AN EXPERIMENTAL INVESTIGATION OF
FLASHING PHENOMENA IN A DEPRESSURIZED VESSEL

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ABSTRACT

AN EXPERIMENTAL INVESTIGATION OF FLASHING PHENOMENA IN A DEPRESSURIZED VESSEL

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This experimental investigation examined temperature and pressure changes in a depressurized vessel.

The sudden drop of pressure in the vessel causes a flashing phenomena, as could occur in pressurized water reactors.

The fluid used was water and an electrically heated vertical cylinder element was used to heat the water in the vessel.

Temperatures were measured at different locations in the vessel and were compared with the saturated temperature corresponding to the pressure measured in the vessel. During the period of the sudden pressure drop, the water temperature change in the top region is very fast and it quickly approaches the saturated temperature. In the bottom region, the water temperature change has a time delay and the temperature remains generally above the saturated temperature. The heating surface temperature drops accordingly, but, it remains 1 to 5°C above the water temperature at the same level.

The measured temperatures were non-dimensionalized. Integration of the non-dimensional temperature yields the reciprocal of temperature sensitivity. The temperatures in the top region are more sensitive to the pressure changes than those in the bottom region.

ACKNOWLEDGEMENTS

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CHAPTER 1

INTRODUCTION

When a liquid is suddenly decompressed to a pressure below the saturation pressure corresponding to its initial temperature, a rapid transient process, known as flashing, occurs.

From their investigations into increases in surface area during the flashing of liquids Hooper and Lee [1] observed that there is a higher pressure within the liquid, than in the space above it, for a large portion of the brief flashing period. This behaviour has been termed the rule of flashing.

Hooper and Kerba [2] using thirteen different fluids found the rule of flashing applied to all the fluids tested and an empirical correlation in terms of fluid properties was presented. Hooper and Chan [3], investigated the pressure-time relationship within the fluids, during flashing. It was determined that the pressure-time relationship depended upon the initial temperature and properties of the fluid being investigated.

Hooper, Faucher and Eidlitz performed experimental investigations into the pressure effects on bubble growth in the flashing of super-heated water, and provided evidence to support the "Law of Flashing" [4].

The aforementioned experiments were carried out as research from the point of view of basic phenomena. The time considered was one to thirty microseconds, a relatively short time.

Recent studies of two phase flow (liquid and vapour) came about as requirements for economical design and optimization of the operating conditions of heat transfer equipments. The necessity for reliability and safety of water cooled reactors accelerated studies.

Ralph, Sanderson and Ward [5] studied post-dryout heat transfer under low flow, low quality conditions and measured the rate of cooling of a vertical cylindrical surface.

A theoretical model of low-flow film boiling, heat transfer, on vertical surfaces, has been investigated by Jens G. Munthe Anderson [6]. Based on the assumption of laminar flow for the film, he solved the continuity, momentum and energy equations for the vapour film.

Leonard, Sun and Dix [7] formulated empirical equations and applied them to loss of coolant accident (L.O.C.A.) analysis of a boiler water reactor (B.W.R.).

Time dependent temperature distribution in cylindrical fuel rods, with cladding, was evaluated analytically by E. Lorenzini and M. Spiga [8].

Thermal-hydraulic analysis was carried out in the Idaho National Engineering Laboratory [9] [10] [11]. The aim being to determine the critical heat flux for design criteria, of a water cooled reactor.

A series of tests (loss of fluid tests) was undertaken involving loss of core coolant and reversal of coolant flow. These experiments were carried out on a semi-scale model of the present day generation pressurized water reactor. The test facility was designed for loss of coolant experiments up to the equivalent of a double ended pipe rupture.

In this experiment the flashing phenomena studied was different from those investigated by Hooper [1,2,3,4]. The flashing was obtained by making a small opening in a pressurized, electrically heated boiler. Such flashing phenomena could occur in pressurized water reactors.

CHAPTER 2

EXPERIMENTAL APPARATUS

The apparatus used for investigating the flashing phenomena consists of the following components as shown in Figure 1.

1. Glass Boiler Vessel
2. Heating Unit (Chromolox Immersion Heater)
3. Amplifier (Hewlett Packard Model 8803A) with Sanborn 7700 A.X. Recording System
4. Transducer Indicator (Pace. Variable Reluctance Model CD25)
5. Pressure Transducer Kit (Pace. Model K.P.15)
6. Pressure Recorder
7. Pressure Gauge
8. Temperature Indicator (Mercury Thermometer)
9. Pressure Control Valve
10. Relief Valve
11. Inlet Control Valve
12. Domestic Water Heater

The choice of a glass boiler vessel enabled direct observation of the water level on filling and on completion of the test. The water used was from a domestic hot water heater and entered the boiler through three branch lines at a temperature of approximately 83°C. (Figs. 2,3,4).

The Chromolox Immersion Heater 500 W was inserted in the boiler vessel to increase the water temperature. The heater was surrounded by compact carbon powder in a one inch, standard, copper pipe. This arrangement was to enable a better heat flux distribution over the surface of the heater cover pipe. Copper-constant thermocouples (Ansi symbol T) were placed at three different levels on the heater element cover pipe and at the same level, close to the pressure vessel wall, in the boiler water. Two thermocouples were located inside the copper pipe, on the surface of the heater unit itself, at the middle of the three levels. (See Thermocouple Arrangement Fig. 5.) The copper line from the thermocouples (hot junction) was connected to a Hewlett Packard Four Channel Amplifier. The chrome line was soldered to another copper line (cold junction) which returned to the amplifier to complete the circuit. This cold junction was placed in a container of melting ice and water. From this circuit the four channel amplifier received voltage signals lineal with the temperature variations on the hot junction of the thermocouples in the boiler.

These electrical input signals were amplified by the amplifier and automatically registered simultaneously on the moving graph paper. As the recorder used had only four channels, only four of the thermocouples temperatures could be monitored simultaneously.

The pressure transducer was connected to the upper cover plate of the boiler by a rubber tube. The pressure transducer was a diaphragm type, split body design, the pressure acting on one surface of the diaphragm. The other surface was open to the atmosphere. The pressure sensed by the transducer produced an output voltage proportional to the pressure and these electrical signals were transmitted to the transducer indicator. The indicator provided a direct reading of the pressure measurement in the system and further amplified the signals to the moving strip chart recording instrument.

The pressure gauge and temperature indicator were installed on the upper cover plate of the boiler vessel (Fig. 1). One plug control valve was installed in the upper cover plate and had a pipe connection which discharged into the drain. A relief valve set at 30 P.S.I. pressure was also installed on this cover plate and the whole boiler unit placed in a plastic, box type, container as a safety measure.

CHAPTER 3

TEST PROCEDURES

To heat up the system the inlet and outlet valves were opened and the water from the domestic hot water heater allowed to flow through the boiler vessel for approximately five minutes.

Meanwhile the pressure transducer vent valve was opened to allow complete filling of the transducer pipe system and then closed. The outlet valve was closed a little ahead of the inlet valve to allow slight over pressure in the vessel, ensuring that the apparatus was completely filled. The immersion heater was then switched on and the contents of the boiler vessel allowed to heat up and reach a pressure of approximately twenty P.S.I. During this time the pressure transducer and temperature amplifier recorders were calibrated.

The test began when the pressure and temperature graph recorders were started and began recording. To synchronize the pressure and the temperature strip chart recording instruments, the time indicator for both instruments was pressed twice simultaneously at the start and completion of the test. After a few seconds the outlet control valve was quickly opened manually by fast turns of the knob and the pressure released.

Tests were of varying times, from one to five minutes. The sequence of events being the same for all tests. The actual time interval considered was from the initial pressure drop until the pressure stabilized at atmospheric pressure. This actual time interval was arbitrarily divided into a first time interval, from zero to six or up to ten seconds, and a second time interval consisting of the remaining seconds.

Temperature measurements were taken at four selected points. Four tests were performed with one thermocouple on the surface of the upper level (Fig. 5) of the heater unit. For the remaining tests this thermocouple was located on the surface of the lower level (Fig. 5) of the heater unit. The other three thermocouples were placed, two at different levels on the surface of the pipe and the third in the water. This applied to all tests, except two, where all three thermocouples were placed on the surface of the heater cover pipe, and two where all three thermocouples were placed in the water.

Pressure measurements were taken at the same time from the cover plate opening at the top of the boiler (Fig. 2). From the recorder chart the pressure measurements could be scaled down as zero and twenty P.S.I. were previously measured and recorded on the chart.

The temperature recorder, recorded in micro-volts through a pre-determined range which could be shifted manually, higher or lower, to accommodate fluctuations in the temperature. The range was marked by hand on the chart, during the test. The value from the chart was added to the range value to arrive at the actual micro-volts measured. The recorder strip chart scale could be changed, but generally twenty micro-volts per division or ten micro-volts per division was used.

The calculated micro-volts were converted to actual celcius temperature from the copper-versus constantan thermocouple table, where the reference junction point was at 0°C.

The major objective of this experimental study was to measure accurately the temperature and pressure changes simultaneously at many locations, during a sudden depressurization, and over a limited time domain.

Since the temperature could be measured at only four locations many separate tests were required. The accuracy of the results from this procedure could be subject to question. Errors are likely to occur during the changing and setting up of each test.

The pressure and temperature synchronization is very important. For example, it can be seen in Fig. 7 that if the measured temperature at thermocouple number 4 was measured 1/3 of a second later it would be equal to the saturated temperature corresponding to the measured pressure. Likewise if the recorded pressure was measured one P.S.I. less, the corresponding saturated temperature would equal the measured temperature at thermocouple number 4. These minute changes in time or pressure would place thermocouple number 4 at the boiling point.

The pressure measurement could be a major cause of error because of the number of stages involved between sensing and recording. The estimated error, however, from all measured sources is less than 3% for each test.

CHAPTER 4

DATA PRESENTATION AND DISCUSSION

The temperature distribution in the water in the boiler was recorded when the water was suddenly decompressed to a pressure below saturation pressure for each test.

4.1 Distribution of Temperatures in the Water in the Boiler. Tests 19 and 20

In Tests 19 and 20 the boiler water temperatures in the upper level (see Fig. 6 and 7) started to drop in approximately one to two seconds. In the middle level, in two to four seconds and the lower level in four to eight seconds. The temperature drops followed the pressure drops very closely. The saturated temperatures corresponding to the pressures at the beginning of the tests (1-10 secs) remained above the temperatures measured at all three levels. Even though the measured temperatures were below saturation temperatures, they started to drop because the bubbles produced on the surface of the heater cover caused convection heat transfer through agitation of the water.

The temperatures for the high level location became 0 to 1°C below the middle level temperatures after the first time interval and 2-3°C below the corresponding saturated temperatures, of the recorded pressures, following their path. As the initial temperatures were highest in the high level of the boiler, the reduction of pressure caused temperature drops, first in the high level, followed successively by temperature drops in the middle and low levels.

The low level temperatures, in the first time interval (1 to 10 sec) did not follow the path of the saturated temperatures, not being affected by heat transfer through agitation. In the second time interval (10 to 20 sec) the temperatures rose above the initial values by about 1 to 1.2^{o}C (see Fig. 6 and 7, T.19 and T.20). In the second interval, also, most temperatures rose above the corresponding saturated temperatures of the recorded pressures. Boiling, therefore, occurred at all three levels. The high and middle level temperatures, after some unsteadiness, reached the same temperatures as the saturated temperatures.

The temperatures on the surface of the heater element (thermocouple 15, Fig. 5) reached a shallow peak and then decreased only gradually. Convection heat transfer in the first interval was low causing a rise in temperature (the shallow peak). In the second interval, heat transfer was higher than in the first interval because of bubble formation and agitation and the temperature, at thermocouple 15, therefore dropped.

4.2 Distribution of Temperatures on the Heating Element, Outside Cover Surface. Tests 17 and 18

The temperature distribution was recorded by three thermocouples located on the surface of the heater element cover. Number 5 thermocouple placed at the high, number 3 thermocouple at the middle and number 1 thermocouple at the low level. A fourth thermocouple (No. 15) was located on the surface of the heater element.

Initial temperatures at thermocouple No. 5 (Figs. 8 and 9) were lower than the saturation temperatures of the corresponding starting pressures. After one second and up to three seconds, these temperatures became higher than the saturated temperatures. They then became lower than, but very closely followed, the saturated temperatures.

The middle level temperatures (thermocouple No. 3) started lower than No. 5 temperatures and the saturated temperatures. After two seconds they became approximately two degrees celcius higher than the saturated temperatures and remained like this for the rest of the time interval. These temperature differences, between saturated and measured temperatures occurred because the heat transfer at the high level was faster, due to heat loss through the glass wall of the boiler vessel and the top cover plate to the environment. When rapid bubble production commences on the surface in the middle level the temperature differences between measured and saturated temperatures must be high because of low heat transfer through the boiler vessel wall to the environment.

The low level temperatures (thermocouple No. 1) started to drop after approximately six to eight seconds and then became higher than the saturated temperatures and followed their pattern for the rest of the time interval. In the first interval, therefore, there was no boiling because of lower than saturated temperatures. In the second interval the superheat caused the boiling. Superheat occurs when the cover temperature and the saturation temperature differences (T-Tsat) are positive.

Temperatures at thermocouple No. 1 in test seventeen were not included in the calculations as the measurements could not be considered valid. There was an almost constant temperature ($1^{o}C$ drop only) throughout the test.

The temperatures on the surface of the heater element at thermocouple No. 15, followed the same pattern as in previous tests (19 and 20) and for the same reasons.

4.3 Temperature Distributions of the Low Level. Tests 15 and 16. See Fig. 10 and 11

The low level thermocouples No. 1 and No. 7, (see Fig. 5) were opposite temperature measurement locations on the surface of the heating element cover. The temperatures at these two locations, after a sudden drop of pressure, dropped moderately and closely followed each other. No. 2 thermocouple was in the water at the low level and here the temperature curve rose slowly in the first time interval, and after peaking,up to seven seconds dropped moderately and followed the shape of temperatures at thermocouples No. 1 and No. 7. The peaking was due to the relatively undisturbed water, because of low convection heat transfer in this area. All three temperatures (1,7,2) in the first time interval were below the saturation temperatures of the corresponding pressures. In the second time interval (after 7 seconds) the temperatures were higher than saturation temperatures at all three thermocouples. This indicates that in the low level the boiling started after the first time interval.

4.4 Temperature Distributions of Test 13 and Test 14

As in previous tests four thermocouples were used. For thermocouple location see Table 1.

Measured temperatures at thermocouples No. 3 and No. 7 showed similar characteristics to those measured in tests 17 and 18 and tests 15 and 16 respectively. Thermocouple No. 8 is in the water at the low level opposite the location of thermocouple No. 2 which was measured in test 19 and test 20. Measured temperatures at No. 8 thermocouple showed measurements similar to those at No. 2 thermocouple.

Although the pressure release was controlled manually and could therefore be subject to slight variation, the measured temperatures for all tests exhibited the same patterns.

The height to diameter ratio of the heating element in this experiment was approximately twelve to one, resulting in relatively large temperature differences between the three levels. In an actual pressurized water cooled reactor, the fuel element height to diameter ratio is much larger and this should be taken into consideration when comparing this test.

4.5 Non-dimensional Temperature and Non-dimensional Time

Temperatures and pressures were investigated by making use of formulas as follows:-

Non-dimensional temperature

$$T^* = \frac{T - Tmin}{Tmax - Tmin}$$

Where T = measured temperature

$Tmin$ = measured minimum temperature

$Tmax$ = measured maximum temperature

Non-dimensional pressure

$$P^* = \frac{P}{Pmax}$$

Where P = measured temperature

$Pmax$ = maximum pressure at start of test

Non-dimensional time

$$t^* = \frac{t - t_o}{t_{st} - t_o}$$

Where t = time

t_o = time at maximum temperature

t_{st} = time at which temperature became steady (time taken at 20 seconds if not steady by that time).

Non-dimensional temperatures were plotted against non-dimensional times for each thermocouple on the tests performed (see Figs. 14 - 20). These non-dimensional temperatures and times were used to obtain a mathematical equation for each thermocouple by a curve fitting method - the method of least squares regression being used to obtain the curves. The temperature - time curves were integrated to represent the sensitivity of temperature changes. The sensitivity of the temperature change is affected by the pressure change.

The sensitivity is defined

$$S = \frac{1}{\int T dt}$$

When the value of ($\int T dt$) is small the temperature drops quickly, it is very sensitive to the pressure change.

When the value of ($\int T dt$) is large the temperature drops slowly, it is not so sensitive to the pressure change.

The reciprocal of sensitivity ($\int T dt$) was plotted against non-dimensional time (see Fig. 21 and 22).

To obtain empirical equations for measured temperature distributions by thermocouples, three programmes were written for a Hewlett Packard Calculator, as follows:-

Programme 1 for a second order polynominal (parabola least square fitting)

$$T^* = a_0 + a_1 t^* + a_2 (t^*)^2$$

Programme 2 for an incomplete m and n order polynominal

$$T^* = a_o(t^*)^m + a_1(t^*)^n + 1$$

m and n are constants which may be varied for different temperature distributions.

Programme 3 for third order polynominal

$$T^* = a_o + a_1 t^* + a_2(t^*)^2 + a_3(t^*)^3$$

Programme 3 is shown in Appendix I.

All measured temperatures were tested for all three programmes to determine the quality of fit achieved by the regression, through calculation of the regression coefficient (r^2). A value of regression coefficient (r^2) close to one, indicates the best fit.

It was determined that non-dimensional temperatures of the water in the boiler are best fitted by second order polynominal equations (Fig. 15, 17, 19).

The $\int Tdt$ was large at the low level and smaller at the upper and middle levels, which indicates the influence of large heat loss from the upper cover plates and less heat transfer from lower half of the boiler (Fig. 22).

Non-dimensional temperatures on the cover surface (Fig. 21) in the high level (Fig. 18) are best fitted by 1.5 order polynominal equations, in the middle level by incomplete polynominal ($m=1$, $n=3$) equations (Fig. 16), and in the low level by incomplete polynominal ($m=2$, $n=3$) equations (Fig. 14).

The $\int Tdt$ was large in the low level, and smaller in the middle level, which indicates the effect of heat transfer by convection due to bubble formation and quantity of bubbles formed. This was even more evident in the high level (Fig. 21).

CHAPTER 5

CONCLUSIONS

Previous experiments have examined flashing phenomena of short duration (milliseconds). In the present experiment the flashing period was extended to seconds by using a small opening.

Flashing occurred consecutively, starting at the top surface of the water, then moving down into the water. This was the case for the entire range of tests. The differences between the measured surface temperatures and the saturated temperatures at the end of the flashing period was small. The experimental results showed that the temperature differences lay on the free convection section of the boiling curve.

After integrating the empirical equations of non-dimensional temperature to obtain the reciprocal of temperature sensitivity, it was determined that on the vertical heater element cover the high level was most sensitive to the pressure changes, and sensitivity decreased gradually to the low level. In the water the high and middle levels exhibited equal sensitivity with less sensitivity at the low level.

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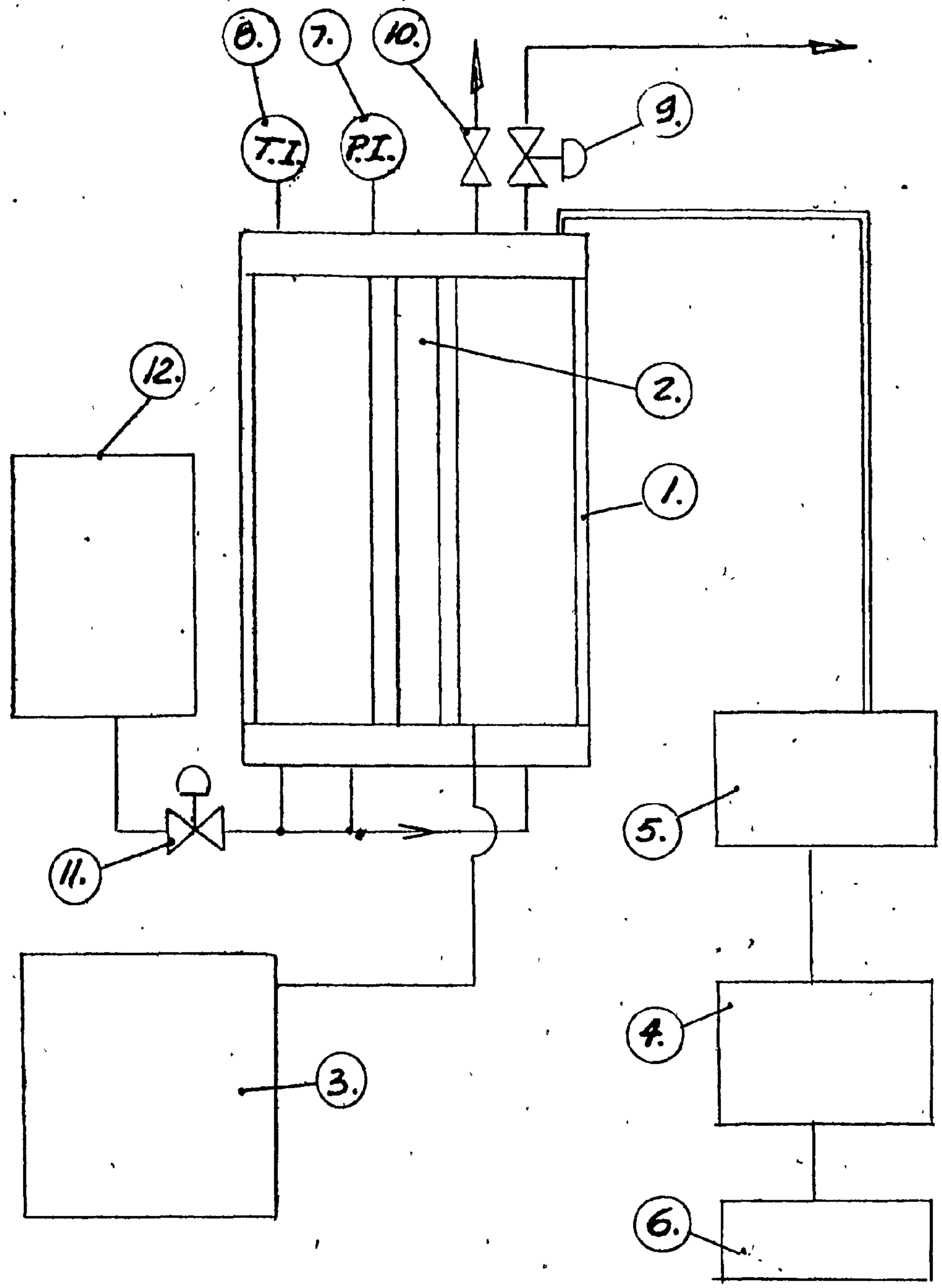
TABLE NO. 1

Thermocouple No. Location	Test No. 13	14	15	16	17	18	19	20
Cover Surface								
1 Low Level			X	X	X	X		
3 Middle Level	X	X			X	X		
5 High Level					X	X		
7 Low Level	X	X	X	X				
In the Water								
2 Low Level			X	X			X	X
4 Middle Level							X	X
6 High Level							X	X
8 Low Level	X	X						
Heater Surface								
15 Low Level	X	X	X	X	X	X	X	X

Location of Thermocouples for all Tests



1. GLASS BOILER VESSEL
2. HEATING UNIT
3. AMPLIFIER, RECORDING OF TEMP.
4. PRESSURE TRANSDUCER INDICATOR
5. PRESSURE TRANSDUCER KIT
6. PRESSURE RECORDER
7. PRESSURE GAUGE
8. TEMP. INDICATOR
9. PRESSURE CONTROL VALVE
10. RELIEF VALVE
11. INLET CONTROL VALVE
12. DOM. WATER HEATER.

FIG. 1. Schematic Diagram of Experimental Set-up

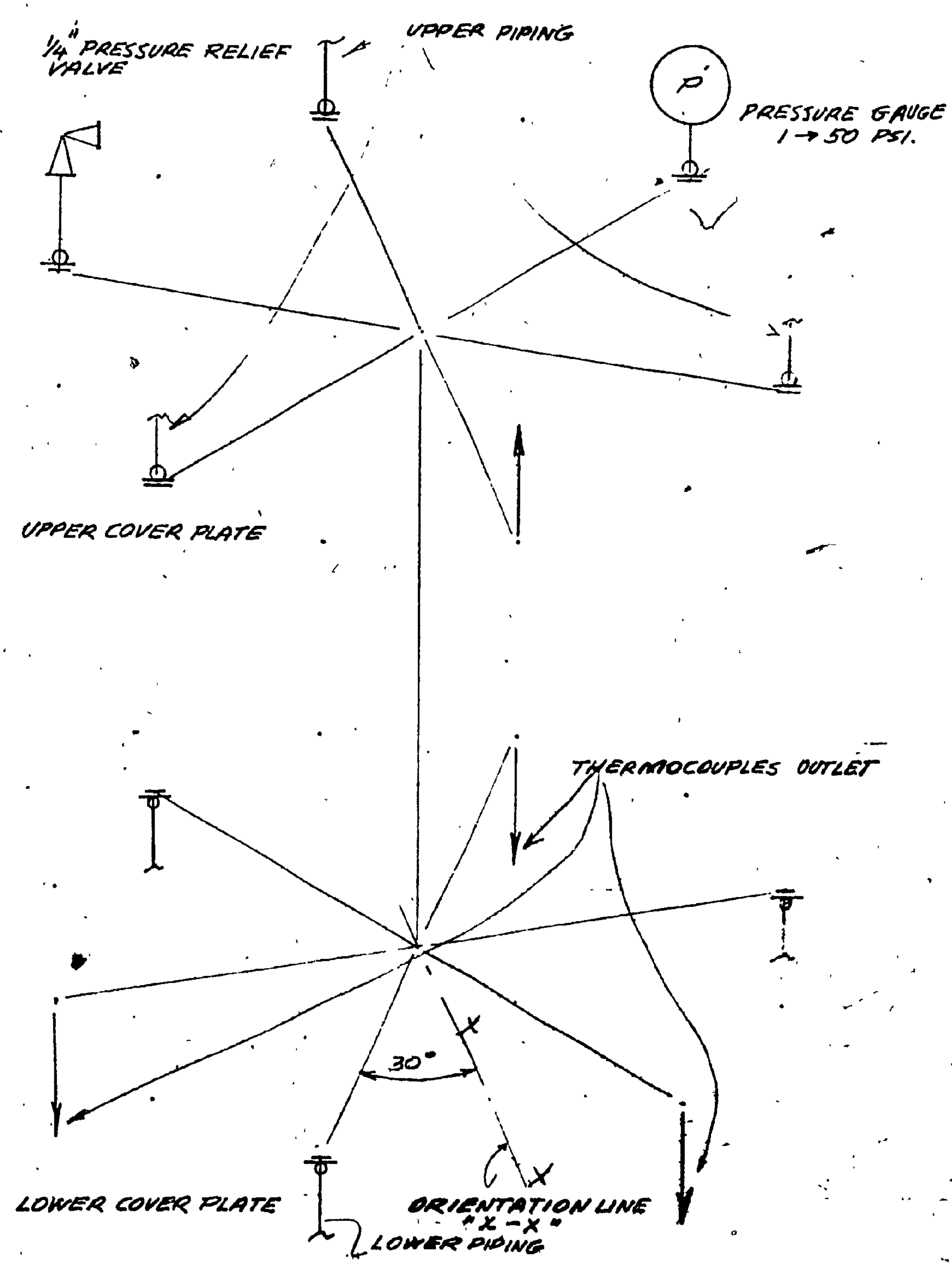


FIG. 2. Schematic Diagram of Cover Plates of the Boiler

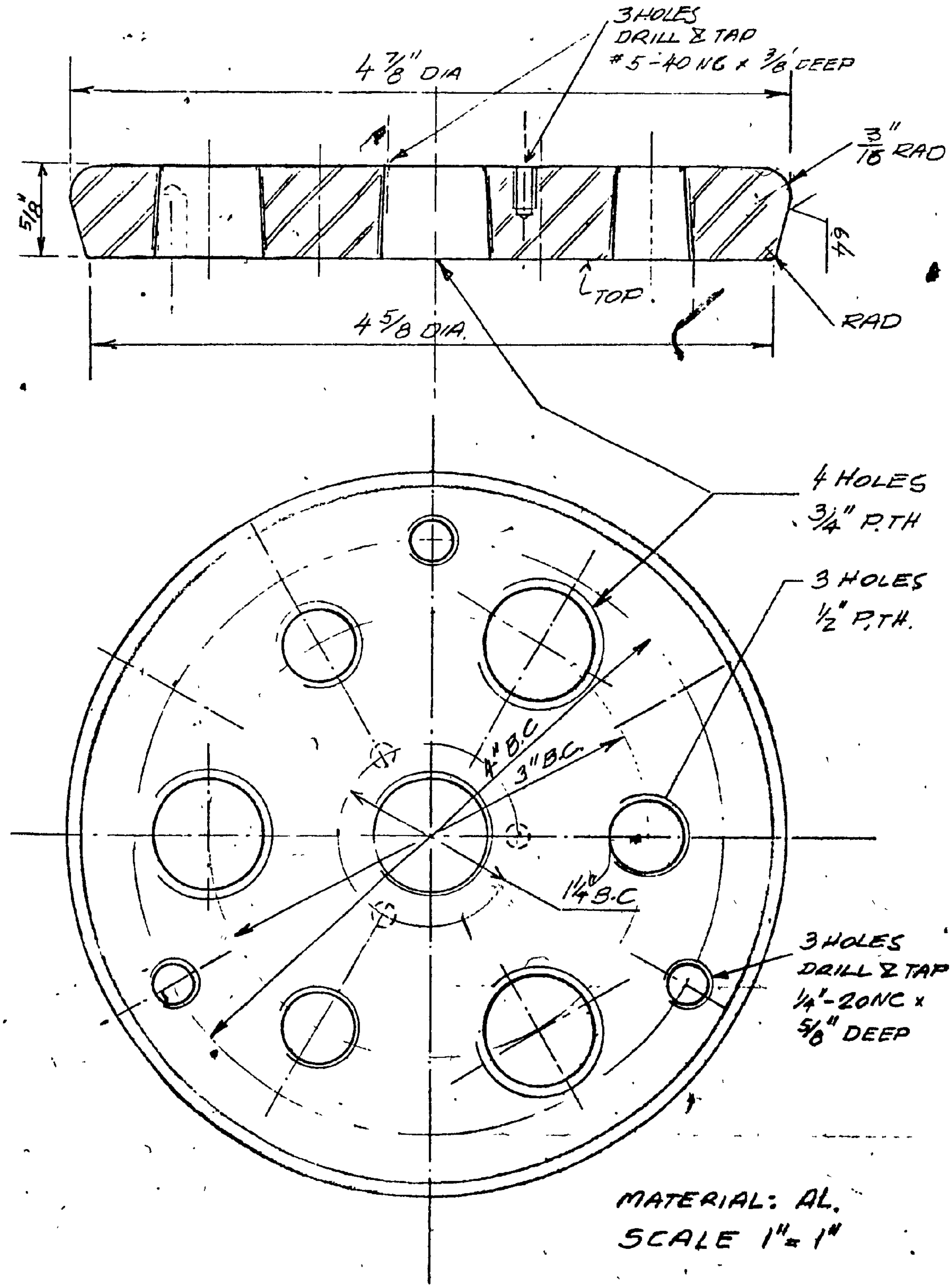


FIG. 3. Cover Plate of Boiler

PART LIST.

PC. NO.	NAME	MAT'L	QANT.	NOTE
1	TUBE END MALE ADAPTER	BRASS.	3	1/2" P.TH
2	UNION	"	3	5/8" - 1/2" P TH.
3	ELBOW	COPPER	5	1" O.D. TUBE
4	TEE	"	1	1" O.D. TUBE
5	REDUCER 5/8" x 1" O.D. PIPE	"	1	
6	TUBE END FEMALE ADAPTER	BRASS	1	1" x 1/2" PTH.
7	TERMOCOUPLE CONECTOR	"	1	3/8" PIPE 1/2" P.TH.
8	GLOBE VALVE	"	1	1" P.TH.
9	TUBE END MALE ADAPTER	"	2	1" P.TH
10	TUBE END FEMALE ADAPTER	"	1	1" P.TH.
11	TUBE 5/8" OD	COPPER	~ 3 FT	
12	TUBE 1" OD	"	~ 8 FT	
13	TEE	"	2	5/8" O.D. TUBE

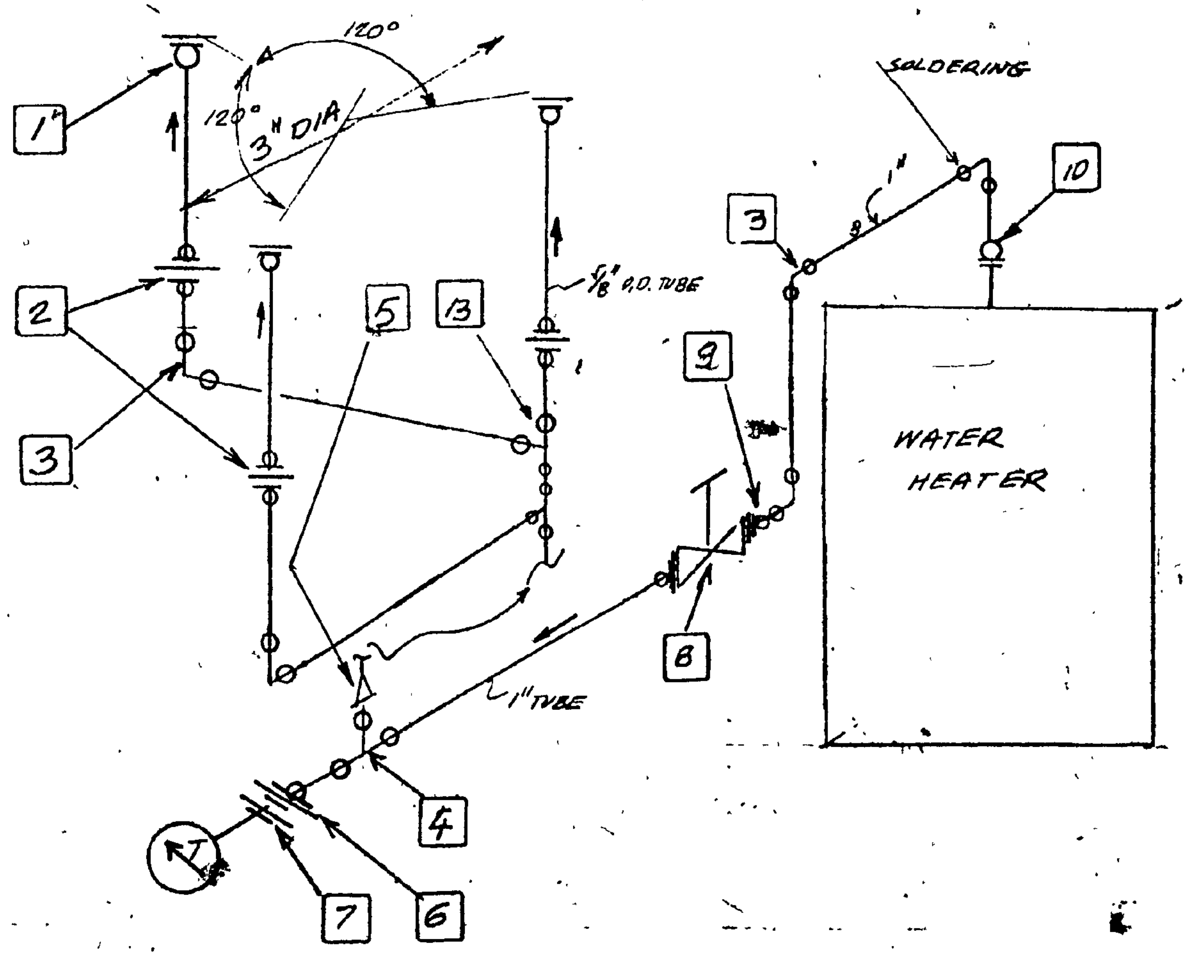
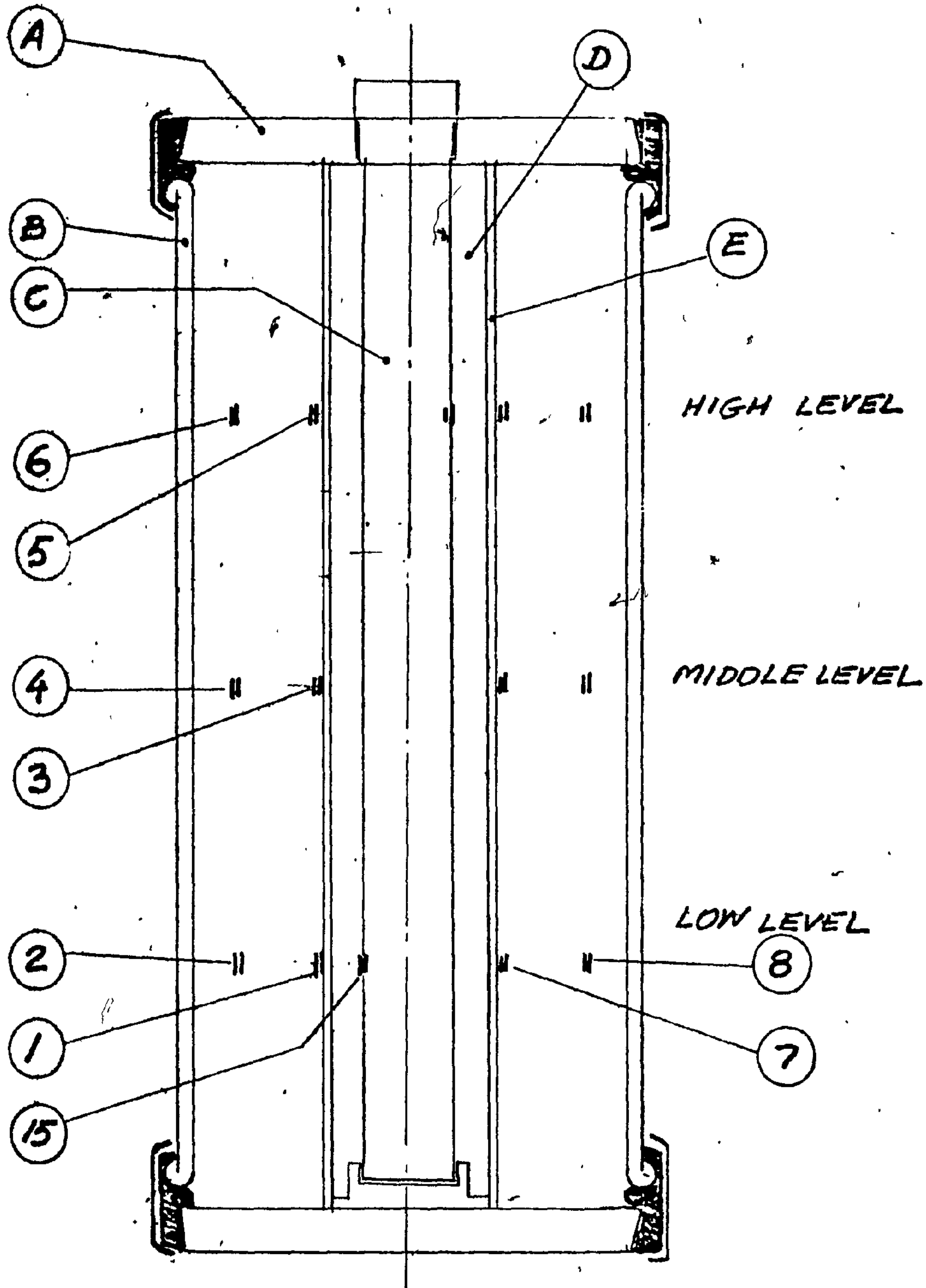


FIG. 4. Lower Piping System of Boiler



A COVER PLATE.
B GLASS VESSEL.
C HEATER ELEMENT.
D CARBON POWDER.
E HEATER ELEMENT.
COVER PIPE.

1 TO 15 THERMO COUPLES.

FIG.5. Location of Thermocouples

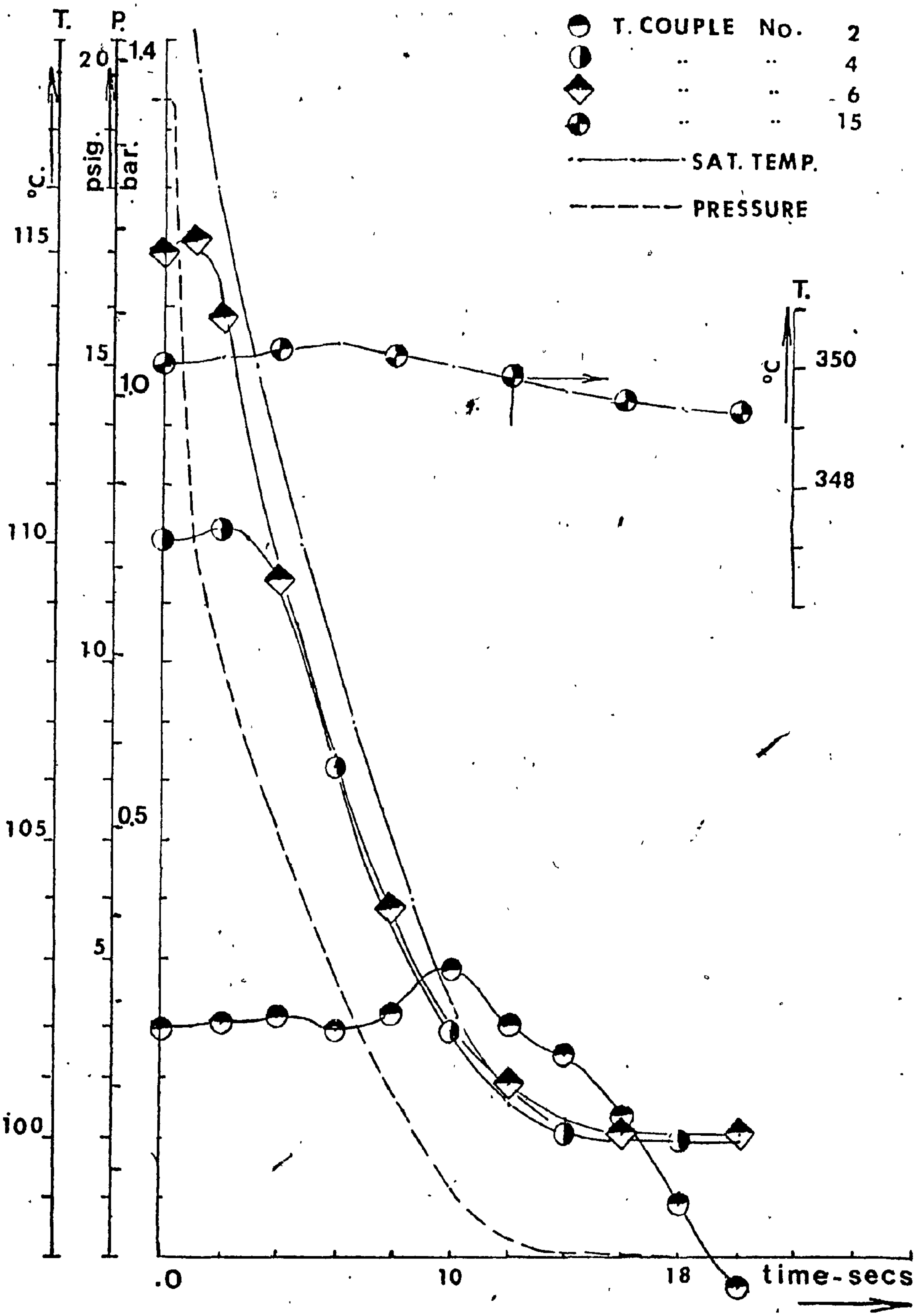


FIG. 6. Temperature and Pressure Distributions Obtained from Test 20

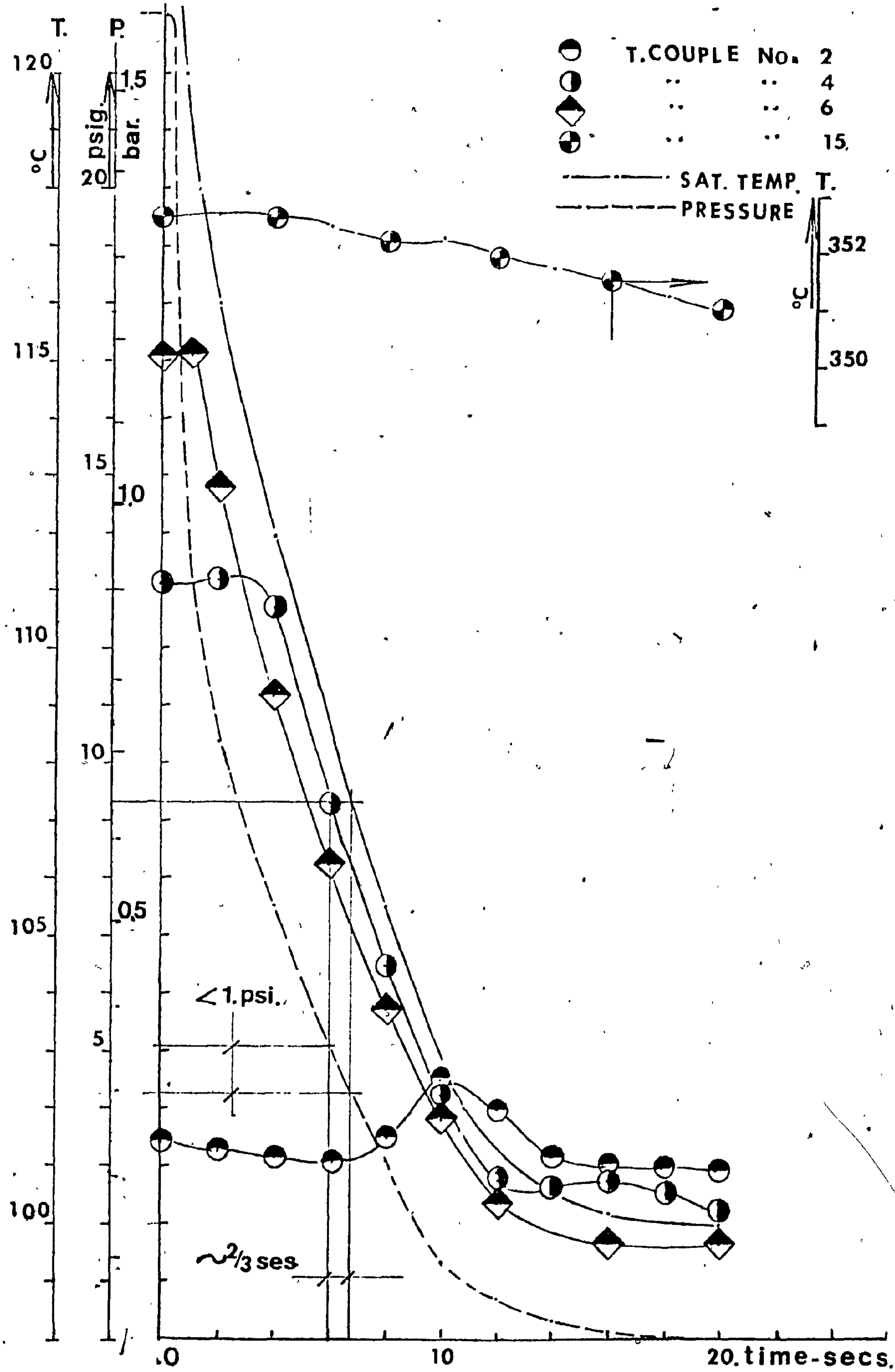


FIG. 7. Temperature and Pressure Distributions Obtained from Test 19

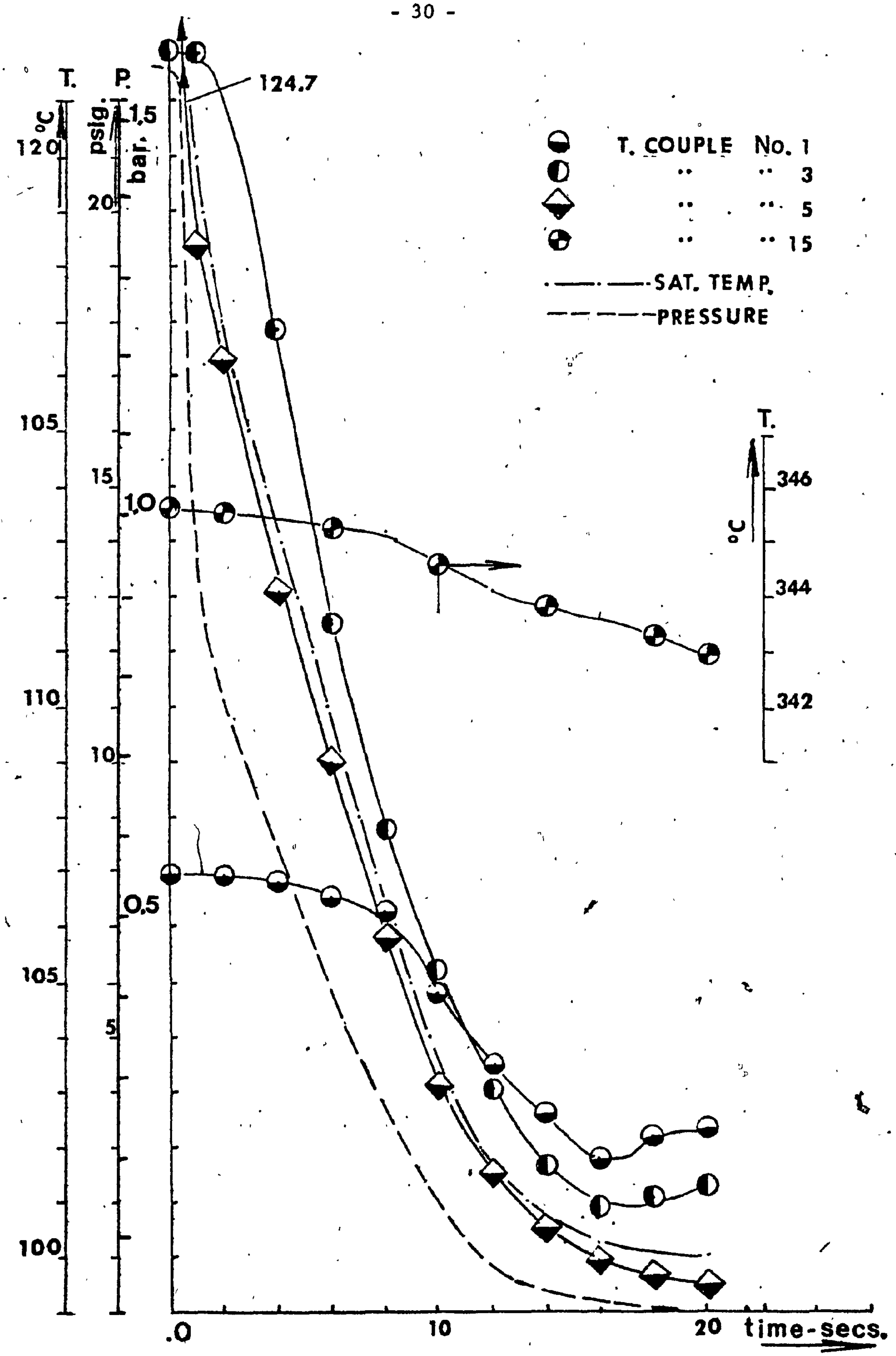


FIG. 8. Temperature and Pressure Distributions Obtained From Test 18

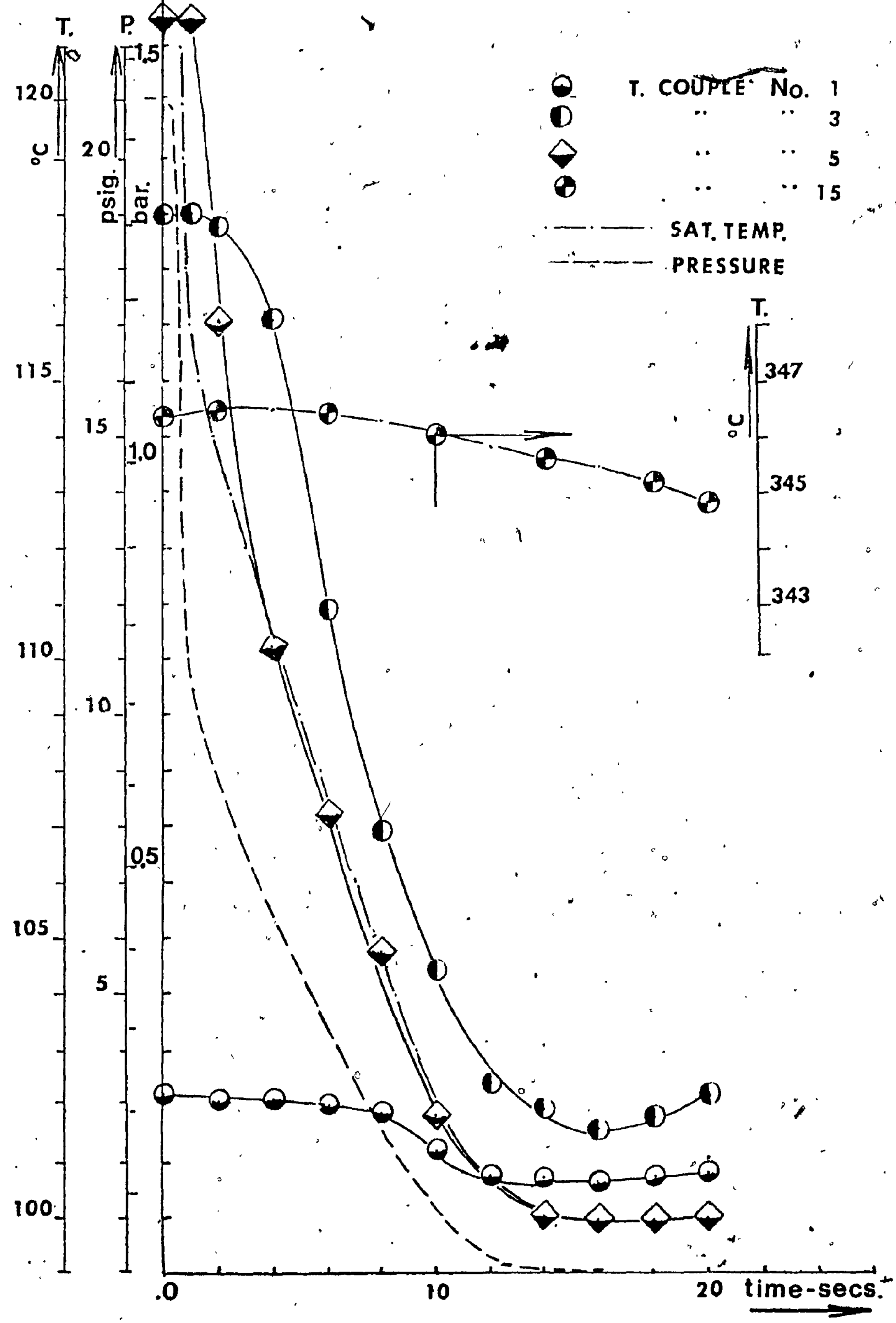


FIG.9. Temperature and Pressure Distributions Obtained from Test 17.

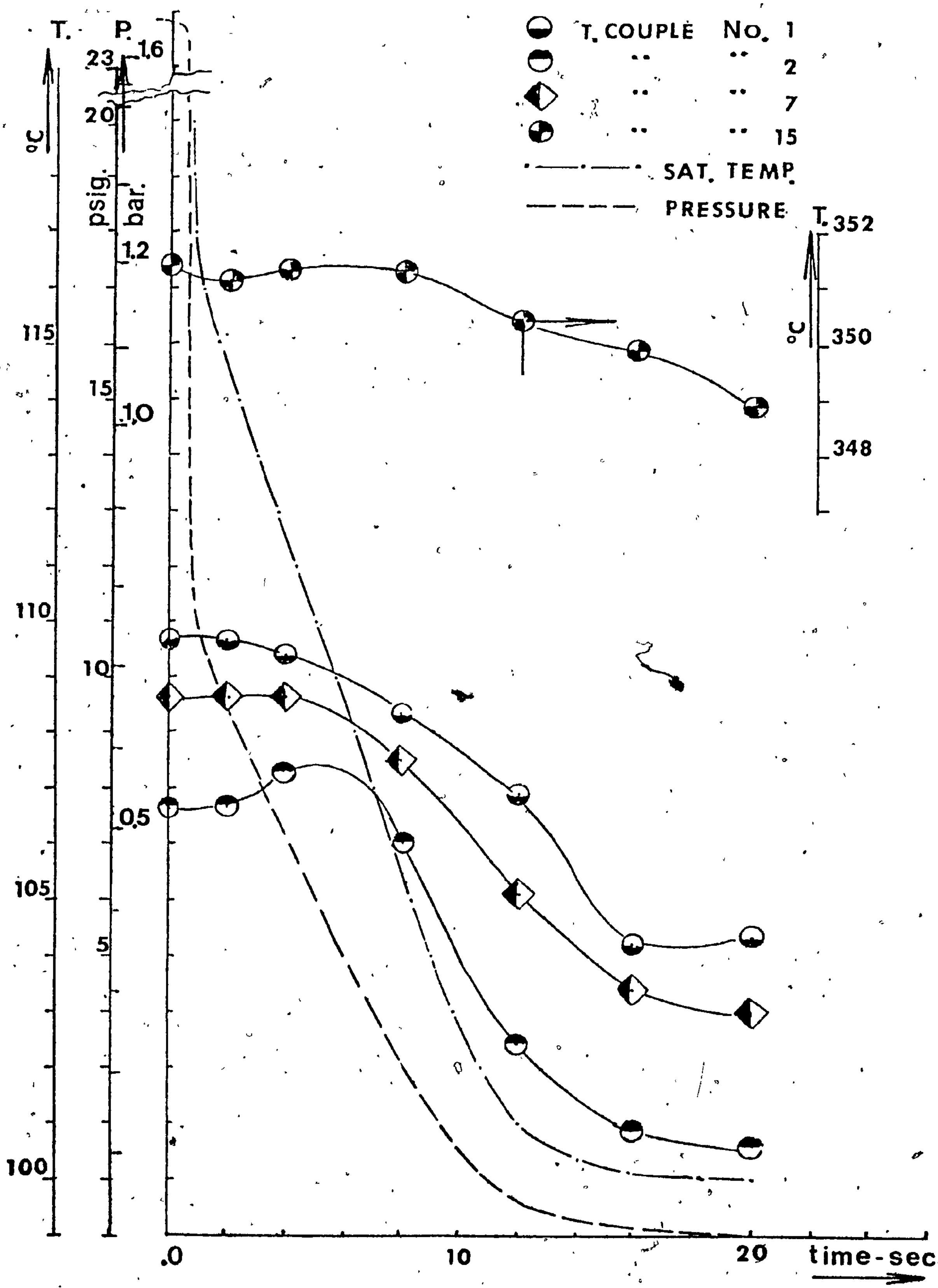


FIG.10. Temperature and Pressure Distributions Obtained from Test 16

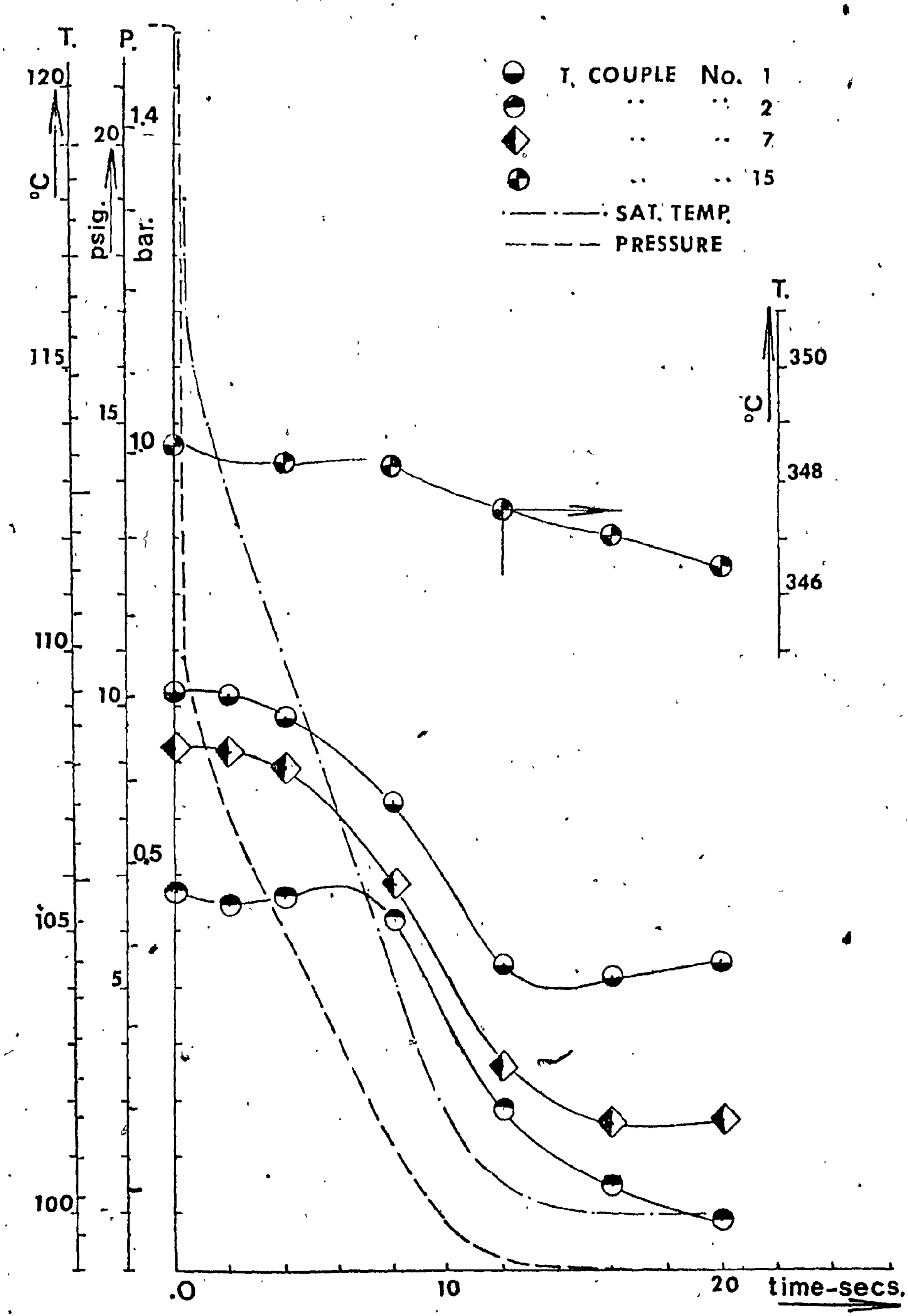


FIG.11. Temperature and Pressure Distributions Obtained From Test 15

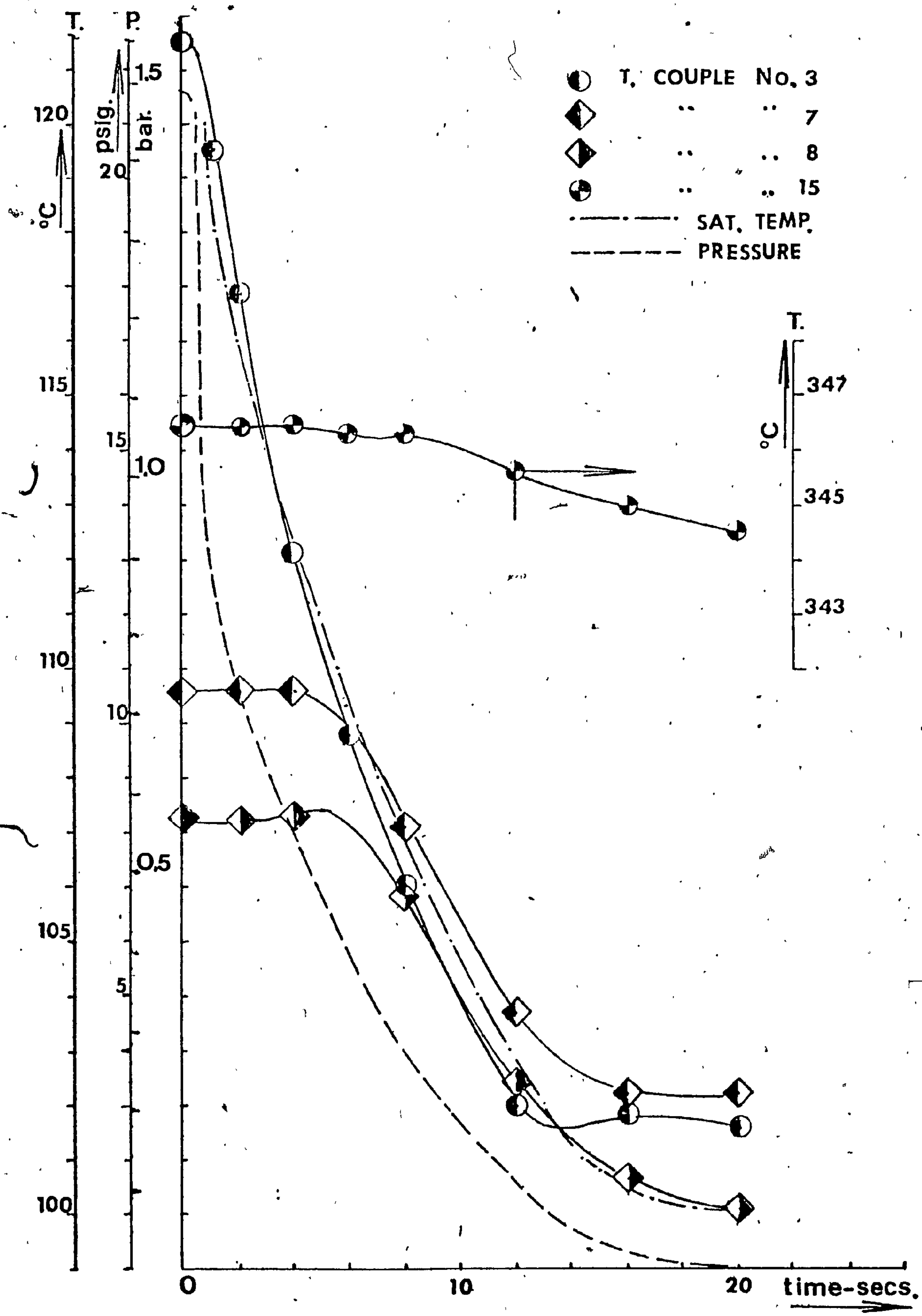


FIG.12. Temperature and Pressure Distributions Obtained From Test 14

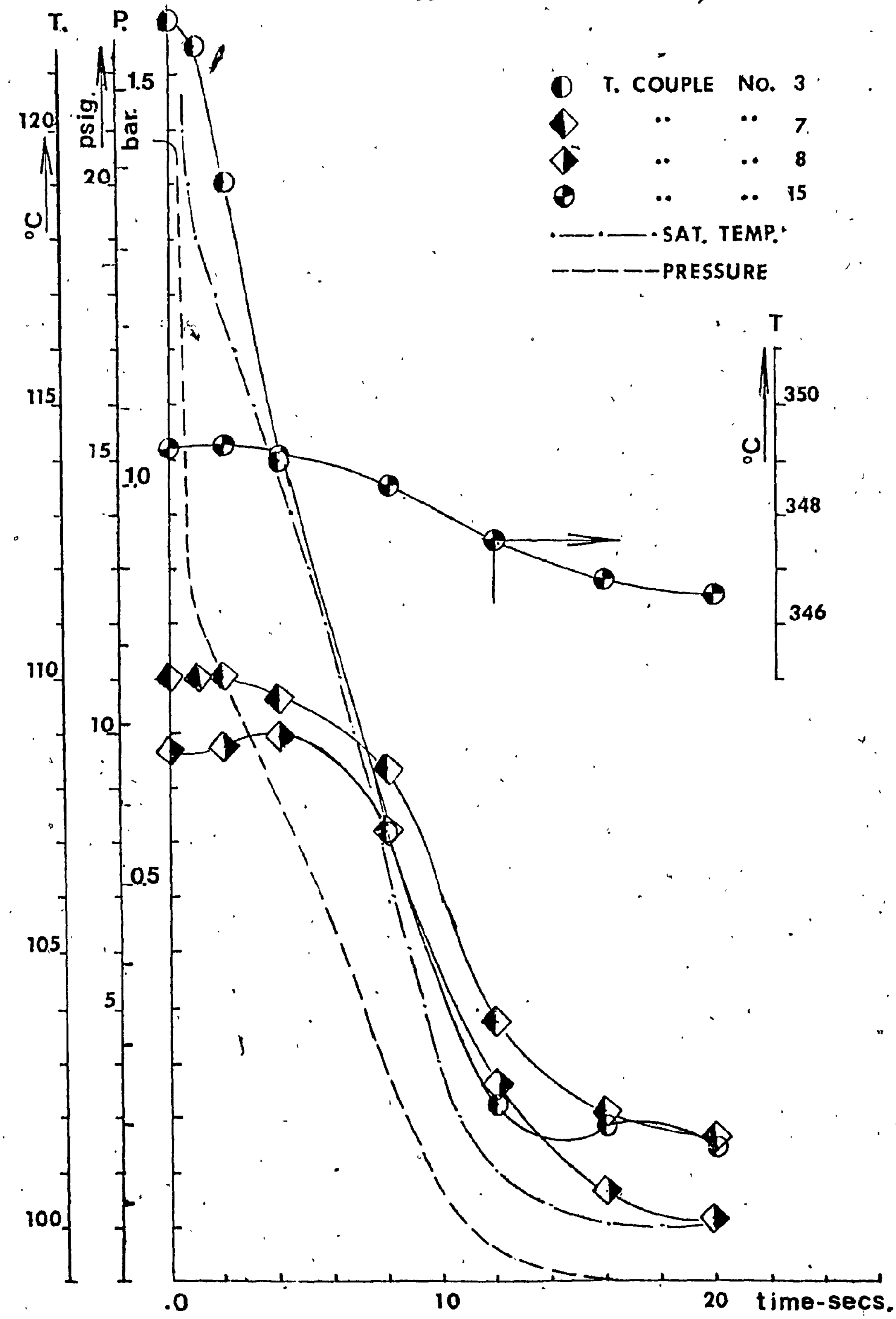


FIG.13. Temperature and Pressure Distributions Obtained From Test 13

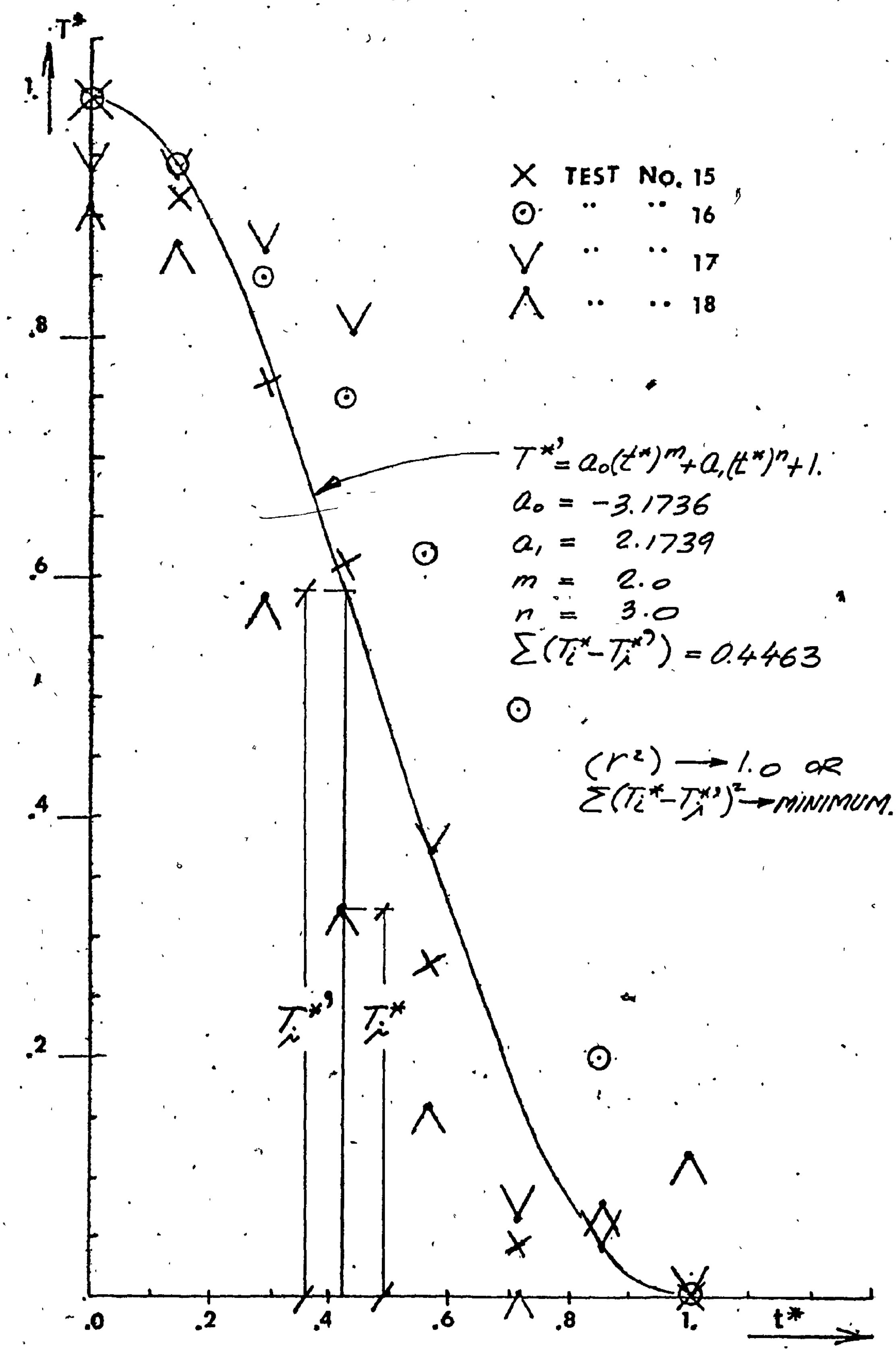


FIG. 14. Non-dimensional Temperature vs. Non-dimensional Time Measured by Thermocouple No. 1

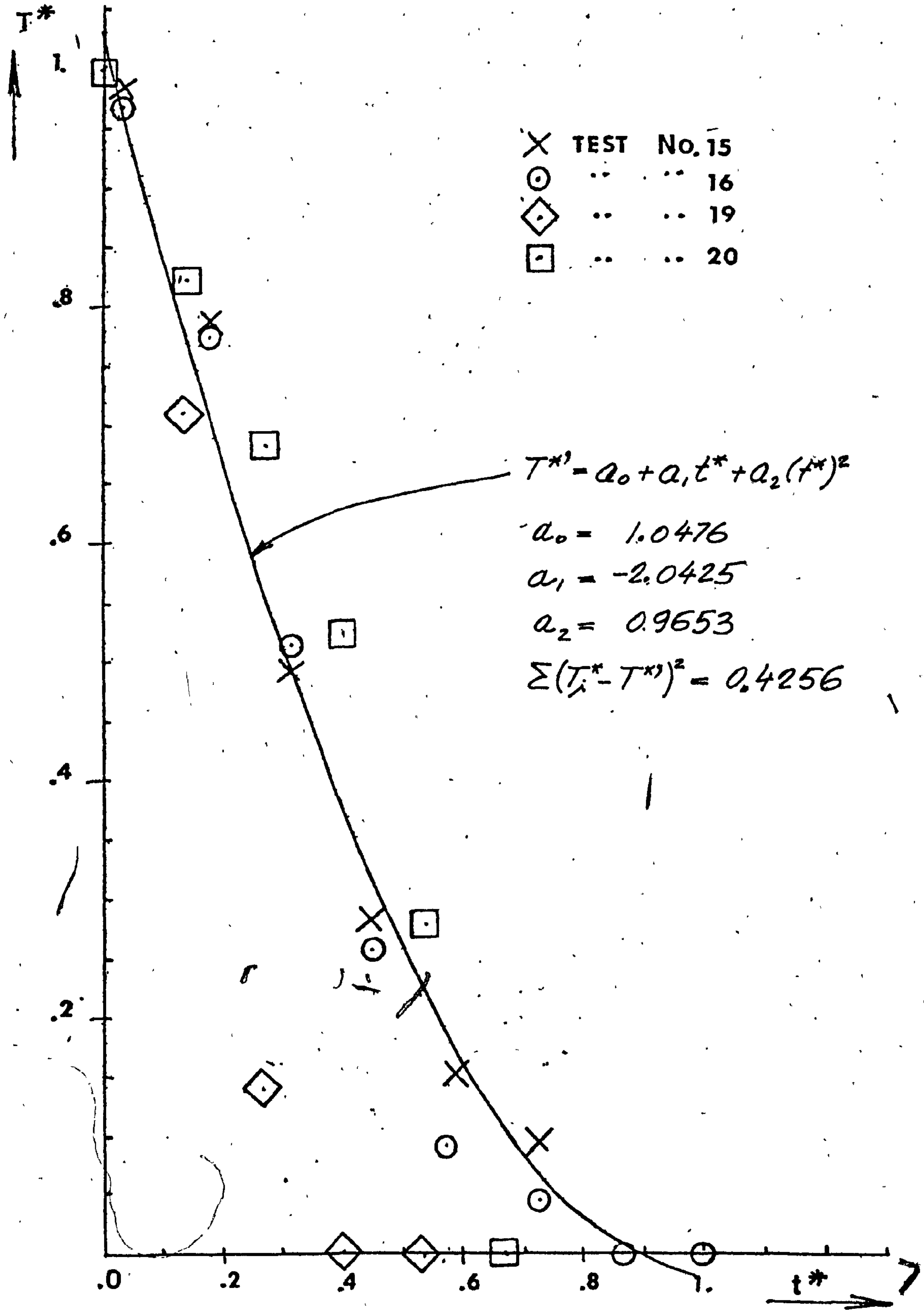


FIG. 15. Non-dimensional Temperature vs. Non-dimensional Time Measured by Thermocouple No. 2

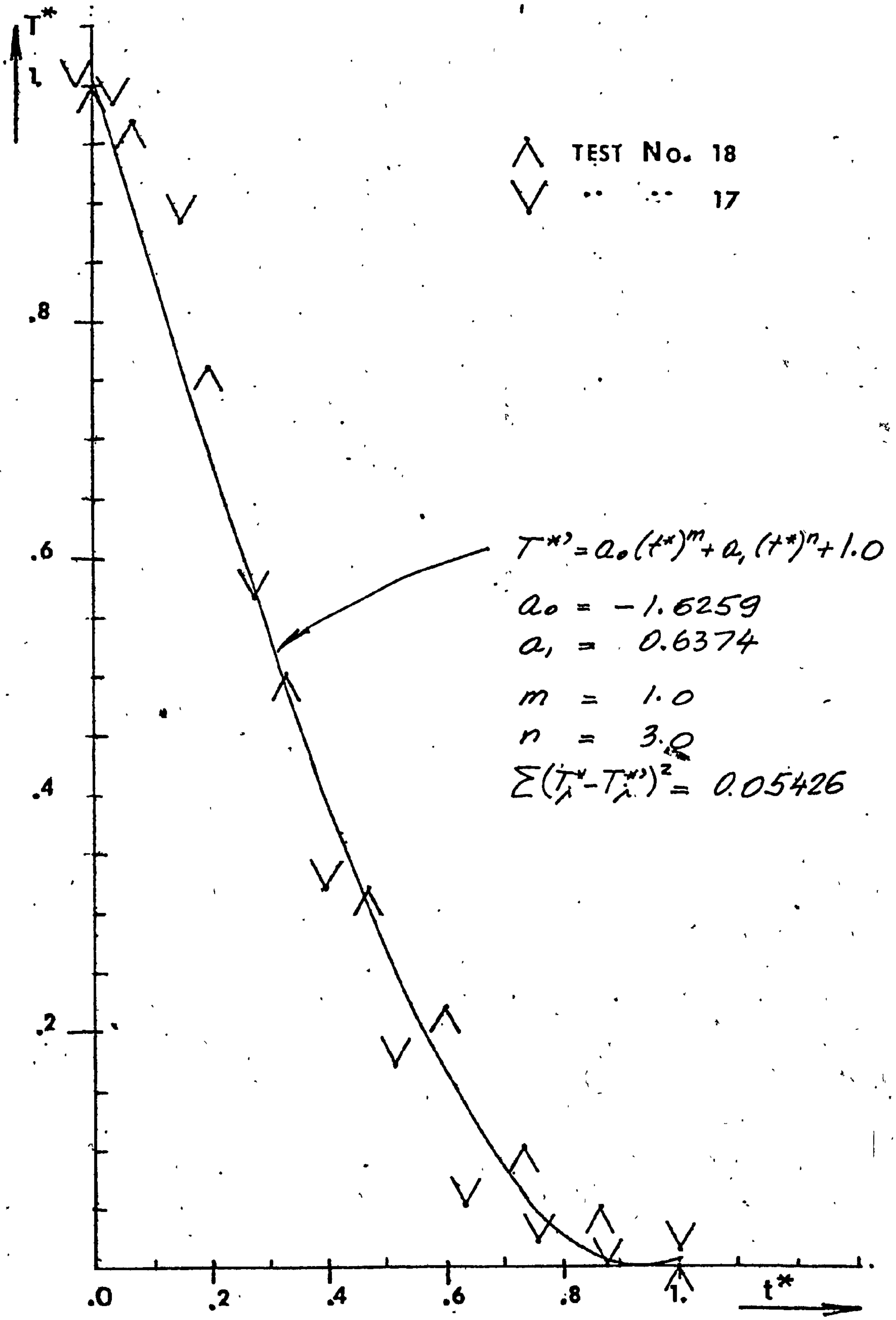


FIG.16. Non-dimensional Temperature vs. Non-dimensional Time Measured by Thermocouple No. 3

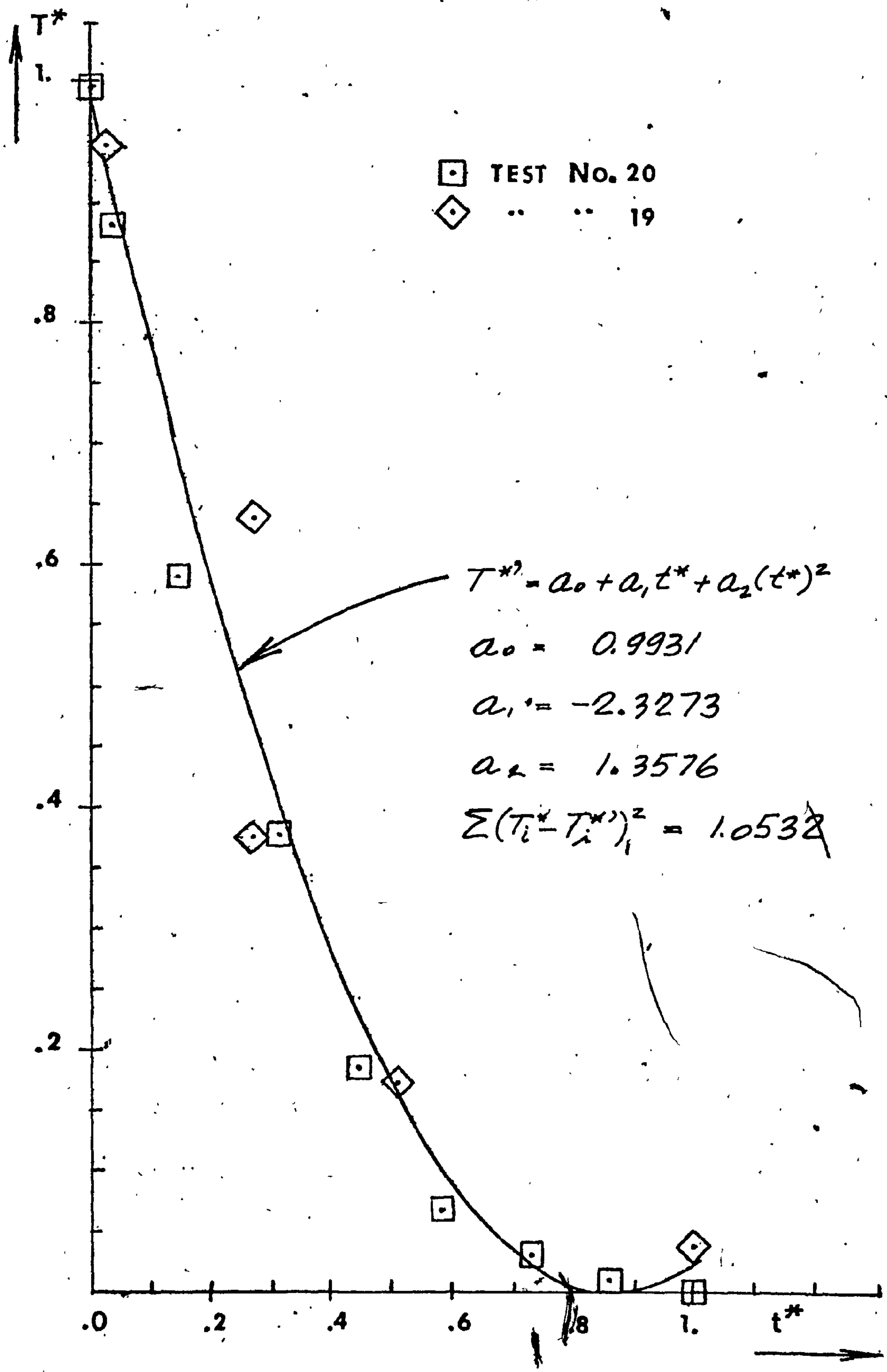


FIG.17. Non-dimensional Temperature vs. Non-dimensional Time Measured at Thermocouple No. 4

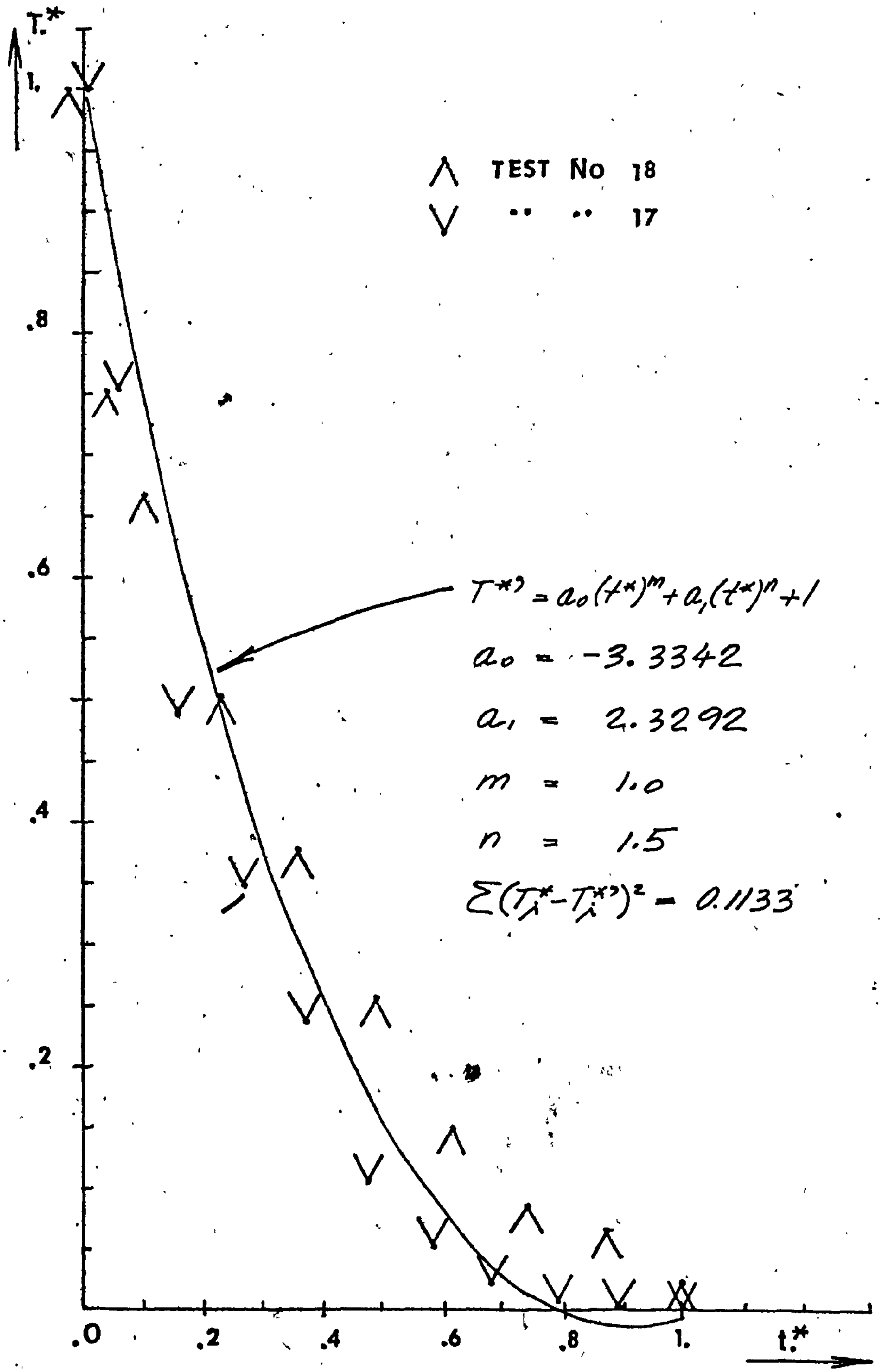


FIG.18. Non-dimensional Temperature vs. Non-dimensional Time Measured at Thermocouple No. 5

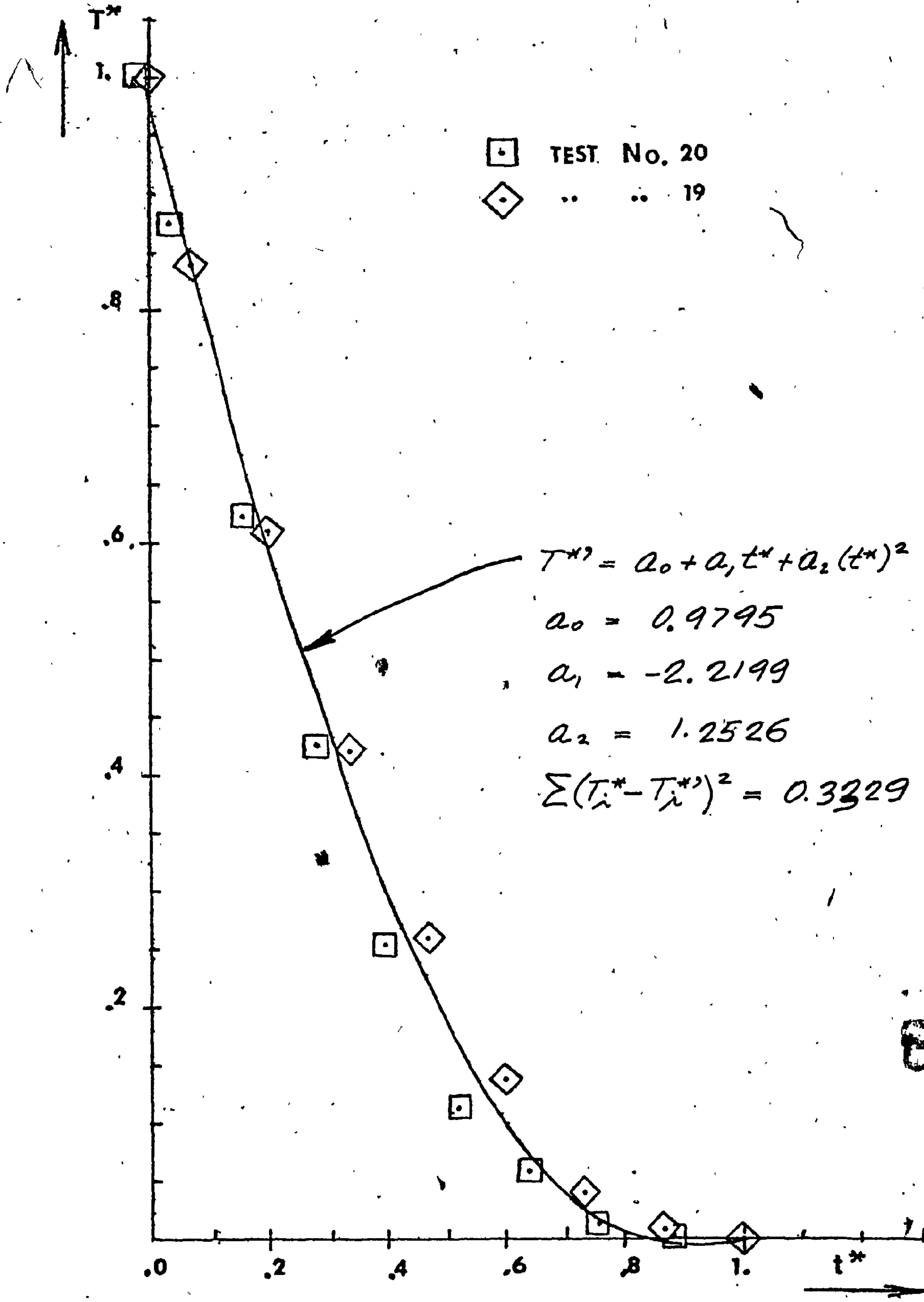


FIG. 19. Non-dimensional Temperature vs. Non-dimensional Time Measured at Thermocouple No. 6

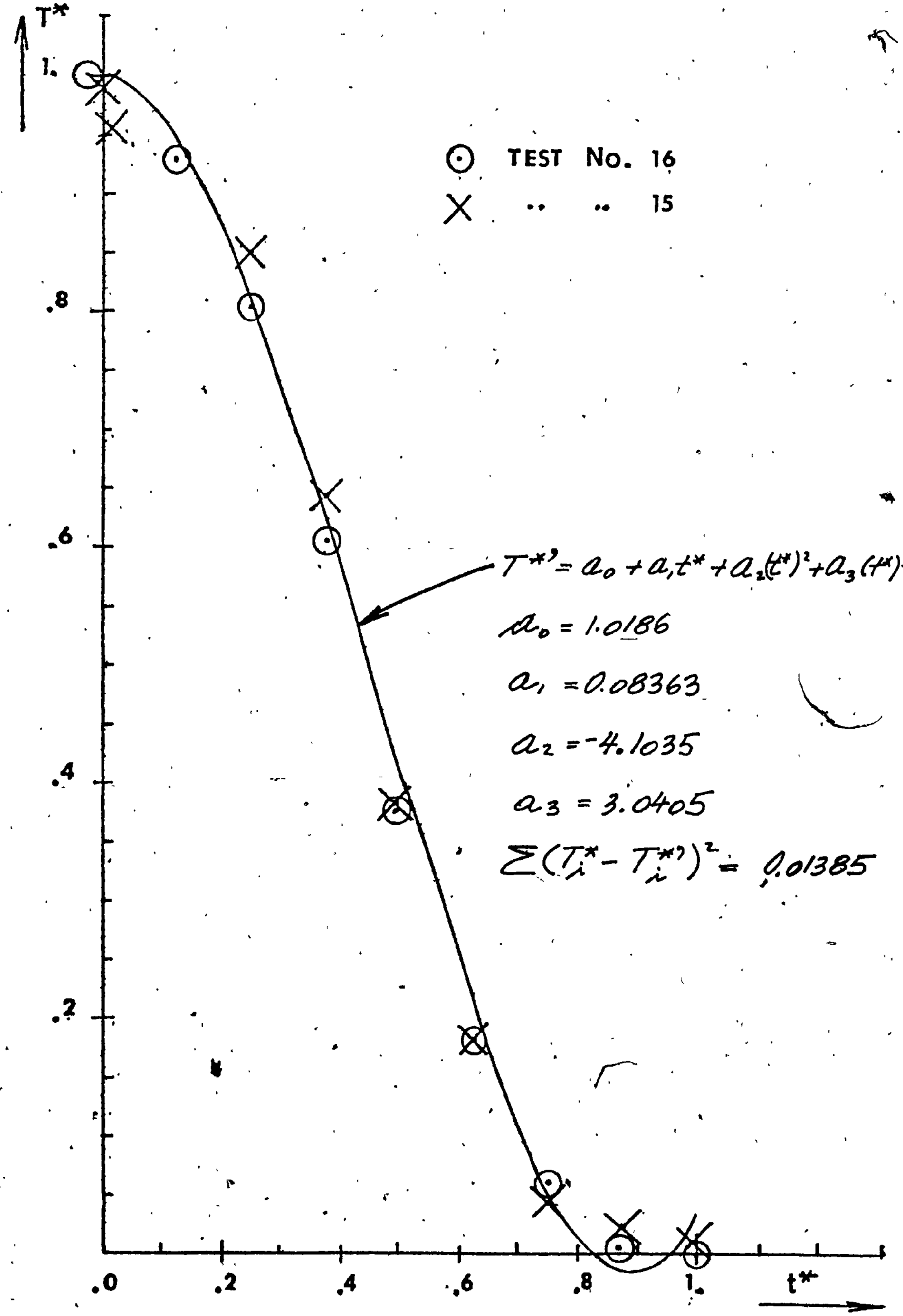


FIG. 20. Non-dimensional Temperature vs. Non-dimensional Time Measured at Thermocouple No. 7

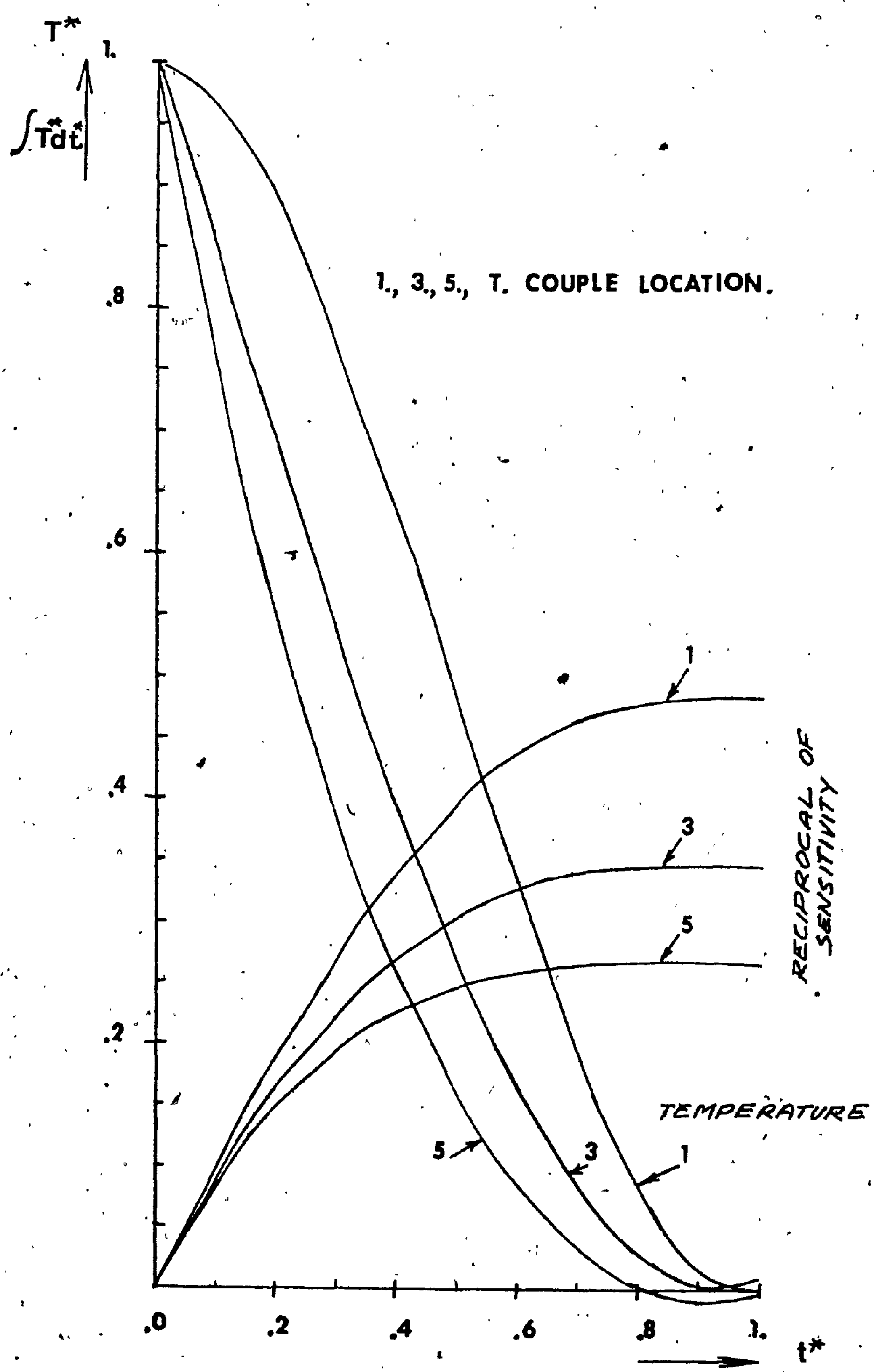


FIG. 21, Reciprocal of Sensitivity and Non-dimensional Temperature vs. Non-dimensional Time on the Surface of the Cover Plate

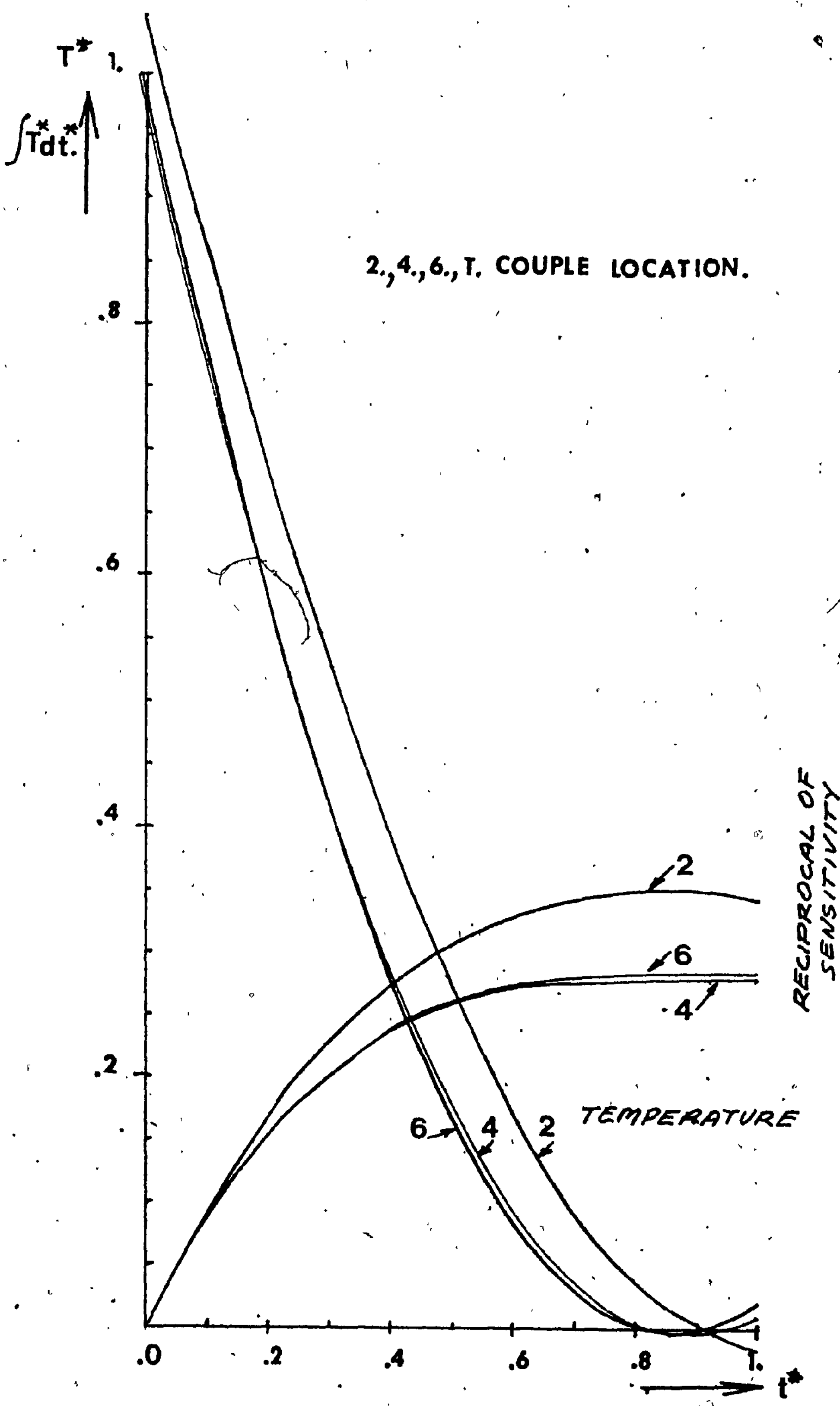


FIG.22. Reciprocal of Sensitivity and Non-dimensional Temperature vs. Non-dimensional Time in the Water

I-1

CLIENT	APPR.	DATE	REV.
CURVE FITTING LEAST SQUARES REGRESSION OF		JULY 20 1979	1 of 2
PROJ. $Y = a_0 + a_1 x + a_2 x^2 + a_3 x^3$	OBJET/SUBJECT		

Step	Key	Reg.	Step	Key	Reg.	Step	Key	Reg.	Step	Key	Reg.
1	A f LBL A	y x	29	×	x^5	57	−		85	RCL 3	a_{33} S_3
2	STO B	y	30	→ STO+5	x^5	8	→ STO A	A_{22}	6	RCL B	A_{21}
3	h ↓		1	1		9	RCL 3	a_{32} S_3	7	RCL 2	A_{31} S_2
4	STO A	x	2	→ STO+0	N	60	RCL C	A_{31}	8	×	
5	→ STO+1	x	3	RCL 0 h RTN		1	RCL 1	A_{13} S_1	9	−	
6	f P⇄S	x	4	B f LBL B		2	×		90	→ STO A	A_{33}
7	RCL B	y x	5	RCL 1	a_{21} S_1	3	−		1	RCL 4	a_{34} S_4
8	→ STO+0	y	6	RCL 0	A_1 S_0	4	RCL A	A_{22}	2	RCL B	A_{21}
9	×	xy	7	÷		5	÷		3	RCL 3	A_{41} S_3
10	→ STO+1_s	xy	8	→ STO B	A_{21}	6	→ STO 9	A_{32}	4	×	
1	RCL A	x	9	RCL 2	a_{31} S_2	7	RCL 4	A_{42} S_4	5	−	
2	×		40	RCL 0	A_1	8	RCL D	A_{41}	6	→ STO 0	A_{34}
3	→ STO+2_s	x^2y	1	÷		9	RCL 1	A_{12}	7	RCL 4	S_4
4	RCL A	x	2	→ STO C	A_{31}	70	×		8	RCL 9	A_{32}
5	×		3	RCL 3	a_{41} S_4	1	−		9	RCL A	A_{33}
6	→ STO+3_s	x^3y	4	RCL 0	A_1	2	RCL A	A_{22}	100	×	
7	f P⇄S		5	÷		3	÷		1	RCL C	A_{31}
8	RCL B	y	6	→ STO D	A_{41}	4	→ STO B	A_{42}	2	RCL 2	A_{13} S_2
9	÷	x^3	7	f P⇄S		5	f P⇄S		3	×	
20	→ STO+3	x^3	8	RCL 0	K_0	6	RCL 1_s	K_1	4	+	
1	g x^2	x^6	9	f P⇄S		7	f P⇄S		5	−	
2	→ STO+6	x^6	50	RCL 0	A_{11}	8	RCL E	A_{51}	6	→ STO 1	A_{33}
3	RCL A	x	1	÷		9	RCL 1	A_{12}	7	RCL 5	a_{43} S_5
4	g x^2	x^2	2	→ STO E	A_{51}	80	×		8	RCL 8	A_{42}
5	→ STO+2	x^2	3	RCL 2	a_{22} S_2	1	−		9	RCL A	A_{33}
6	g x^2	x^4	4	RCL B	A_{21}	2	RCL A	A_{22}	110	×	
7	→ STO+4	x^4	5	RCL 1	A_{12} S_1	3	÷		1	RCL D	A_{41}
8	RCL A	x	6	×		4	→ STO 7	A_{52}	112	RCL 2	A_{13} S_2

REGISTERS:

	0	1	2	3	4	5	6	7	8	9
	N, A_{11}, a_0	Σx, A_{44}, A_{35}, a_1	Σx^2, A_{53}, a_2, a_3	Σx^3, A_{43}	Σx^4	Σx^5	Σx^6	A_{52}	A_{42}	A_{32}
S	y	(xy)	(x^2y)	(x^3y)						

A	B	C	D	E	I
A_{22}, A_{33}, A_{34}	A_{21}	A_{31}	A_{41}	A_{51}	

I-2 1

CLIENT	APPR.	DATE	REV.
THIRD DEGREE POLYNOMINAL FITTING OF DATA BY LEAST SQUARES REGRES.		JULY 20 1979	2 of 2

PROJ. $Y = a_0 + a_1X + a_2X^2 + a_3X^3$

OBJET/SUBJECT

113	X	141	→ STO A A_{34}	169	+	197	+
4	+	2	RCL 6 $^{A_{44}}_{S6}$	170	−	8	RCL B A_{21}
5	−	3	RCL D A_{41}	1	RCL 1 A_{44}	9	RCL 1 a_1
6	RCL 1 A_{33}	4	RCL 3 A_{14}	2	% A_{54}	200	X
7	%	5	X	3	→ STO 3 a_3	1	+
8	→ STO 4 A_{43}	6	RCL 8 A_{42}	4	RCL 2 A_{53}	2	− a_0
9	f P⇄S	7	RCL 0 A_{24}	5	RCL 4 A_{43}	3	→ STO 0 a_0
120	RCL 2_S K_2	8	X	6	RCL 3 a_3	4	h RTN
1	f P⇄S	9	+	7	X	5	
2	RCL 7 A_{52}	150	RCL 4 A_{43}	8	− a_2	6	
3	RCL A A_{33}	1	RCL A A_{34}	9	→ STO 2 a_2	7	
4	X	2	X	180	RCL 7 A_{52}	8	
5	RCL E A_{51}	3	+	1	RCL 8 A_{42}	9	
6	RCL 2 $^{A_{13}}_{S2}$	4	−	2	RCL 3 a_3	210	
7	X	5	→ STO 1 A_{44}	3	X	1	
8	+	6	f P⇄S	4	RCL 9 A_{32}	2	
9	−	7	RCL 3_S K_3	5	RCL 2 a_2	3	
130	RCL 1 A_{33}	8	f P⇄S	6	X	4	
1	%	9	RCL 2 A_{53}	7	+	5	
2	→ STO 2 A_{53}	160	RCL A A_{34}	8	− a_1	6	
3	RCL C A_{31} / RCL 5 $^{a_{43}}_{S5}$	1	X	9	→ STO 1 a_1	7	
4	RCL 3 A_{24}	2	RCL 7 A_{52}	190	RCL E A_{51}	8	
5	X	3	RCL 0 A_{24}	1	RCL D A_{41}	9	
6	RCL 9 A_{32}	4	X	2	RCL 3 a_3	220	
7	RCL 0 A_{24}	5	+	3	X	1	
8	X	6	RCL E A_{51}	4	RCL C A_{31}	2	
9	+	7	RCL 3 $^{A_{14}}_{S3}$	5	RCL 2 a_2	3	
140	−	8	X	6	X	224	

I-3

CLIENT	APPR.	DATE	REV.
CURVE FITTING (LEAST SQUARES REGRESSION OF		JULY 2 1979	

PROJ.	OBJET/SUBJECT
$Y = cX^a + dX^b + 1$	

Step	Key	Step	Key	Step	Key	Step	Key
113 1	A g LBL A f a	29	STO+8	57	STO A c	85	STO E
2	STO 2	30	RCL 9	175 8	h RTN	6	RCL B
3	h↓	1	g x^2	9		7	×
4	STO 1	2	STO+7	60	Solution of equ.	8	RCL E
5	h RTN	3	h RTN (f P⇄S, STO+0, RCL 0, f P⇄S)	1	$y = cx^a + dx^b + 1$	9	g x^2
6	B g LBL B y_i x_i	151 4	C g LBL C	178 2	D f LBL D x	90	RCL C
7	STO 0 y_i	5	RCL 8	3	ENT↑ x x	1	×
122 8	h↓	6	RCL 4	4	STO E x x	2	+
9	STO 3 x_i	7	×	5	RCL 1 a x	3	RCL A
10	RCL 1	8	RCL 6	6	h y^x x^a	4	+
123 1	h y^x	9	RCL 5	7	h x⇄y x x^a	5	STO D
2	STO A	40	×	8	RCL 2 b x x^a	6	RCL E
3	RCL 0	1	−	9	h y^x x^b x^a	7	h x⇄y
4	×	2	RCL 7	70	RCL B d x^b	269 8	h RTN
5	STO+6	3	RCL 5	1	× dx^b x^a	9	
6	RCL 0	161 4	×	2	h x⇄y x^a dx^b	100	
7	RCL 3	5	RCL 5	3	RCL A c x^a	1	
8	RCL 2	6	g x^2	4	× cx^a dx^b	2	
9	h y^x	7	−	5	+ y 1	3	
20	STO 9	167 8	÷	6	STO D y +	4	
1	×	9	STO B d	7	RCL E x y	5	
2	STO+4	50	RCL 5	8	h x⇄y y x	6	
3	RCL A	1	×	193 9	h RTN	7	
4	RCL 9	2	RCL 6	80		8	
5	×	3	h x⇄y	1	Solution of equ.	9	
6	STO+5	4	−	2	$y = a_0 + a_1x + a_2x^2$	110	
7	RCL A	5	RCL 8	194 3	E f LBL E x_0	1	
28	g x^2	56	÷	4	ENT↑	112.	

REGISTERS

0	1	2	3	4	5	6	7	8	9
y_i	a	b	x_i	$\Sigma x_i y_i$	Σx_i^{a+b}	$\Sigma x_i^a y_i$	Σx_i^{2b}	Σx_i^{2a}	x_i^b

50	51	52	53	54	55	56	57	58	59

A	B	C	D	E	I
x_i^a, c	d	i	y_0	x_0	

I-4

CLIENT	APPR.	DATE	REV.
CURVE FITTING PARABOLA (LEAST SQUARES FIT)		JULY 2 1979	
PROJ. $y = a_0 + a_1 x + a_2 x^2$	OBJET/SUBJECT		

1	A f LBL A	$Y_m X_m$	29	RCL 9	n a	57	RCL 9	$n, a, f,$	85	RCL 9	n p
2	STO A	Y X	30	RCL 3	Σx^2y n a	8	RCL 0	$\Sigma x^4, n, a, f.$	6	RCL 1	$\Sigma x^3, n\, p$
3	h x⇄y	X Y	1	×	$n\Sigma x^2y$ a	9	×	$n\Sigma x^4, a, f$	7	×	$n\Sigma x^3, p$
4	STO B	X Y	2	RCL 5	Σx^2 a	60	RCL 5	Σx^2 a f	8	RCL 4	$\Sigma x, \, , p$
5	g x^2	X^2Y	3	RCL 6	Σy Σx^2 a	1	g x^2	$(\Sigma x^2)^2$ a f	9	RCL 5	$\Sigma x^2, \Sigma x, \, , p$
6	×	X^2Y	4	×	$\Sigma y\Sigma x^2, n\Sigma x^2y, a$	2	−	g, a, f, f	90	×	$\Sigma x\Sigma x^2, \, , p$
7	→ STO+3	ΣX^2Y	5	−	b a	3	×	i f	1	−	r, p
8	RCL B	X	6	×	e	4	RCL 1	$\Sigma x^3, i$ f	2	RCL C	a_2, r, p
9	3		7	STO 2	e	5	RCL 9	n $\Sigma x^3, i, f$	3	×	s, p
10	h y^x	X^3	8	RCL 9	n e	6	×	$n\Sigma x^3$ i f	4	−	v, p
11	→ STO+1	ΣX^3	9	RCL 8	$\Sigma xy, n, e$	7	RCL 4	Σx i, f	5	RCL B	a, v, p
12	RCL B	X	40	×	$n\Sigma xy, e$	8	RCL 5	Σx^2 i, f	6	÷	a_1, p
13	×	X^4	1	RCL 4	Σx e	9	×	$\Sigma x\Sigma x^2$ i, f	7	STO B	a_1 p
14	→ STO+0	ΣX^4	2	RCL 6	Σy Σx e	70	−	l, f	8	RCL 6	Σy p
15	RCL A	Y	3	×	$\Sigma x\Sigma y$ e	1	g x^2	l^2 f	9	RCL 5	$\Sigma x^2, \Sigma y, p$
16	RCL B	X, Y	4	−	c, e	2	−	r	100	RCL C	a_2 $\Sigma x^2, \Sigma y, p$
17	f P⇄S		5	RCL 9	n, c, e	3	RCL 7	Σy^2	1	×	$a_2\Sigma x^2, \Sigma y, p$
18	Σ+	Σ+	6	RCL 1	$\Sigma x^3, n, c, e$	4	h x⇄y	σ Σy^2	2	−	w, p
19	f P⇄S		7	×	$n\Sigma x^3, c, e$	5	÷	a_2	3	RCL 4	$\Sigma x, w, p$
20	h RTN		8	RCL 4	Σx c, e	6	CHS		4	RCL B	a_1 $\Sigma x, w, p$
21	B f LBL B		9	RCL 5	Σx^2 $, c$	7	STO C	a_2	5	×	$, w, p$
22	RCL 9	n	50	×	$\Sigma x\Sigma x^2$ c, c	8	RCL 9	n	6	−	t p
23	RCL 5	Σx^2 n	1	−	d, c, c, c	9	RCL 8	Σxy	7	RCL 9	n, t, p
24	×	Σx^2_m	2	×	h	80	×	$n\Sigma xy$	8	÷	a_0
25	RCL 4	Σx	3	RCL 2	e	1	RCL 4	Σx	9	STO A	a_0
26	x^2 g	$(\Sigma x)^2$	4	−	f	2	RCL 6	Σy	110	h x⇄y	
27	−	a	5	STO .7	f	3	×	$\Sigma x\Sigma y$	1	RCL C	
28	STO B	a	56	RCL B	a, f	84	−	p	112	h RTN	

$i = g \cdot a$ $\quad$ $l = i - \Sigma x\Sigma x^2$ $\quad$ $f = h - e$ $\quad$ $h = dc$

Σ+

REGISTERS

0	1	2	3	4	5	6	7	8	9
Σx^4	Σx^3	e	Σx^2y	Σx	Σx^2	Σy	Σy^2	Σxy	Σn
30	31	32	33	34	35	36	37	38	39

A	B	C	D	E	I
Y_m, a_0	x_m, a_1	a_2			

$a = n\Sigma x^2 - (\Sigma x)^2$

$b = n\Sigma x^2y - \Sigma x^2\Sigma y$

$e = a \times b$

$c = n\Sigma xy - \Sigma x\Sigma y$

$d = n\Sigma x^3 - \Sigma x\Sigma x^2$

$f = n\Sigma x^4 - (\Sigma x^2)^2$

$a_0 = t/n$

$t = w - a_1\Sigma x$

$v_1 = \Sigma x\, w$

$p = \Sigma y - a_2\Sigma x^2$

$a_1 = \frac{v}{a}$

CTL 0060-0-01

$v = p - s$ | $s = a_2 r$ | $r = n\Sigma x^3 - \Sigma x\Sigma x^2$ $\quad p = n\Sigma xy - \Sigma x\Sigma y$ $\quad a_2 = \frac{\Sigma y^2}{\sigma}$ | $\sigma = f - l^2$

TEST-20

TIME ↓ 10" | P ↓ | 15 | 6 | 4 | 2 | THERMO COUPLES.

TIME	P	15		6		4		2	
0'-0"	40.5 (psig)	22.		24.0		23.		22.2	
	19.5	17820.	349.98 °C	4980.	114.85 °C	4750	110.04 °C	4362.	101.82 °C
0.1"	31								
	14.68								
1"	25.5	22.5		24.5		23.3		22.4	
	11.90	17825.	350.07	4990.	115.06	4753	110.10	4364.	1.86
2"	21.5	23.		20.0		23.8		22.6	
	10.88	17830	0.15	4900.	113.18	4758	110.20	4366.	1.91
						3.5" 26.0			
4"	16.0	23.5		11.		20.0		23.0	
						4780.	110.66		
	7.08	17835	0.23	4720.	109.41	4720.	109.41	4370	102.00
6"	11.0	24.0		4		5.0		22.0	
	4.55	17840	0.32	4580.	106.44	4570.	6.23	4360	1.78
8"	7.5	23.0		-2.		-6.0		26.0	
	2.78	17830	0.15	4460.	3.89	4460.	3.90	4400	102.63
								9" 28	
10"	4.0	22.0		-7.0		-16.0		27.	
								4420	3.05
	1.01	17820	349.98	4360.	1.78	4360.	1.78	4410	2.84
12"	2.5	21.0		-9.0		-22.0		22.5	
	0.25	17810	9.82	4320.	100.93	4300.	100.51	4365.	1.89
14"	2.0	19.8		-10.5		-24.0		19.0	
	0.0	17798.	9.62	4290.0	100.30	4280.	100.08	4330.	1.14
16"		18.6		-11.0		-25.0		15.0	
		17786	9.42	4280.0	100.08	4270.	99.85	4290.	100.30
18"		18.3		-11.		-25.0		9.0	
		17783	9.37	4280.0	100.08	4270	99.85	4230	98.99
20"		18.0		-11.		-25.5		2.0	
		17780	9.32	4280.	100.08	4265.	99.74	4160.	97.49

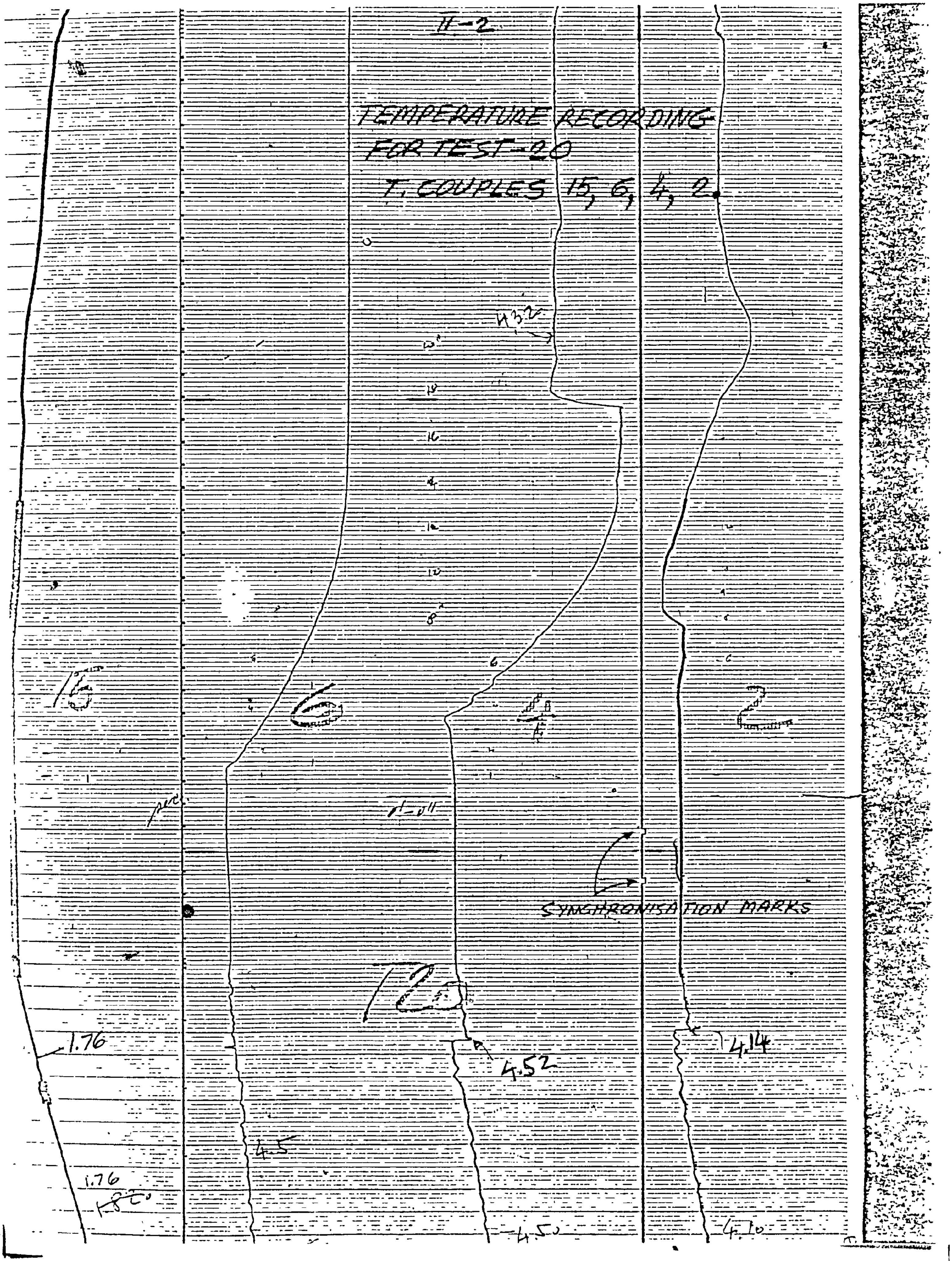
3.5"

Pressure:
(41.5 - 2)/20 = 1.975

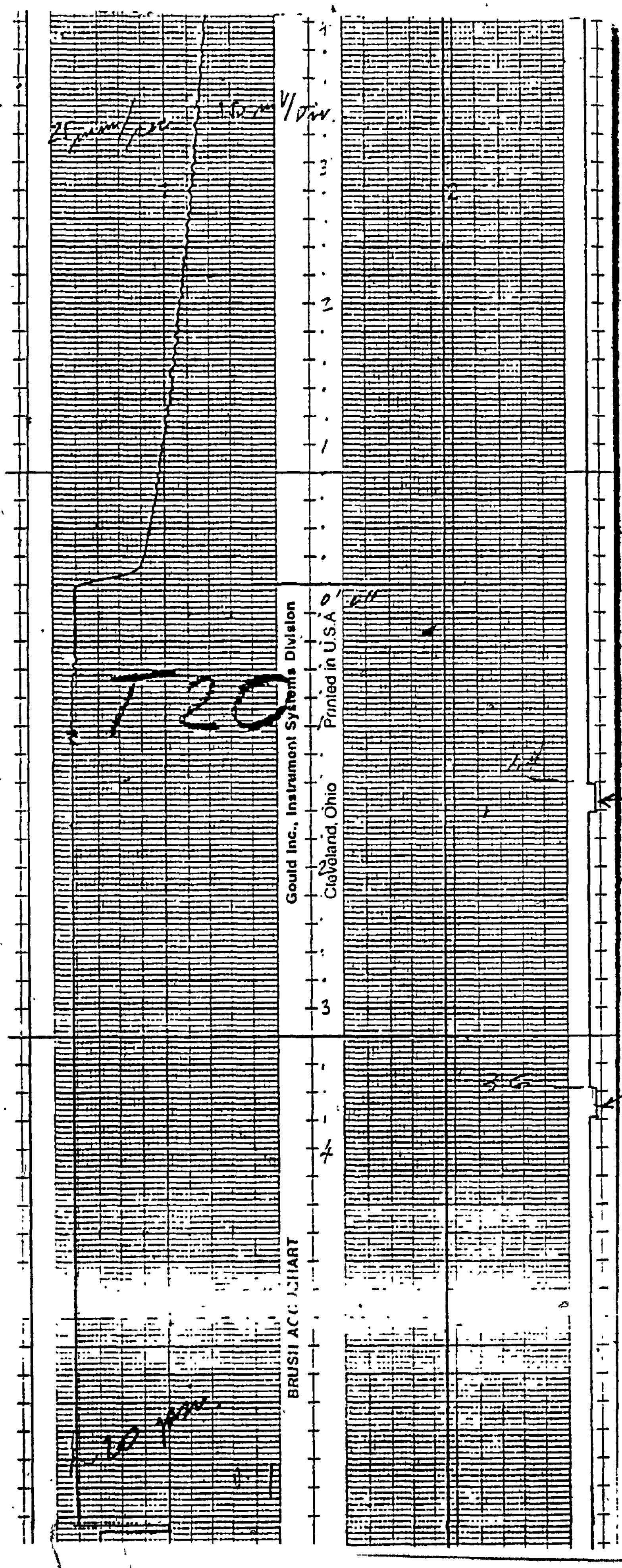
Temp. 17600 ... | 17600 µV | 4500 µV | 4520 µV | 4160 µV |

220 = 22 × 10
17820

10 µV/DIV | 20 µV/DIV | 10 µV/DIV | 10 µV/DIV


TEMPERATURE RECORDING
FOR TEST-20
T. COUPLES 15, 6, 4, 2.
15
6
4
2
SYNCHRONISATION MARKS
T2
1.76
4.52
4.14
4.5
1.76
1.80
4.50
4.10

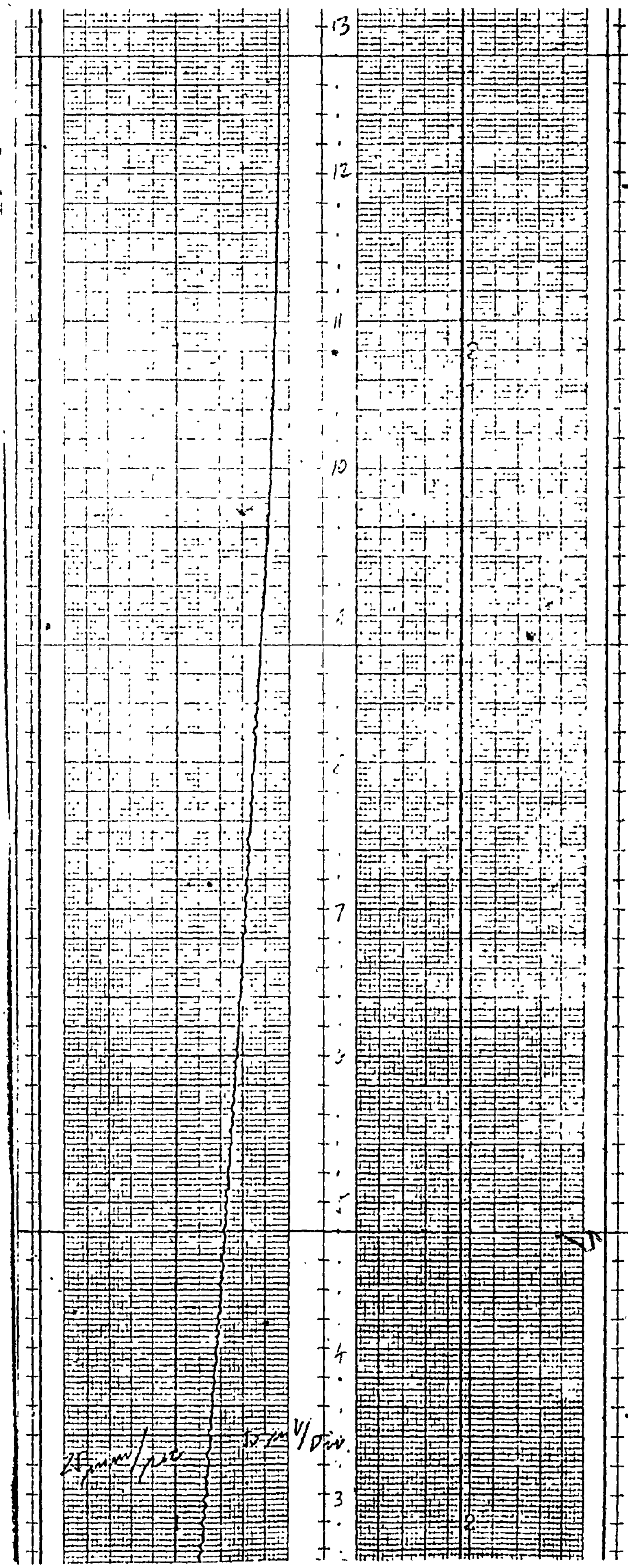
II-3.0 ↑ CONTD. ON II-3.1



PRESSURE
RECORDING
FOR TEST-20

SYNCHRONISATION
MARKS

II-3.1



II-3.1

CONTD
FROM
II-3.0

II-4

TEST-18

THERMO COUPLES

TIME	p (psig.)	15		7		5		3	
0'-0" (10")	49	16		20.5		23		21	
	22.6	17560	345.64 °C	4605	106.97 °C	5450	124.68 °C	5320	121.96 °C
0.1"	35			20.5		23			
	15.26					5450			
1"	31	16		20.5		17		21	
	13.16	17560	345.64			5150	118.40	5320	121.96
2	27	15.6		20.5		15		19.5	
	11.05	17556	5.57	4605	106.97	5050	116.31	5290	121.33
4	22	15.0		20.		11		9.	
	8.42	17550	5.47	4600.	6.86	4850	112.13	5080	116.94
8	13	13.0		12.5		5		-13.0	
	3.68	17530	5.14	4575	6.33	4550	105.81	4640.	107.71
12	7.5	7.0		4.0		1		-24.0	
	0.80	17470	4.14	4440	103.47	4350	101.57	4420	103.05
16	6.5	4.0		-4.0		-0.5		-19.0	
	1.26	17440	3.64	4360	101.78	4275	99.96	4320	100.91
20	6.0	0.0		-1.5		-1.0		-18.0	
	0.0 psi	17400.	2.97	4385.	102.31	4250	99.43	4340	101.36
24	6.0								

6	[illegible]		8.		-4.0	
	[illegible]	16.50	4700	109.00	4820	111.51
10	10.25		2.5		-19.0	
	4502	104.80	4425	103.15	4520	105.17
14	4.0		0.5		-29.	
	4400	102.62	4325	100.5*	4370	102.0
18	-2.0		-1.75		-16.5	
	4380	102.19	4262	99.69	4330	101.13

44-6/20 8.90

17400 + 160 = 10 × 16 → 17560

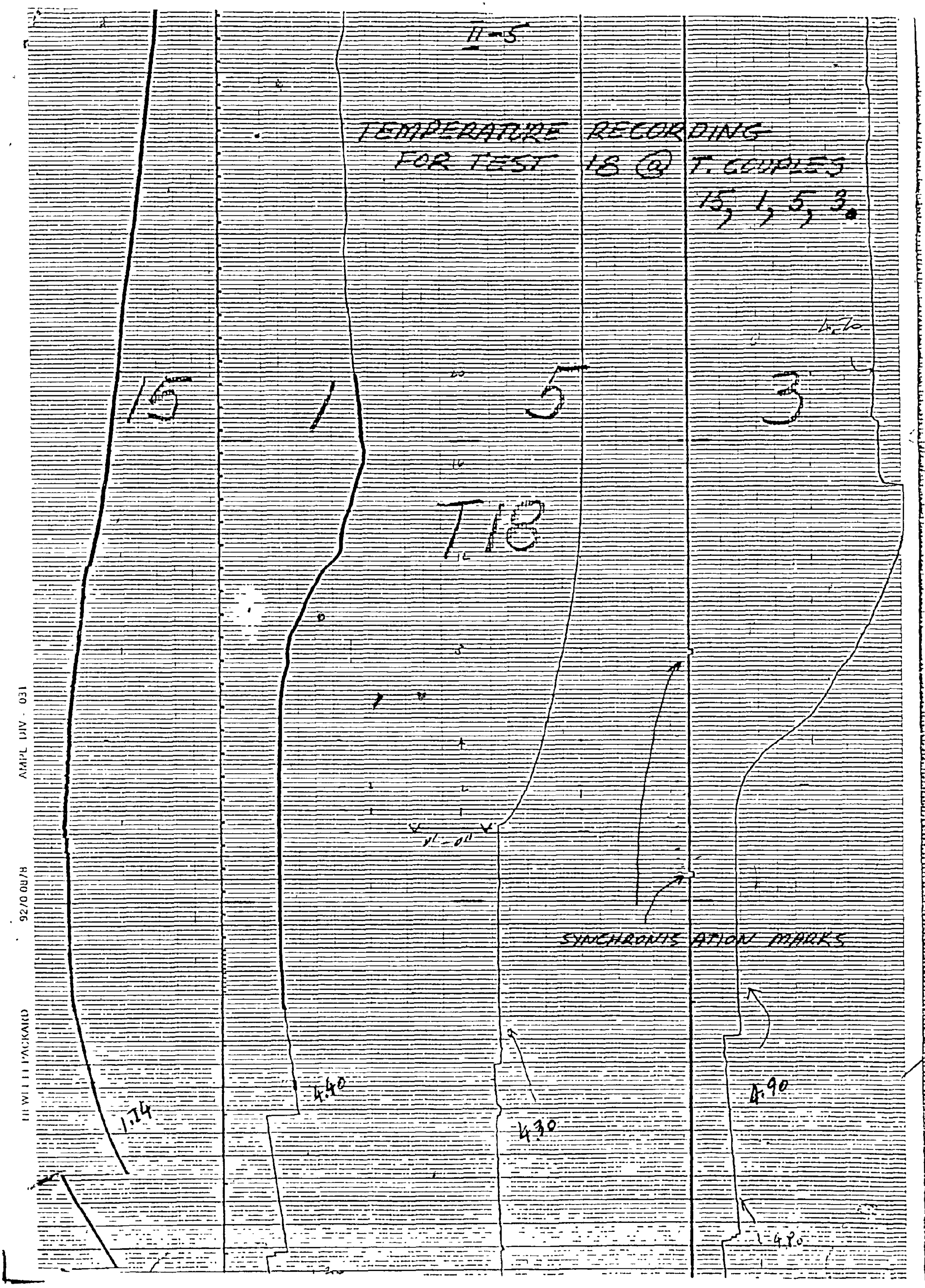
4400 + 205 = 20.5 × 10 → 4605

4300 + 1150 = 23 × 50 → 5450

4900 + 420 = 21 × 20 → 5320

1 17400. μV 1 | 4400. μV 1 | 4300. μV 1 | 4900. μV 1 4700.

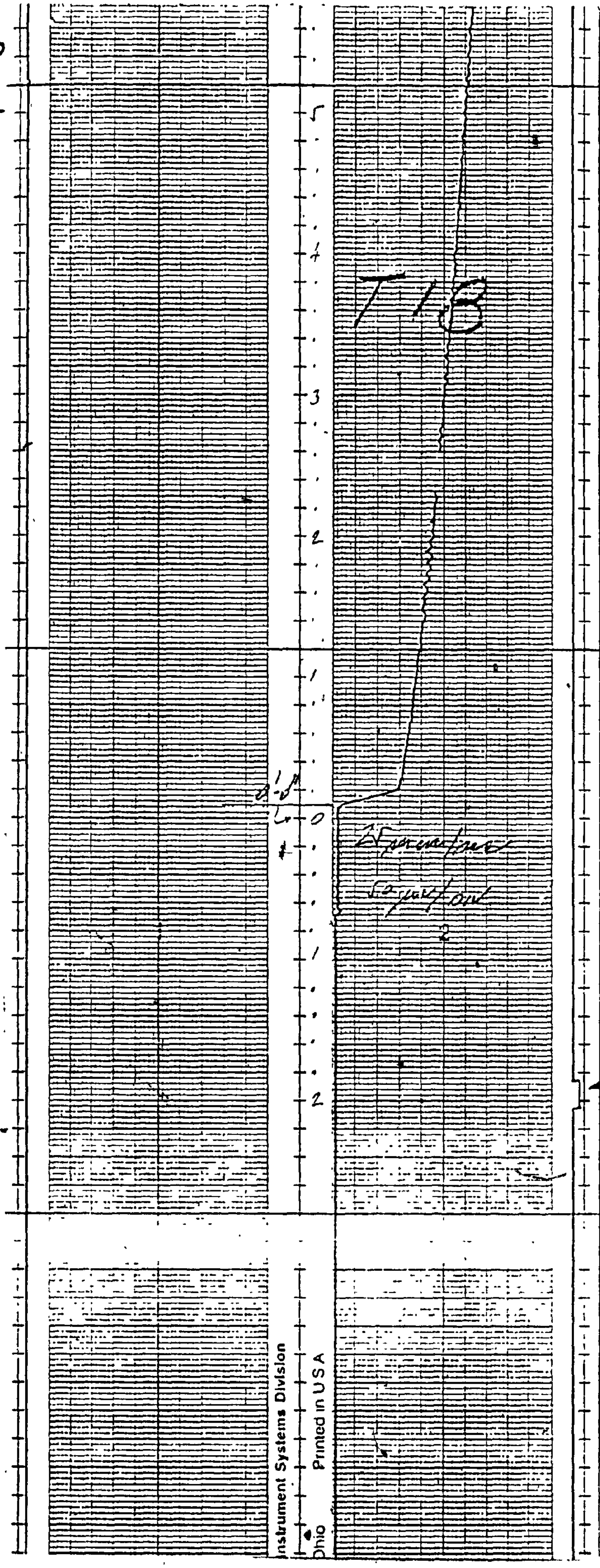
10 μV/DIV | 10 μV/DIV | 50 μV/DIV | 20 μV/DIV


II-5
TEMPERATURE RECORDING
FOR TEST 18 @ T. COUPLES
15, 1, 5, 3.
15
1
5
3
T18
SYNCHRONISATION MARKS
1.74
4.40
4.30
4.90
4.80
HEWLETT PACKARD 9270 0876 AMPL DIV 031

II-6.0

↑ CONTD. ON II-6.1

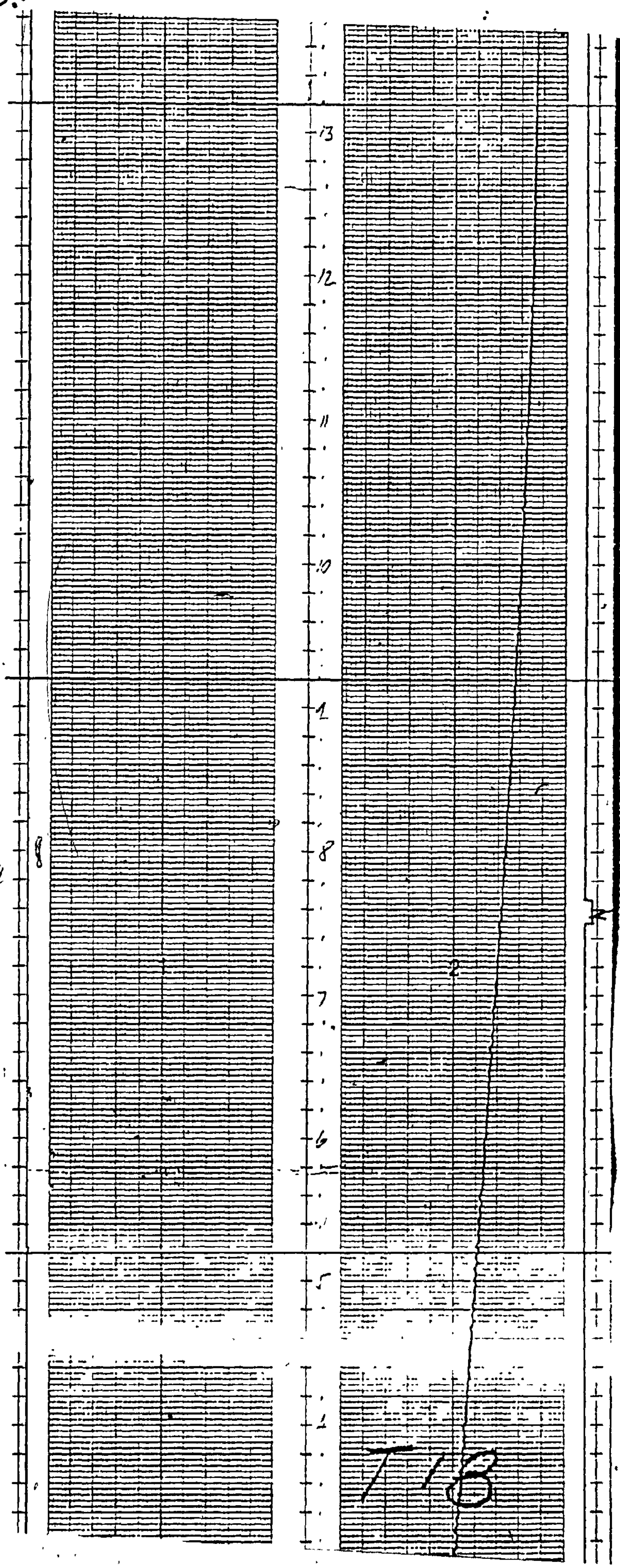
PRESSURE RECORDING FOR TEST 18.



SYNCHRONISATION MARK

II-6.1

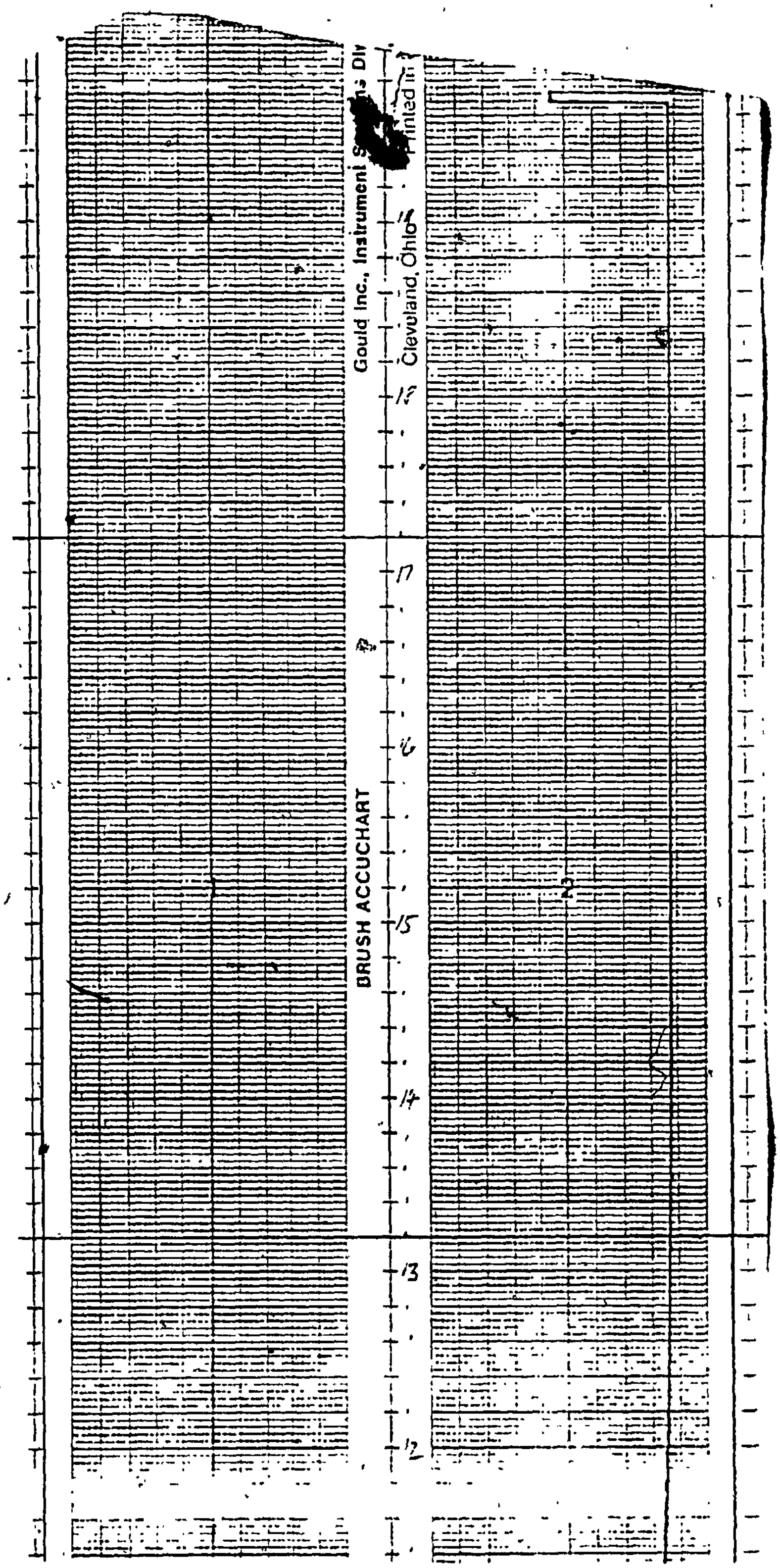
CONTD. ON II-6.2



SYNCHRONISATION MARK.

FROM II-6.0

II-6.2



↑ CONTD. FROM II-6.1