted for in the simulations. Oxygen tank pressures dropping below approximately 860 psia in the figures are caused by the simulation of pressure collapses caused by SPS engine thrusting or spacecraft spin-up or spin-down maneuvers during the PTC mode. Table 1 presents the SPS burn schedule and Table 2 presents the periods of PTC planned. While the actual magnitude of the pressure collapse may be in error due to the simplicity of the statification model, the simulation does indicate when pressure collapses are most likely to occur. It is anticipated that the pressure collapses which do occur during the flight will not be as great as simulated. None of the collapses resulted in the thermodynamic state of the oxygen tanks entering the two phase region. As a result of the collapsed pressure, the heater-on time immediately subsequent to the event was relatively long. This resulted in a high heater temperature. The highest temperature (on the column) simulated was approximately 830°R in tanks 1 and 2 which occurred during the high flow period early in the mission. The heater-on time (and therefore heater temperature) is directly related to the simplified stratification model. Since the pressure collapse is greater than expected, the subsequent heater temperature is also greater than expected during the actual flight. Other than this early occurrence of high heater temperature, the temperature remains below 800°R which is below the specification value. In general the sensor temperature was 20 to 30 degrees lower than the hot spot temperature. These results indicate that additional tuning of the model is required. The results do, however, indicate the times during the mission in which the system should be carefully monitored.

The addition of the third hydrogen tank for this mission significantly reduced the flowrate demand on the other hydrogen tanks. Thus, heater cycling in these tanks was less frequent than in past missions.

During the EVA one heater cycle occurred in each oxygen tank with a maximum heater column temperature of approximately 690°R in oxygen tanks 1 and 2, and a maximum heater column temperature of approximately 580°R in oxygen tank 3.

The temperature of the oxygen flowing into the fuel cells generally remained between 300 and 450°R. During the EVA, the temperature rapidly dropped approximately 100°R. Subsequent to the EVA, the temperature of the fluid in the line from tank 1 recovered to 350°R in approximately 0.8 hours while the fluid from tank 2 recovered to approximately 390°R over a 1 hour period.

The results of the check valve malfunction case indicated that the tank 2 pressure tended to track the tank 3 pressure when the heaters in tank 2 were inactive and the heaters in tank 3 were on. The failure did not significantly effect the performance of the system and resulted only in a difference in remaining oxygen tank quantities as a function of time. At the end of the mission, the tank quantities were 37.7, 42.4 and 24.7 percent for tanks 1, 2, and 3, respectively. The quantities remaining at the end of the nominal mission were 43.6, 38.3, and 27.4 percent for tanks 1, 2, and 3, respectively.

The loss of an oxygen tank heater element during the EVA did not effect the ability of the system to provide the required flows. The only significant effect was that the tank 3 heater remained on during the entire EVA and that the tank 1 and 2 heater-on times were longer than in the nominal case. The heater-on time during the nominal mission simulation was 15.3 minutes while the heater-on time with the malfunction was 22.8 minutes for tanks 1 and 2.

The results of the malfunction case to investigate the degraded performance of the tank vacuum annulus indicated that, for an initial jacket pressure of 0.001 mm Hg, no significant problems would occur. The effects of the increased heat leak, approximately four to five times that which occurred during the nominal mission simulation, were compensated for by the high flowrate demand early in the mission. No venting of the system occurred.

5. CONCLUSIONS

Based on the results of the nominal CSS preflight simulation, it is concluded that the system is capable of successfully completing the mission. Sufficient amounts of hydrogen and oxygen in excess of the nominal requirements are available for contingency demands.

The malfunction cases investigated had no significant effects on the capability of the system to fulfill the mission successfully.

6. REFERENCES

1. TRW Report 17618-H153-R0-00, "Apollo Cryogenic Integrated Systems Program," R. K. M. Seto, C. E. Barton, and J. E. Cunningham, May 1971.

2. NASA Document, "Apollo 15 (July 26, 1971) AS-510/CSM112/LM-10, Preliminary Flight Plan," 20 April 1971.

3. NASA Document MSC-04102, "The Spacecraft Operational Trajectory for Apollo 15 (Mission J-1) Launched July 26, 1971, Volume I - Mission Profile," 16 April, 1971.

4. Tank and Component End Item Acceptance Test Data obtained from the Beech Aircraft Corp., May, 1971.

TABLE 1

CSM BURN SCHEDULE*

MANEUVER	TIME (GET) Hr:Min:Sec	DURATION Min:Sec	ΔV FPS	ENGINE
Translunar Injection	2:50:05	5:57.5	10004.1	S-IV B
CSM/LM Ejection	4:16:00	0:03	0.4	RCS
MCC-1	11:56:02	--	--	--
MCC-2	30:56:02	--	--	--
MCC-3	56:31:15	--	--	--
MCC-4	73:31:15	--	--	--
Lunar Orbit Insertion	78:31:15	6:32	2997.9	SPS
Descent Orbit Injection	82:39:33	0:22.9	207.6	SPS
Undock & Separation	100:13:56	0:03.3	1.0	RCS
Circularization	101:34:55	0:03.9	70.8	SPS
Plane Change	165:12:51	0:16.5	308.6	SPS
LM Jettison	177:35:27	0:06.4	1.0	RCS
Transearth Injection	223:43:48	1:39	3046.7	SPS
MCC-5	238:43:48	--	--	--
MCC-6	272:58:20	--	--	--
MCC-7	291:58:20	--	--	--

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* It is anticipated that the CSM burns may result in the destratification of the oxygen storage tanks.

TABLE 2

CSM PASSIVE THERMAL CONTROL SCHEDULE

	PTC Initiation Time (GET) Hr:Min	PTC Termination Time (GET) Hr:Min	ΔTime In Mode Hr:Min
1	11:00	30:20	19:20
2	36:10	55:30	19:20
3	57:00	73:00	16:00
4	227:50	237:25	9:35
5	245:35	251:05	5:30
6	252:00	263:05	11:05
7	264:10	267:35	3:25
8	277:00	288:40	11:40

TABLE 3

CSS PHYSICAL AND OPERATING CHARACTERISTICS

	Oxygen Storage System			Hydrogen Storage System		
	Tanks			Tanks		
	Tank 1	Tank 2	Tank 3	Tank 1	Tank 2	Tank 3
Serial Number	XTA0030	XTA0031	XTA0018	HTA0042	HTA0036	HTA0039
Volume*, ft^3	4.75	4.75	4.75	6.80	6.80	6.80
Minimum dQ/dM Flow, lbm/hr	0.637	0.715	0.669	0.0477	0.0631	0.0462
Annulus Vacuum Level, mm Hg	4.7×10^{-6}	2.8×10^{-6}	4.0×10^{-6}	2.0×10^{-6}	1.5×10^{-6}	--
Heater Input*, per element, BTU/hr	145.1	145.1	145.1	31.75	31.75	--
Heater Input*, Total, BTU/hr	435.3	435.3	435.3	63.5	63.5	--
Fan Input*, per unit, BTU/hr	--	--	--	11.95	11.95	11.95
Fan Input, Total, BTU/hr	--	--	--	23.9	23.9	23.9
	Valve Modules			Valve Modules		
Serial Number	J220103		H500103	J041915		H500103
Weight, lbm	8.35		8.1	7.69		8.1
Relief Valve Operation						
Cracking Pressure, psig	1003.0	998.2	999.7	281.2	281.3	280.7
Full Flow Pressure, psig	1003.3	1000.5	1000.3	281.2	281.3	280.7
Reseat Pressure, psig	975.5	974.1	996.7	275.1	274.5	275.7
Pressure Switch Operation						
High Pressure, psia	924.8	923.0	922.0	254.8	253.9	252.7
Low Pressure, psia	888.2	876.3	879.0	235.8	234.5	235.8
Dead Band, psid	36.6	46.7	43.0	19.0	19.0	16.9
Pressure Drop**,$^{++}$ psid	22.0	23.0^{+}	33.0	1.0	3.5^{+}	3.0

*Nominal value

**8.8 SCFM nitrogen at 400 psia for oxygen and ambient temperature

$^{+}$With check valve

$^{++}$1.7 SCFM helium at 27 psia for hydrogen and ambient temperature.

TABLE 4
CSS OXYGEN TANK HEATER MODE SCHEDULE

TIME (GET) Hr:Min	MODE Tank 1	 Tank 2	 Tank 3
00:00	AUTO	AUTO	OFF
3:35	AUTO	AUTO	AUTO
4:20	AUTO	AUTO	OFF
15:00	OFF	OFF	AUTO
74:20	AUTO	AUTO	OFF
95:00	OFF	OFF	AUTO
109:00	AUTO	AUTO	OFF
190:00	OFF	OFF	AUTO
203:00	AUTO	AUTO	OFF
241:25	AUTO	AUTO	AUTO
243:30	AUTO	AUTO	OFF

TABLE 5
CSS HYDROGEN TANK HEATER AND FAN MODE SCHEDULE

TIME (GET) Hr:Min	MODE Tank 1	 Tank 2	 Tank 3*
00:00	AUTO	AUTO	ON
15:00	AUTO	AUTO	AUTO
25:00	OFF	OFF	AUTO
74:00	AUTO	AUTO	OFF

* Hydrogen Tank 3 does not contain a heater. The schedule for Tank 3 is for the fans only.

TABLE 6

FUEL CELL PURGE TABLE

TIME (GET) Hr:Min	Oxygen Fuel Cell Purge		Hydrogen Fuel Cell Purge	
	Number	ΔTime Hr:Min	Number	ΔTime Hr:Min
10:30	1	10:30		
30:40	2	20:10	1	30:40
56:10	3	25:30		
73:15	4	17:05	2	42:35
97:38	5	24:23		
125:15	6	27:37	3	52:00
146:55	7	21:40		
170:25	8	23:30	4	45:10
193:55	9	23:40		
221:50	10	27:55	5	51:25
244:00	11	22:10		
272:40	12	28:40	6	50:50

TABLE 7

CSS OXYGEN AND HYDROGEN LOADS

	QUANTITIES LOADED		QUANTITIES AT LAUNCH		QUANTITIES AT START OF SIMULATION GET =2.9	
	Lbm	Percent	Lbm	Percent	Lbm	Percent
OXYGEN						
Tank 1	330.1	100.0	313.8	95.0	310.61	93.98
Tank 2	330.1	100.0	313.8	95.0	310.56	93.96
Tank 3	330.1	100.0	313.8	95.0	313.12	94.75
TOTAL	990.3		941.4			
HYDROGEN						
Tank 1	29.3	100.0	27.4	93.2	27.29	92.82
Tank 2	29.3	100.0	27.4	93.2	27.29	92.82
Tank 3	29.3	100.0	27.4	93.2	27.02	91.87
TOTAL	87.9		82.2			

FIGURE 1

APOLLO J TYPE CRYOGENIC STORAGE SYSTEM

OXYGEN SCHEMATIC

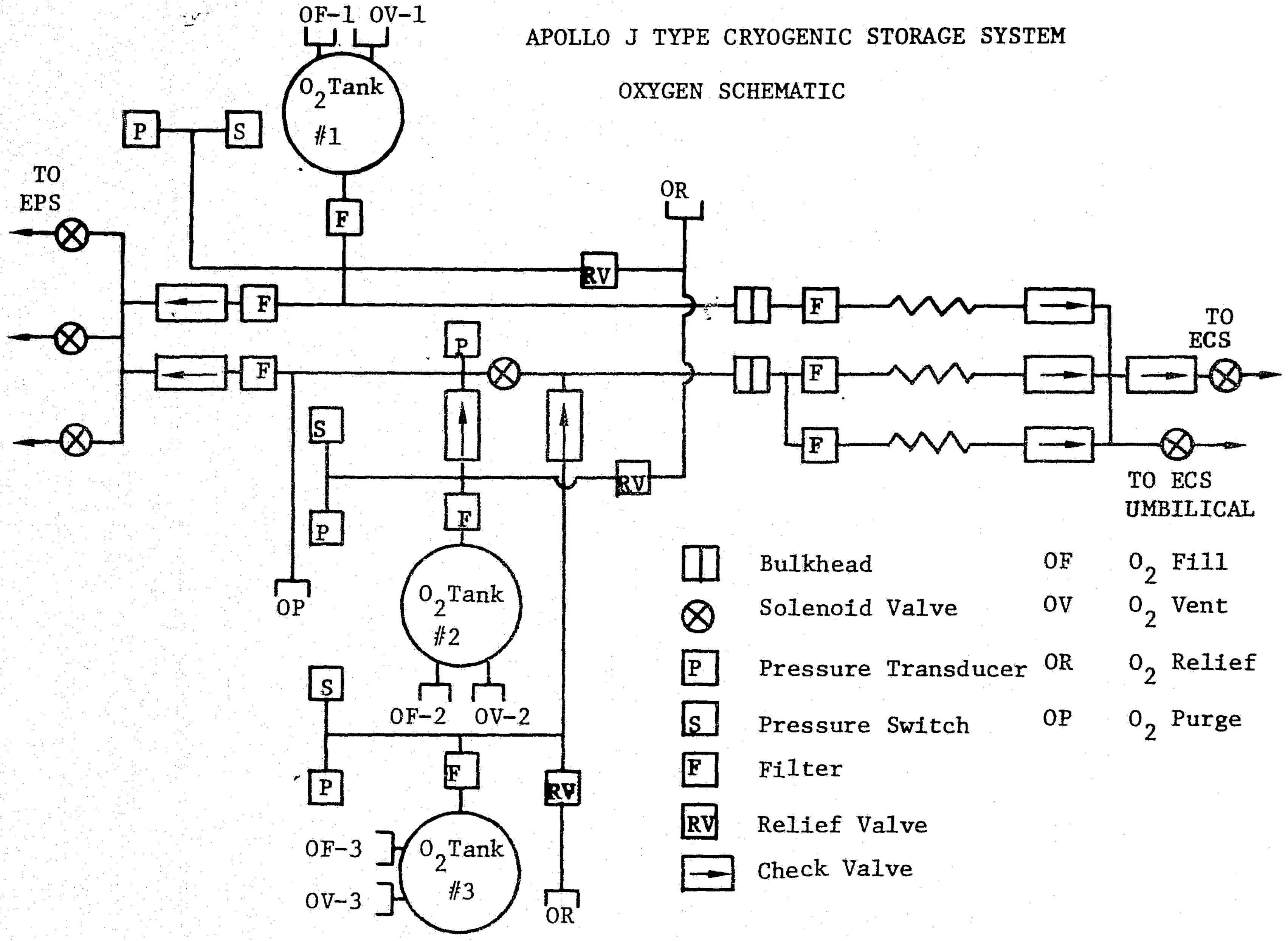
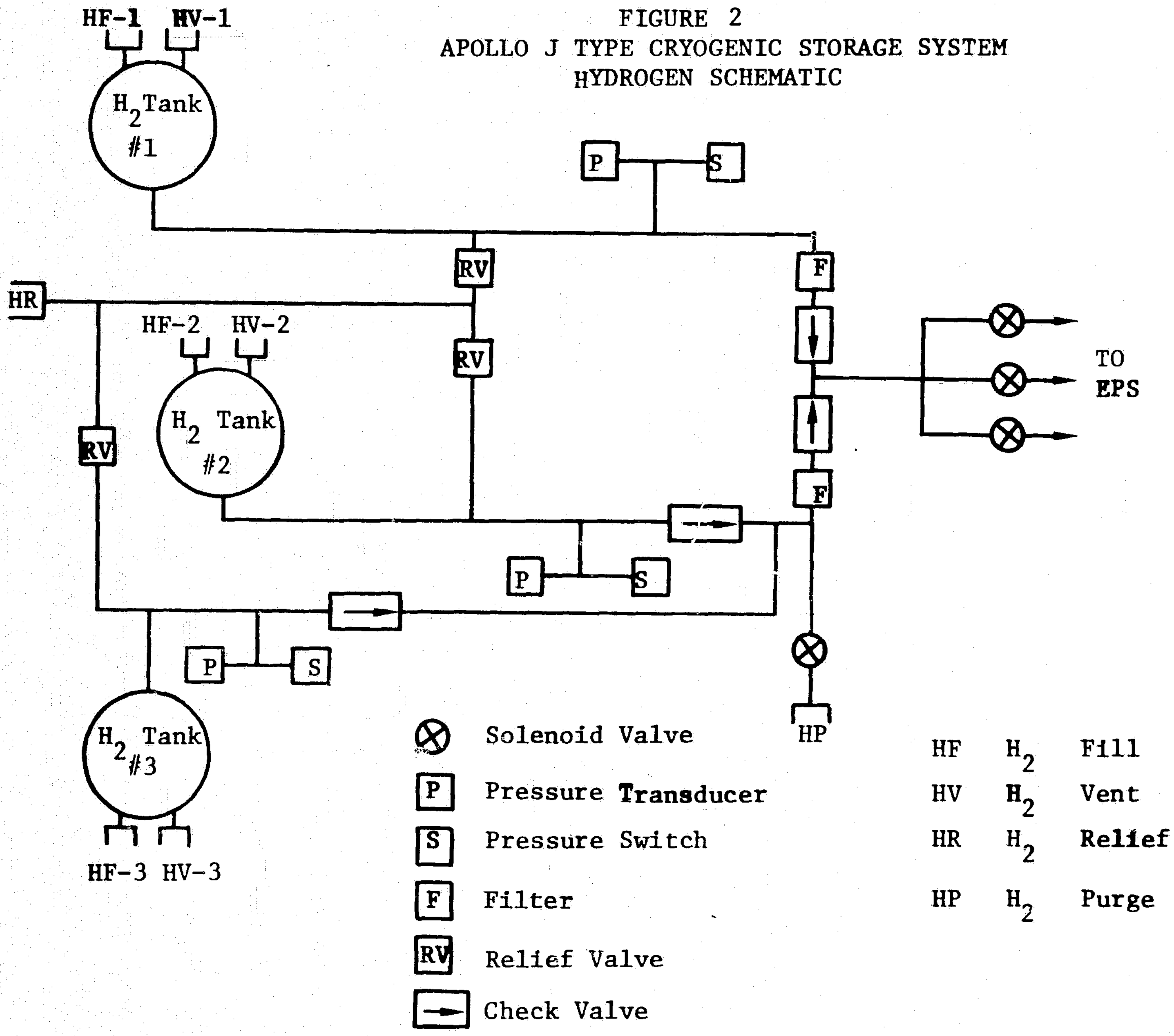


FIGURE 2
APOLLO J TYPE CRYOGENIC STORAGE SYSTEM
HYDROGEN SCHEMATIC



APOLLO 15 ECS DEMAND

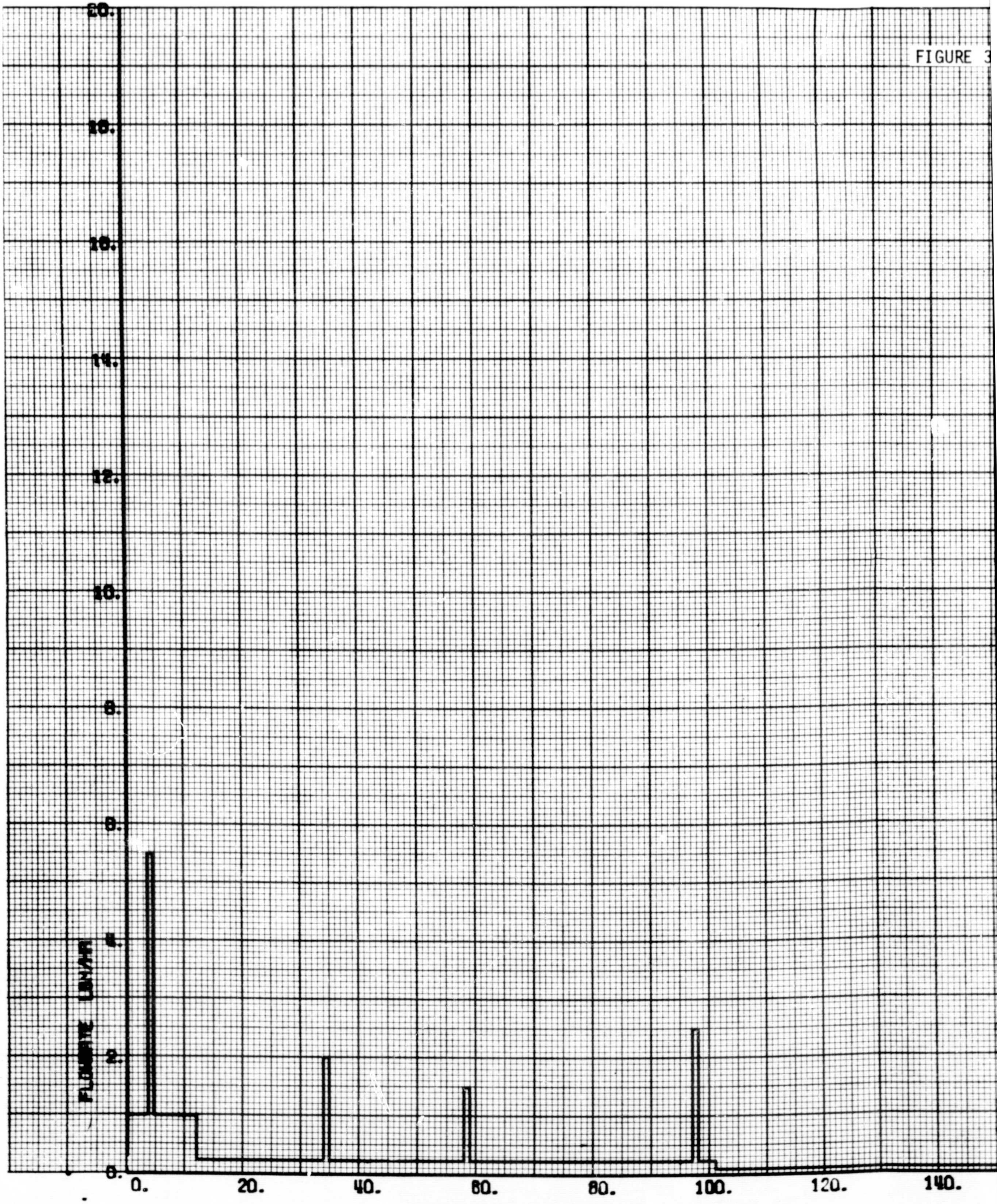


FIGURE 3

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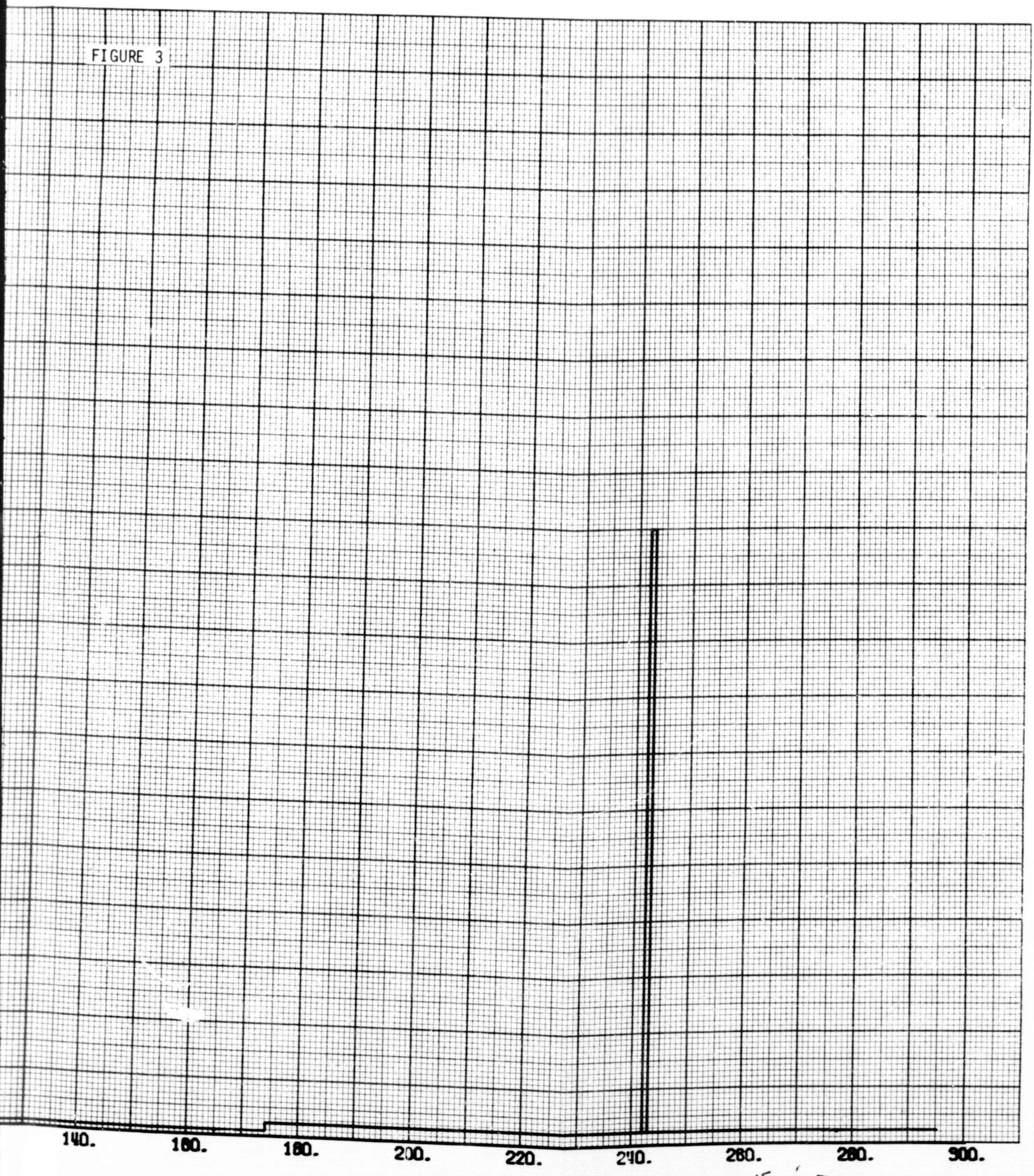
FIGURE 3



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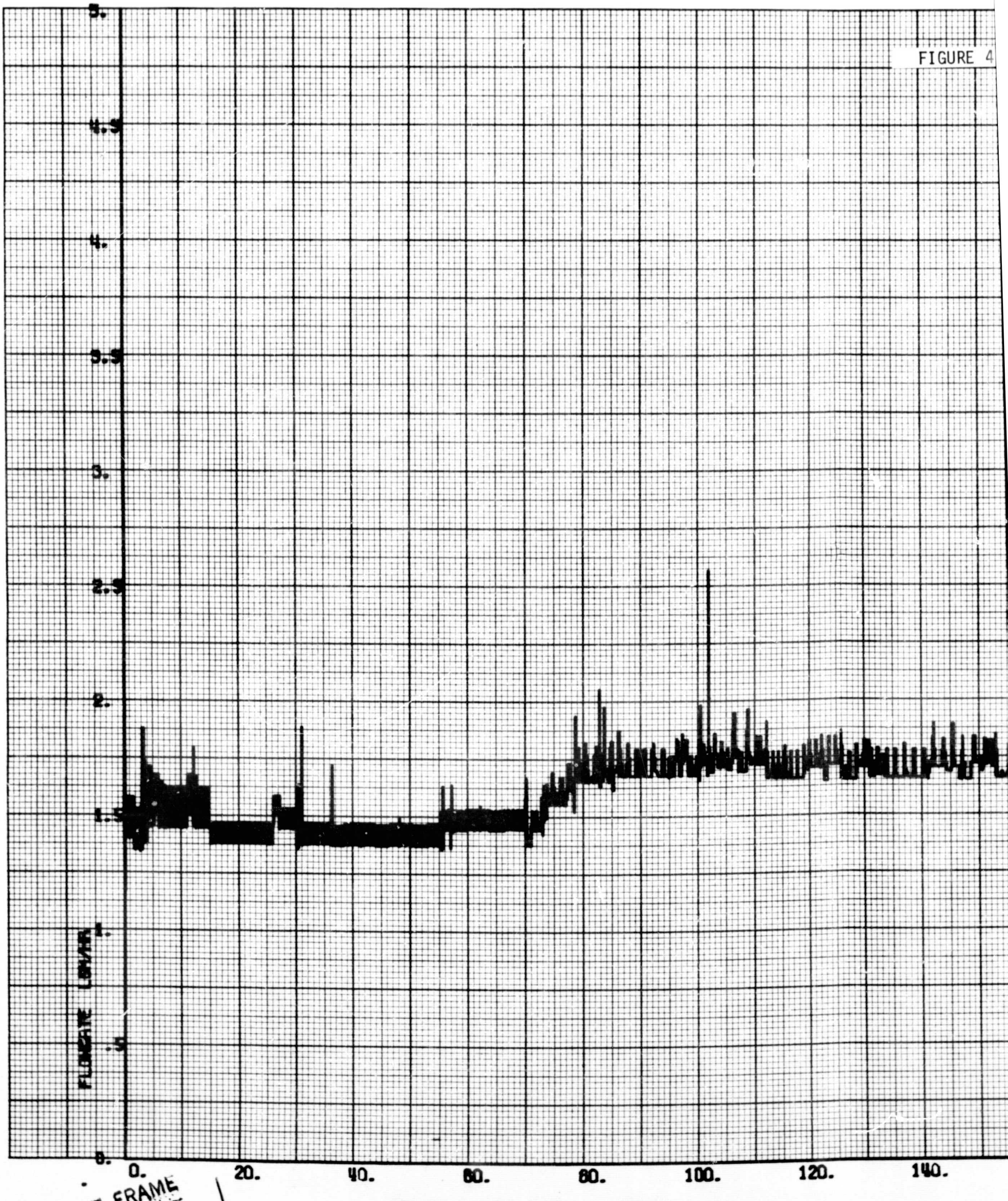
APOLLO 15 EPS OXYGEN DEMAND

FIGURE 4



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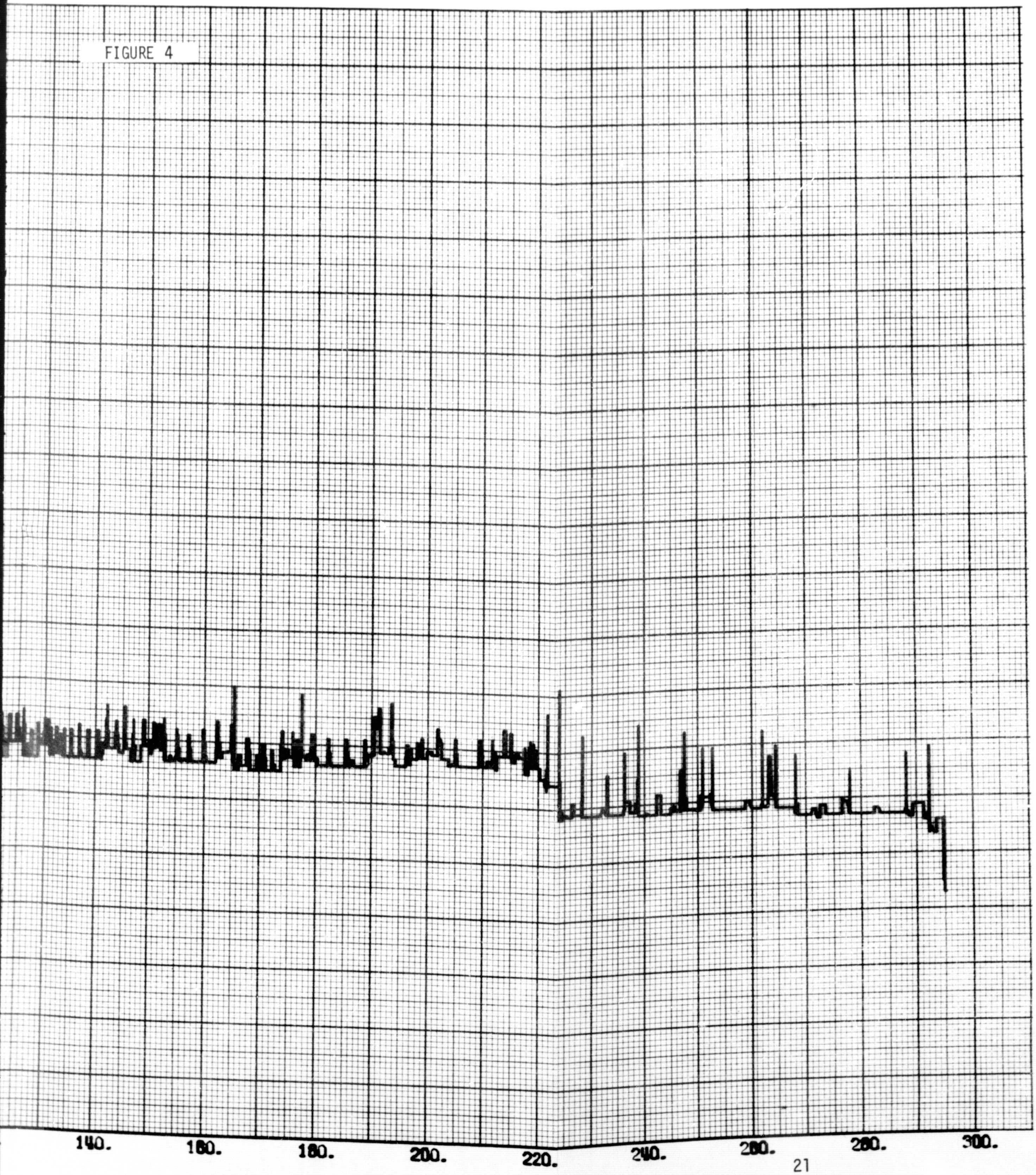


APOLLO 15 EPS HYDROGEN DEMAND

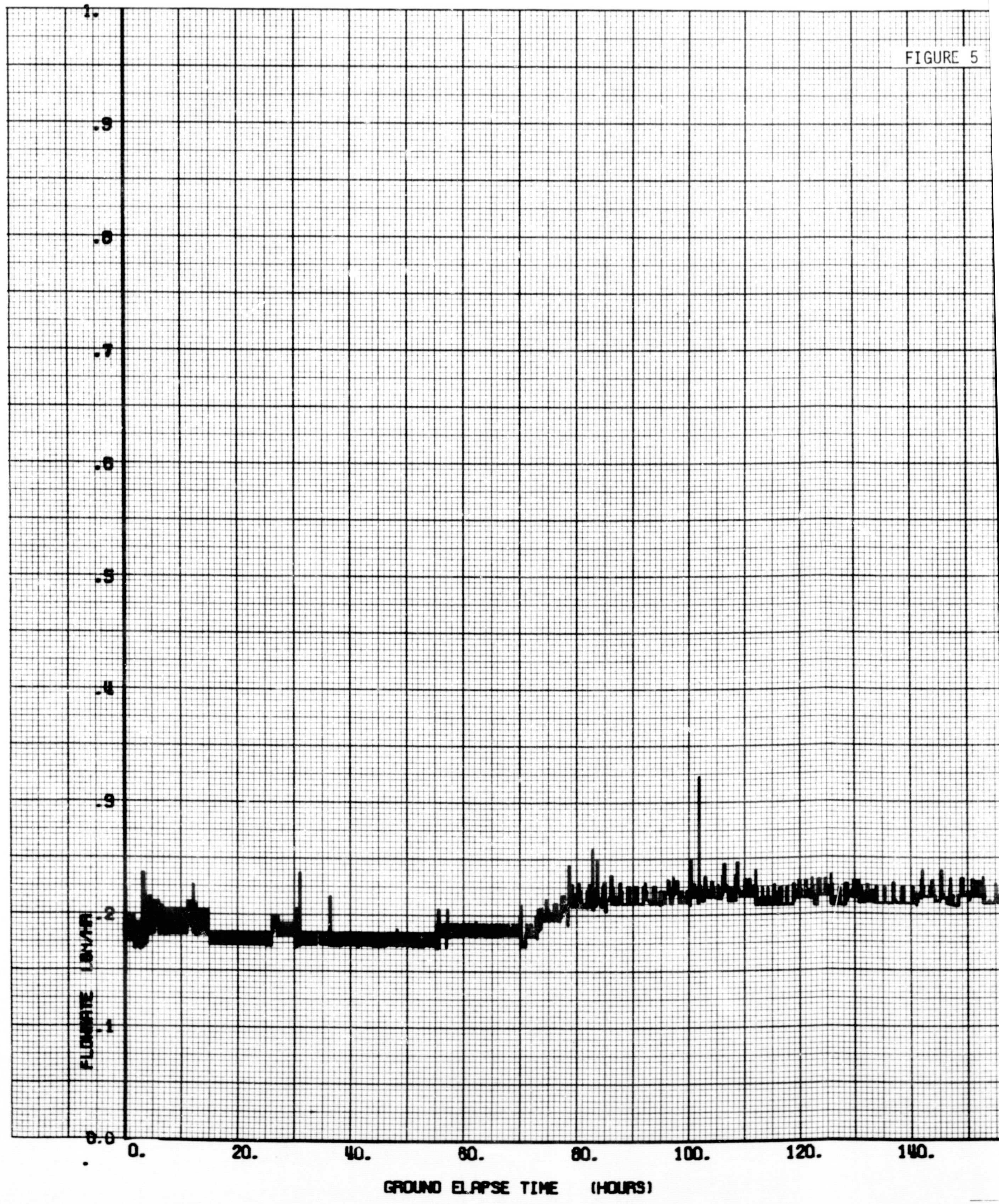
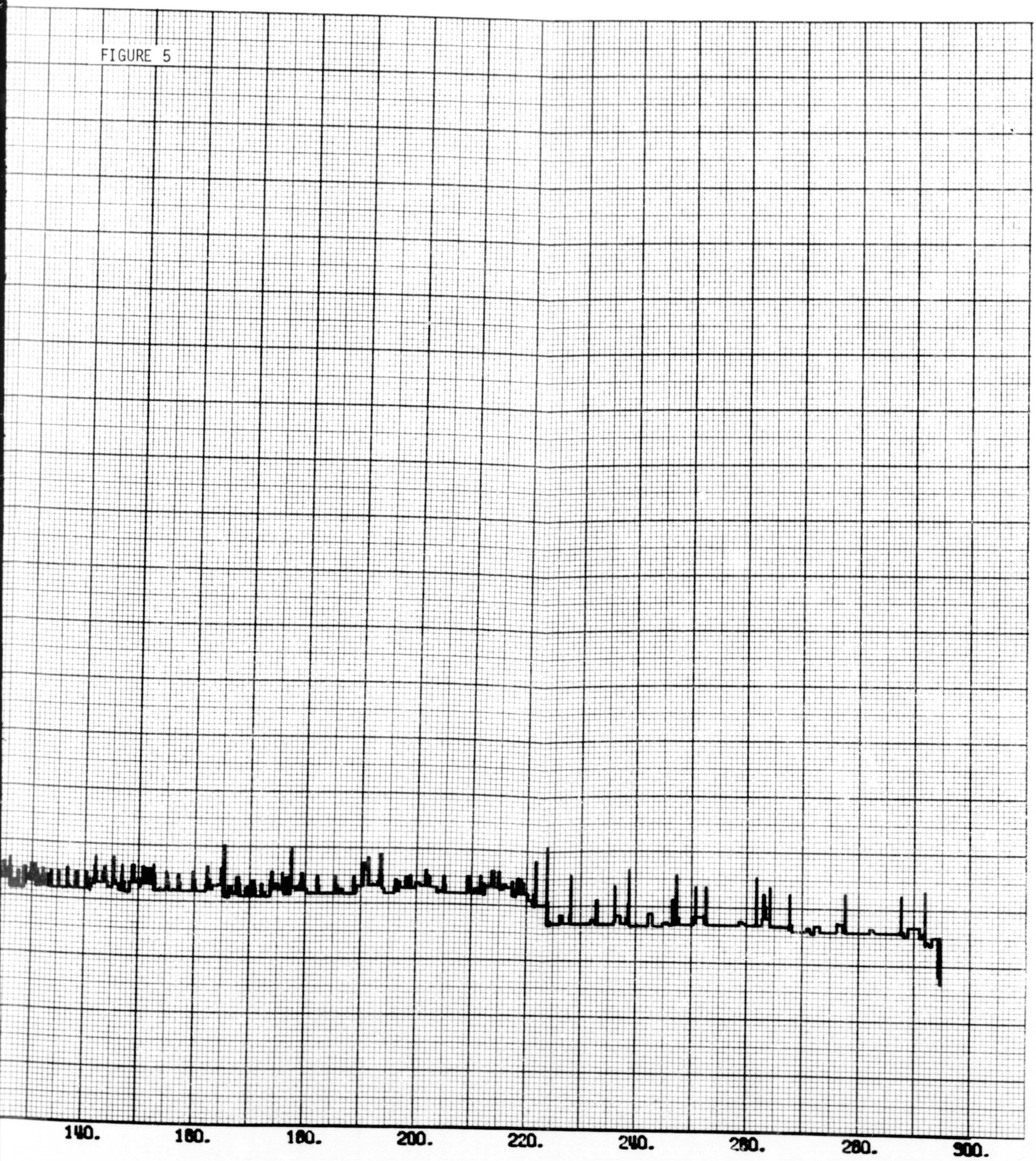


FIGURE 5

FIGURE 5



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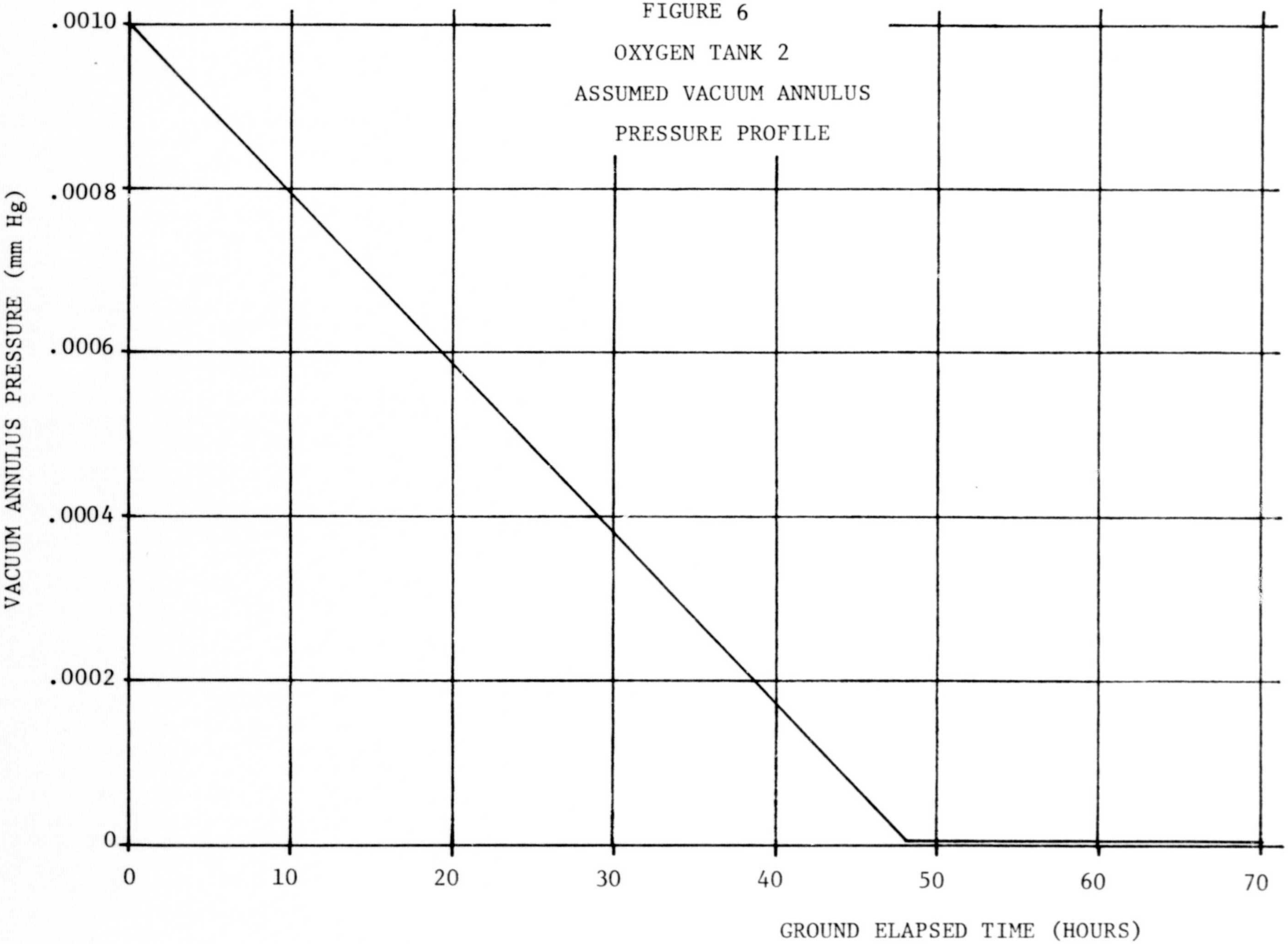

FIGURE 6

OXYGEN TANK 2

ASSUMED VACUUM ANNULUS

PRESSURE PROFILE

APOLLO 15 CSS OXYGEN TANK QUANTITIES

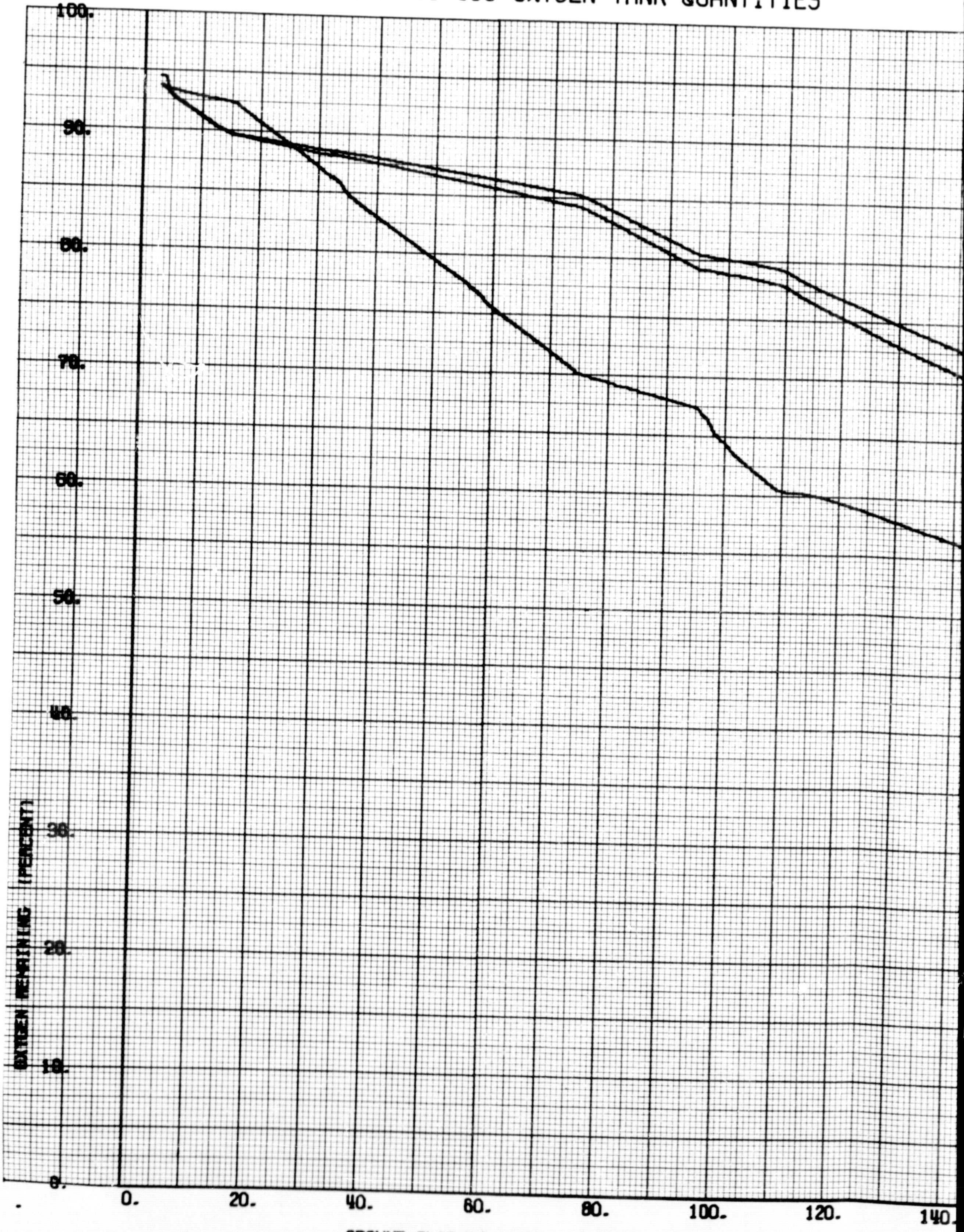

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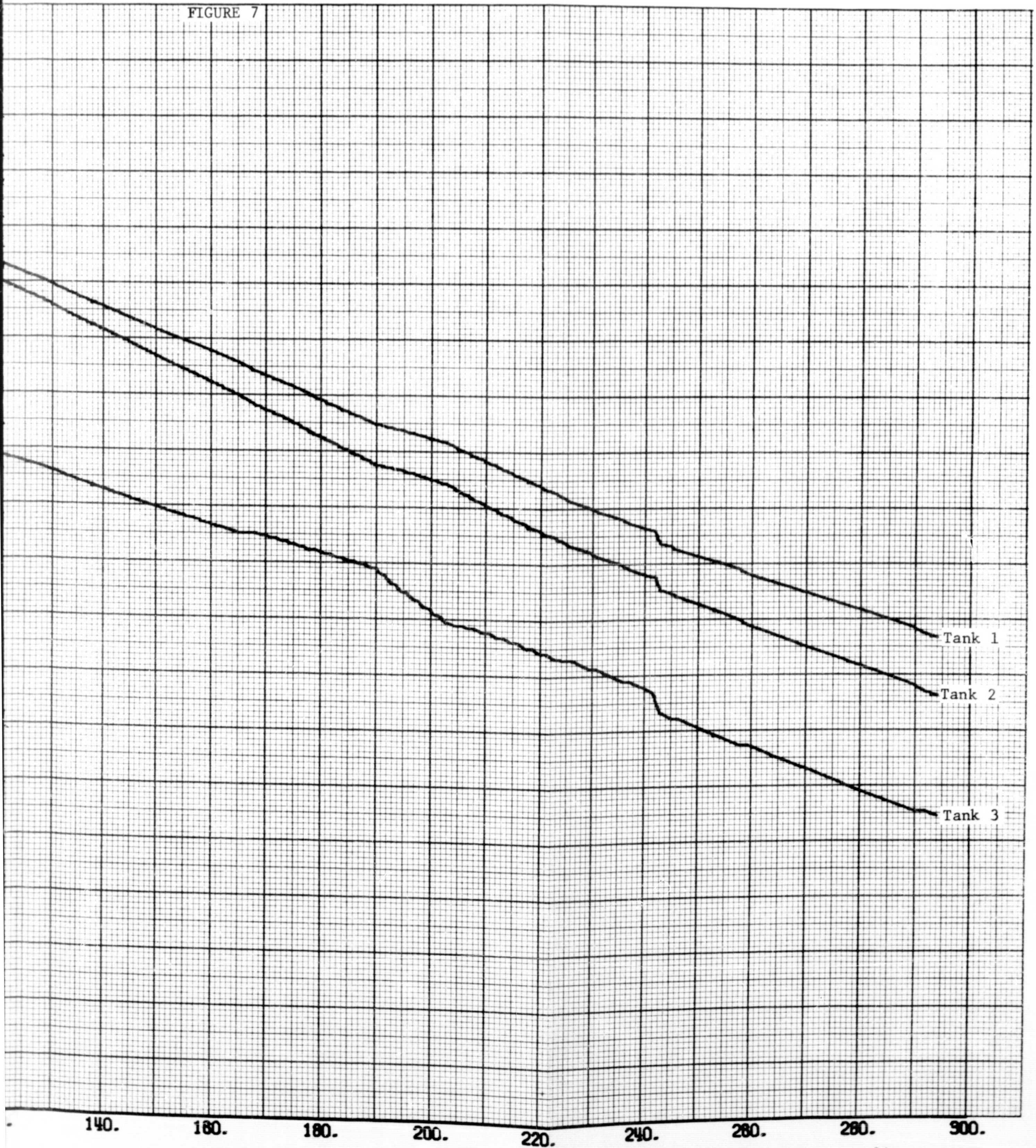
FIGURE 7



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APOLLO 15 CSS HYDROGEN TANK QUANTITIES

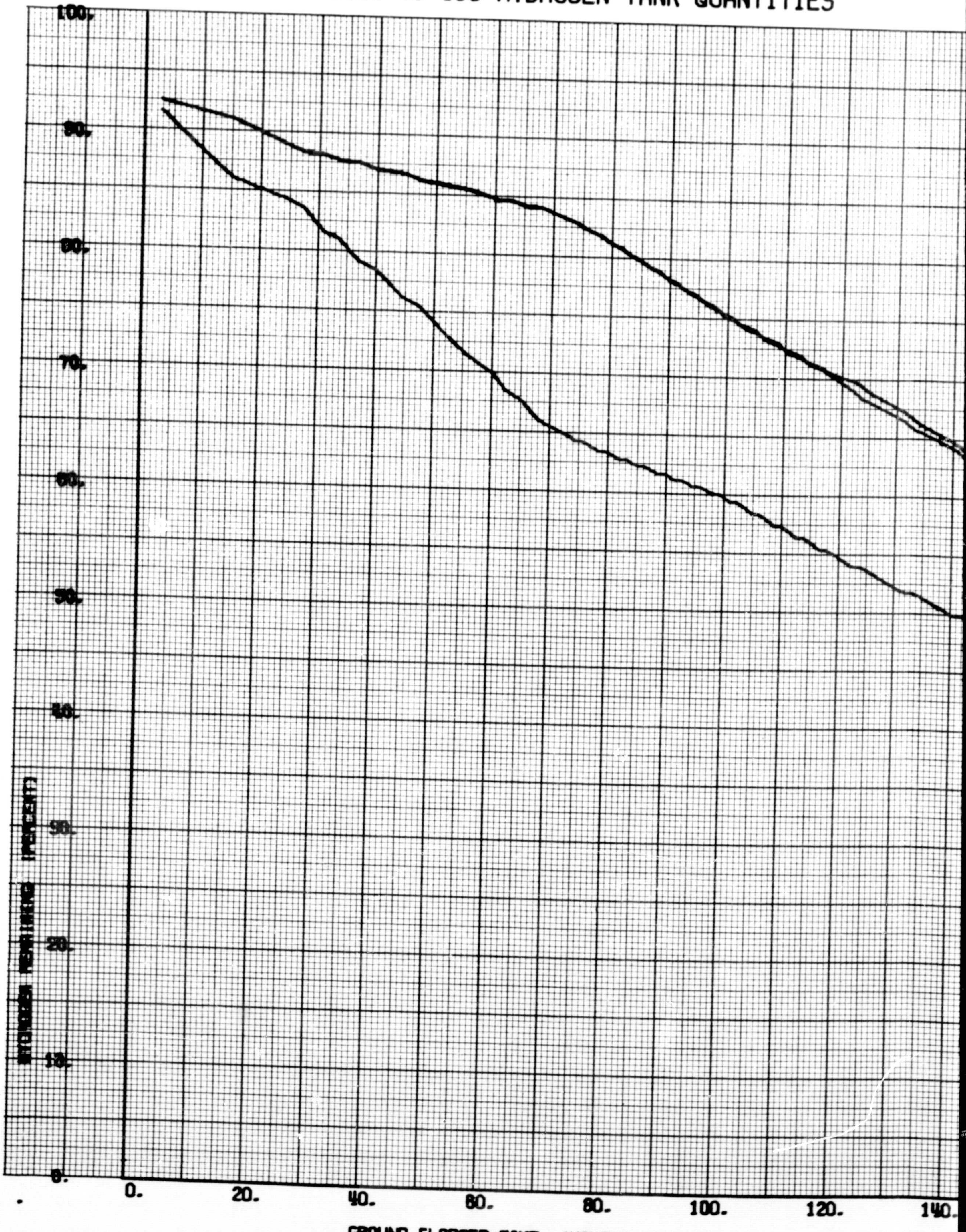

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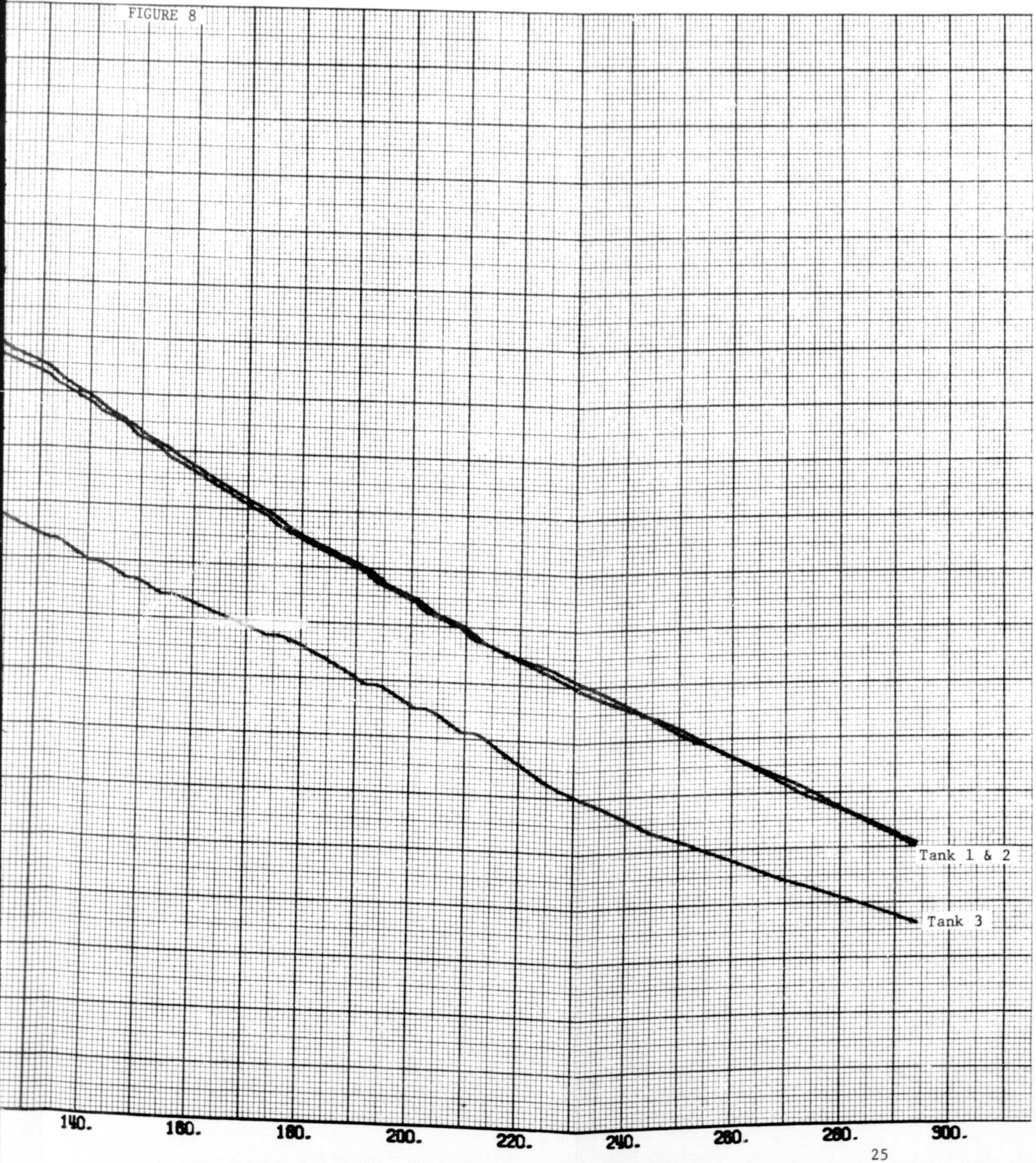
FIGURE 8



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APOLLO 15 CSS OXYGEN TANK BULK TEMPERATURES

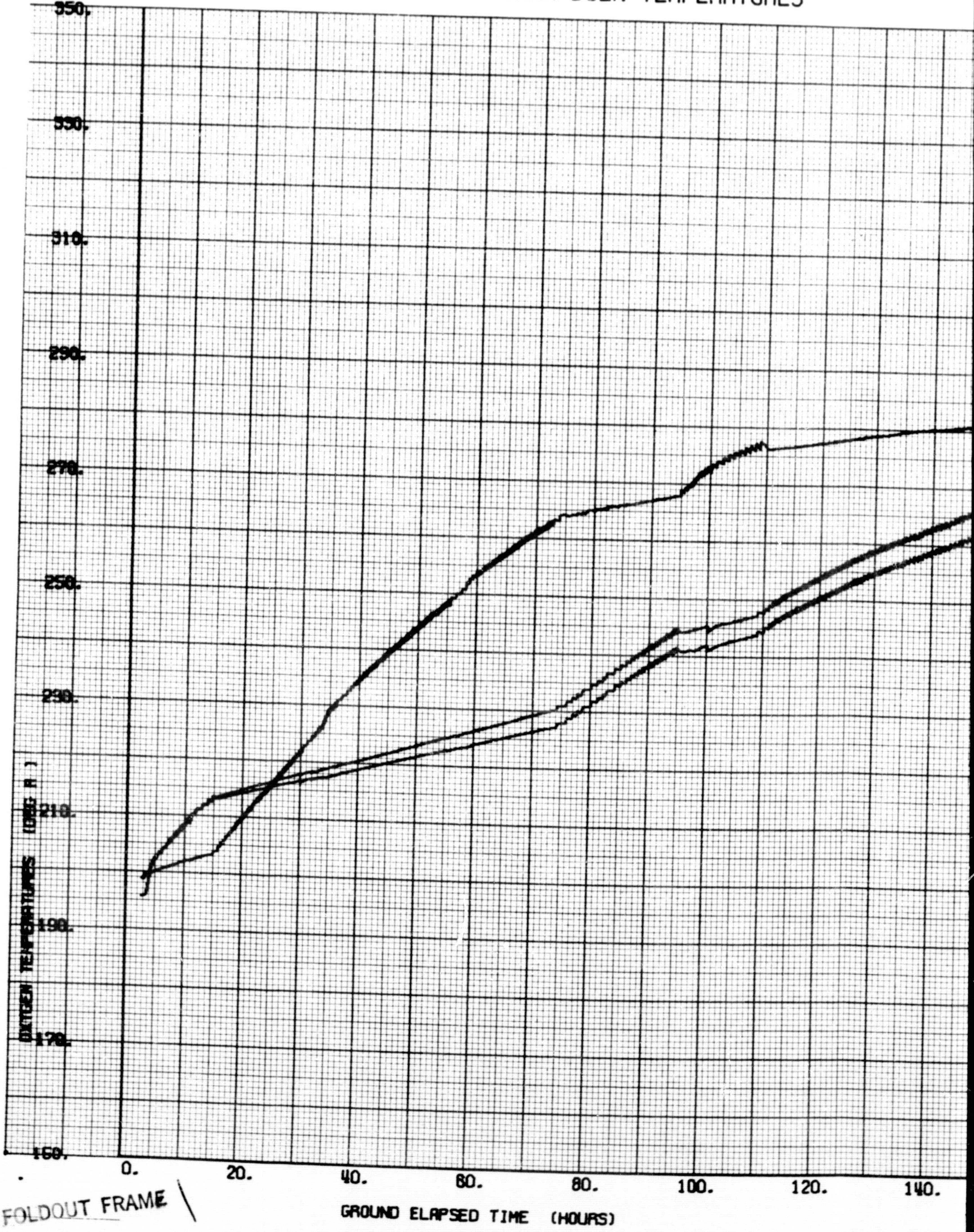

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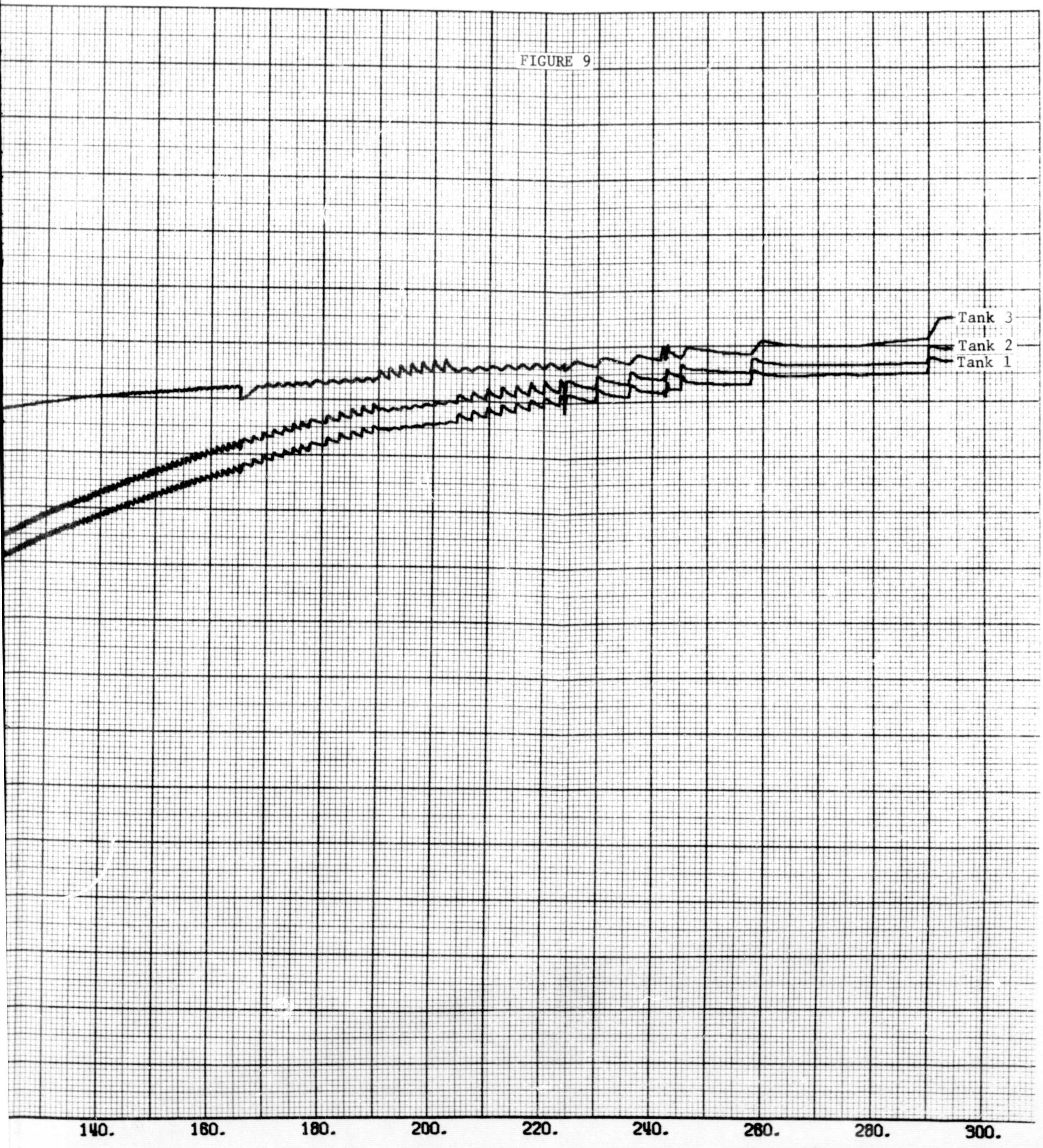
FIGURE 9



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APOLLO 15 CSS HYDROGEN TANK BULK TEMPERATURES

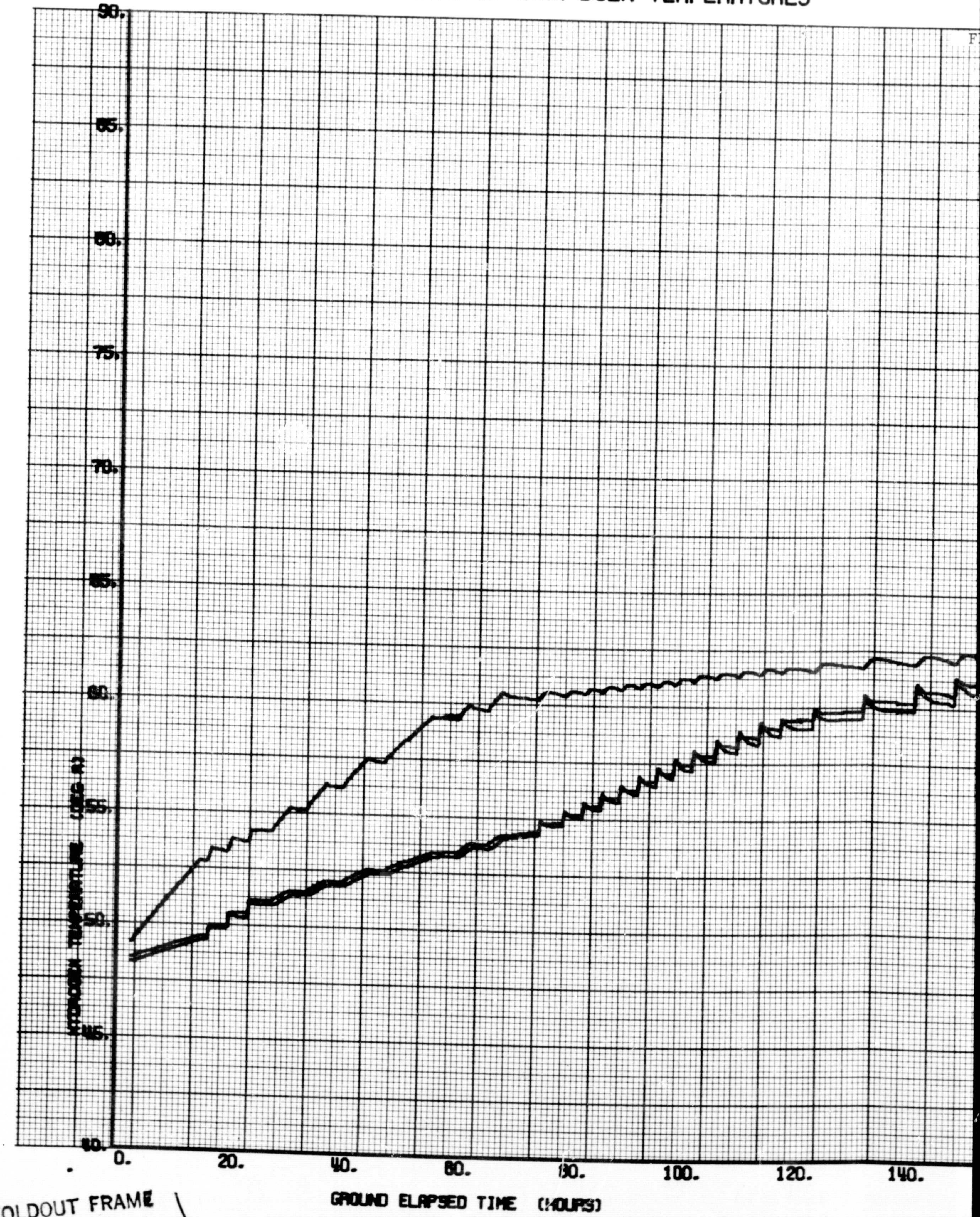

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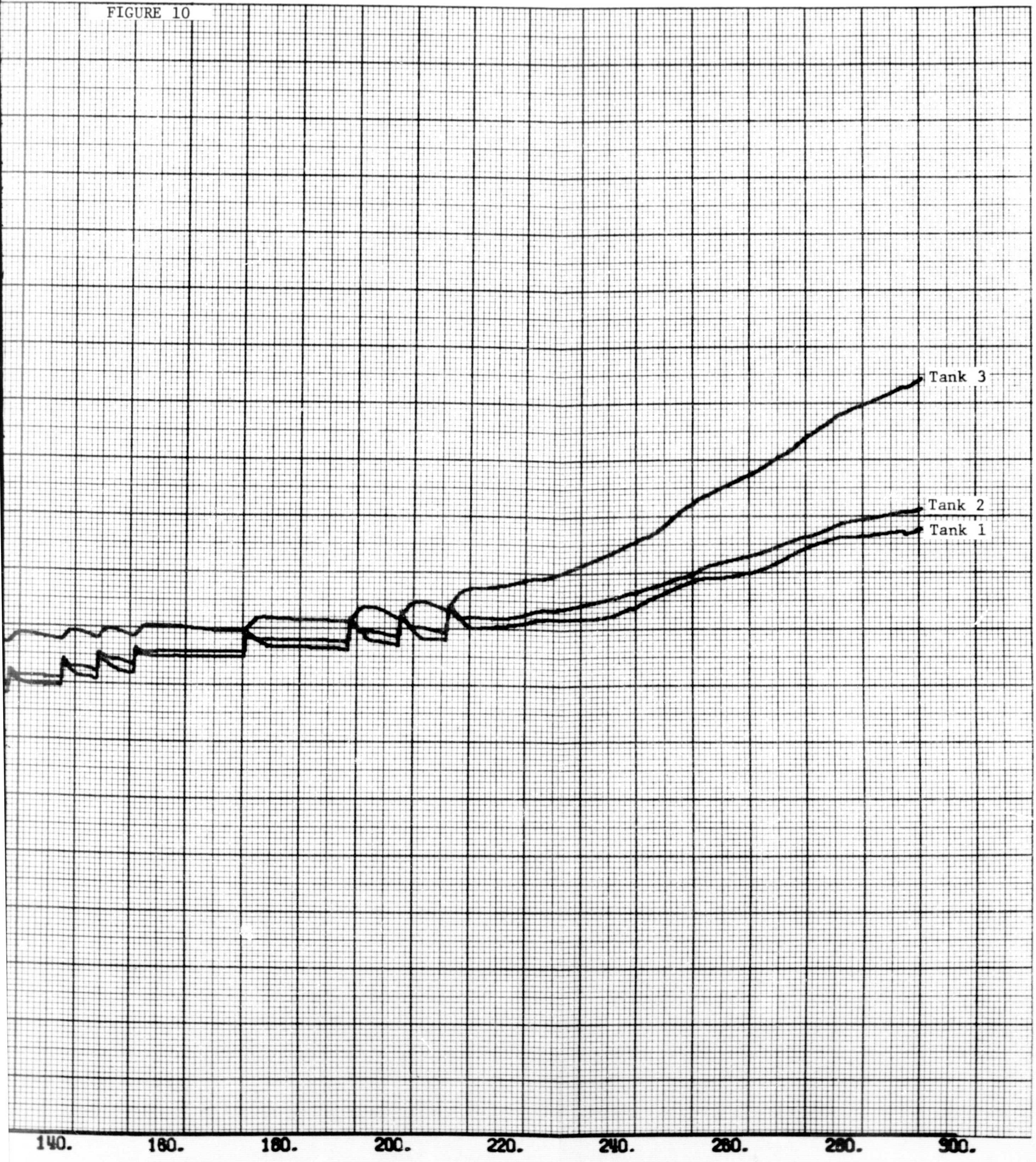
FIGURE 10



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OXYGEN TANK PRESSURE CYCLING VERSUS GET (0 TO 75 HRS)

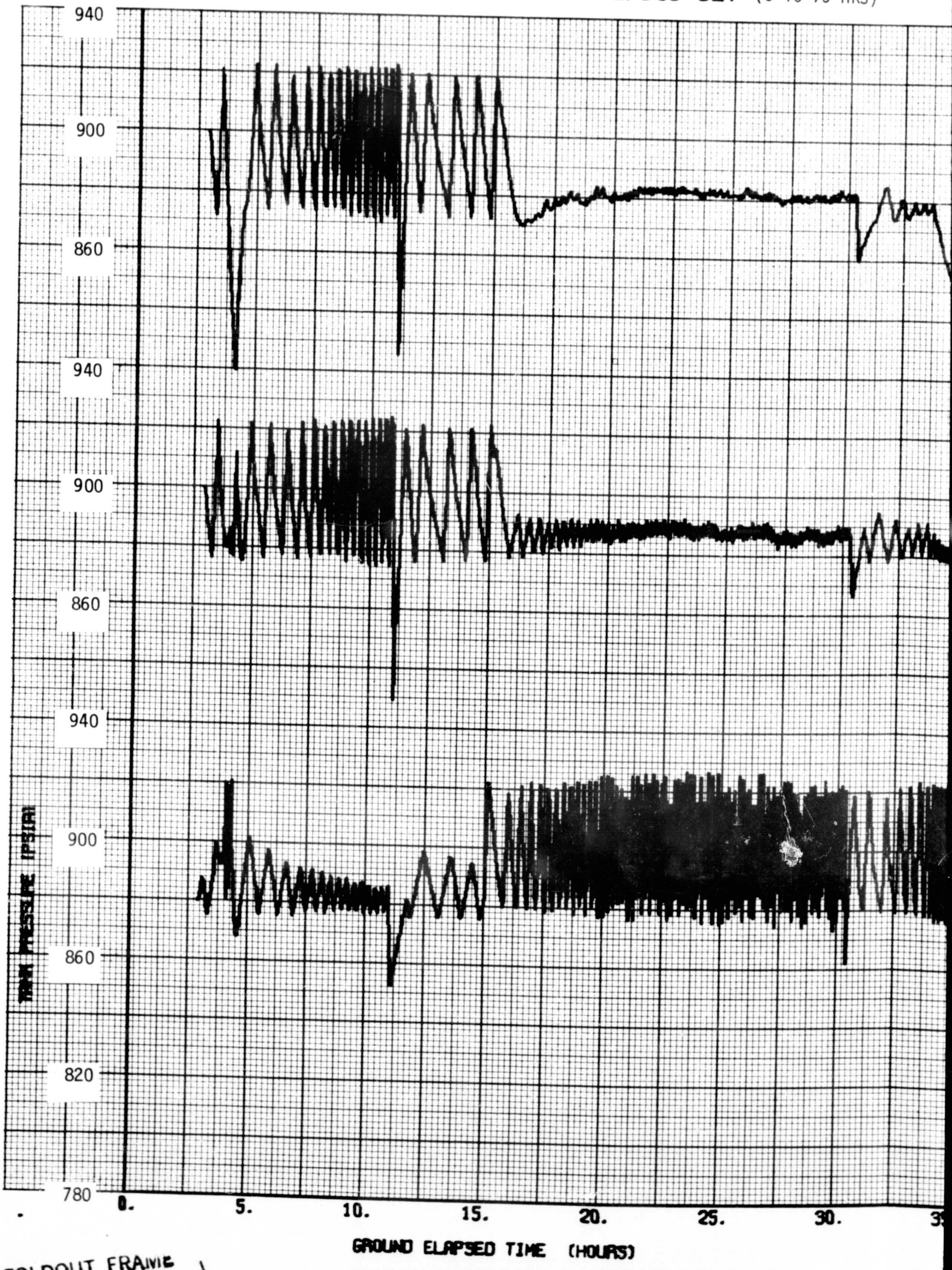

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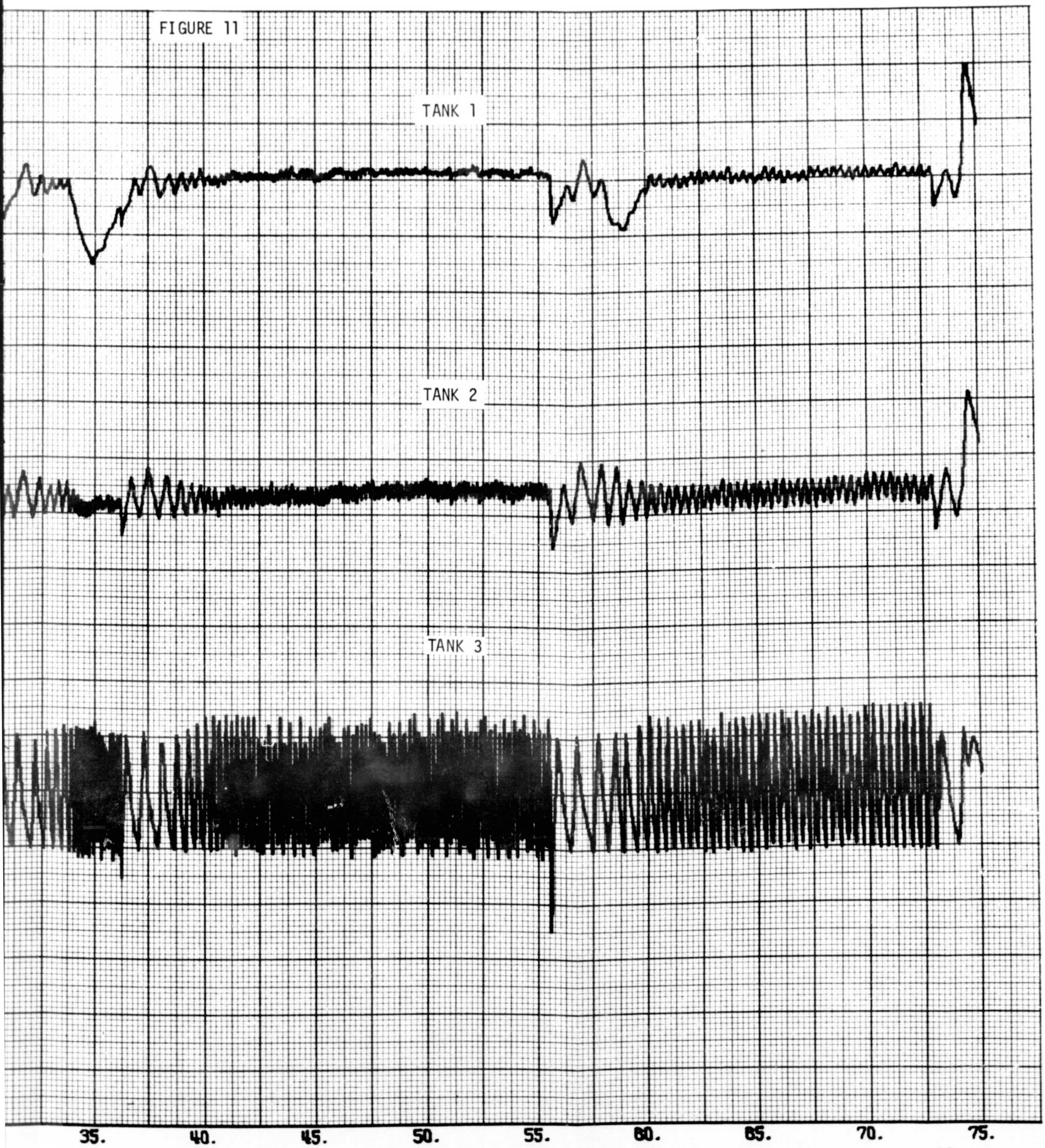
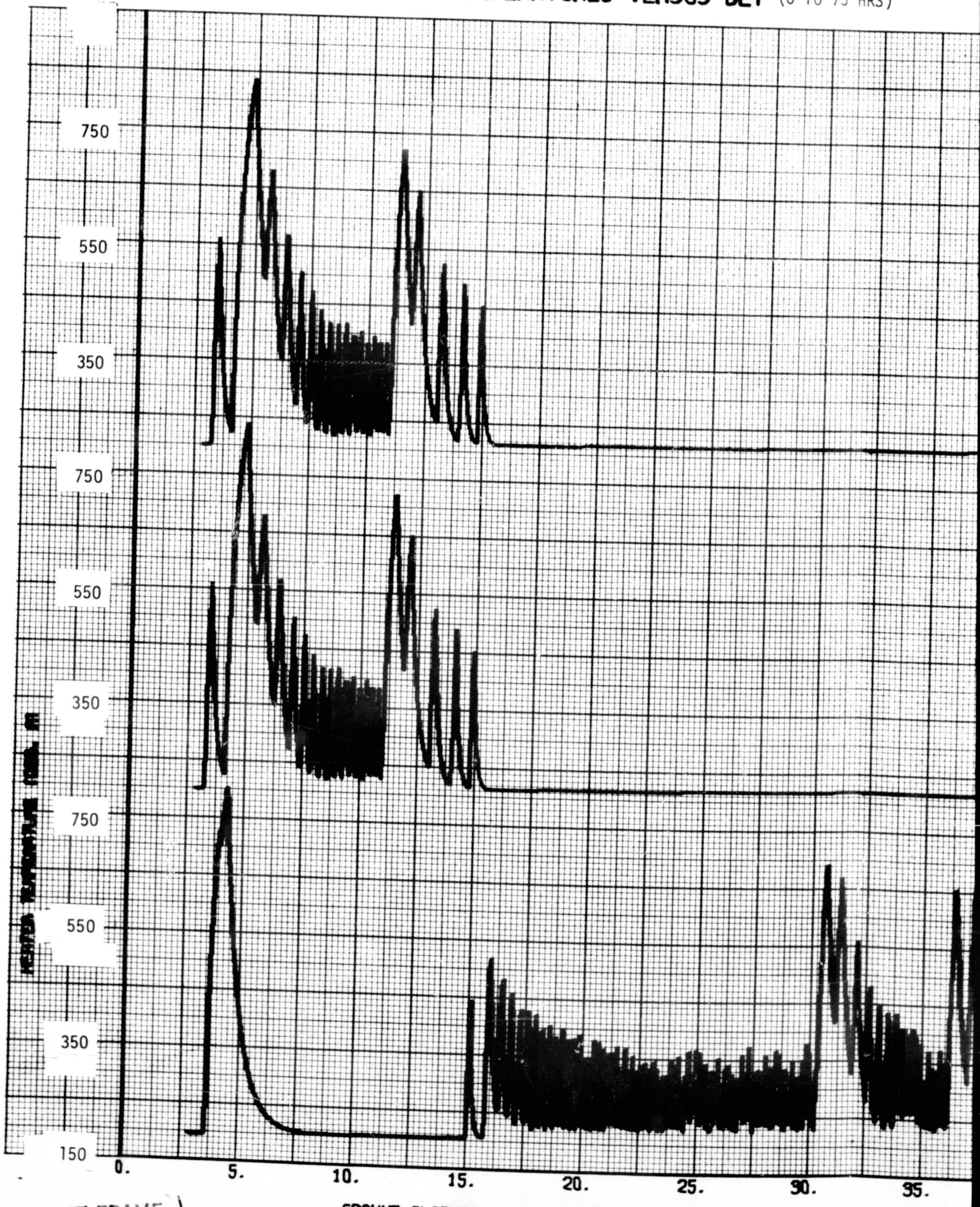
FIGURE 11

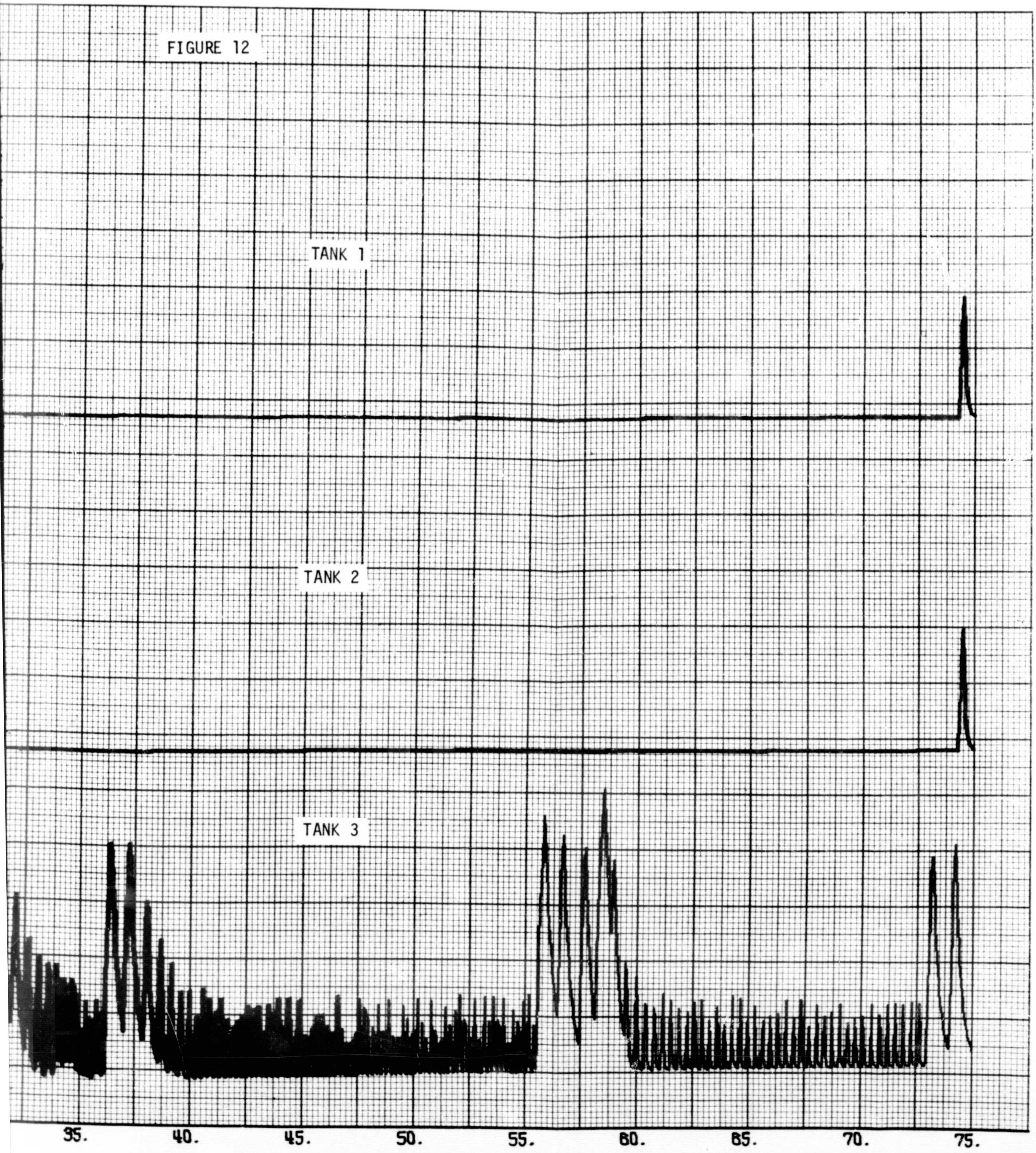


OXYGEN TANK HEATER TEMPERATURES VERSUS GET (0 TO 75 HRS)



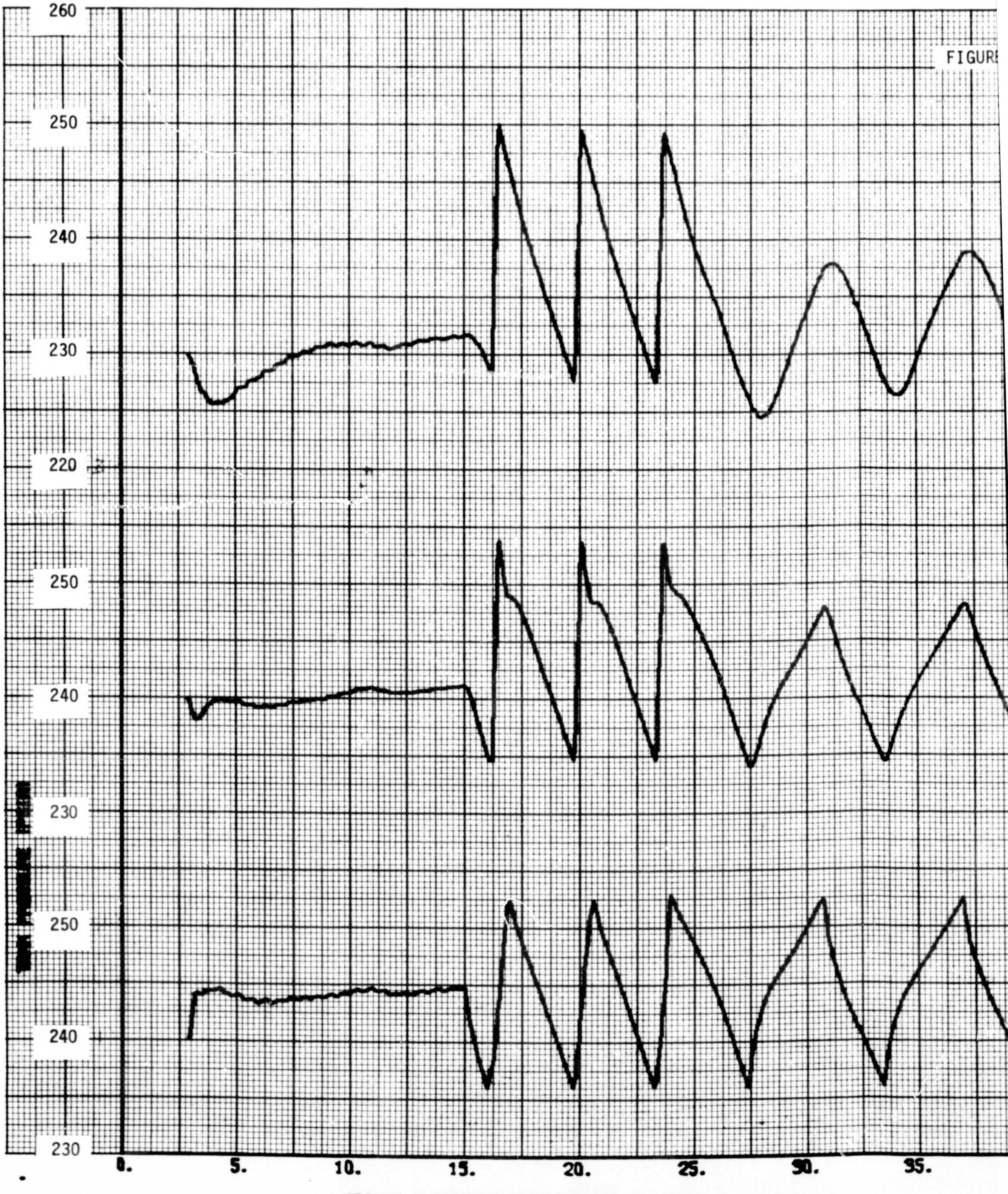
FOLDOUT FRAME

HRS)



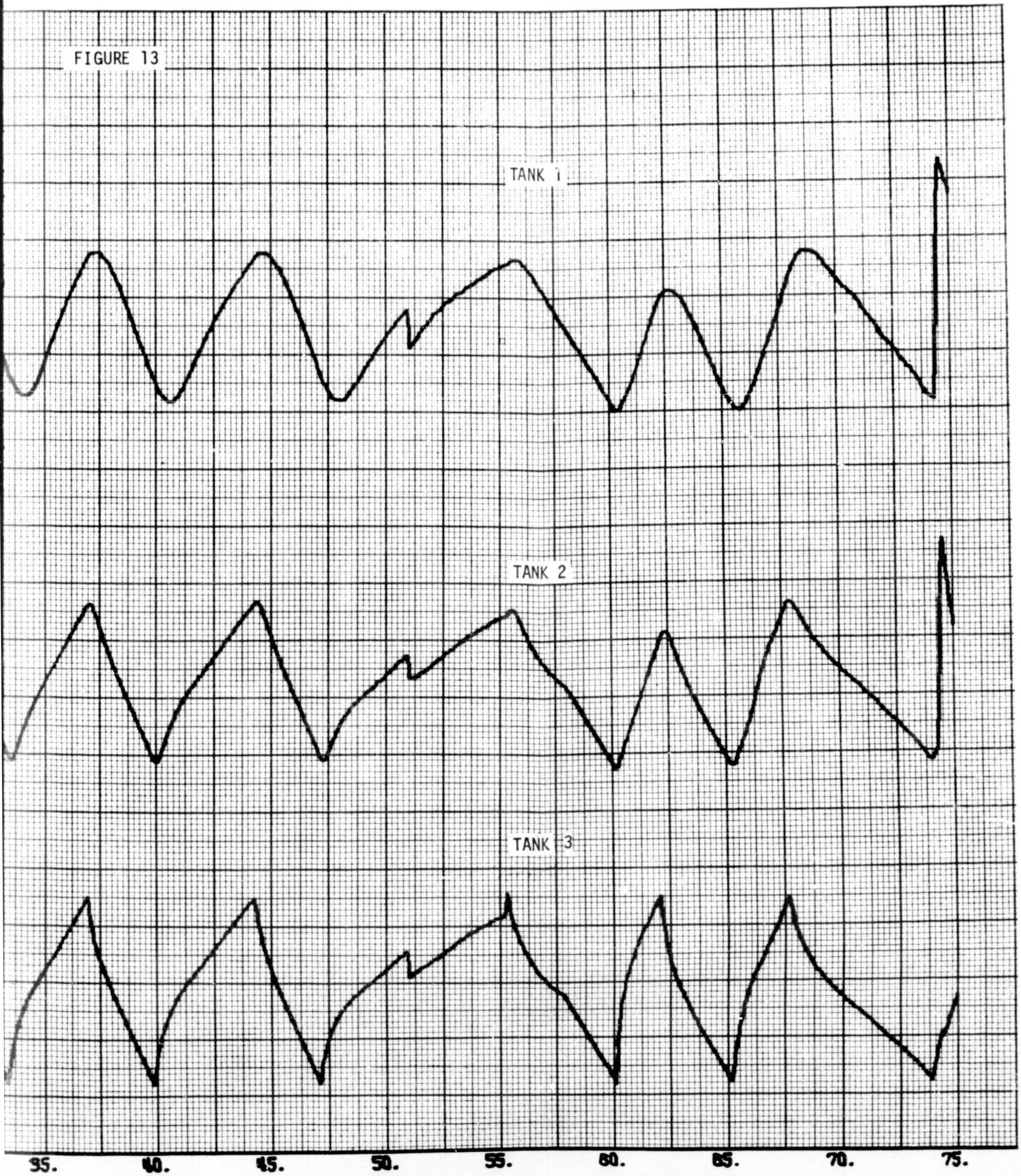
FOLDOUT FRAME 2

HYDROGEN TANK PRESSURE CYCLING VERSUS GET (0 TO 75 HRS)



FOLDOUT FRAME 1

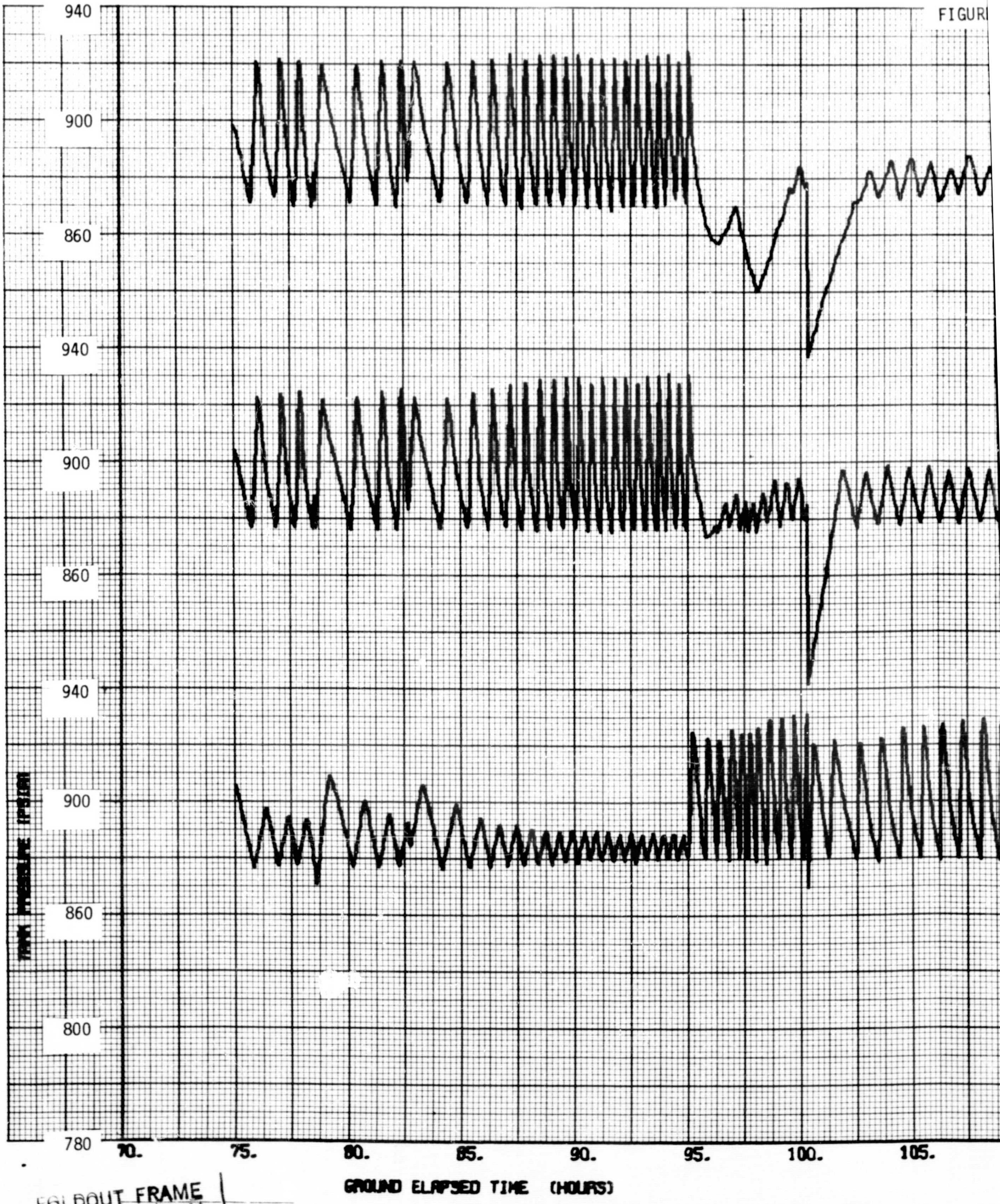
FIGURE 13



FOLDOUT FRAME 2

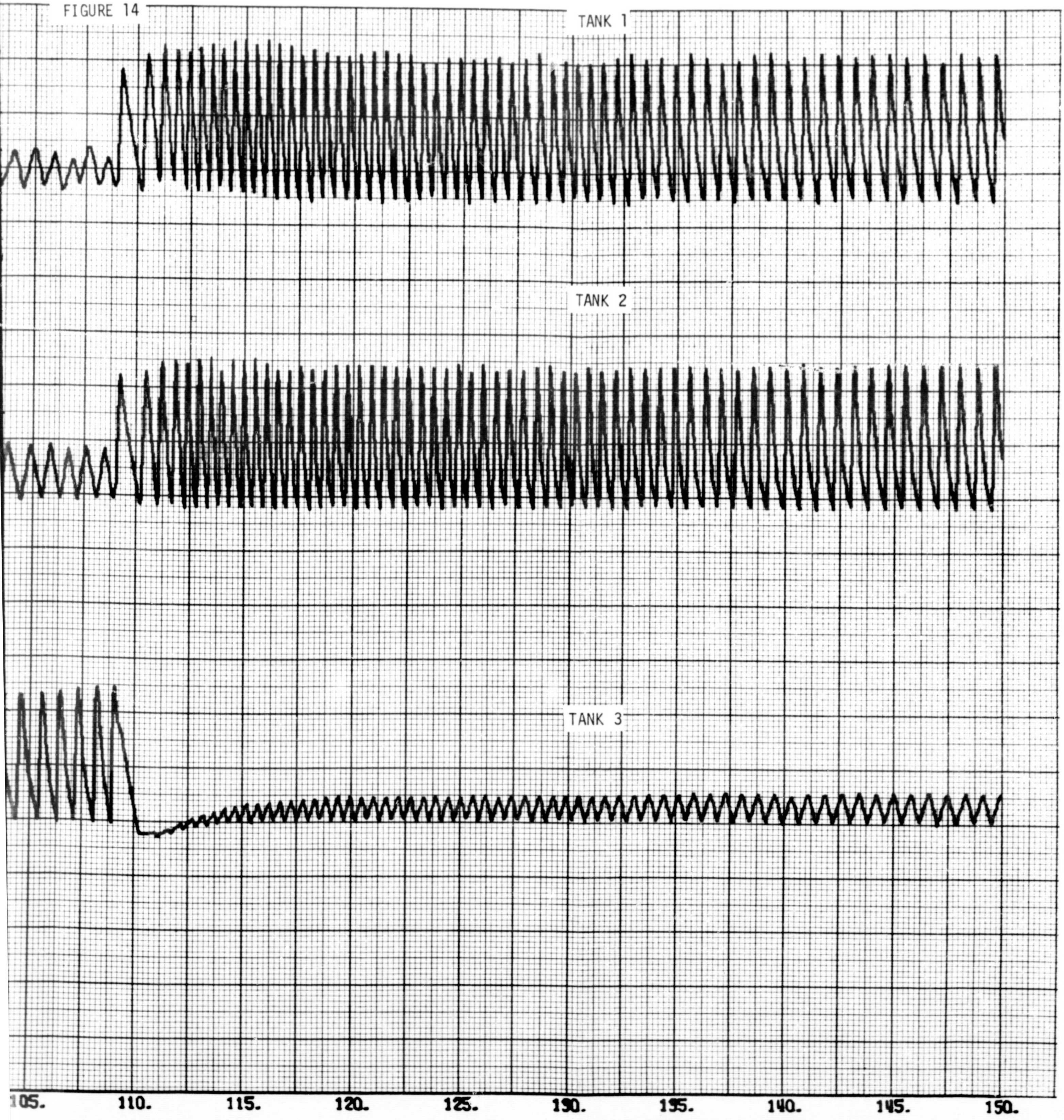
OXYGEN TANK PRESSURE CYCLING VERSUS GET (75 TO 50 HRS)

FIGUR

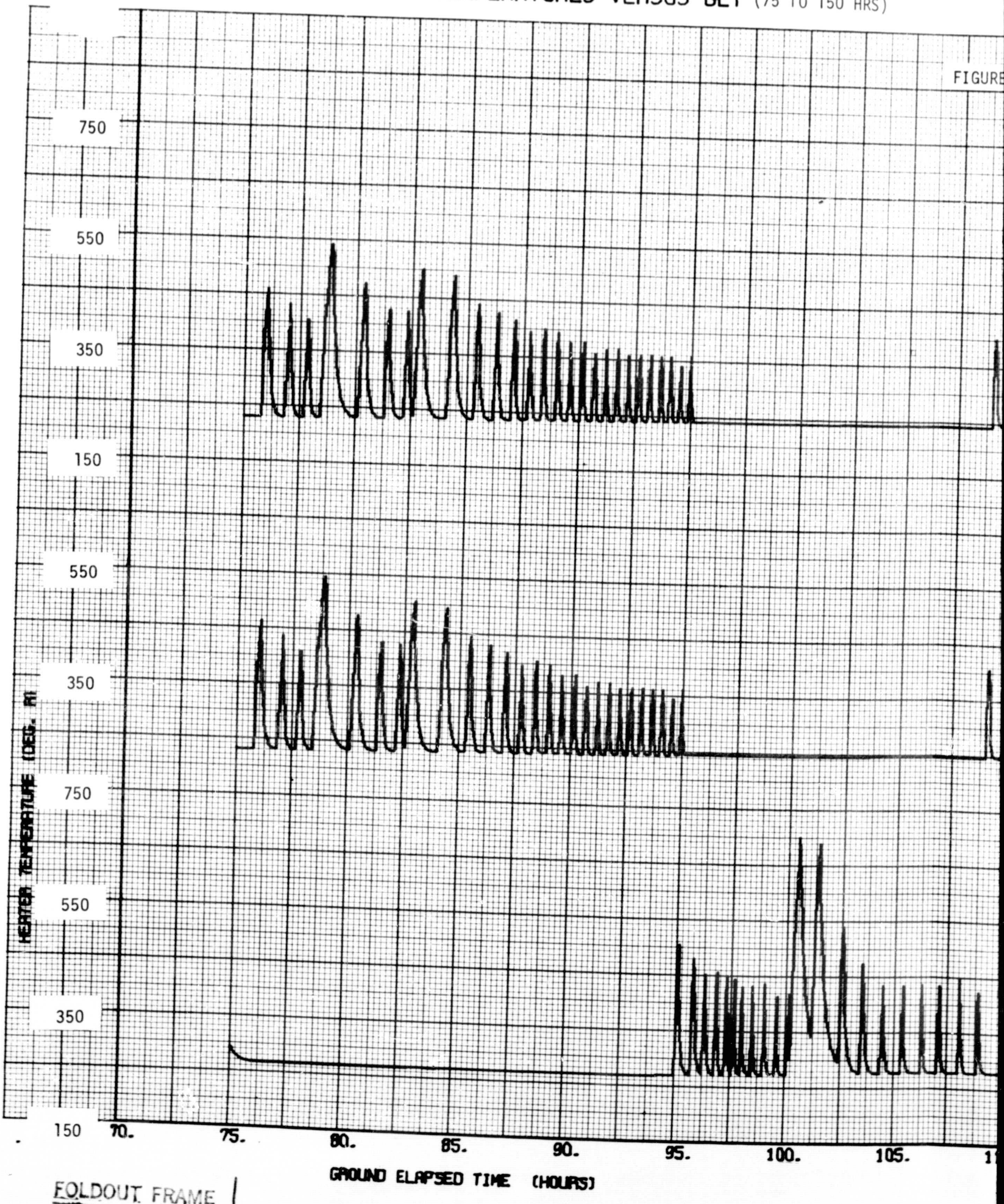


FOLDOUT FRAME |

FIGURE 14

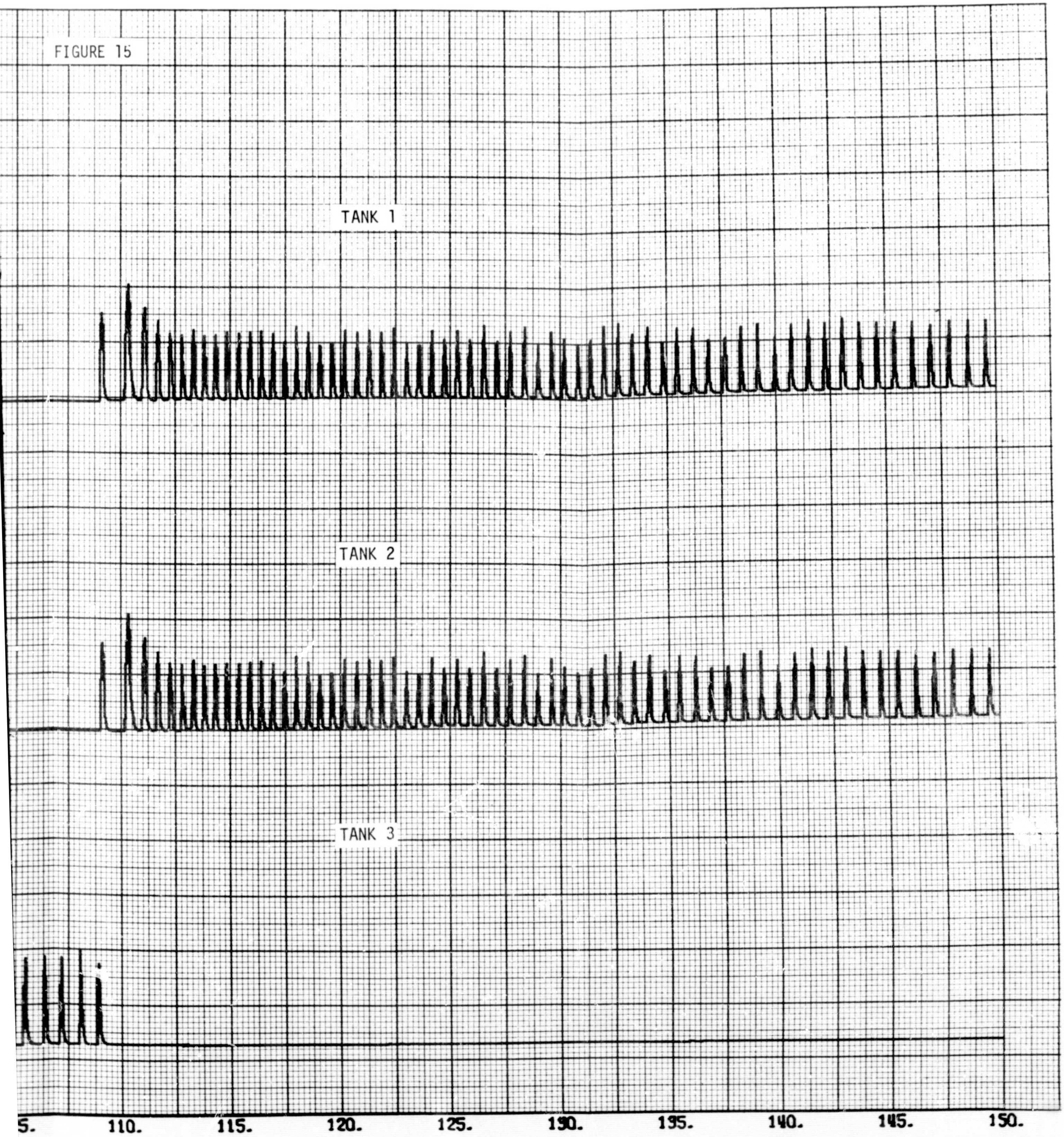


OXYGEN TANK HEATER TEMPERATURES VERSUS GET (75 TO 150 HRS)



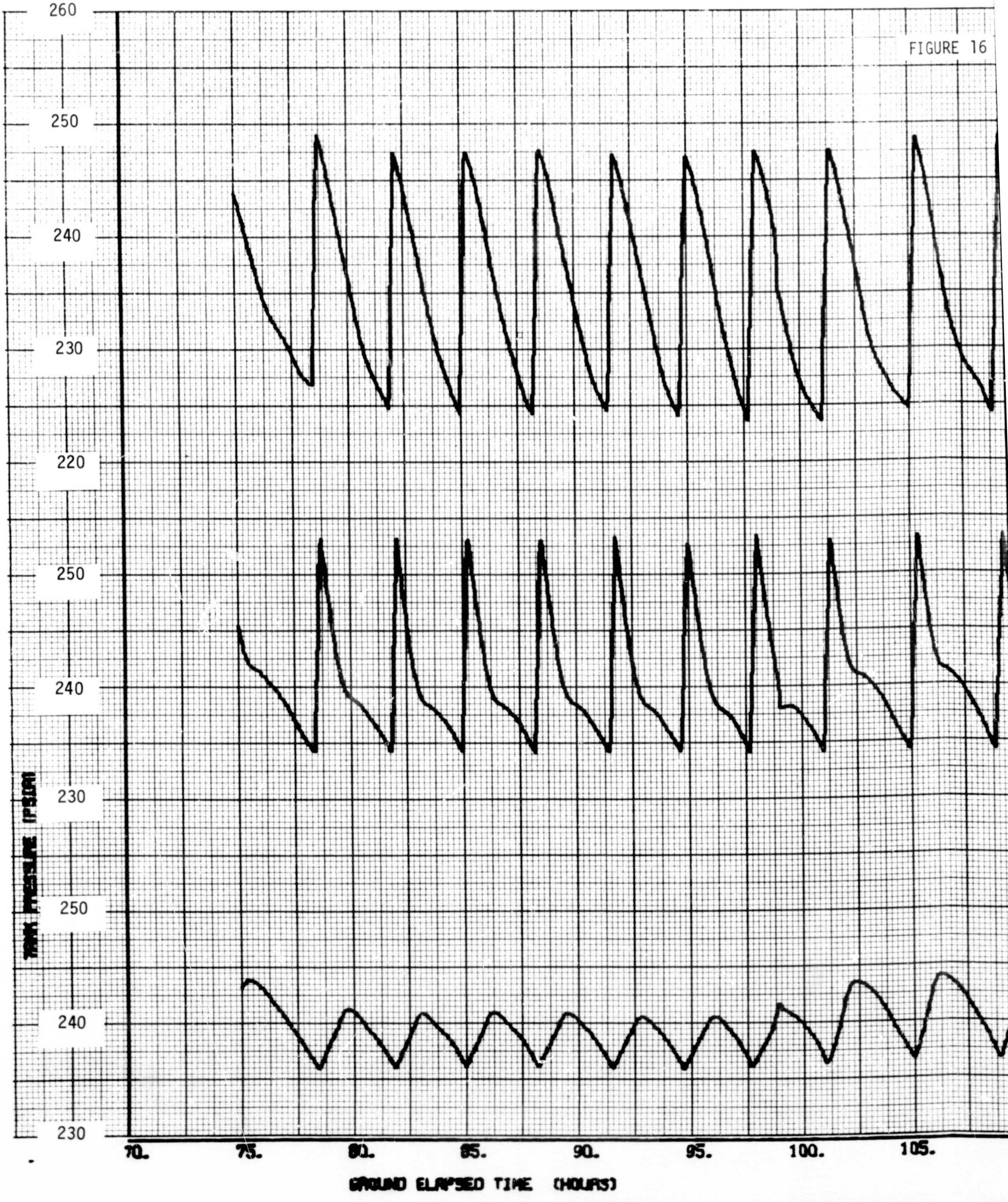
FOLDOUT FRAME

FIGURE 15



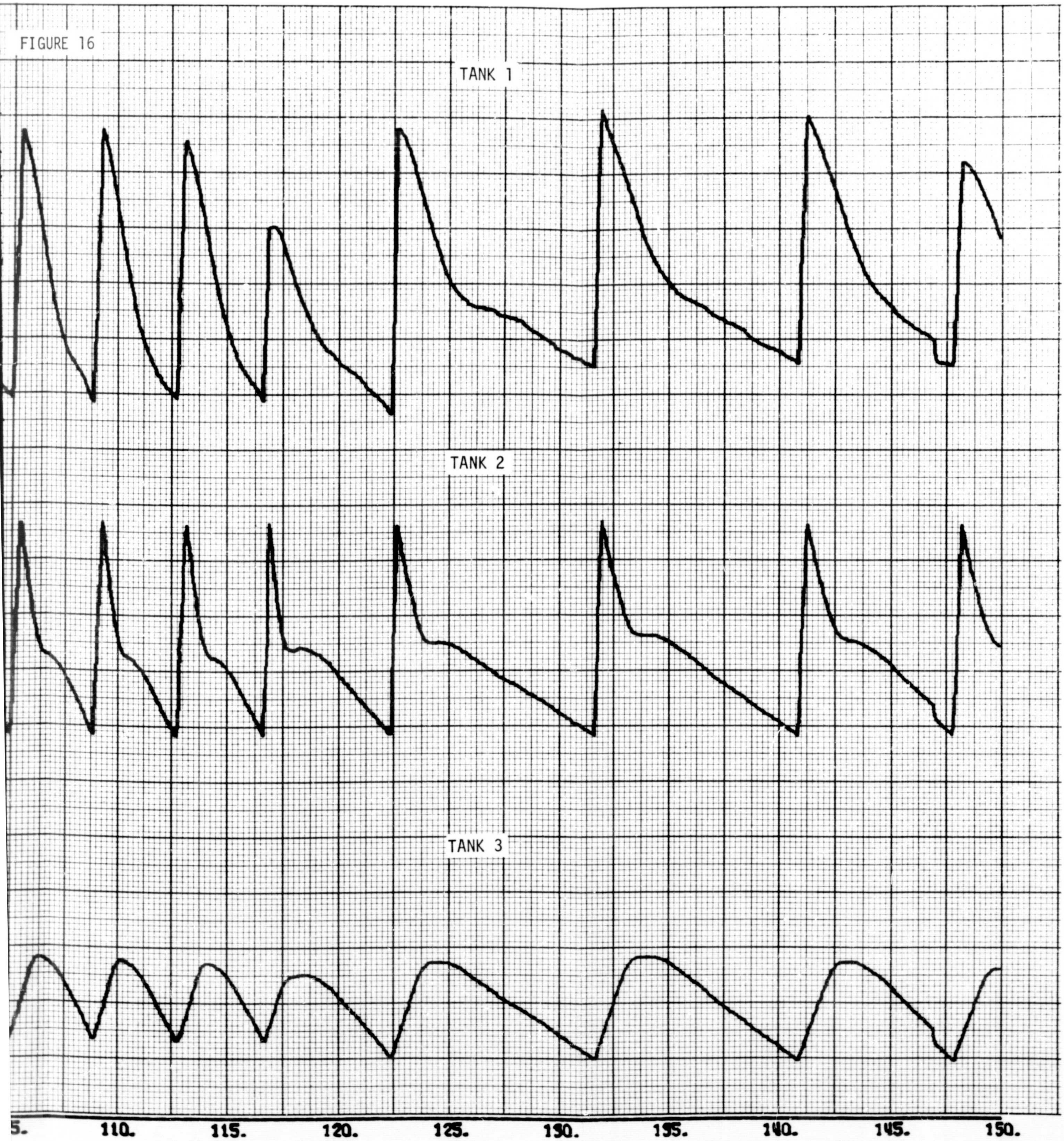
HYDROGEN TANK PRESSURE CYCLING VERSUS GET (75 TO 150 HRS)

FIGURE 16

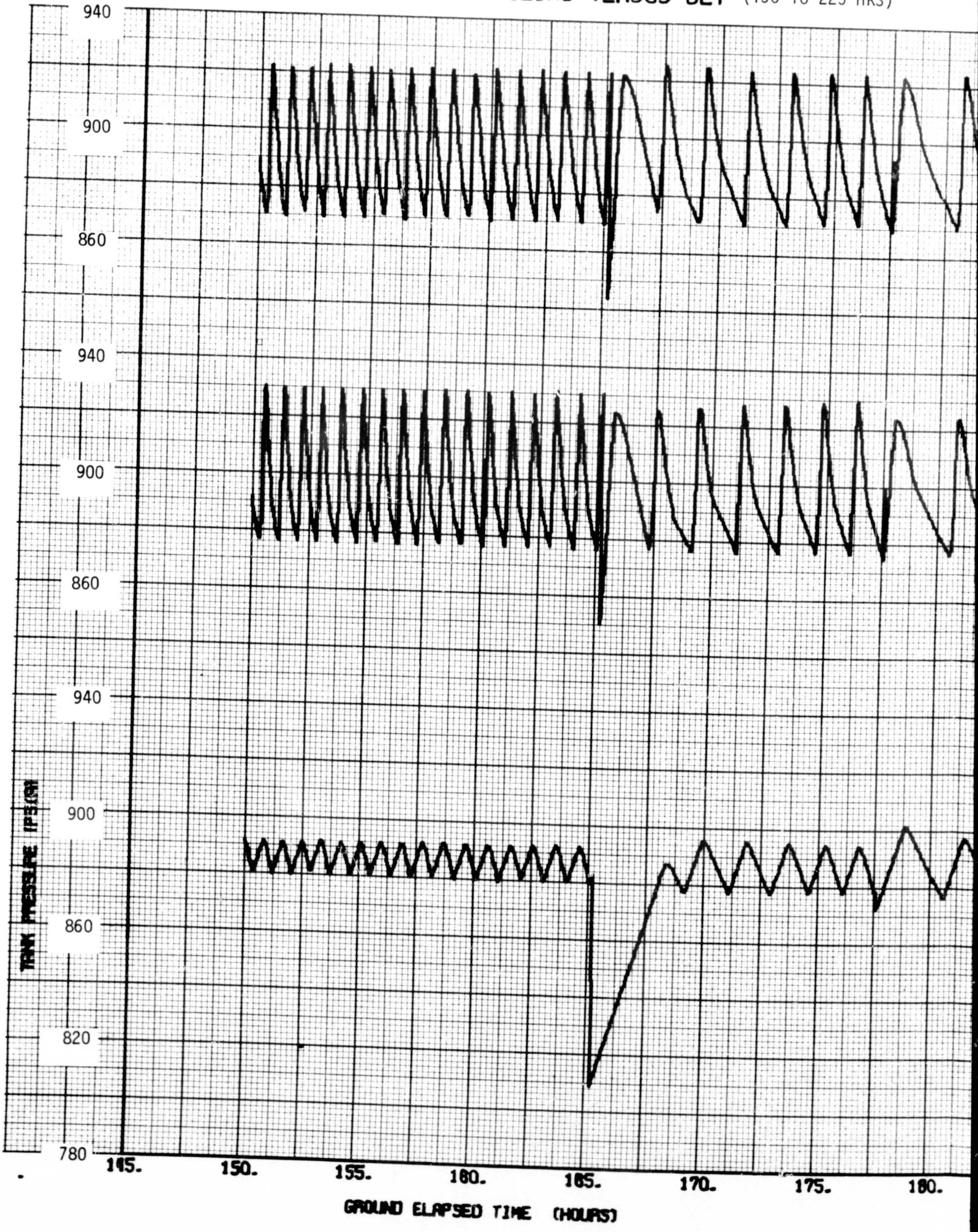


FOLDOUT FRAME 1

FIGURE 16

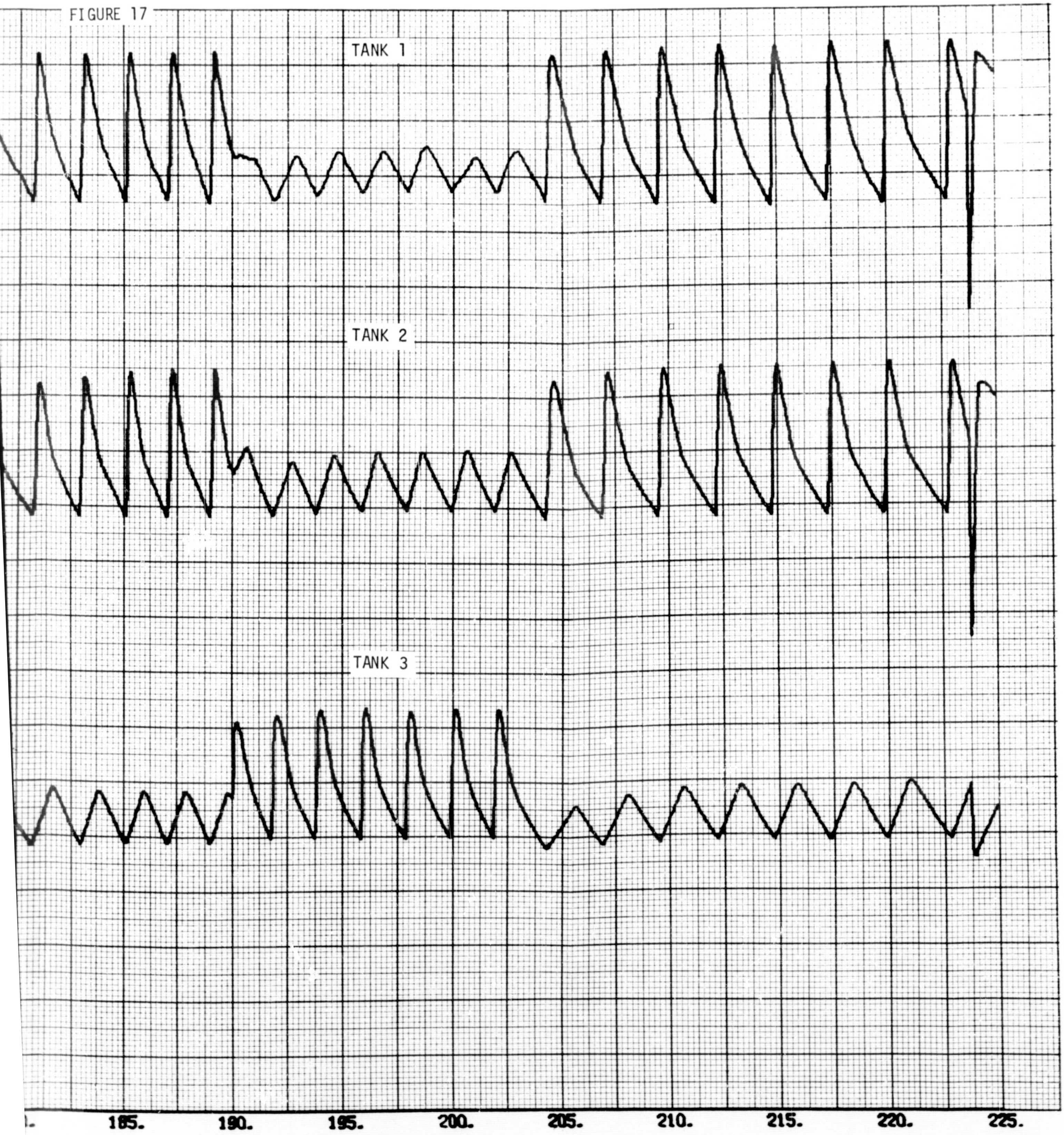


OXYGEN TANK PRESSURE CYCLING VERSUS GET (150 TO 225 HRS)



FOLDOUT FRAME

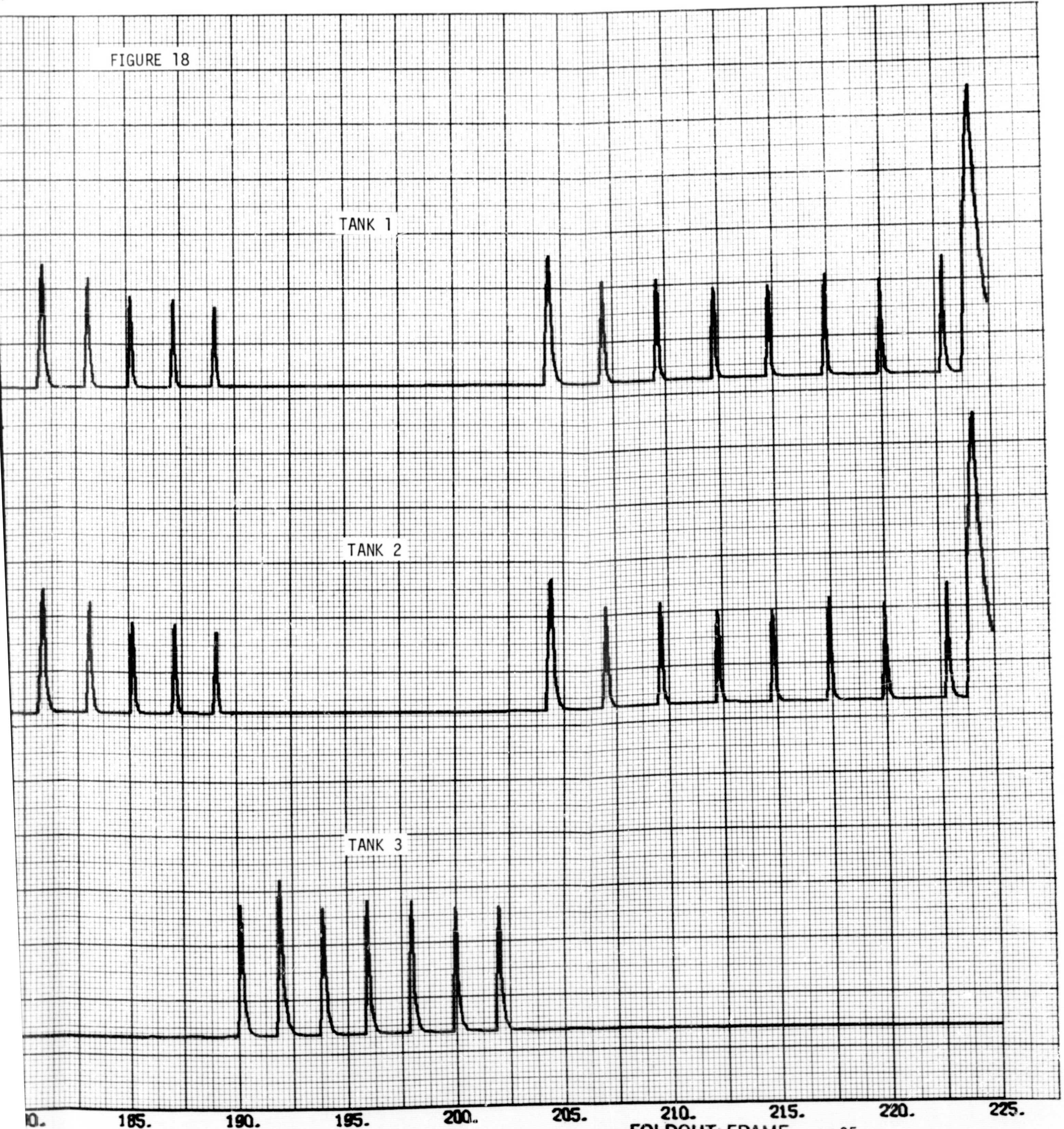
FIGURE 17



OXYGEN TANK HEATER TEMPERATURES VERSUS GET (150 TO 225 HRS)

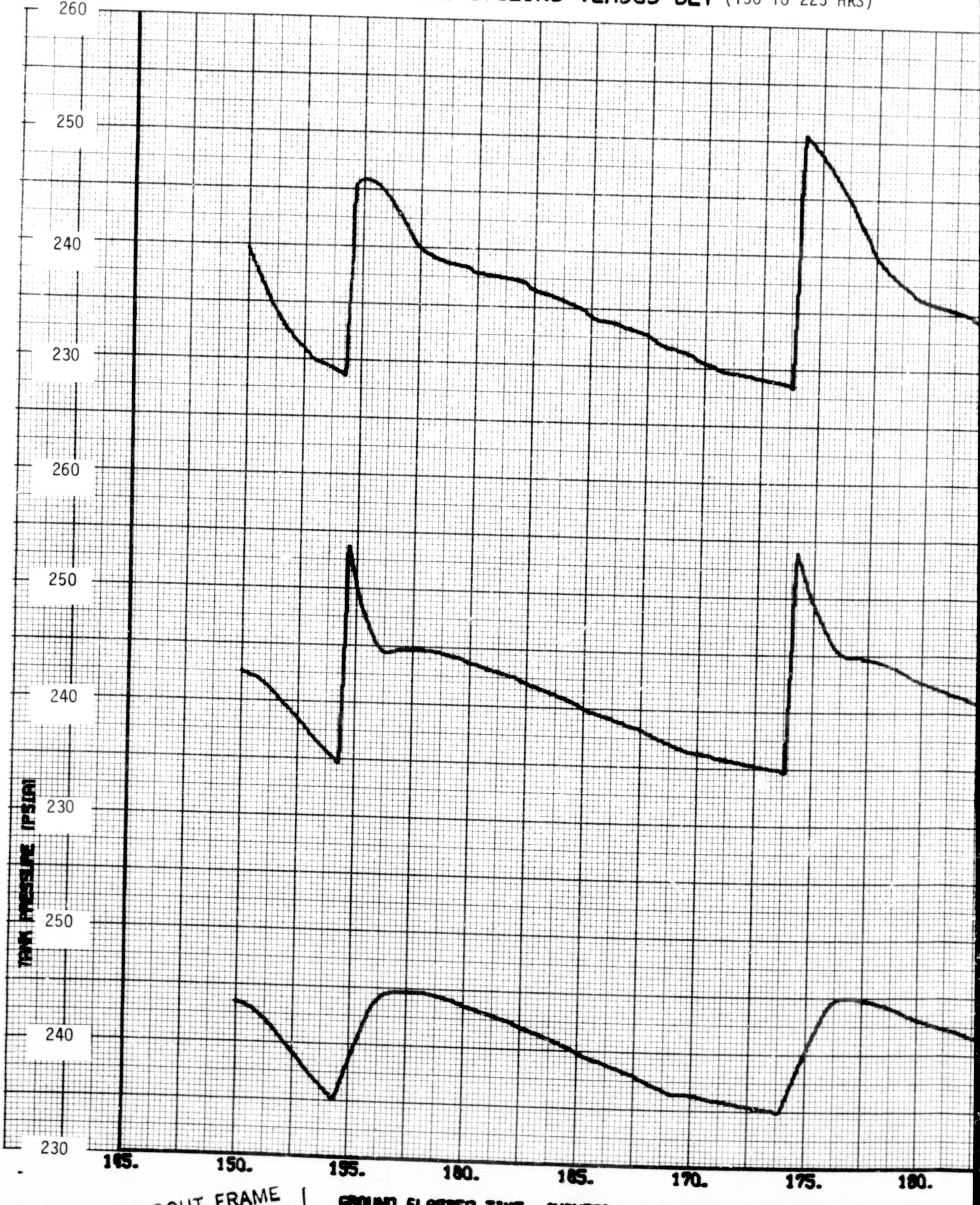
FOLDOUT FRAME

FIGURE 18



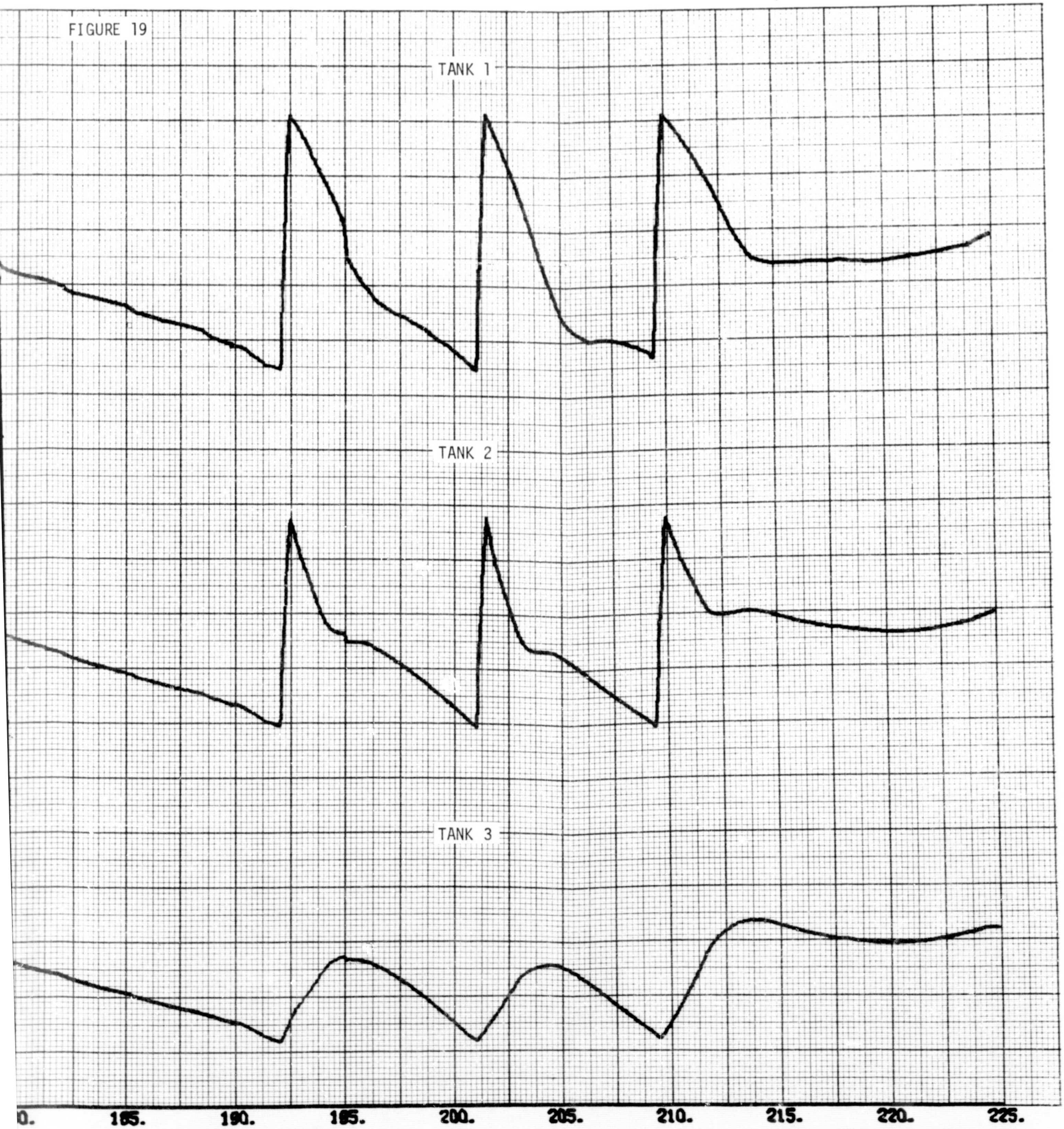
FOLDOUT FRAME 2

HYDROGEN TANK PRESSURE CYCLING VERSUS GET (150 TO 225 HRS)



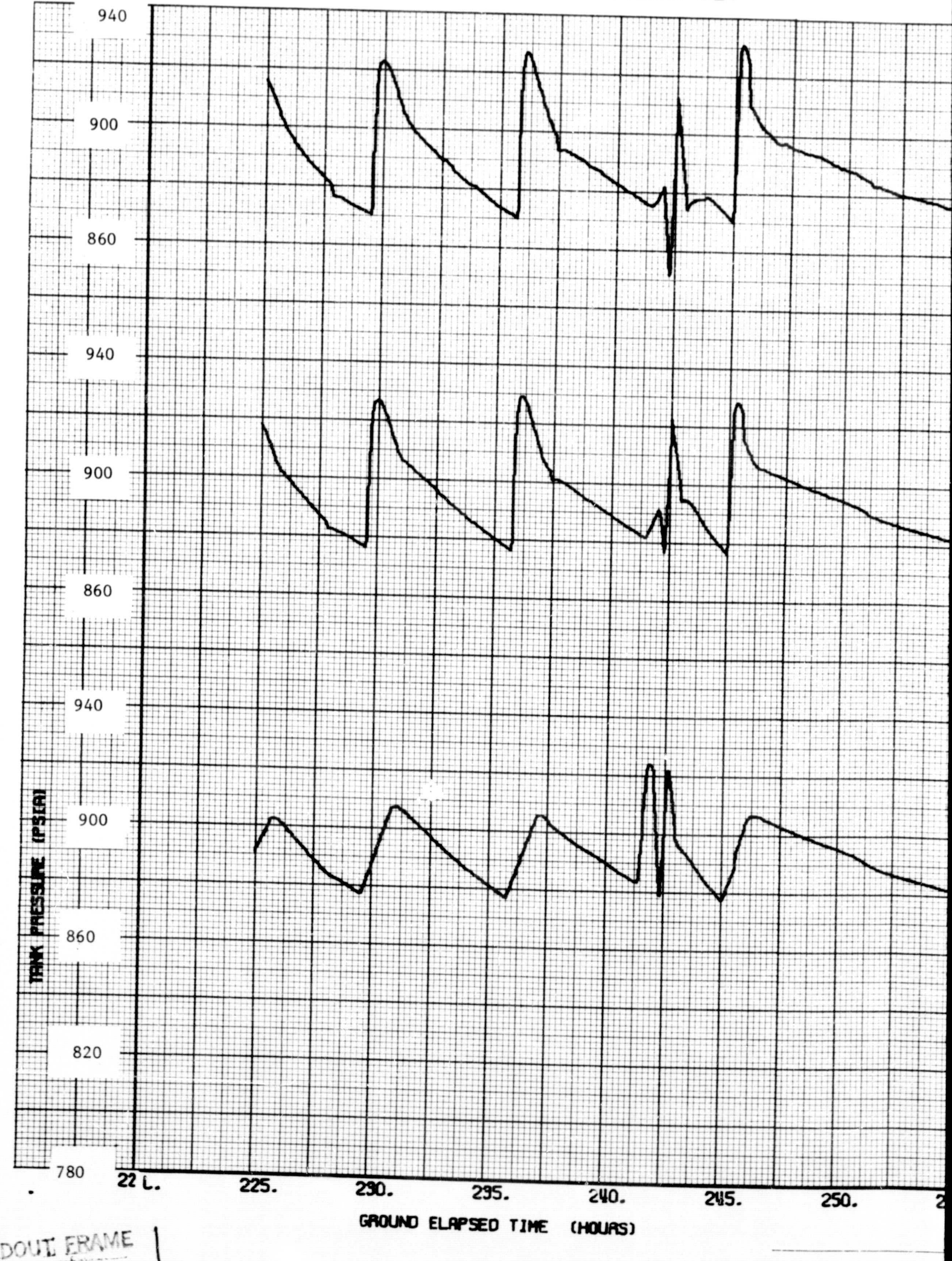
FOLDOUT FRAME

FIGURE 19



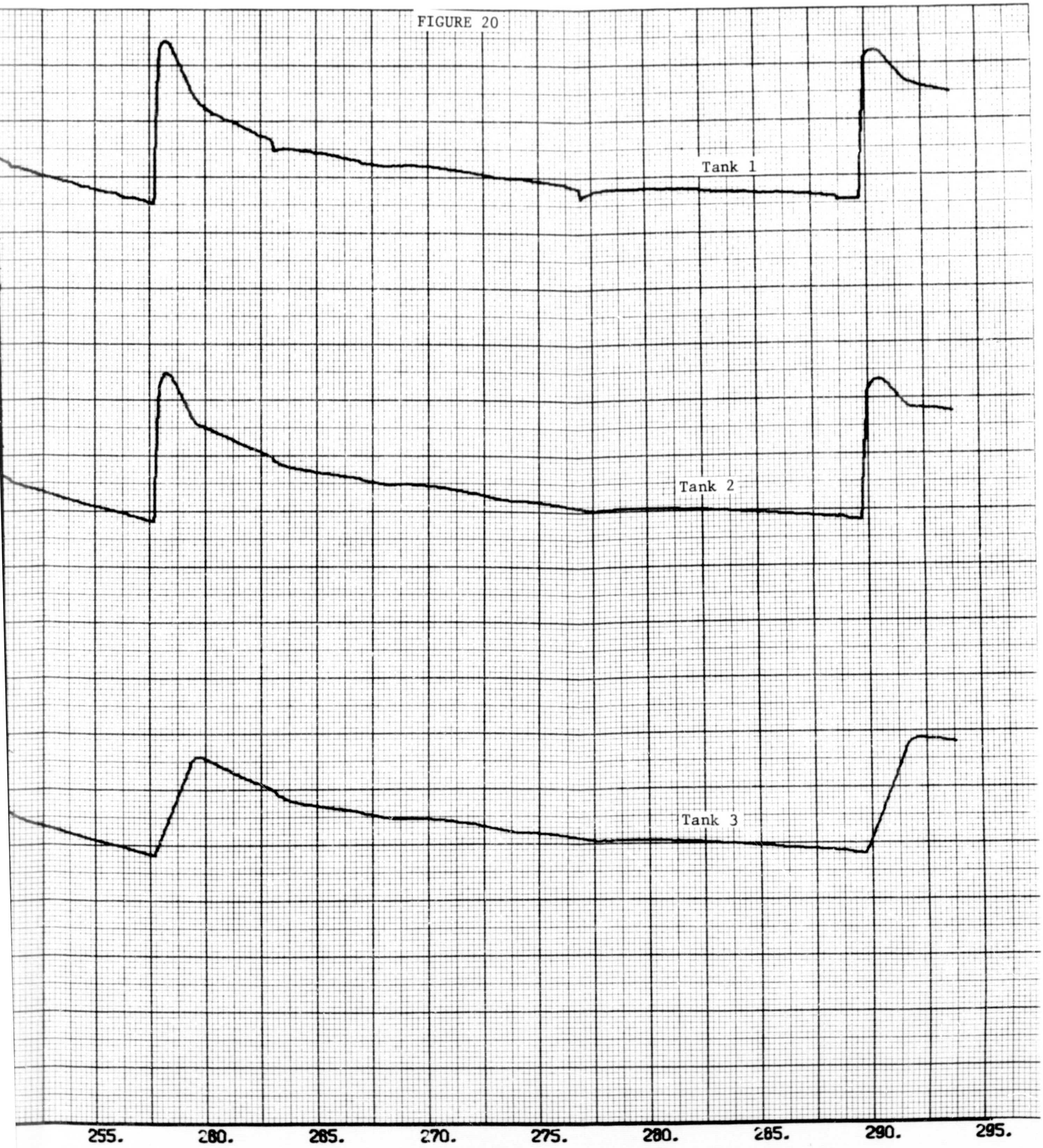
FOLDOUT FRAME

OXYGEN TANK PRESSURE CYCLING VERSUS GET



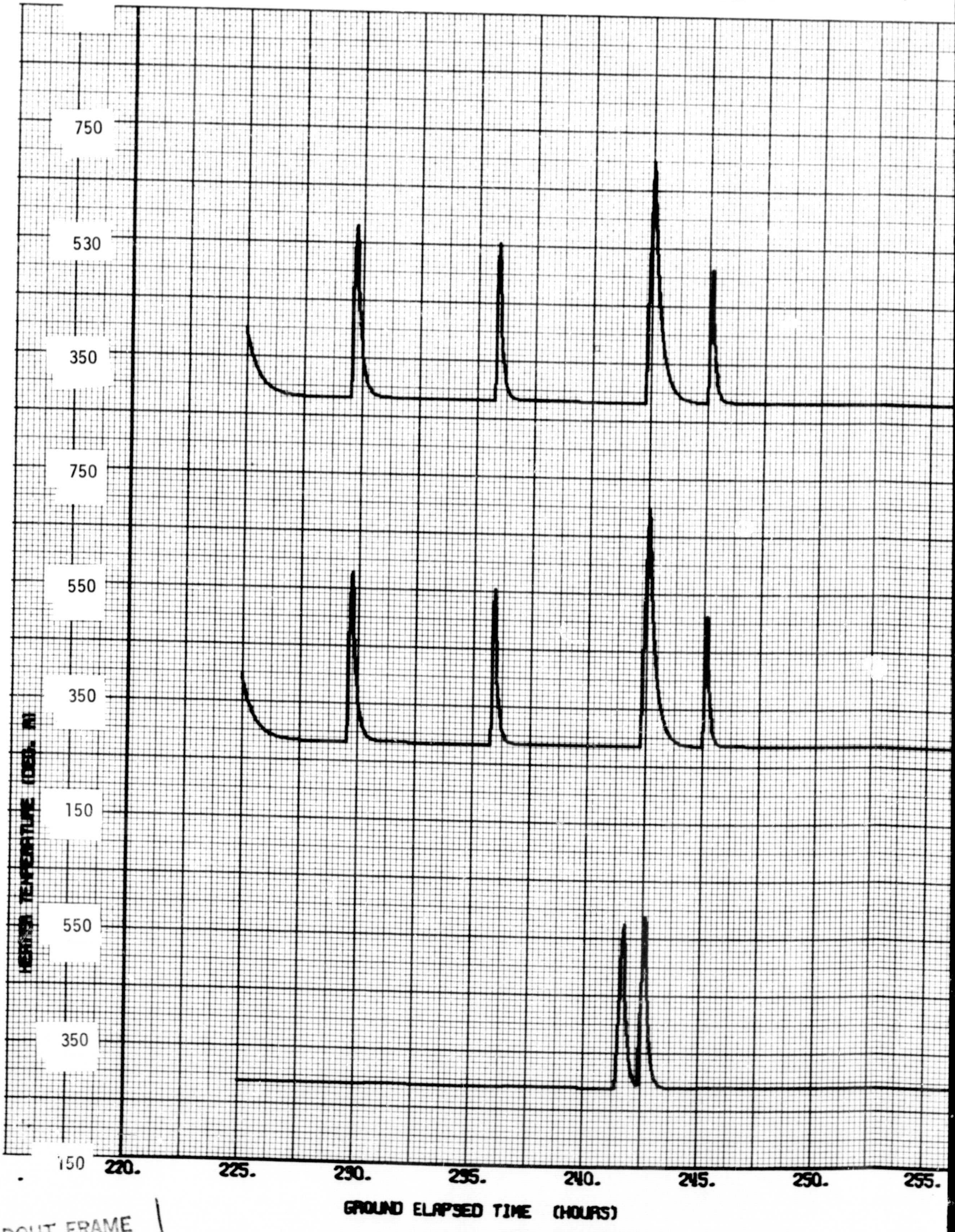
FOLDOUT FRAME

FIGURE 20



FOLDOUT FRAME 2

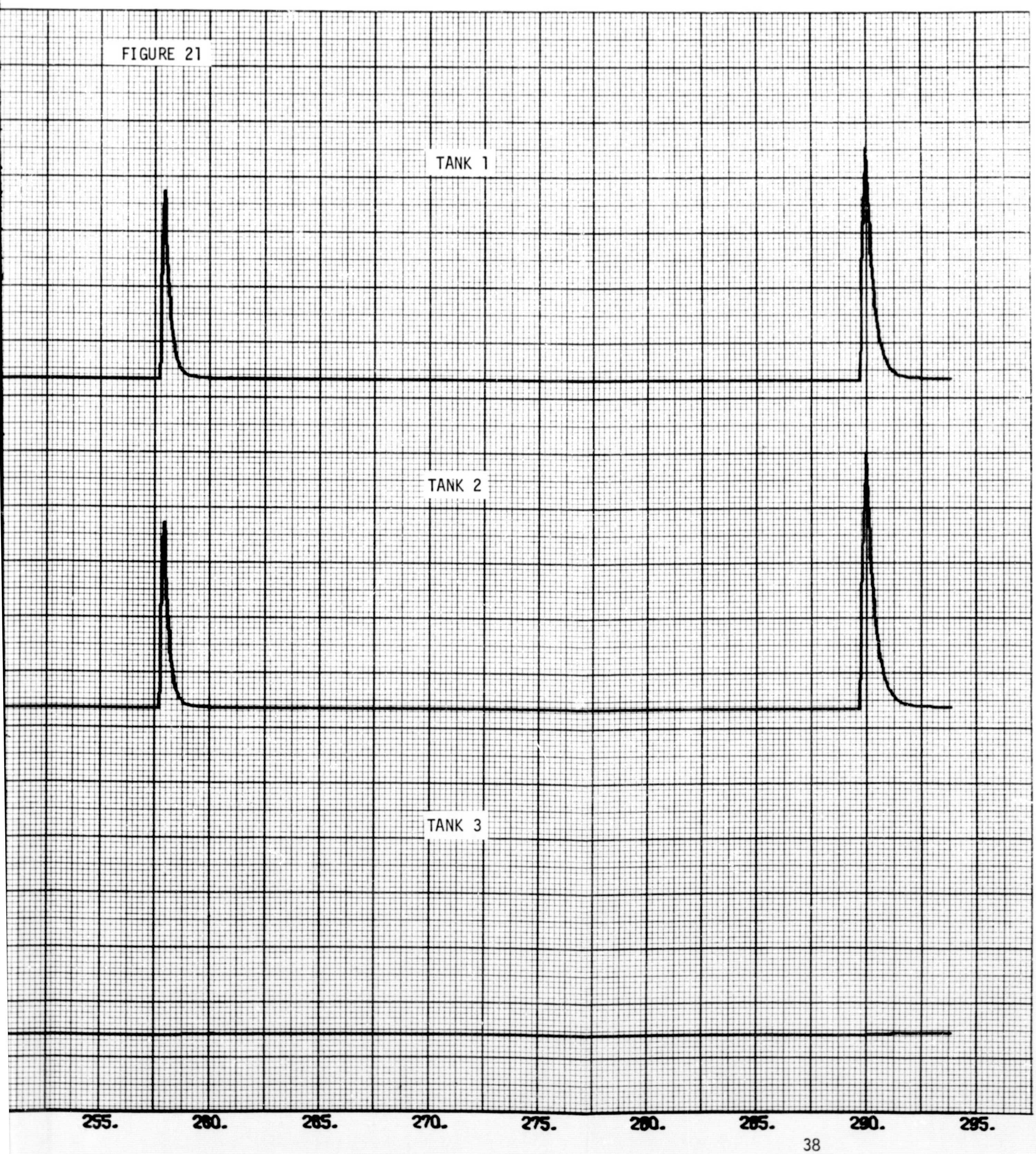
OXYGEN TANK HEATER TEMPERATURES VERSUS GET (225 TO 300 HRS)



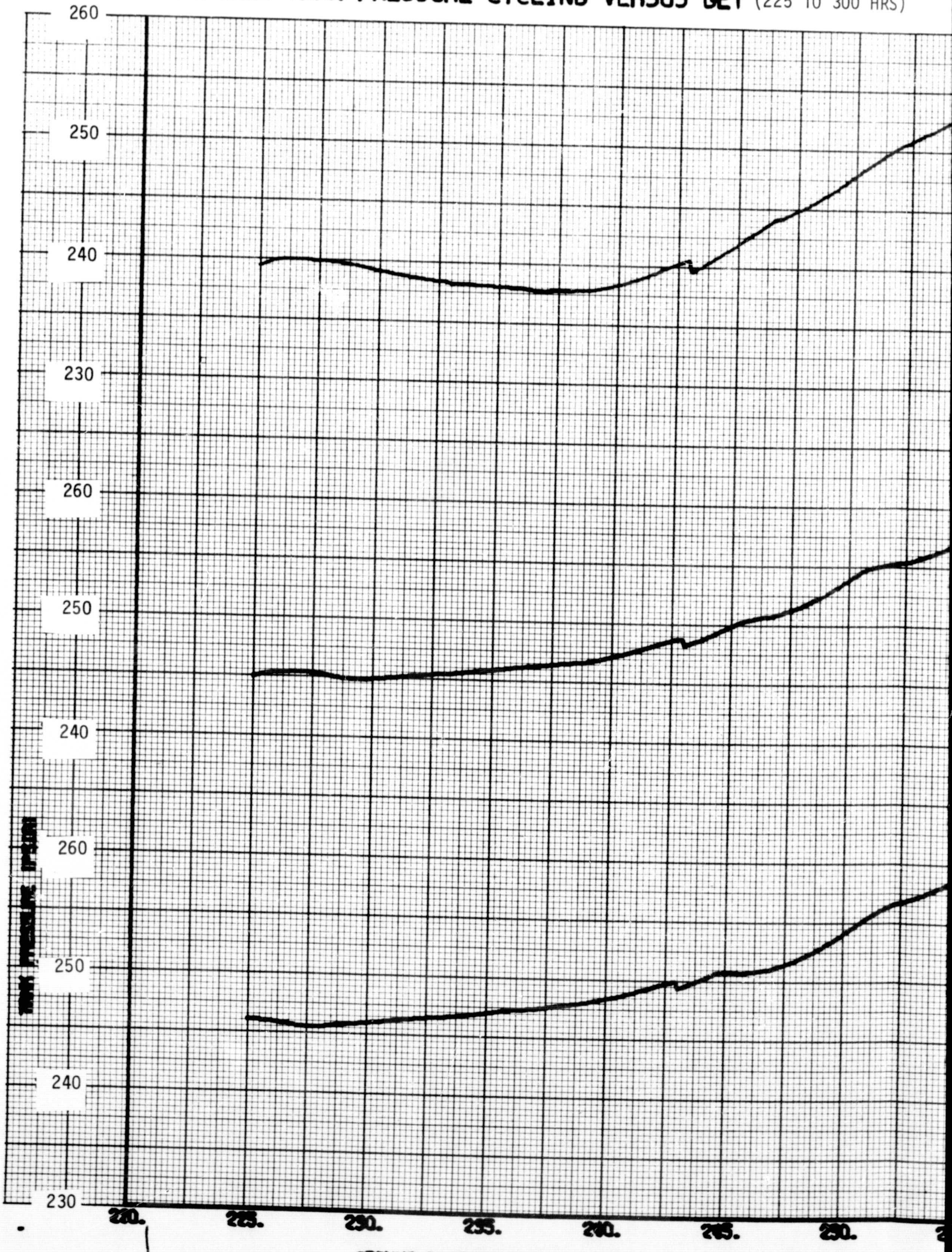
FOLDOUT FRAME

300 HRS)

FIGURE 21



HYDROGEN TANK PRESSURE CYCLING VERSUS GET (225 TO 300 HRS)



FOLDOUT FRAME

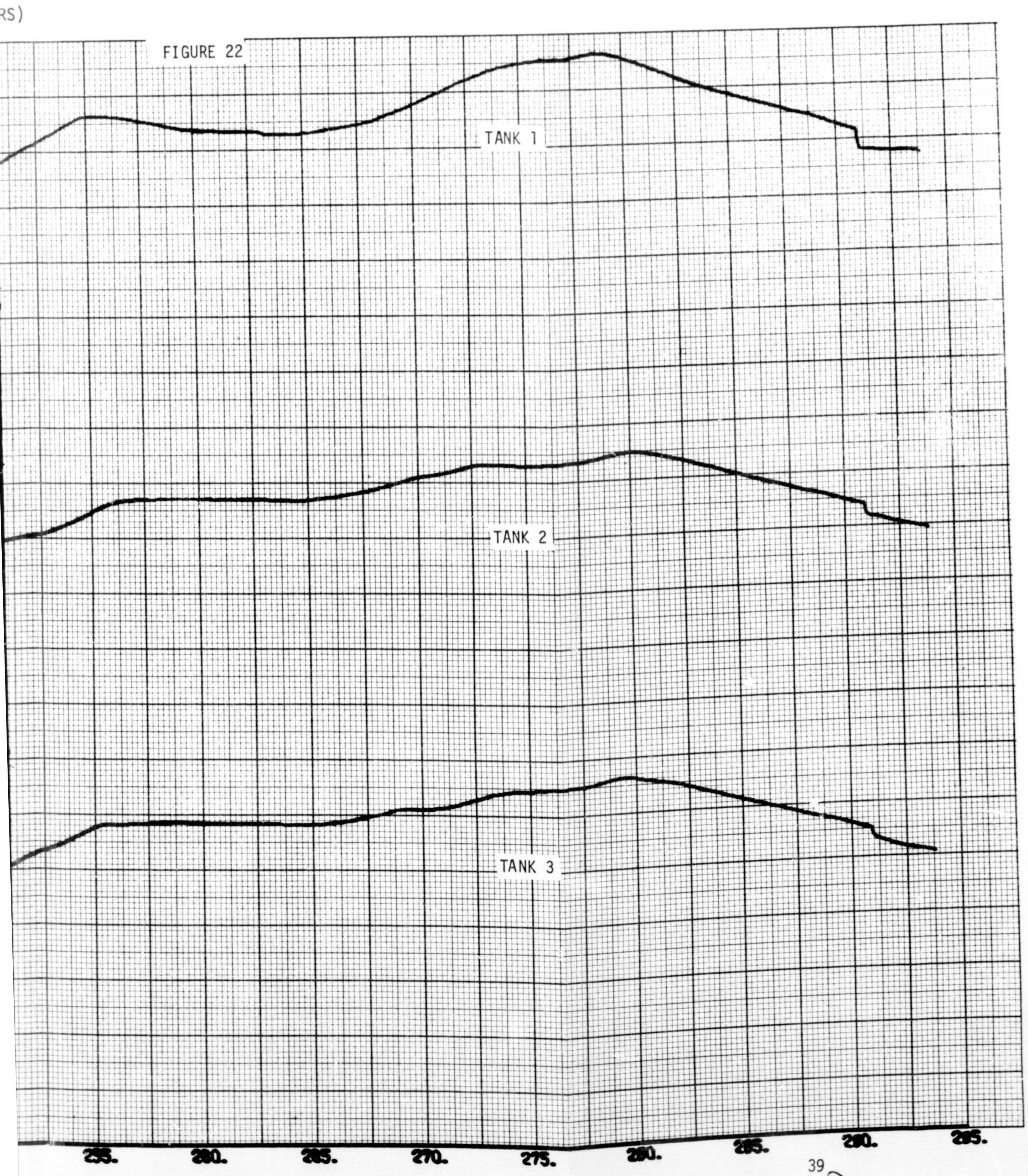
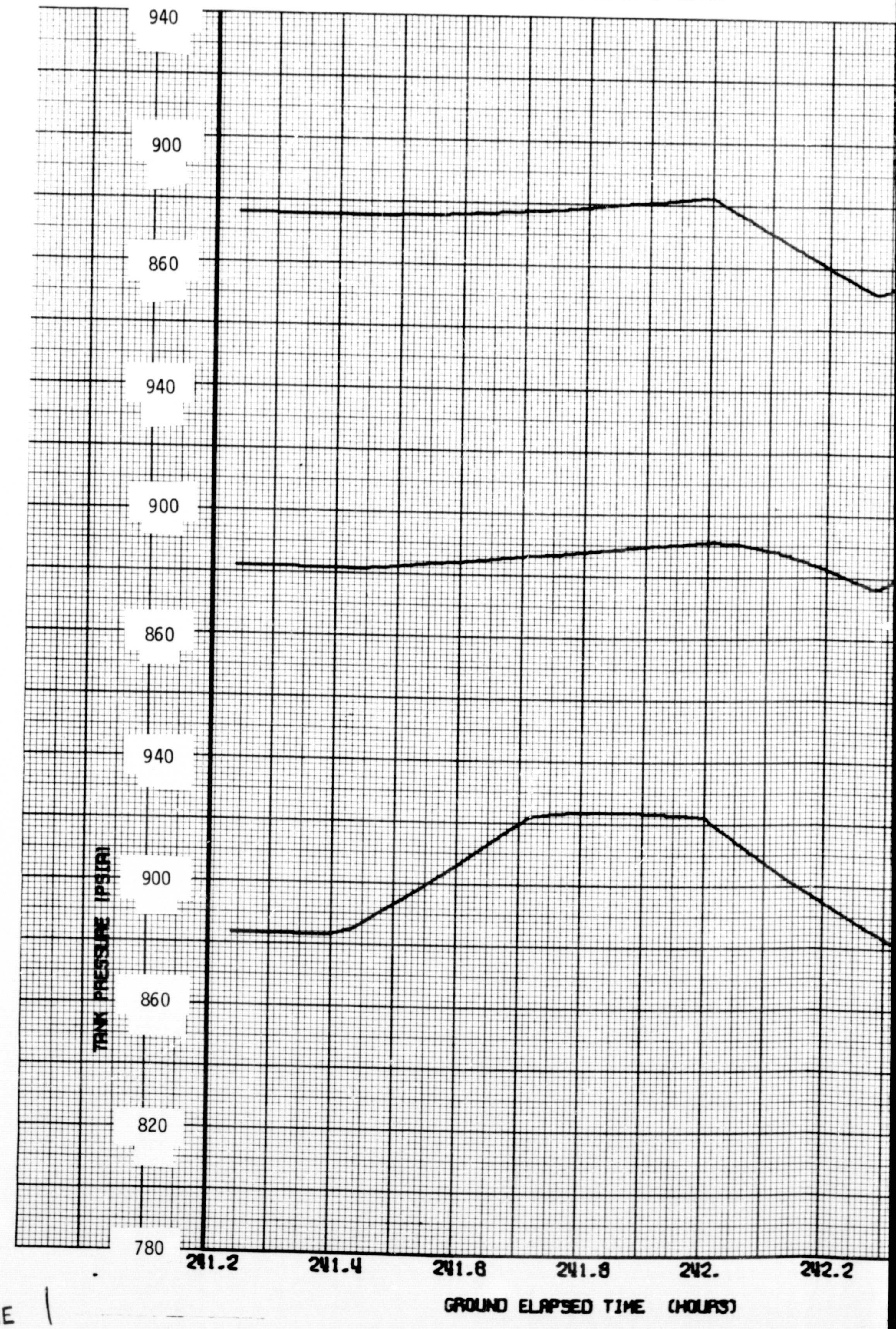


FIGURE 22

2

OXYGEN TANK PRESSURES DURING EVA



FOLDOUT FRAME

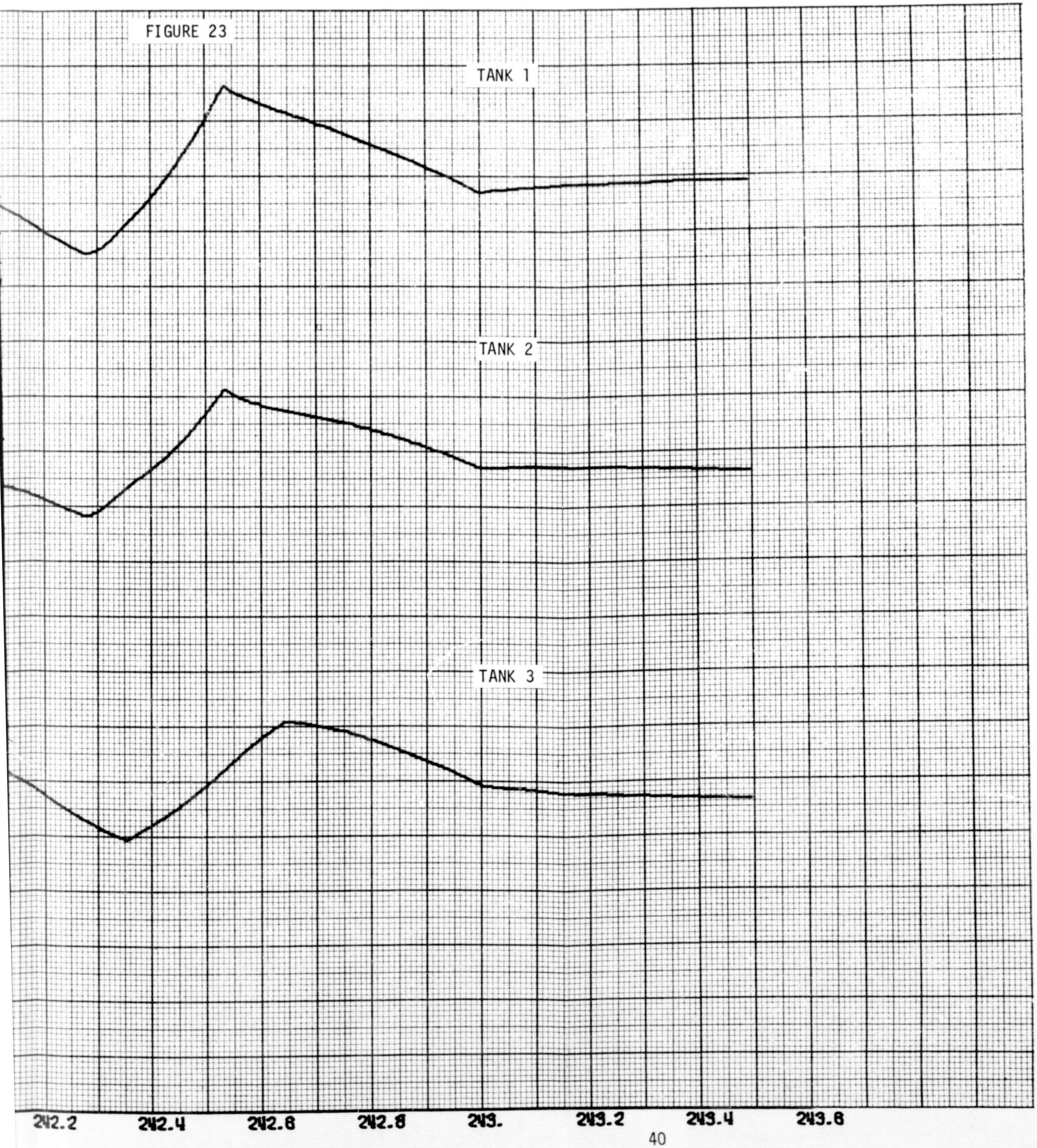
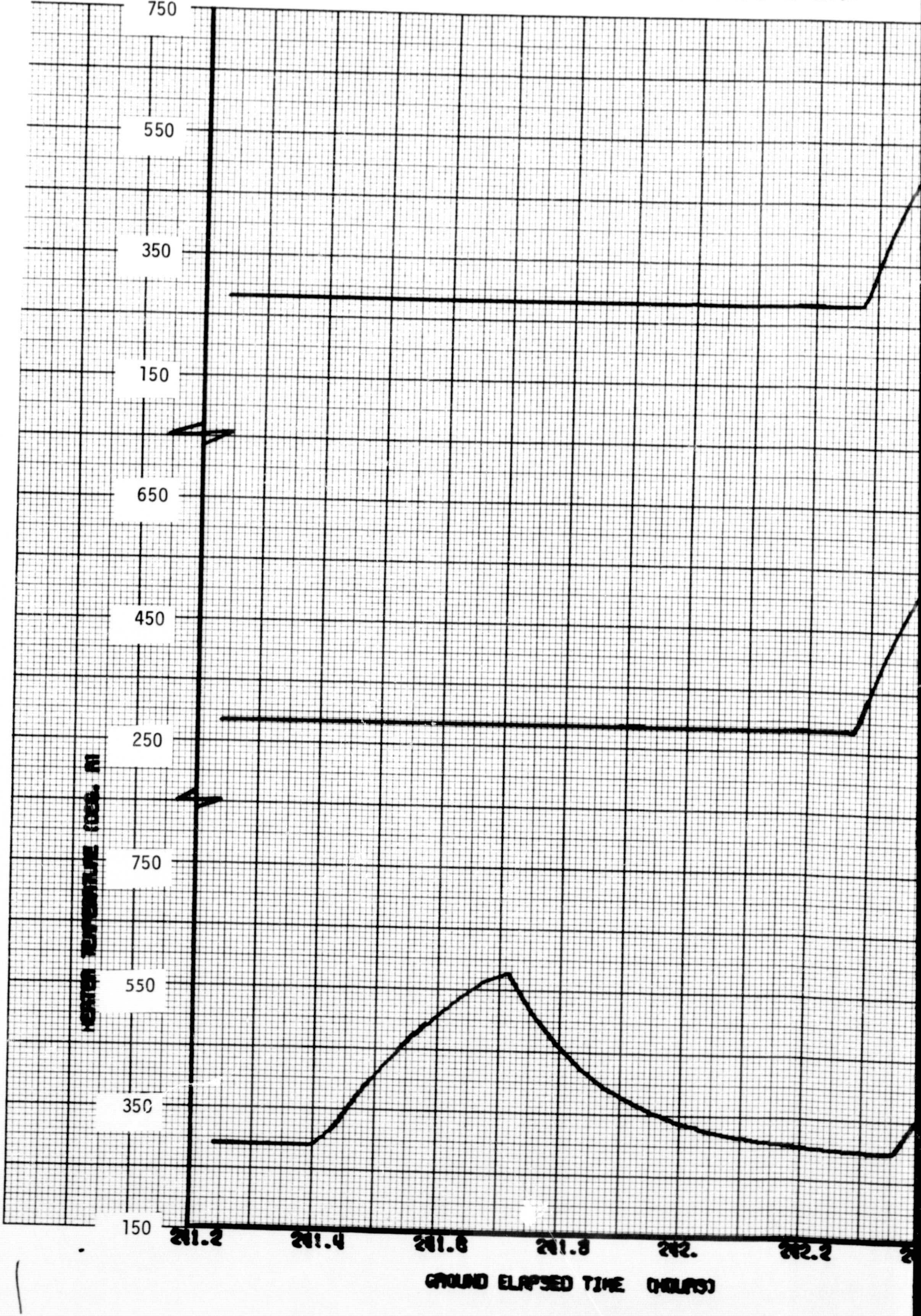


FIGURE 23

FOLDOUT FRAME

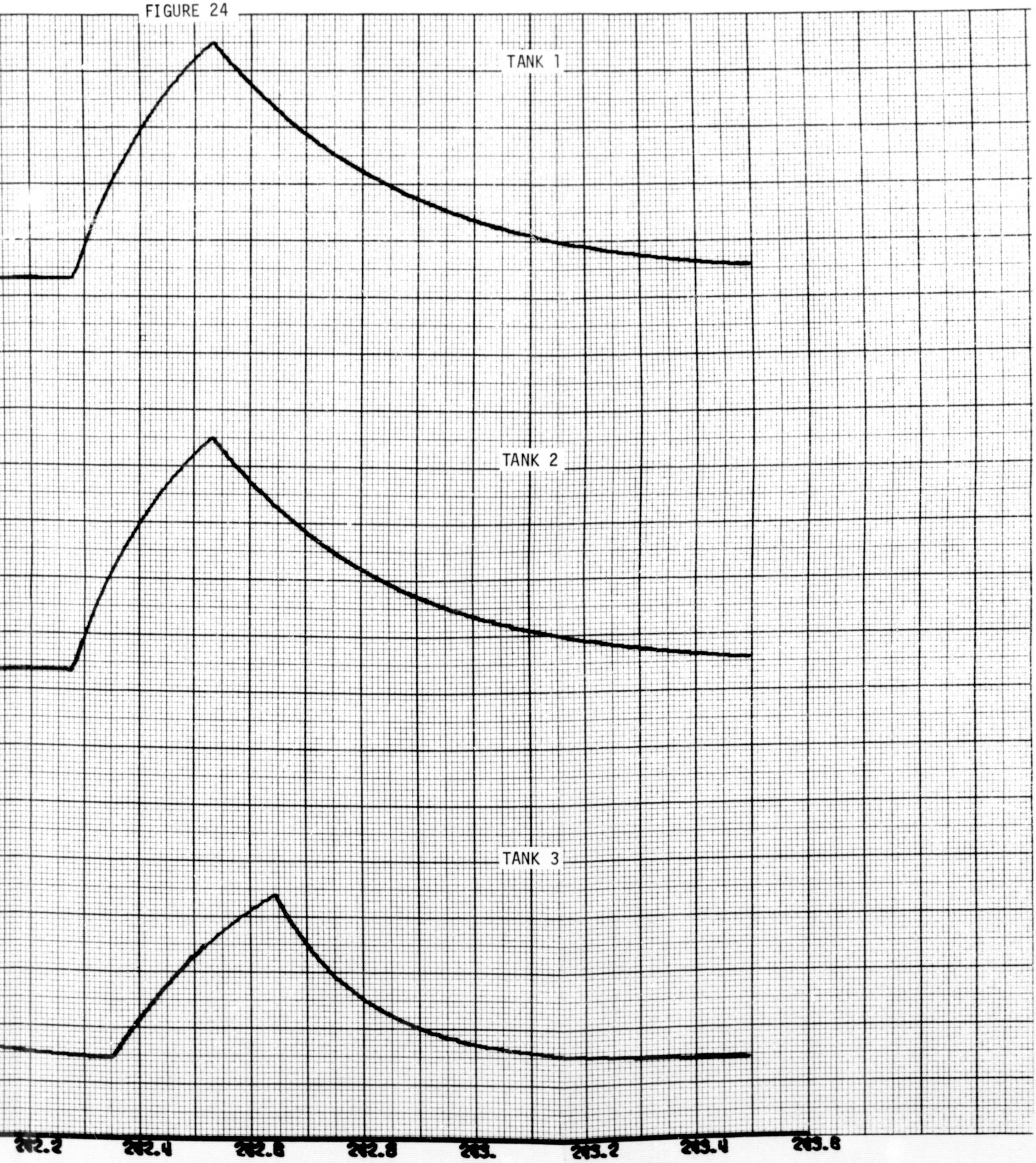
OXYGEN TANK HEATER TEMPERATURES DURING EVA



FOLDOUT FRAME

EVA

FIGURE 24



FOLDOUT FRAME 2