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Initial Report on Calorimetry for the Tore Supra Outboard Pump Limiter

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ABSTRACT

This report describes the instrumentation locations of the Tore Supra Phase III Outboard Limiter, including the locations and signal names of the flowmeters and thermocouples. Shot 11044 was evaluated in some detail. The heat loads in the fourteen cooling tubes that form the limiter head were calculated from the data and the results compared with the heat loads predicted using a 3-D model heat transfer calculation that calculates the distribution of power on the limiter based upon the power scrape-off length, the mag magnetic configuration and the shape of the limiter.

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Table of Contents

1.0 Measurements of Water Flow and Water Temperature	1
2.0 Data for Shot 11044	6
3.0 Comparison of Calorimetric Results with Modeling of Heat Load	11
4.0 Development of User Access for Calorimetry Data from the Limiter	14
Appendix A: Diagnostic Names and Locations	A1
Appendix B: Calorimetric Data for Shot 11044	B1

Tables

Table 1: Results of Calorimetry for Shot 11044	10
Table 2: Comparison of Calorimetric Results for Shot 11044 with Results from 3-D Model of Heat Load on Limiter	13

List of Figures

Figure 1: Piping in the Phase III Outboard Pump Limiter 2

Figure 2: Flow through exit line from central header 3

Figure 3: Inlet water temperature for Tube 2I 4

Figure 4: Outlet water temperature for Tube 2I 5

Figure 5: Outlet flow in Tube 7I 6

Figure 6: Temperature at outlet on leading edge Tube 7I 8

Figure 7: Tube 7 tile cross section 8

Figure 8: Outlet water temperature in Tube 7I measured downstream at manifold 9

Figure 9: Comparison of calculated heat distribution with calorimetry for Shot 11044 11

Figure 10: Sample on-screen output of calorimetry program for users 14

Initial Report on
Calorimetry for the Tore Supra Outboard Pump Limiter

R. E. Nygren, T. J. Lutz and J. D. Miller
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The objectives of this report are (1) to explain what data are available from thermocouples and flowmeters on the outboard pump limiter (OPL) and (2) to show an example (for shot 11044) of a calorimetric analysis using these data.

Among the positive results during successful operation of the limiter on Thursday and Friday, May 13th and 14th, 1993, was confirmation that 30 of the 32 thermocouples and all 10 flowmeters operated well and provided useful data for calorimetry on the limiter. Selected data from shot 11044 shows examples of the data available. Additional details are given in Appendices A and B.

With the instrumentation on the Phase III Limiter, we can analyze the heat received by each tube in the limiter head (and the shelves). This information can be used, for example, to calculate λ_q (power scrape-off-length) and total power received by the limiter. During its initial operation, the limiter received about 0.8 MW. The calorimetric data can also be used to discern asymmetries in the power loading on the limiter. Another important use for these diagnostics is to protect the limiter.

Some signals from the limiter will be useful (and we believe absolutely necessary) for the warning systems (interlocks) that are needed to operate the limiter safely. In the past, and including the experiment reported here, the signals from the limiter have been collected only on a dedicated VAX. In the future, it will be necessary to provide some signals directly to the Tore Supra control system.

1.0 Measurements of Water Flow and Water Temperature

Water flow in the OPL is monitored by flowmeters on the 10 exit lines downstream from the fourteen tubes and two shelves on the limiter head.[a] Water temperatures are monitored with 32 thermocouples. Figure 1 shows the piping in the limiter head. Figure A-1 in Appendix A shows the locations of the flowmeters and thermocouples. Tables A1 and A2 give the signal names and locations of the flowmeters and typical flow rates at "full flow" and the signal names and locations of the thermocouples.

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[a]The shelves are just outboard of the throat openings. The shelves each consist of a Glidcop plate bolted to a stainless steel plate on the limiter module. A single water line is pressed into a groove in the Glidcop plate. Graphite armor is bolted to the outside of the shelves. Sets of four Langmuir probes are mounted on the insides of both the ion side and electron side shelves.

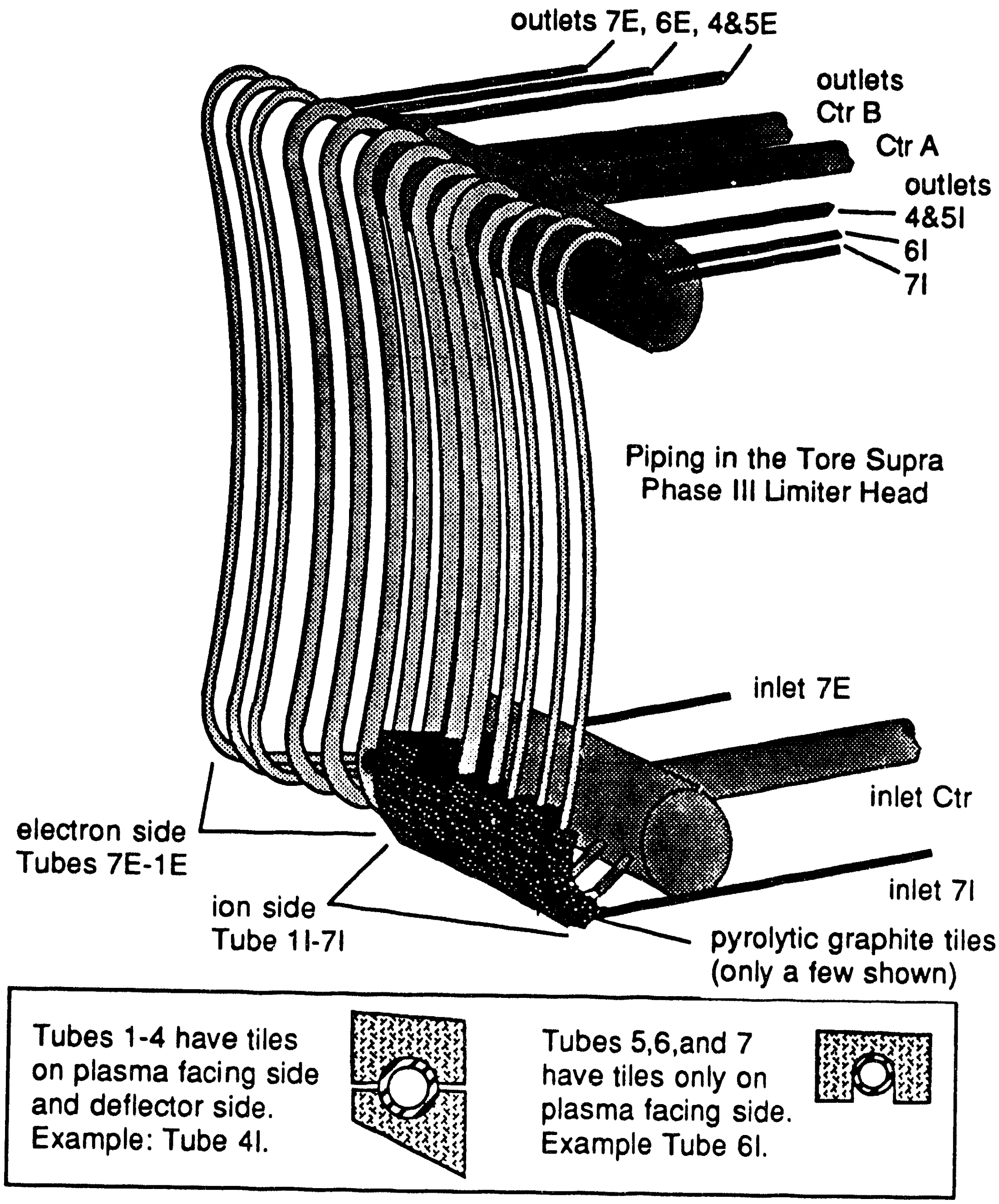

Figure 1. Piping in the Phase III Outboard Pump Limiter -- From left to right the tubes are numbered from 7I (leading edge tube) to 1I on the ion side and 1E to 7E (leading edge tube) on the electron side. The leading edge tubes, 7I and 7E, and Tubes 6I and 6E each have (separate) flowmeters. Tubes 4I and 5I are joined to a single manifold which has a flowmeter; the same is true for 4E and 5E. The center tubes flow into a single header which has two outlet pipes (Center A and Center B). Tubes 1-6 one each side plus the shelves (the heat sink and armor just outboard of the throat) are fed from a single header supplied by one large inlet pipe. The leading edge tubes (7I and 7E) are fed by a separate inlet line that splits into two lines before the diagnostic flange. (See also Figure A1 in Appendix A.)

The general pattern for the flow in all tubes is typified by the flow in one of the two exit lines for the central portion of the limiter for shot 11044, shown in Figure 2. Well before the shot, the flow circuit is at a steady "standby" flow.[c] About 60 seconds before the shot (-60s), the feedwater was changed from warm water to cold water and the flow increased to ~62 gpm (~14.1 m^3/hr) and remained at this value during the shot. About 25 seconds after the start of the shot, the shutdown sequence began and the circuit was isolated (valves closed) while the pumps were switched back to the standby configuration.

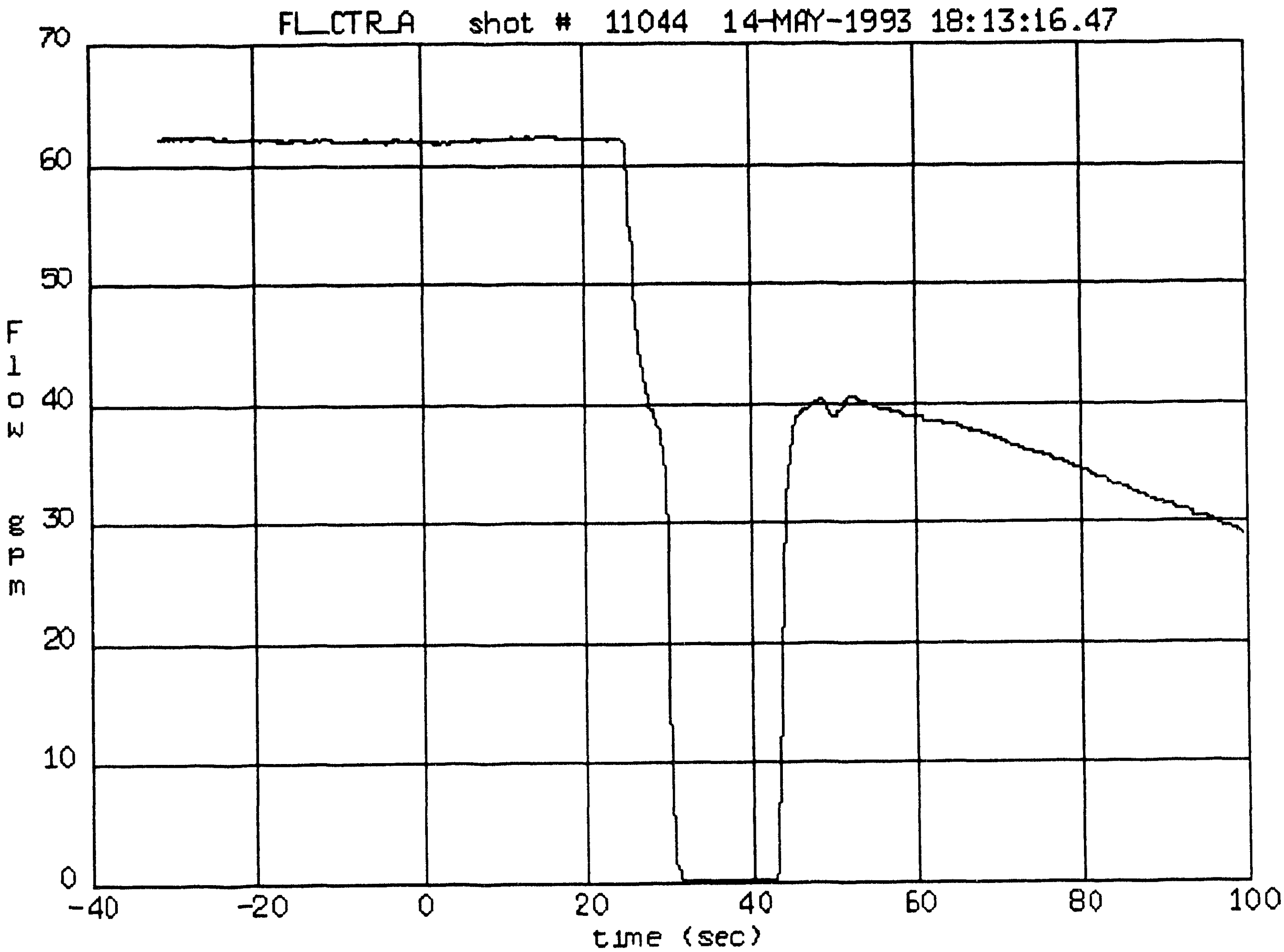

Figure 2. Flow through exit line from central header

Figure 3 (next page) shows the temperature of the thermocouple on the exterior of Tube 2I at the inlet. This location is just downstream of the header that feeds all tubes except the leading edge tubes. After the changeover at -60 seconds, the

[c]The data acquisition system was reinitialized at -30 seconds and data prior to this time is not valid, so the plots do not include this time period.

incoming cold water gained some heat as it passed through the previously hot piping. The temperature was about 32°C just after the flow changed and then decreased to about 25°C at the time the shot began. The inlet temperature (Fig. 3) for Tube 2I appears to have been relatively constant over the duration of the shot except for the offset which occurs during the shot.[d]

Figure 4 (next page) shows the temperature at the outlet of the Tube 2I. A sharp rise in the outlet temperature began at 3 seconds as the plasma contacted the limiter. The outlet thermocouple on Tube 2I, T_T_2I, is just downstream of the heated portion of the tube, on the stainless steel nipple that joins the tube to the outlet pipe. The small spike at 0 seconds is presumed to be an anomalous "signature" as the shot commences.

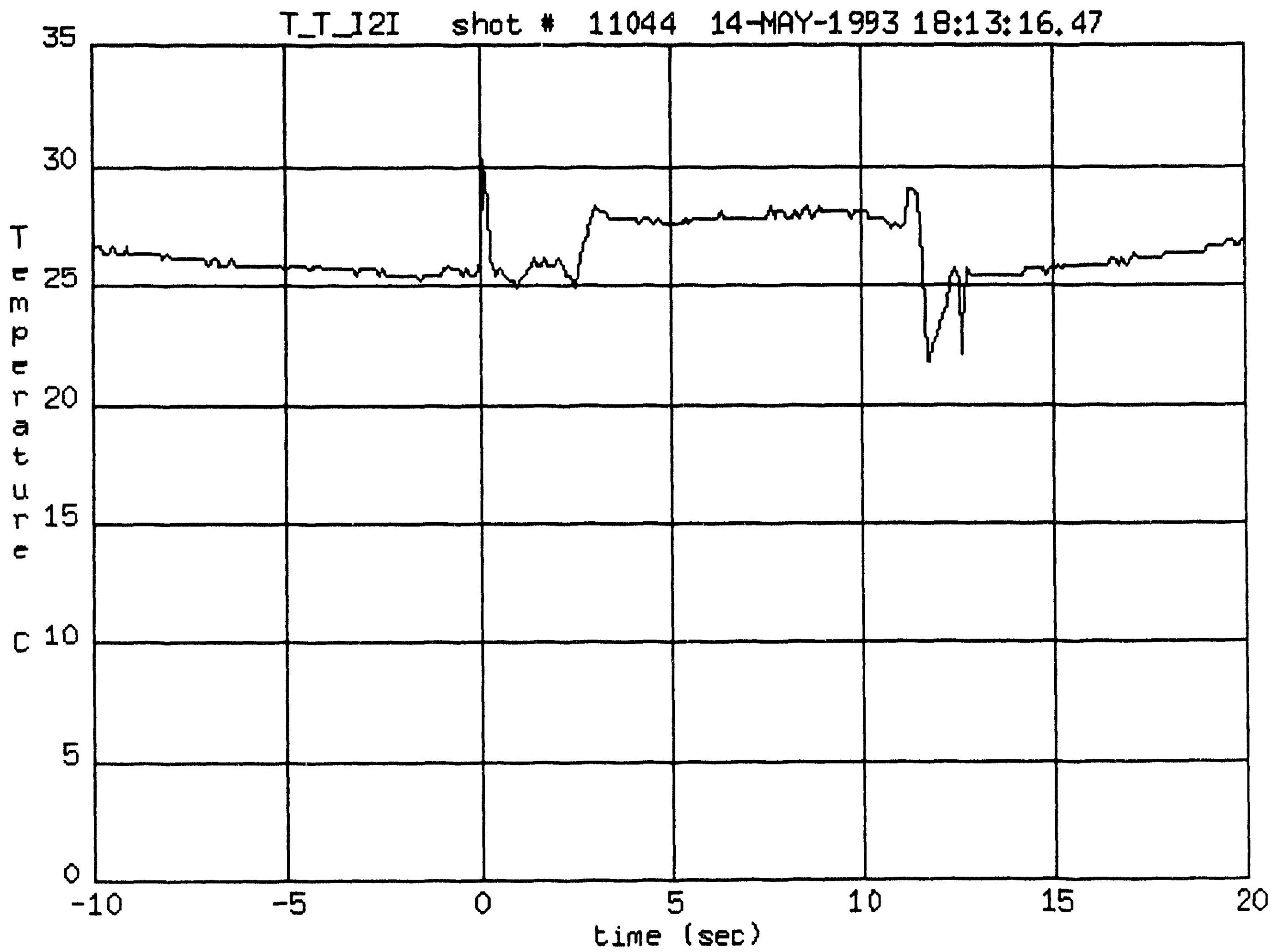

Figure 3. Inlet water temperature for Tube 2I.

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[d]For some signals, an offset appears during the shot while the plasma contacts the limiter and thus must be subtracted from the signal during this time. (See further comments in Appendix B.)

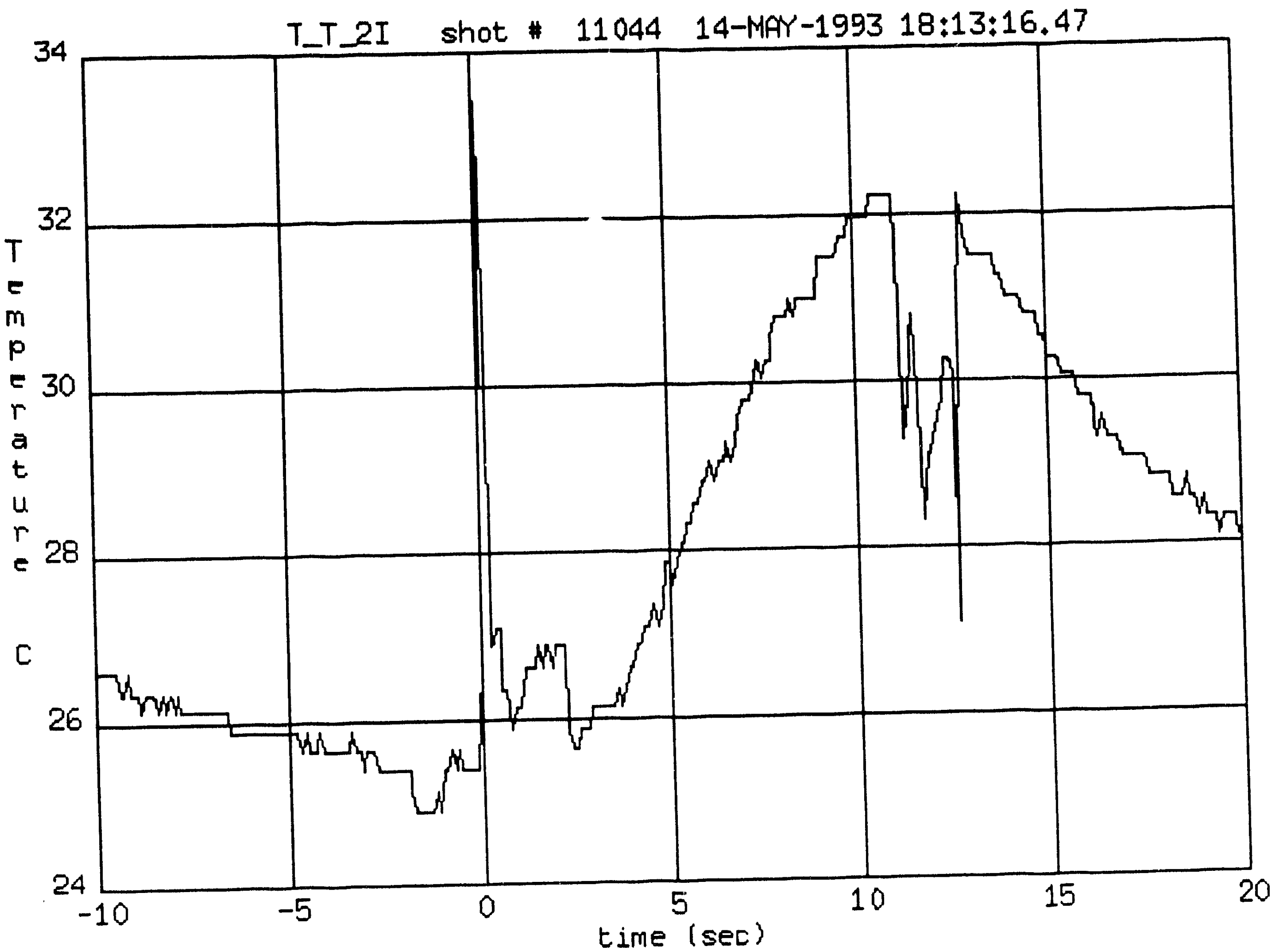

Figure 4. Outlet water temperature for Tube 2I.

The power incident upon Tube 2I can be calculated from the temperature rise of about 9.5°C (and flow parameters). The heat load on Tube 2I includes heating on both the back face (deflector side) and the front face. (This is true for the central portion of the limiter from Tubes 1-4 on each side which constitute the deflector on the back face of the limiter.) The rise of 9.5°C corresponds to a heat gain of about 53 kW. This heat gain, in turn, corresponds to an estimated heat flux on the center tiles of about 267 W/cm^2, based upon heating profiles along the tube from earlier calculations at Sandia. A more complete analysis of this type for all the tubes is presented in the next section.

An analysis of the uncertainties in the calorimetry has not yet been done but a few simple observations can provide some insight. The thermocouples closest to the heat source are those on the outlet of each tube on the limiter head plus the one on the inlet of Tube 2I. These thermocouples, mounted externally on the tubes, are coupled to the water through the thickness of the tube (and its heat capacity). The signals from these thermocouples will lag behind the actual water temperature by some characteristic response time and will slightly underestimate the temperature rise during transient heating. For longer shots, such as 11044, where the temperature rise reaches a constant value, this should not be an issue in interpreting the data. Also, while most of the thermocouples seemed to perform well, some of these thermocouples may be exposed to and affected by the plasma. For example, the thermocouple on the outlet of the electron side leading edge tube (T_T_7E) appears to have been severely affected. (See plot in Appendix B.) The primary sources of uncertainty are (1) the effects of plasma on the thermocouple readings and (2) the projection of a reference temperature from which to subtract the peak temperature as one determines the temperature rise.

2.0 Data for Shot 11044

Shot 11044 was typical of the limiter operation with longer pulses. During this series of shots, the duration over which plasma contacted the limiter started at about 1.5 seconds and then was progressively extended. Typical values of plasma

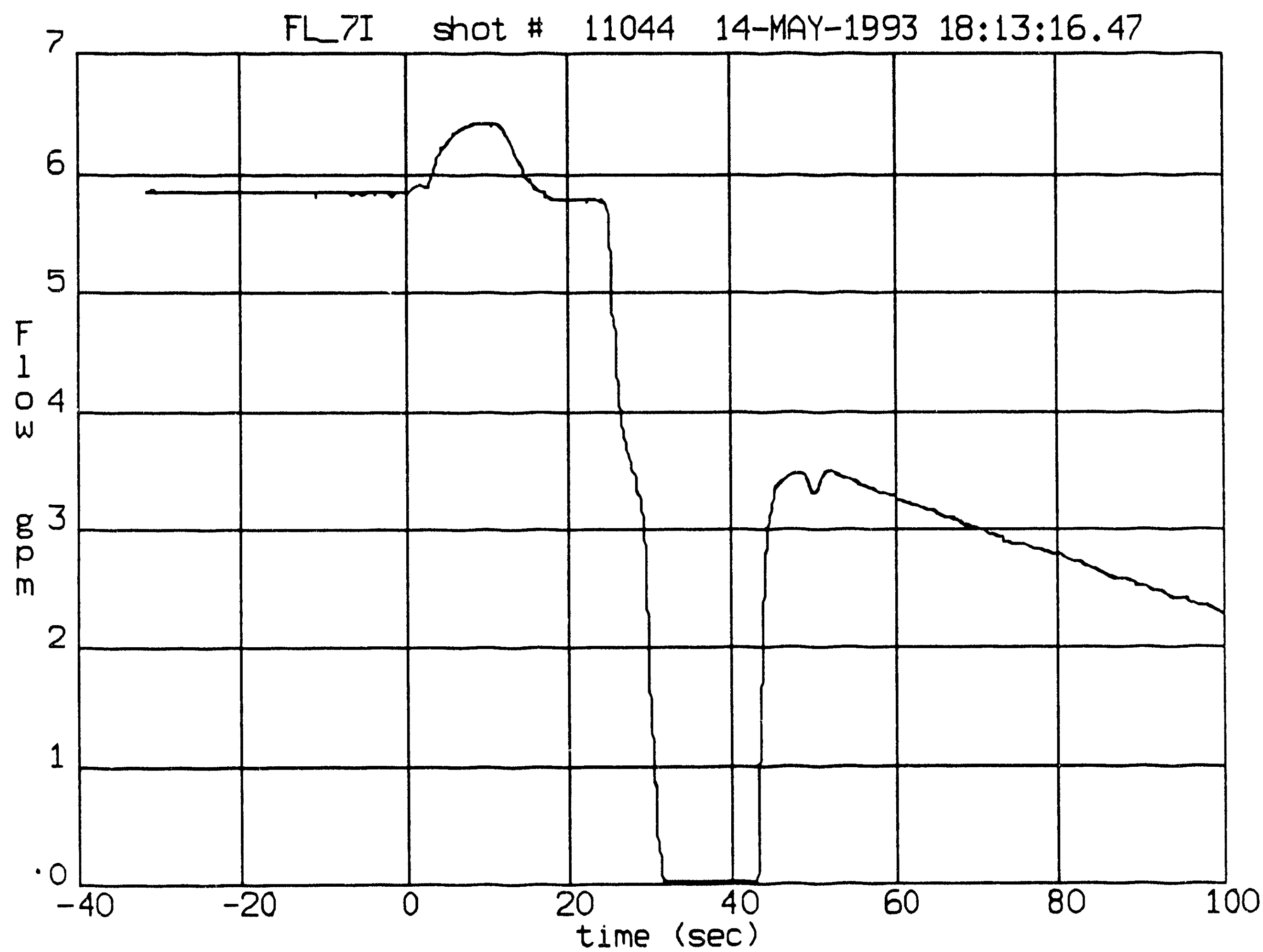

Figure 5. Outlet flow in Tube 7I

density and loop voltage respectively were $3x10^{19}$ m^{-3} and 1.0 V. For shot 11044, the plasma current reached 1.5 MA at 2.1 s (seconds) and remained at this value until rampdown began at 11 s (~9s flattop). The plasma started on the inner wall, moved onto the OPL at about 3 s and contacted the limiter for about 8 s. Appendix B contains a compilation of the signals from thermocouples and flowmeters.

Figure 5 (previous page) shows the water flow in the ion side leading edge tube (7I) over the period including the shot. The leading edge tubes receive most of the attention here because they set the limit for the acceptable heat load to the limiter.[e] The flow was roughly constant at 5.9 gpm (1.34 m^3/hr) during the shot. This flow rate corresponds to a velocity of 10 m/s. During the shot, the flow rate increased slightly, presumably due to the decrease in density with increasing water temperature, the creation of vapor with local boiling, and some decrease in flow resistance due to a slight dilation of the tube.

The signal from thermocouple T_T_7I on the outlet pipe of Tube 7i is shown in Figure 6 (next page). The temperature rose from about 34°C to a maximum of 112°C during the shot. The temperature rise was roughly 80°C but depends on the value chosen to subtract from the peak temperature.

Figure 6 also shows the overall shape of the signal from thermocouple T_T_7I from before to well after the shot. The inlet water temperature decreased during or shortly after the shot and the maximum temperature was determined assuming a decrease of 0.4°C/s. (This differs from Figure 2, T_T_I2I, where the inlet temperature just downstream of the header that supplies all tubes except 7I and 7E, appeared to be relatively constant .)

The estimated temperature rise along tube 7I based on Figure 6 is 81°C. The uncertainty in the "reference" temperature (subtracted from the peak temperature of 112°C to give the temperature rise) corresponds to an uncertainty in the temperature rise of less than 5%.

The temperature rise of 81°C corresponds to a heat load of 135 kW on Tube 7I. This heat load corresponds to a peak heat flux on Tube 7I over its central portion of about 1.7 kW/cm^2.

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[e]The surface curvature of the limiter was designed with a λ_q of 1.0 cm as the reference. With a longer λ_q there is proportionately a greater fraction of the total heat load to the limiter taken by the leading edge. The flawed tiles on tubes 1 and 3 result in lower allowable heat loads for these tubes but the leading edge tubes still appear to have the more stringent limits. These comparative analyses will be reported in the future.

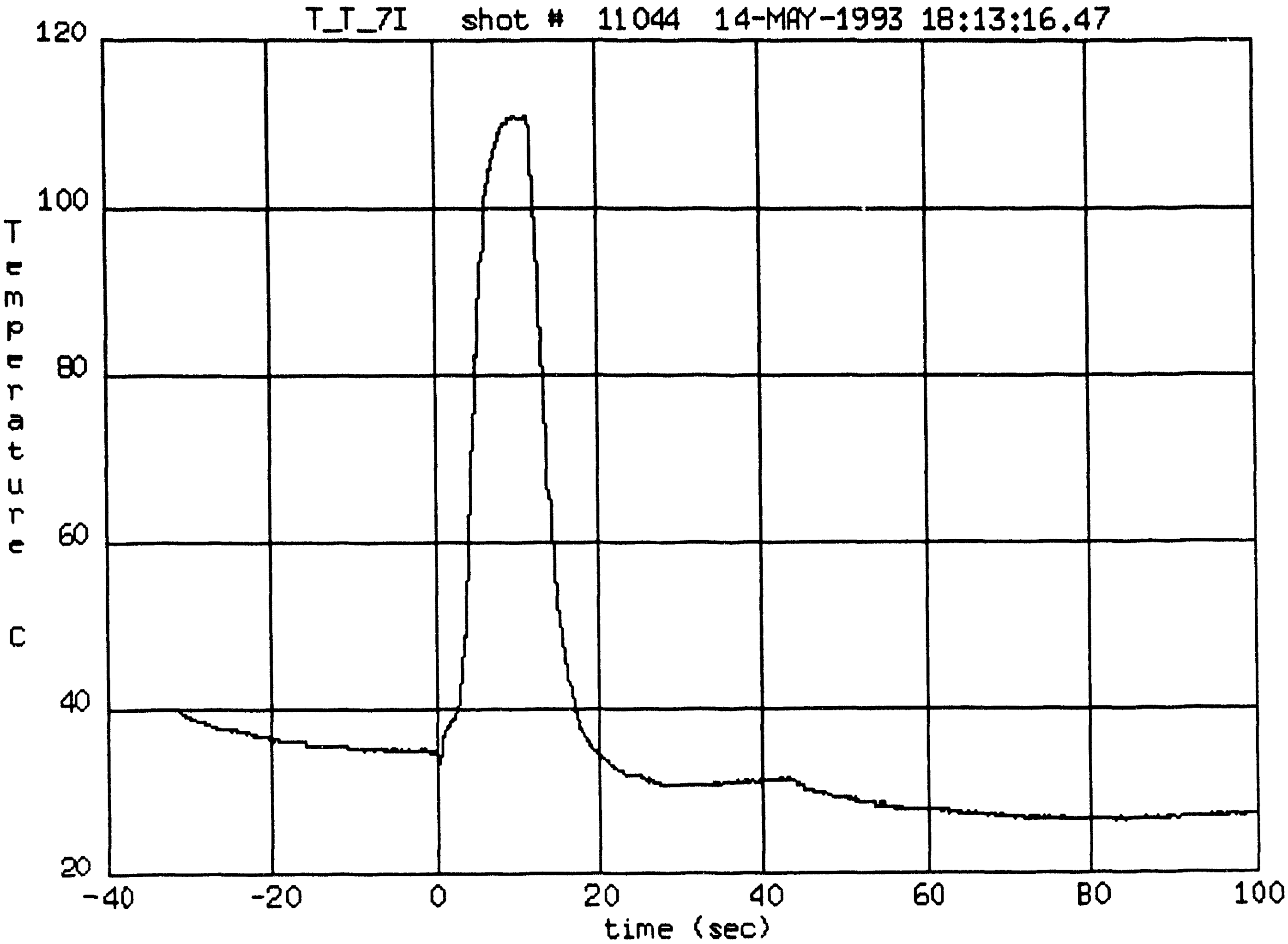


Figure 6. Temperature at outlet on leading edge Tube 7I

The heat flux varies significantly around the (toroidal) curvature of a tile on a leading edge tube. Figure 7 shows the cross section of a tile on the leading edge. The power along the field lines decreases with increasing minor radius ("a" in figure) but the angle of incidence of the field lines increases with increasing distance down the curved part of the tile. The maximum surface heat flux occurs somewhere above the middle of the tile.

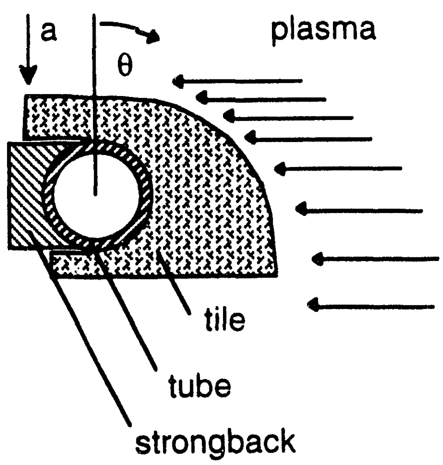


Figure 7. Tube 7 tile cross section

Figure 8 shows the rise in water temperature measured in the exit line of Tube 7I. The values for temperature rise (assuming the decreasing inlet water temperature) and heat load are 78°C and 130 kW. The peak temperature measured at the tube itself is slightly higher, as would be expected, since some of the heat in the water will be lost along the manifold. The outlet thermocouple on Tube 7E was not useful, but we can estimate the heat load that would have been measured on Tube 7E itself as being 121 kW, equal to 135 kW (from 7I) times 116/130 (the ratio of the heat loads calculated for the exit lines). The flow through Tube 7E is essentially the same as that for 7I, so that the smaller temperature rise through Tube 7E does indicate a lesser heat load by about 10%.

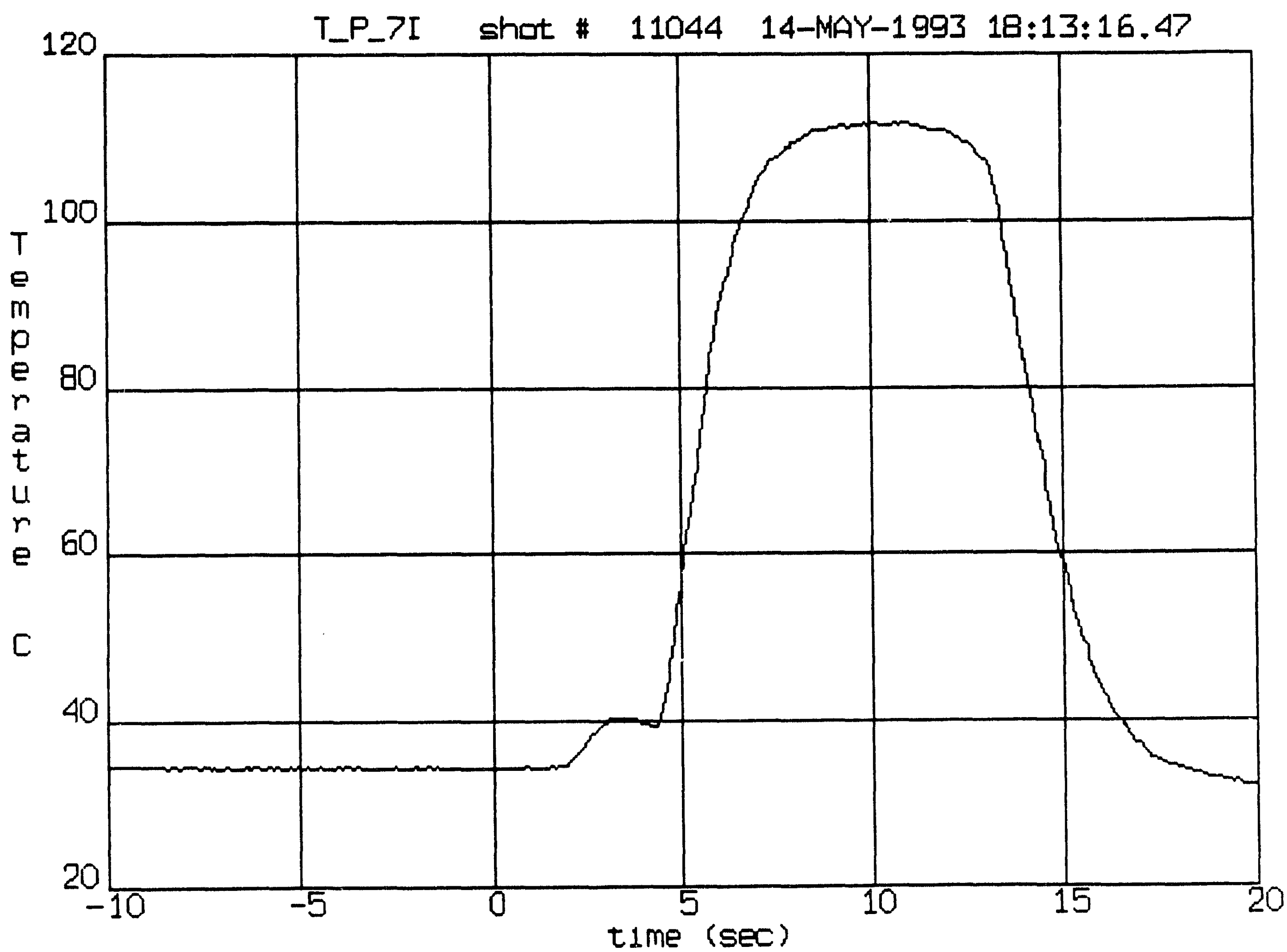


Figure 8. Outlet water temperature in Tube 7I measured downstream at manifold.

Table 1 (next page) gives the results of calorimetry on the limiter head for shot 11044. The overall heat load from the calorimetric analysis is 0.72 MW based upon the data from thermocouples on the tubes on the limiter head (left side of Table 1) and 0.84 MW based upon data from the thermocouples in the water flow at the diagnostic flange (right side of Table 1). For the leading edge tubes and Tubes 6I and 6E, the temperature rises measured at the tube and at the manifold agree fairly well. For Tubes 4I and 5I and Tubes 4E and 5E, there is fair agreement, but the heat loads estimated from the manifold temperatures are larger, especially for Tubes 4&5I. For the center tubes (3I, 2I, 1I, 1E, 2E and 3E), the heat flow estimated from the manifolds is almost 20% greater than that from the tubes. This discrepancy has the largest overall impact upon the comparison of heat loads because the central portion of the limiter receives roughly 40% of the total heat load. For these tubes, the flow volume is typically large and the temperature rises are small. Consequently, inaccuracies in the thermocouples or in reducing the data lead to larger uncertainties in the estimated heat loads.

Table 1. Results of Calorimetry for Shot 11044

tube	flow m^3/hr	velocity m/s	T rise °C	power kW	manifold	flow m^3/hr	T rise °C	power kW
7I	1.46	10.0	81	135	7I	1.46	78.0	130
6I	1.30	6.9	25.2	38	6I	1.30	27.2	41
5I	1.98	6.7	12.3	28				
4I	1.98	6.7	18	41				
4&5I				69	4&5I	3.96	15.9	87
3I	4.80	6.7	9.8	54				
2I	4.80	6.7	9.5	53				
1I	4.80	6.7	8.8	49				
1E	4.80	6.7	6.5	36				
2E	4.80	6.7	5.2	29				
3E	4.80	6.7	8.5	47				
center				268	ctr A&B	28.83	11.0	367
4E	2.01	6.8	22.5	52				
5E	2.01	6.8	6.7	16				
4&5E				68	4&5E	4.02	19.0	74
6E	1.37	7.3	14.1	22	6E	1.37		*23
7E	1.46	10.0	*71.1	*121	7E	1.46	68.5	116
total				**721**				**838**

* These values were estimated based upon other values in the table; 71.1 = 81*(68.5/78.0) and 23=41*(22/38)

3.0 Comparison of Calorimetric Results with Modeling of Heat Load

Heat loads on the outboard pump limiter were calculated by Joel Miller using the three dimensional model HF3D (PATRAN/ ABAQUS) that was used to design the limiter. For the specified power scrape-off-length, the model distributes a specified power (or a specified parallel heat flux on the last closed flux surface) over surfaces that intercept the magnetic field lines. The mesh in the model has been modified slightly so that the model now calculates the incident heat fluxes over both the front and back faces of the limiter and the cells are equivalent to the faces of individual tiles. To describe the magnetic field, the model uses coil specifications by Koski (Sandia) and codes (FIFL, RELI, GENFI and RECOGE) written by the Magnetic Field Design Group at Princeton Plasma Physics Laboratory and is believed to describe accurately the field, including ripple, in Tore Supra.

Figure 9 compares the calorimetric data for shot 11044 (line plot) with the power loads calculated by the model. Several values of power scrape-off-length from the model are shown in the histograms. The heat loads on each tube were obtained by summing over the heat loads on the front and back tiles on each tube. The

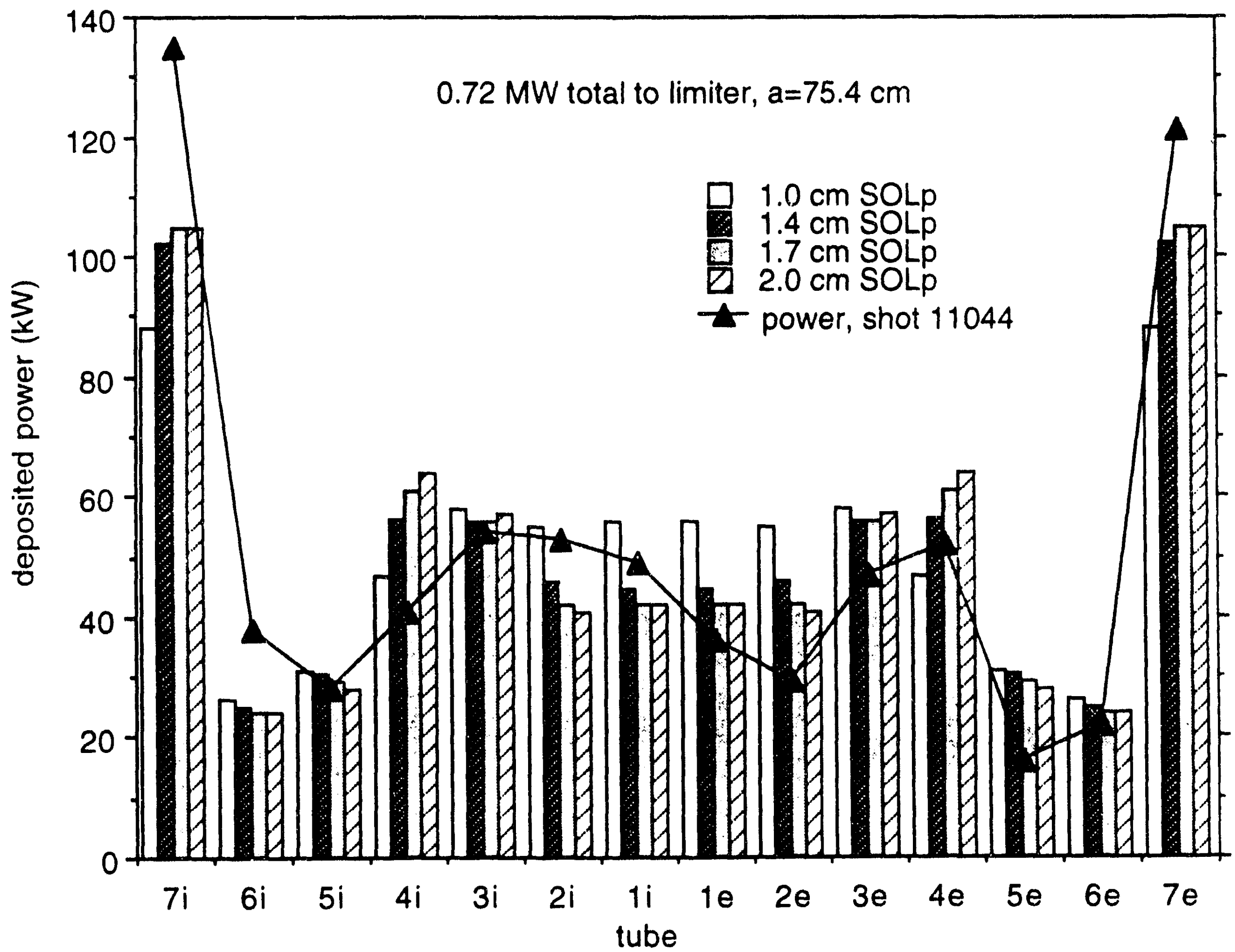


Figure 9. Comparison of calculated heat distribution with calorimetry for shot 11044

calculations were done for an heat load of 1 MW and these results were normalized to the value of 0.721 MW measured on the limiter head in shot 11044.

In general, regarding the shape of the heat load profile, the agreement between the measurements and the results obtained with the model is fairly good. Some discrepancies can most likely be associated with deviations in the positions of the tubes from the ideal alignment assumed in the model. There also appears to be a slight toroidal asymmetry in the measured heat loads. As may be seen in Figure 9, the heat loads on the leading edge tubes (7I and 7E) are roughly 20-30% higher than those calculated with the model. This has important consequences in operating the limiter, since these tubes are the most vulnerable to overheating.

Some possible reasons we can consider for the comparatively higher heat loads on the leading edges are: 1) the value of λ_q of 1.4 cm is too low; 2) the description of the power distribution in the scrape-off-layer is wrong; and 3) the description of the field or field ripple in the model is incorrect.

We can probably rule out #1 and #3. While the trend of proportionately more heating on the leading edges is consistent with a longer λ_q, a simple change in λ_q in the modeling does not provide significantly better agreement with the observed power loading, as may be seen from Figure 9. The model has been inspected to determine that the specified field description installed by Koski is being correctly used; however, an evaluation of whether the specifications themselves are accurate has not been done.

The normalization used in comparing the heating profiles for differing values of λ_q must be kept in mind in interpreting the comparison made here because we are used to seeing experimental data where λ_q decreases as the overall power to the limiter increases with current. In the comparison here, there is little change in the power to the leading edge tubes as λ_q increases for two reasons.

First, the overall power to the limiter has been normalized to 0.721 MW so the trend of increasing power to the limiter with increasing current (and decreasing λ_q) is eliminated by the normalization. Although somewhat more power goes into the throat with increasing λ_q, nearly all of that power is still deposited on the deflector side of the limiter.

Second, the leading edge tubes cover the range from 1.0 cm to 2.5 cm of minor radius from the last closed flux surface to the throat. As the deposited power shifts outward with increasing λ_q, the leading edge is still intercepting all the power between roughly 1.0 and 2.5 cm (ignoring the effect of ripple) from the last closed flux surface. Varying λ_q through the region of interest of 1.4 to 1.7 cm or even to 2.0 cm may move the peak heat flux on the leading edge tubes a bit but does not drastically alter the proportional distribution of power from tube to tube on the limiter.

A distribution of power in the scrape-off region somewhat different than the assumed exponential decay might account for the higher power on the leading edge tubes. For example, in TEXTOR, power dissipation characterized by scrape-off lengths of about one centimeter adjacent to the last closed flux surface and much longer scrape-off lengths after the first 1-2 centimeters has been observed in the ALT-I and ALT-II limiters. Similar behavior of the power dissipation in the scrape-off region in Tore Supra could account for the somewhat higher than expected power to the leading edge tubes. Further use of the model to explore the effects of poloidal asymmetry and a scrape-off region characterized by two zones may be useful in explaining the observed heat load distribution on the limiter.

Table 2 compares numerical results for the heat loads calculated with the model for a λ_q of 1.4 cm with the calorimetric results from shot 11044. Table 2 (and Figure 9) shows the transfer of power from the front face to the back face (deflector) with increasing λ_q. As a fraction of the overall power to the limiter, the power received by the deflector side varies from 8% for a λ_q of 1.0 cm to 27% for a λ_q of 2.0 cm. For Tubes 3I and 3E, the transfer of power off the front face is balanced by the increase in the heat load to the deflector tiles (back face) and the histogram is fairly level. For Tubes 4I and 4E, which have the steepest angle to the field lines on the deflector side, the received power increases as λ_q increases.

Table 2. Comparison of Calorimetric Results from Shot 11044 with Results from a 3-D Model of Heat Load on the Limiter

tube	comparison meas:calc heat load	calc heat load kW	calc. front face kW	calc. back face kW	ratio back:total
7i	132%	102.2	99.5	2.7	3%
6i	151%	25.1	22.9	2.3	9%
5i	92%	30.5	26.1	4.4	14%
4i	73%	56.1	27.7	28.4	51%
3i	97%	56.0	43.5	12.5	22%
2i	115%	45.8	41.9	3.9	9%
1i	109%	44.8	40.7	4.1	9%
1e	81%	44.8	40.7	4.1	9%
2e	63%	45.8	41.9	3.9	9%
3e	84%	56.0	43.5	12.5	22%
4e	93%	56.1	27.7	28.4	51%
5e	51%	30.5	26.1	4.4	14%
6e	89%	25.1	22.9	2.3	9%
7e	118%	102.2	99.5	2.7	3%
total		**720.8**	**604.5**	**116.3**	**16%**

4.0 Development of User Access for Calorimetry Data from the Limiter

The data presented here on shot 11044 was reduced by hand shortly after these data were obtained. A program for automatic data reduction is being developed by Tom Lutz and will be available for the future operation of the limiter.

The basic characteristics of the program are as follows. Similar signals (e.g., all thermocouples on manifolds) are grouped in a single plot. When appropriate the signal levels before the shot are normalized to a single value. For example, the temperature differences for each tube and each pipe are all normalized to zero over a period just before start of plasma.

A sample preliminary output of the overview of the data as would be seen on a computer screen is shown in Figure 10. In the developed program, the individual signals will be separately identified (e.g., differing line styles) and the peak values will be labeled. Also, a user will be able to obtain plots of individual signals with a simple command.

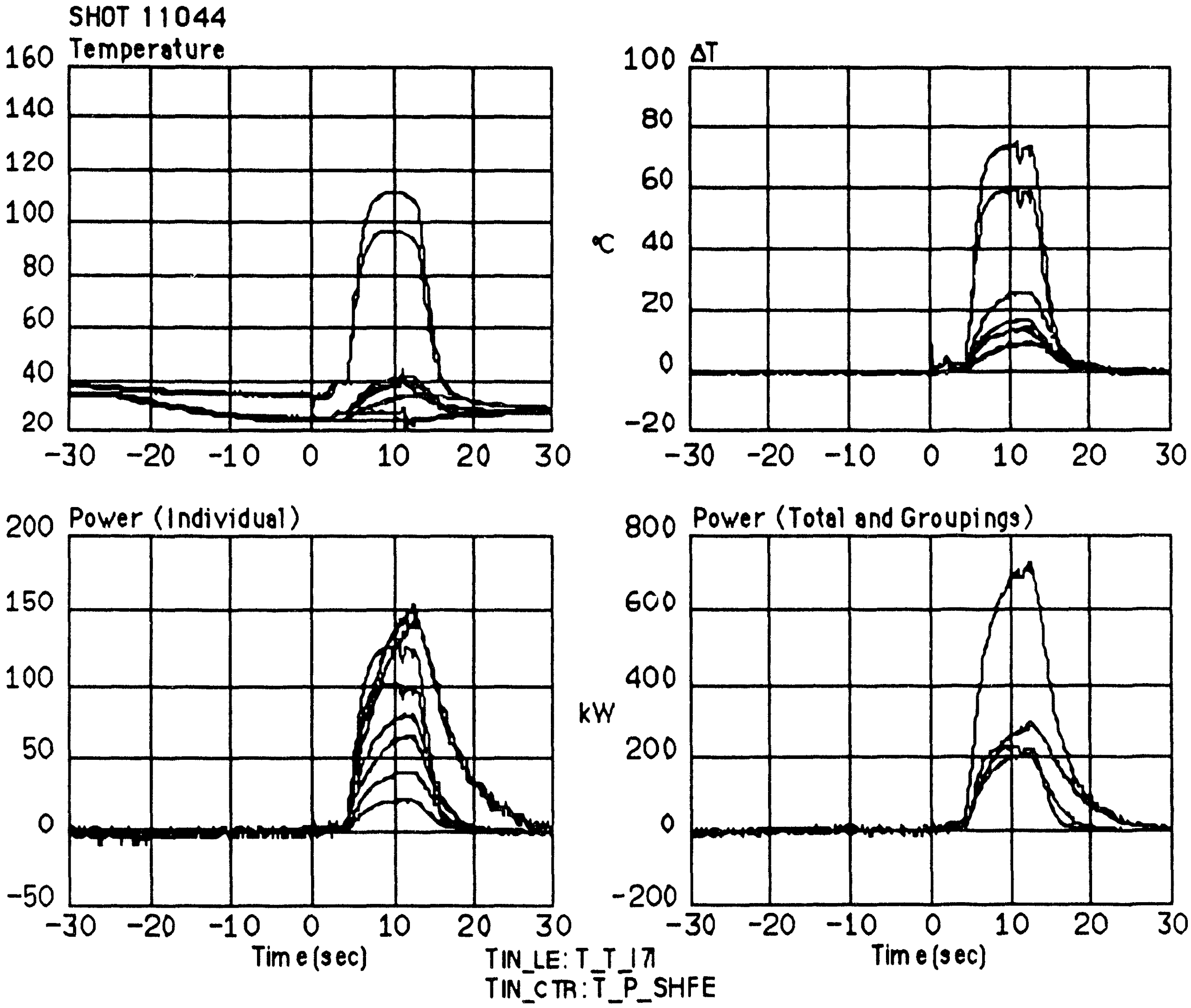


Figure 10. Sample on-screen output of calorimetry program for users

APPENDIX A: DIAGNOSTIC NAMES AND LOCATIONS

TABLE A1. Flowmeters on the Outboard Pump Limiter
Signals appear in their order in the output program.

signal name:	location (all on exit flow):	GPM	m^3/hr (full flow)
FL_7I	ion side leading edge tube	5.9	1.3
FL_4_5I	manifold for tubes 4 & 5 ion side	17.4	4.0
FL_6I	tube 6 ion side	5.8	1.3
FL_SHLFI	shelf on ion side	5.2	1.2
FL_CTR_A	upper manifold (tubes 1e,2e,3e,1i,2i,3i), A side common with B (FL_CTR_B)	61.4	13.9
FL_CTR_B	upper manifold (tubes 1e,2e,3e,1i,2i,3i), B side common with A (FL_CTR_A)	59.2	13.4
FL_SHLFE	tube 6 electron side	5.5	1.2
FL_6E	shelf* on electron side	5.9	1.3
FL_4_5E	manifold for tubes 4 & 5 electron side	17.2	3.9
FL_7E	electron side leading edge tube	6.0	1.4

TABLE A2. Thermocouples on the Outboard Pump Limiter
Signals in their order of output program. "I" and "E" denote ion and electron sides.

signal name:	location:	signal name:	location:
T_P_7I	outlet pipe, ion side leading edge tube (7I)	T_T_8E	outlet, tube electron (E) side shelf
T_P_4_5I	outlet manifold, tubes 4I & 5I	T_T_2E	outlet, tube 2E
T_P_6I	outlet pipe, tube 6I	T_T_3E	outlet, tube 3E
T_P_SHFI	outlet pipe, ion side shelf	T_T_4E	outlet, tube 4E
T_P_CTRA	outlet pipe, tubes 3I,2I,1I,1E, 2E,3E common with CTRB	T_T_2I	outlet, tube 2I
		T_T_1I	outlet, tube 1I
T_P_CTRB	outlet pipe, tubes 3I,2I,1I,1E, 2E,3E common with CTRB	T_T_1E	outlet, tube 1E
		T_T_5I	outlet, tube 5I
T_P_SHFE	outlet pipe, ion side shelf	T_T_4I	outlet, tube 4I
T_P_6E	outlet pipe, tube 6I	T_T_3I	outlet, tube 3I
T_P_4_5E	outlet manifold, tubes 4I & 5I	T_T_8I	outlet, tube ion side shelf
T_P_7E	outlet pipe, tube 7i	T_T_7I	outlet, tube 7I
T_P_ICTR	inlet pipe, tubes 1-6E & 1-6I	T_T_6I	outlet, tube 6I
T_P_ILE	inlet pipe, 7E & 7I	T_T_I2I	inlet, tube 2I
T_T_7E	outlet, tube 7E	T_T_I7I	inlet, tube 7I
T_T_6E	outlet, tube 6E	T_T_I8I	inlet, tube E side shelf
T_T_5E	outlet, tube 5E	T_T_I7E	inlet, tube 7E

"T_P" TC's are probes inside pipes; "T_T" TC's are attached to the outside of tubes.

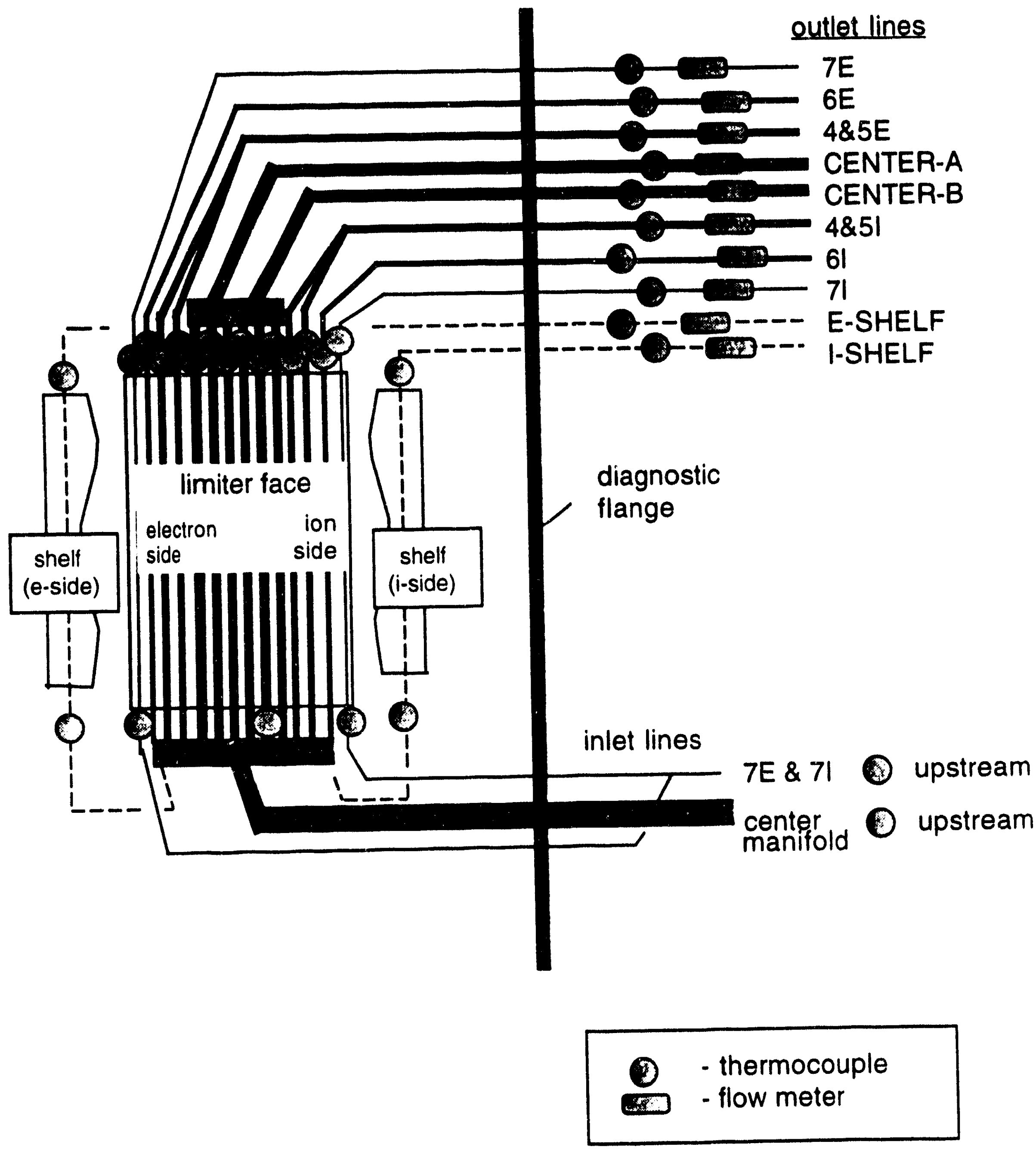


Figure A1. Thermocouples and flow meters on the Tore Supra Phase III Outboard Pump Limiter Module

APPENDIX B: CALORIMETRIC DATA FOR SHOT 11044

Calorimetric data, i.e., the signals from thermocouples and flowmeters listed in Appendix A, for shot 11044 are compiled in this Appendix. The figures presented are in the order listed below. The comments below pertain to these figures, some of which were also presented in the main text.

Table B-1: List of Plots in Order Presented

FL signals	TP signals	TT signals	
FL_7I (a)	T_P_ILE	T_T_I7I	T_T_2I
FL_7I (b)	T_P_ICTR	T_T_I7E	T_T_1I
FL_7I (c)	T_P_7I	T_T_I2I	T_T_1E
FL_4_5I	T_P_6I	T_T_I8I	T_T_2E
FL_SHLFI	T_P_4_5I	T_T_8I	T_T_3E
FL_CTR_A	T_P_CTRA	T_T_7I (a)	T_T_4E
FL_CTR_B	T_P_CTRB (a)	T_T_7I (b)	T_T_5E
FL_SHLFE	T_P_CTRB (b)	T_T_6I	T_T_6E
FL_4_5E	T_P_4_5E	T_T_5I	T_T_7E
FL_6E	T_P_6E	T_T_4I	T_T_8E
FL_7E	T_P_7E	T_T_3I	
	T_P_SHFI		
	T_P_SHFE		

Comments

1. The leads for thermocouples on the manifolds (T_P_XX type signals) were reversed from the ion to electron side; the incorrect signal names on the plots have been corrected by hand.

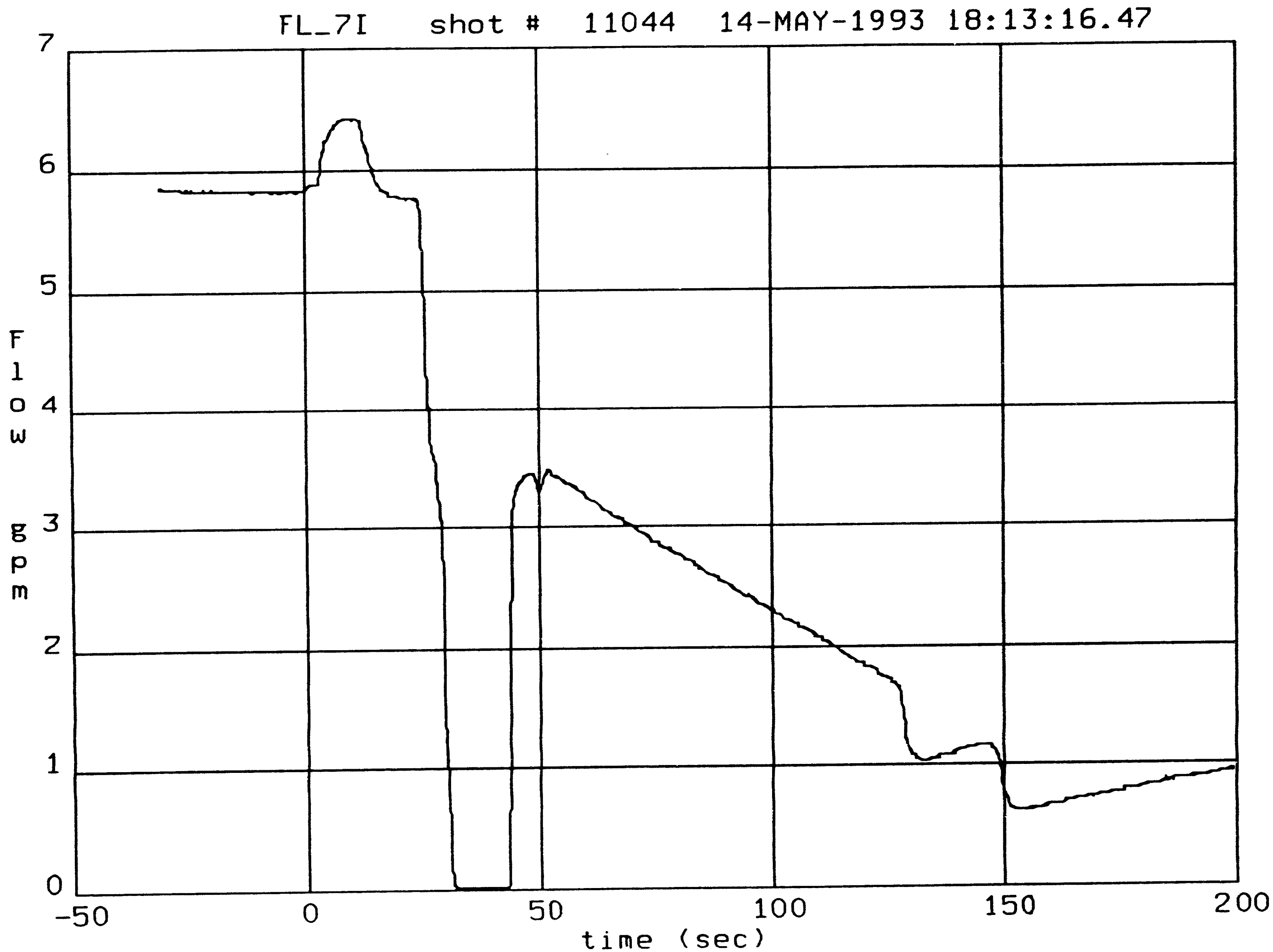
2. For the most part, the data are plotted over the time range from 10 seconds before the shot (-10) to 20 seconds after the shot. Some plots cover a wider range of time (-50 to 200 s) that includes the change over from hot feed water to cold feed water for the limiter. In these plots, the origin of the data before -30 seconds is uncertain. The system was reinitialized automatically at -30 seconds and the data plotted before this time was whatever was previously stored in the memory for that interval.

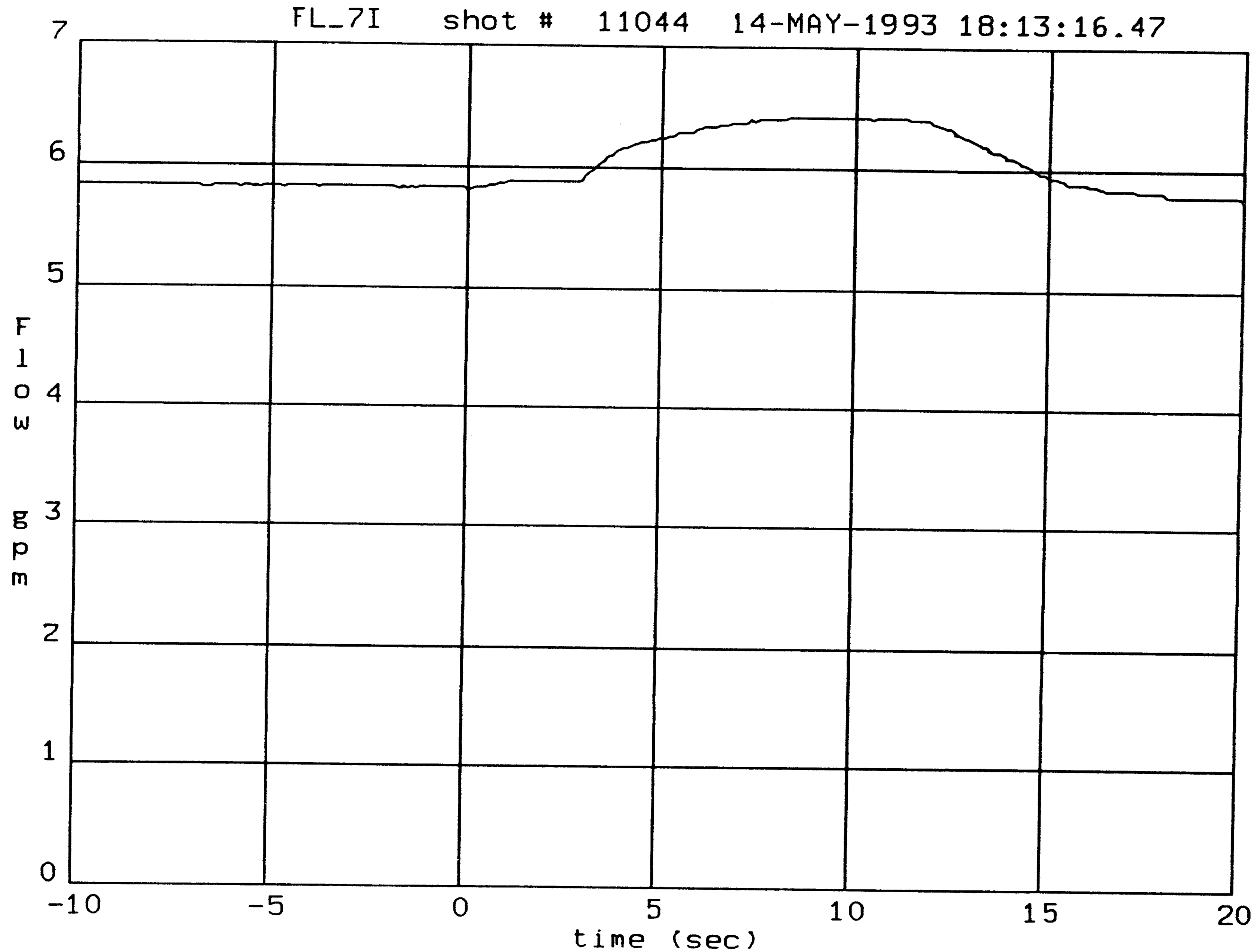
3. In several Figures, there is an offset during the shot that begins when the plasma contacts the limiter. This is true for signals T_T_I7I, T_T_I7E, T_T_I7E, T_T_I2I, T_T_I8I, T_T_1E, T_T_2E, T_T_3E, T_T_4E, T_T_5E, T_T_7E, T_T_8I and T_T_8E. The important point here is whether the offset persists, in which case it can be ignored in estimating the temperature rise, or whether the offset ceases at about 5 s, e.g., at the end of the current ramp. For the signals on the manifolds (T_P_7I and

T_P_7E), such "signatures at the onset of the plasma were believed to be temporary and were ignored. For the signals on the tubes (T_T_I7E, T_T_I7E, T_T_I2I, T_T_I8I, T_T_1E, T_T_2E, T_T_3E, T_T_4E, T_T_5E, T_T_7E, T_T_8I and T_T_8E). The offsets were usually treated as being induced by the presence of the plasma and the offsets were subtracted from the signal in an appropriate way. This is often obvious from the handwritten notes on the figures.

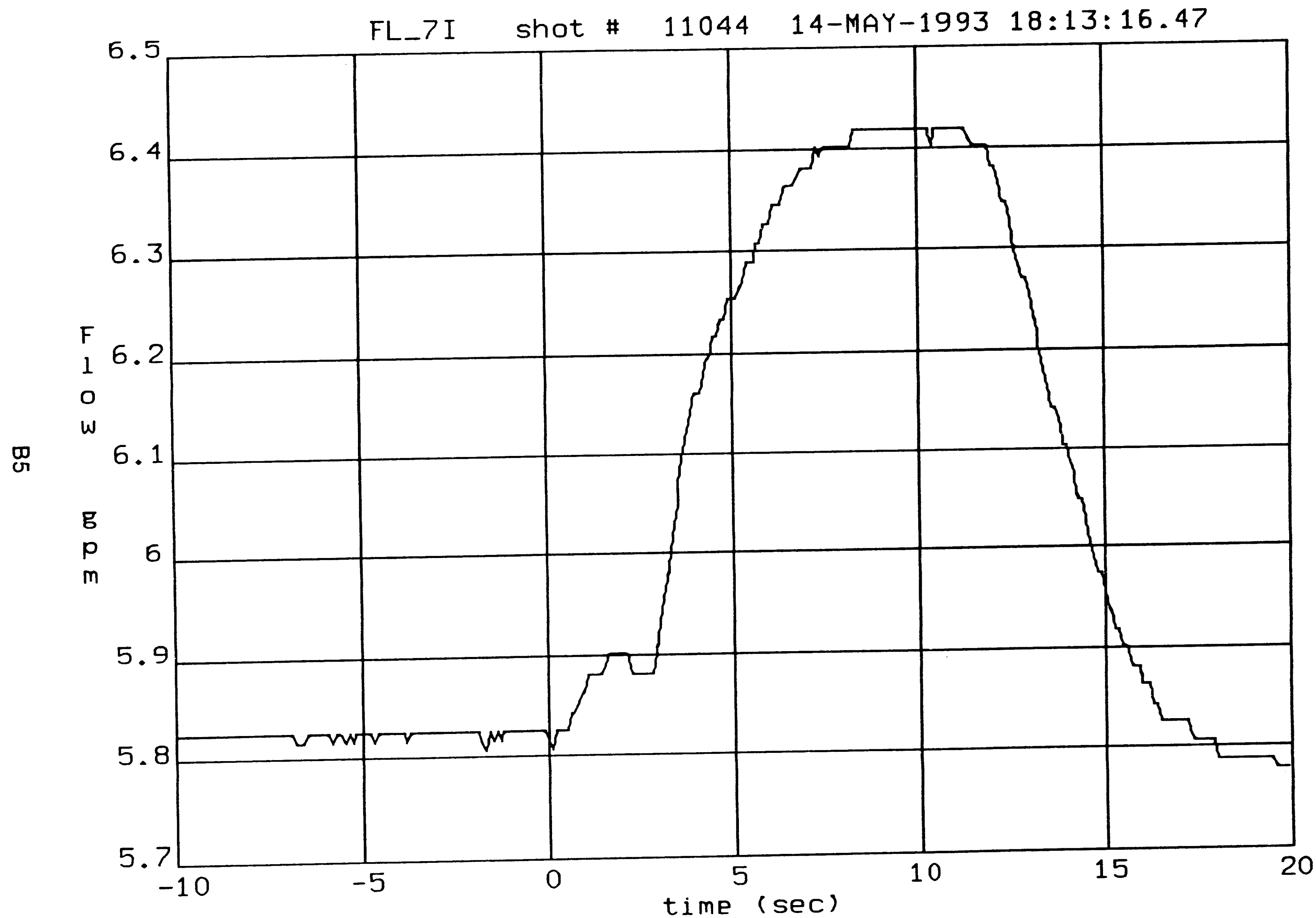
4. The temperature of the inlet water apparently decreases slightly during the shot for the leading edge tubes but not for the other tubes. The decreasing inlet temperature means one must a somewhat lower temperature from time 0 rather than using the temperature at time 0 as a reference point to subtract from the maximum temperature in order to determine the rise in temperature during the shot.

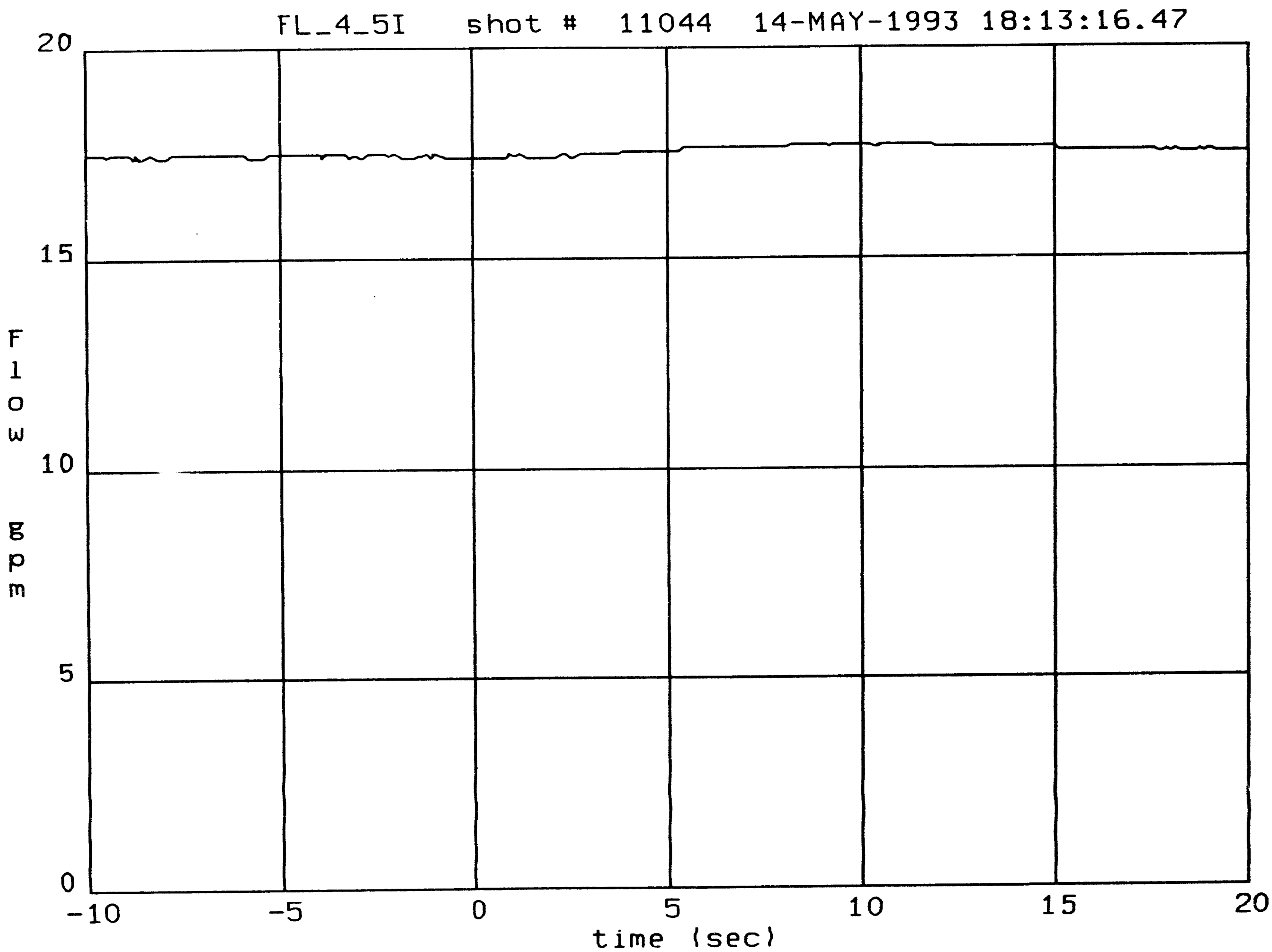
5. The values given in the text are shown in Table B-1, a spreadsheet used to process the calorimetry data.

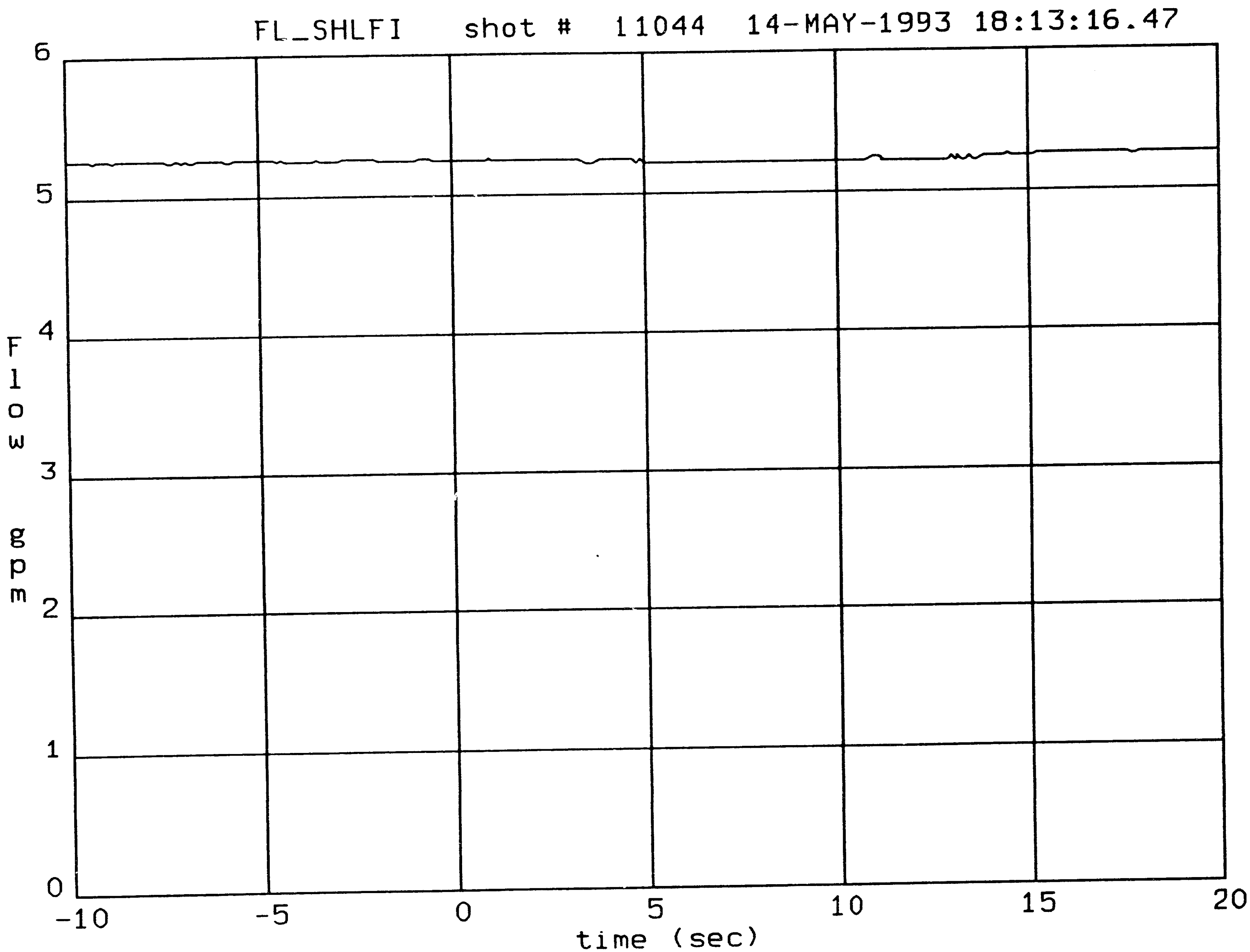

FL_7I shot # 11044 14-MAY-1993 18:13:16.47
Flow gpm
0
1
2
3
4
5
6
7
-50
0
50
100
150
200
time (sec)


FL_7I shot # 11044 14-MAY-1993 18:13:16.47
Flow gpm
time (sec)
0
1
2
3
4
5
6
7
-10
-5
0
5
10
15
20

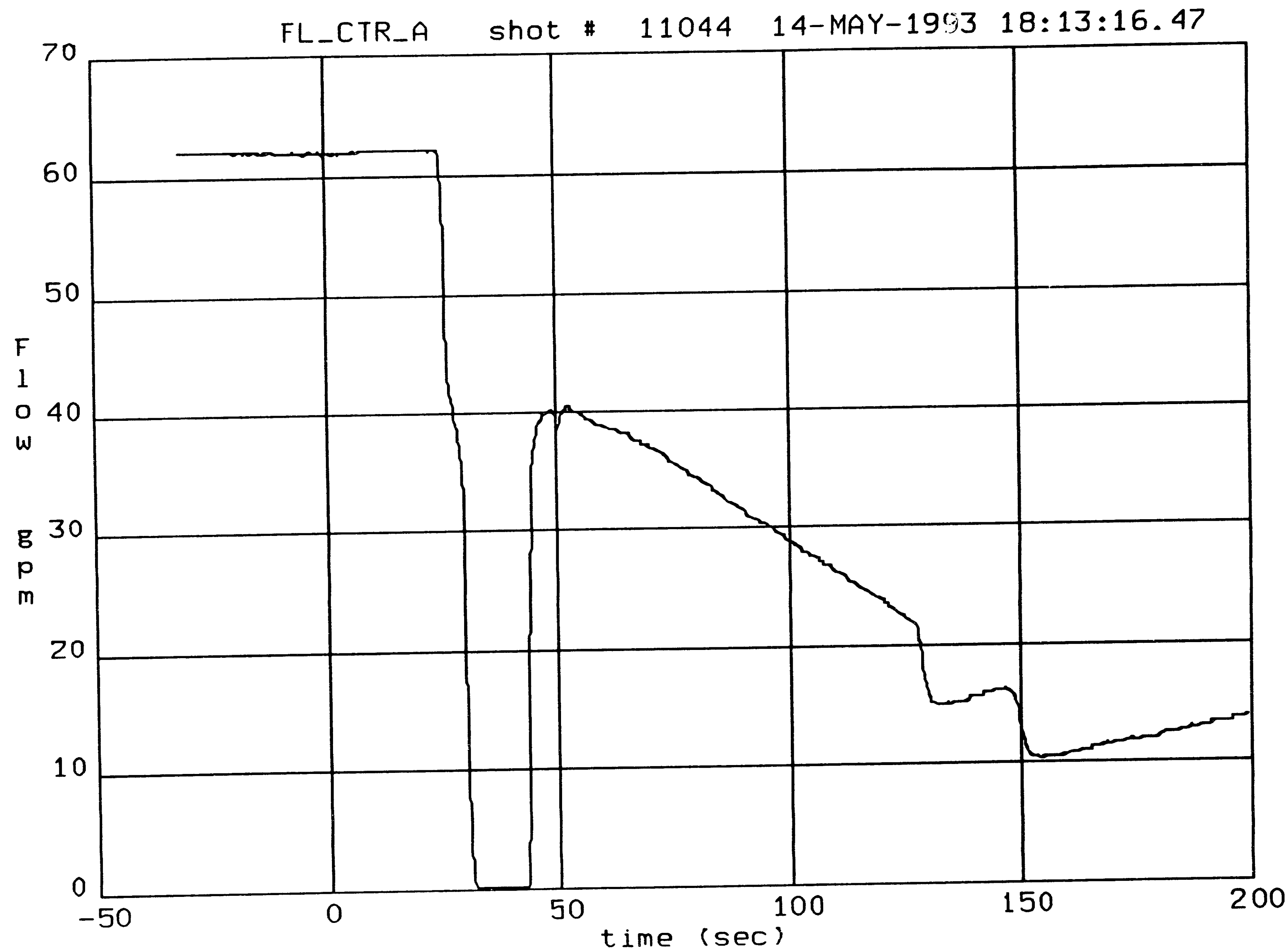
B4

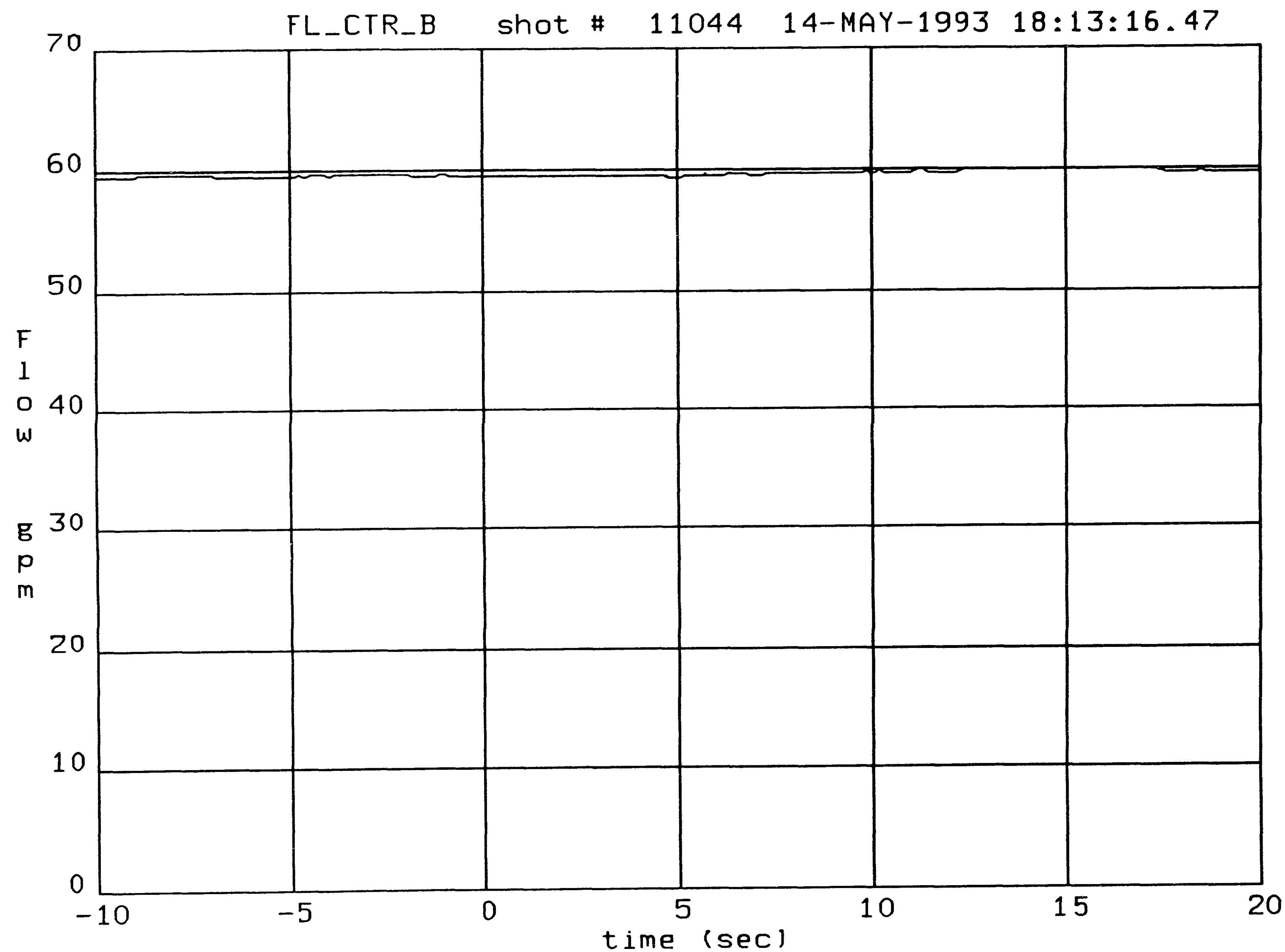

FL_7I shot # 11044 14-MAY-1993 18:13:16.47
6.5
6.4
6.3
6.2
6.1
6
5.9
5.8
5.7
Flow gpm
B5
-10
-5
0
5
10
15
20
time (sec)


FL_4_5I shot # 11044 14-MAY-1993 18:13:16.47
Flow gpm
time (sec)
20
15
10
5
0
-10
-5
0
5
10
15
20


FL_SHLFI shot # 11044 14-MAY-1993 18:13:16.47
Flow gpm
6
5
4
3
2
1
0
-10
-5
0
5
10
15
20
time (sec)

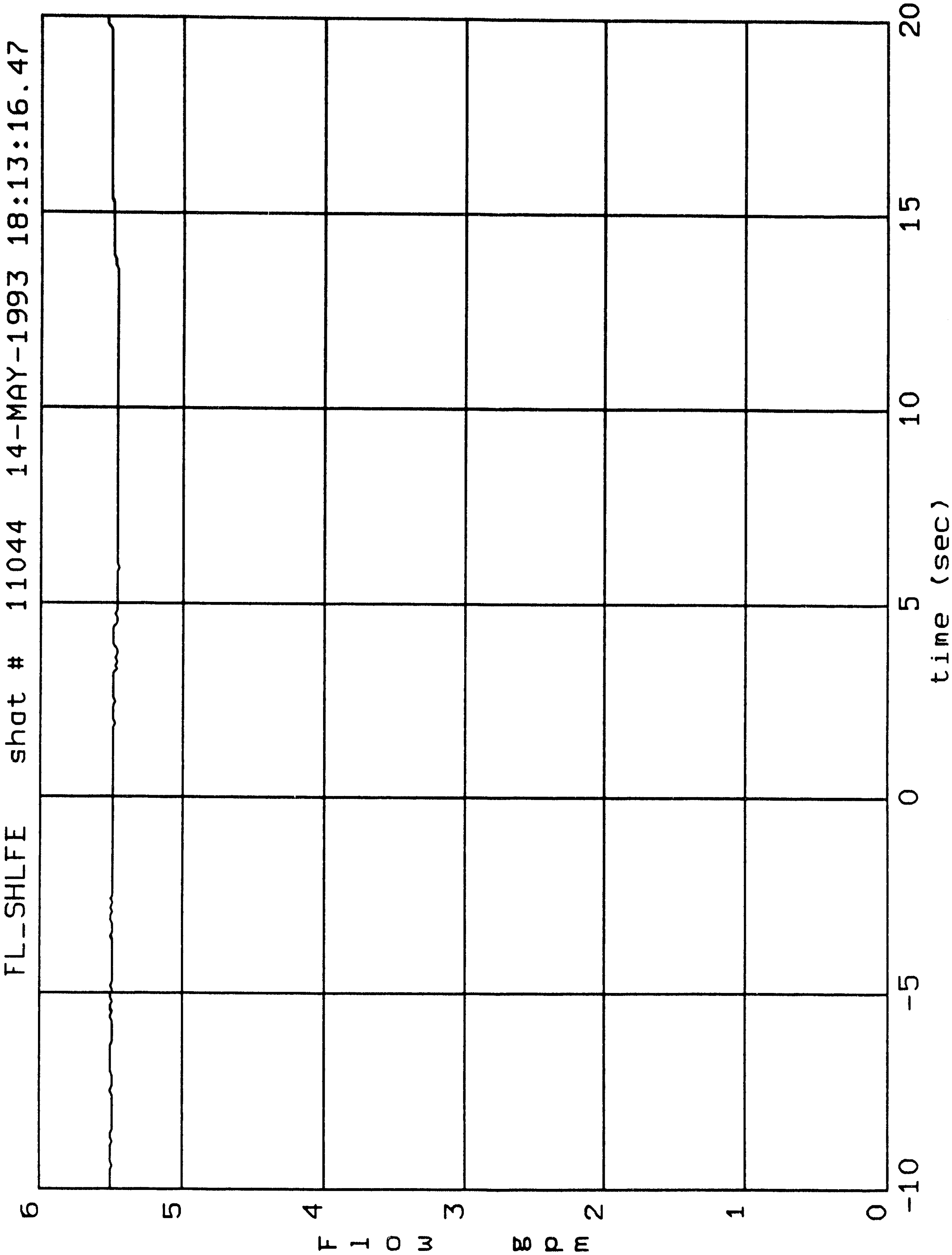
B7

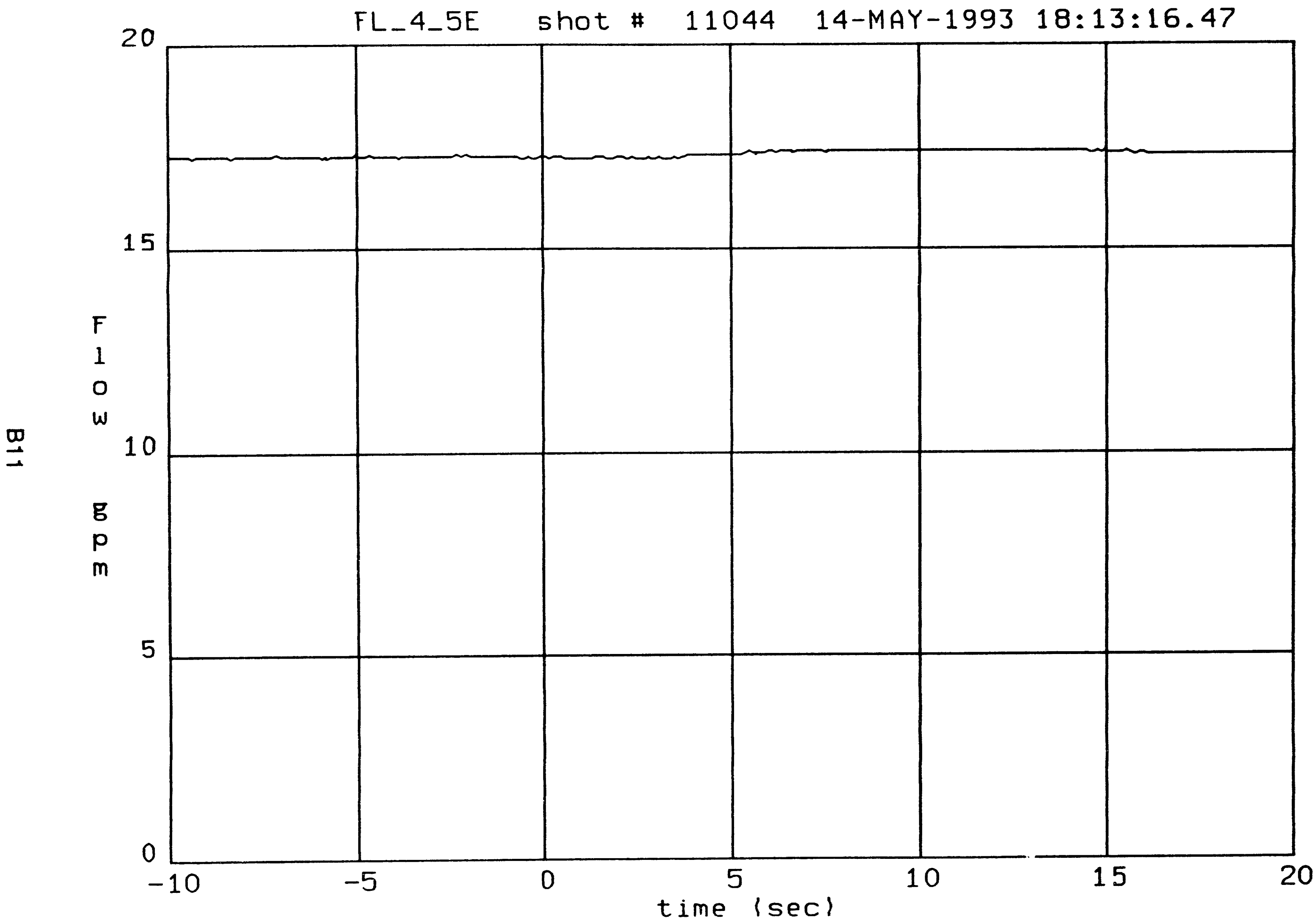

FL_CTR_A shot # 11044 14-MAY-1993 18:13:16.47
70
60
50
40
30
20
10
0
Flow gpm
-50
0
50
100
150
200
time (sec)



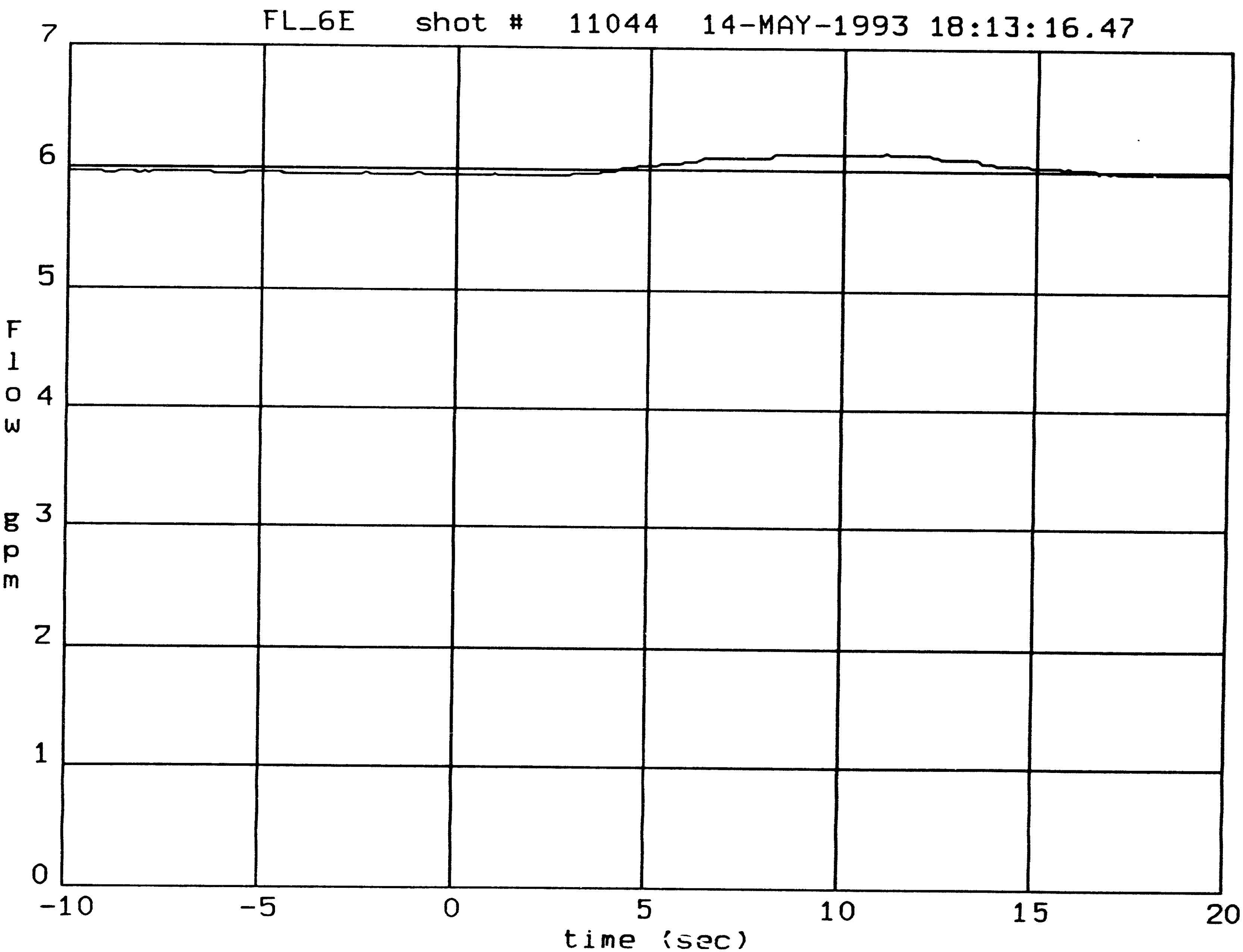
FL_CTR_B shot # 11044 14-MAY-1993 18:13:16.47
70
60
50
40
30
20
10
0
Flow gpm
-10
-5
0
5
10
15
20
time (sec)

B9


FL_SHLFE shat # 11044 14-MAY-1993 18:13:16.47
Flow gpm
time (sec)
-10
-5
0
5
10
15
20
0
1
2
3
4
5
6

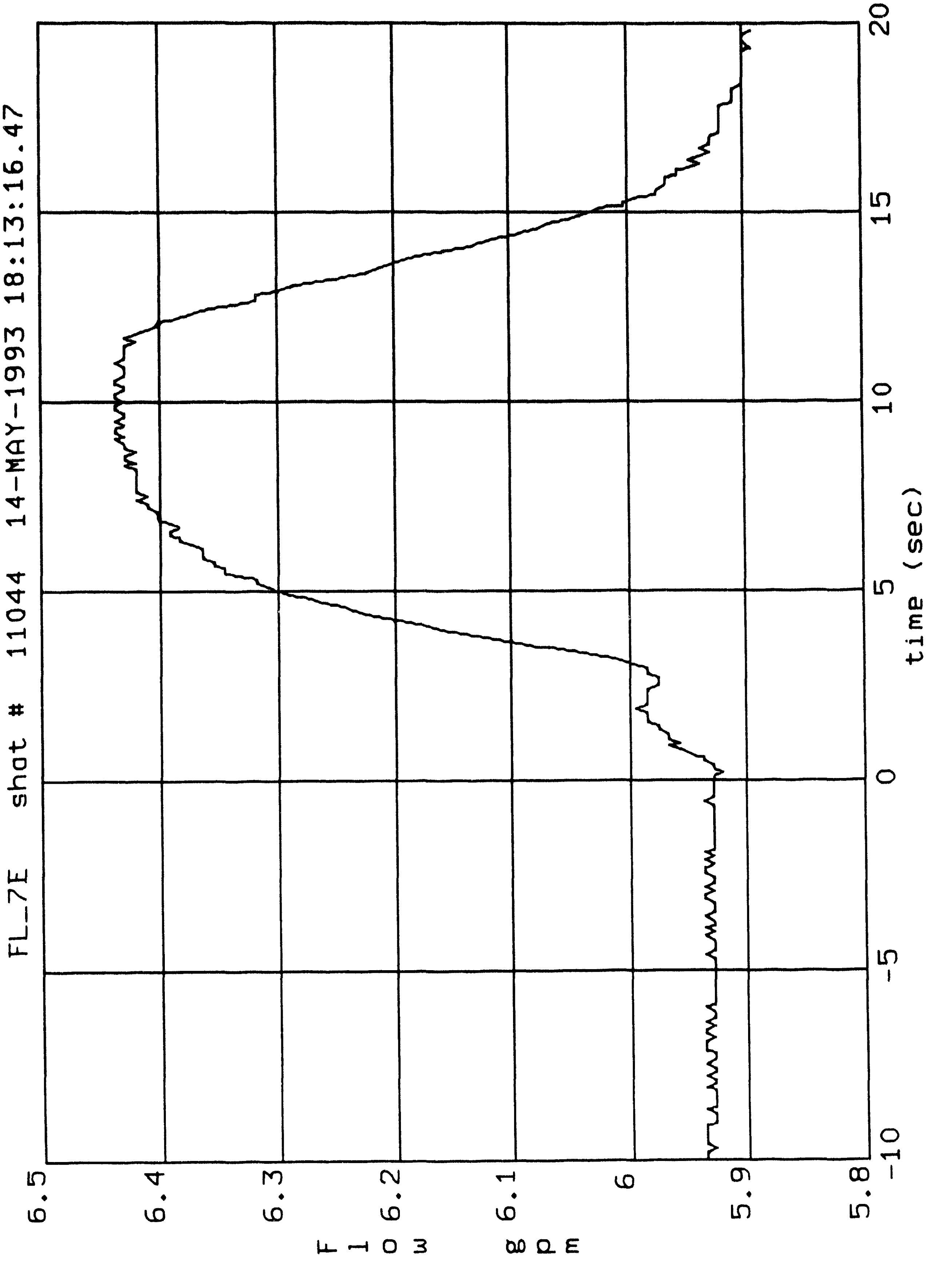


FL_4_5E shot # 11044 14-MAY-1993 18:13:16.47
20
15
10
5
0
Flow gpm
B11
-10
-5
0
5
10
15
20
time (sec)

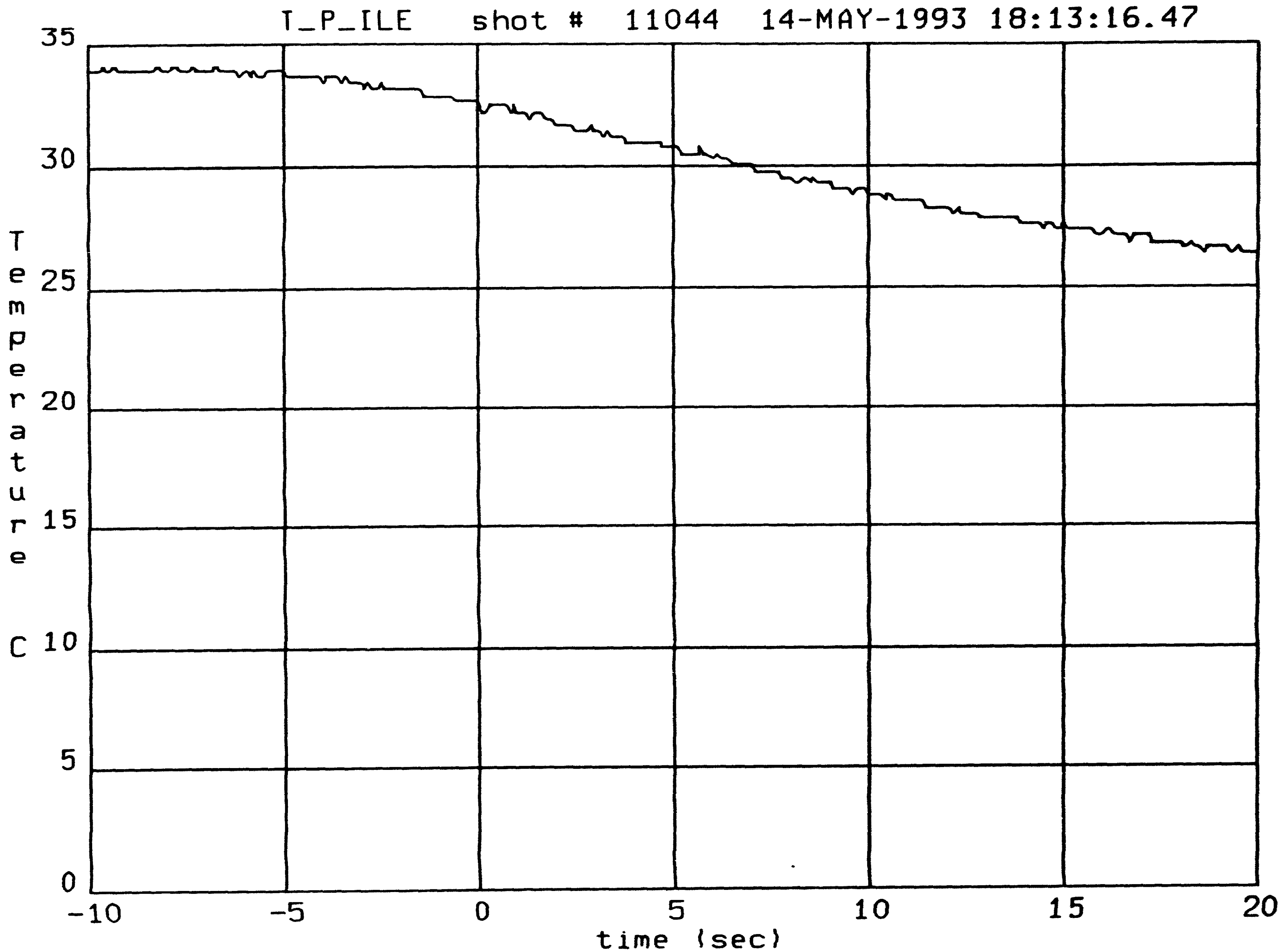


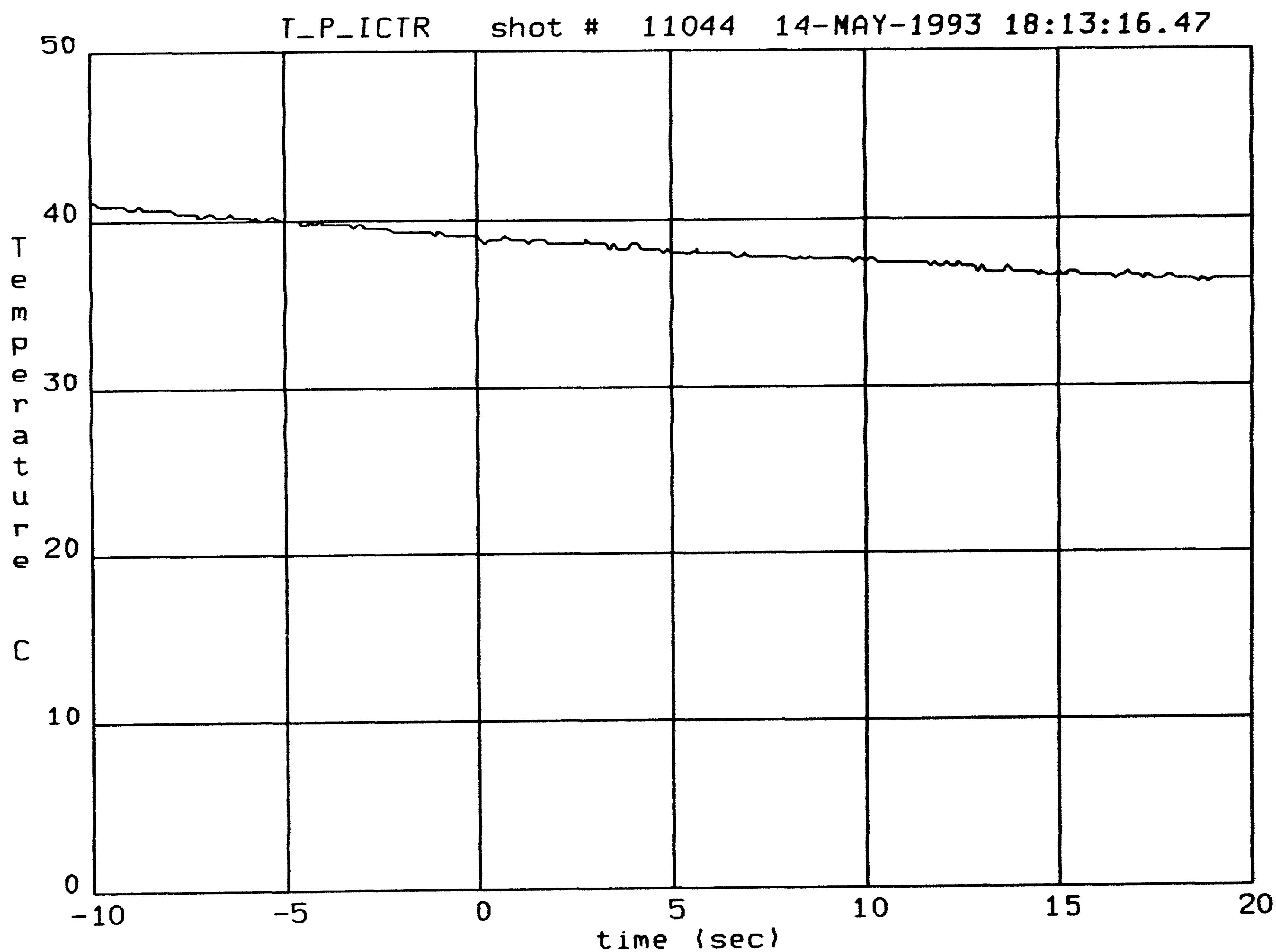
FL_6E shot # 11044 14-MAY-1993 18:13:16.47
7
6
5
4
3
2
1
0
Flow gpm
-10
-5
0
5
10
15
20
time (sec)

B12

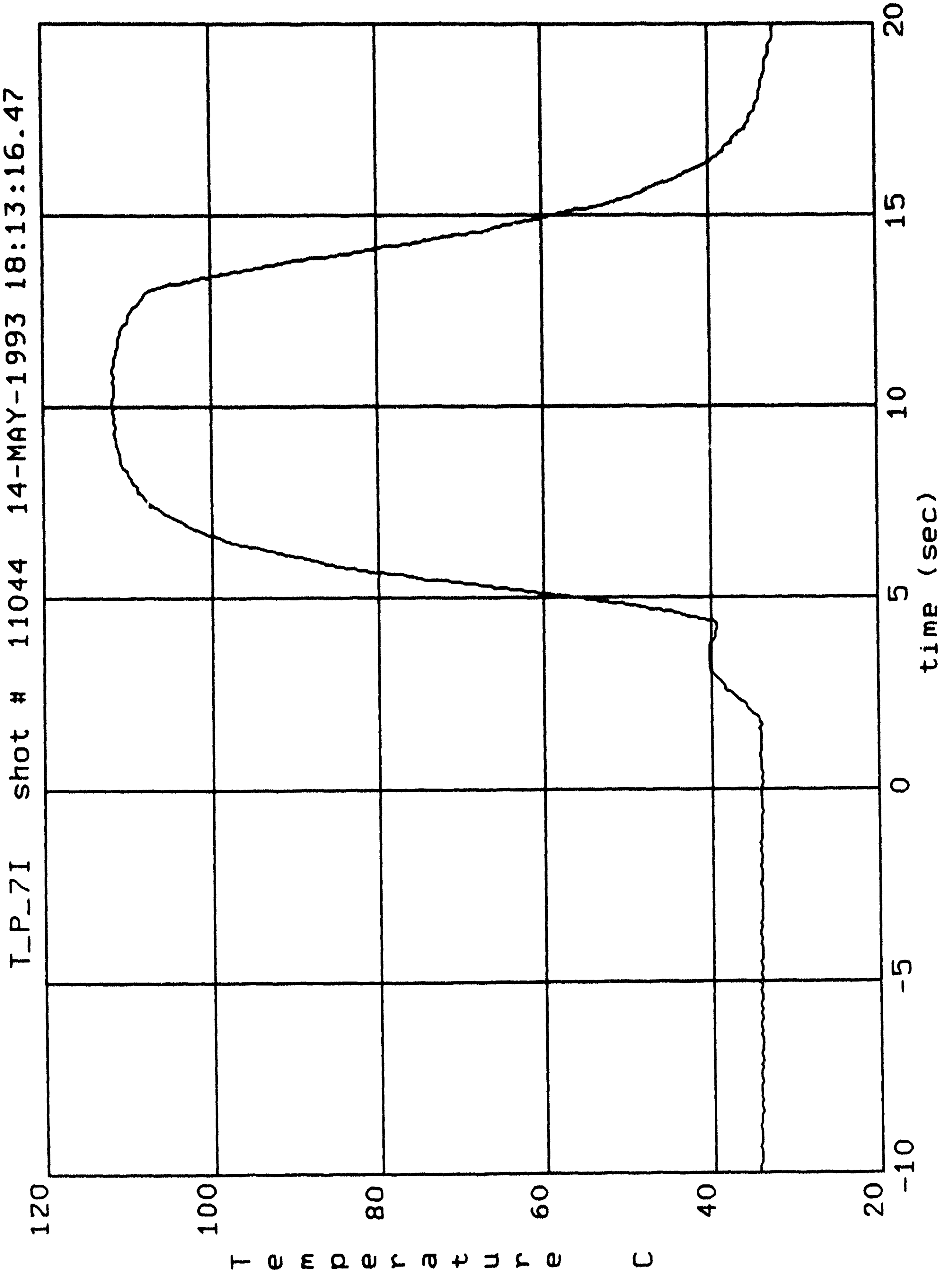


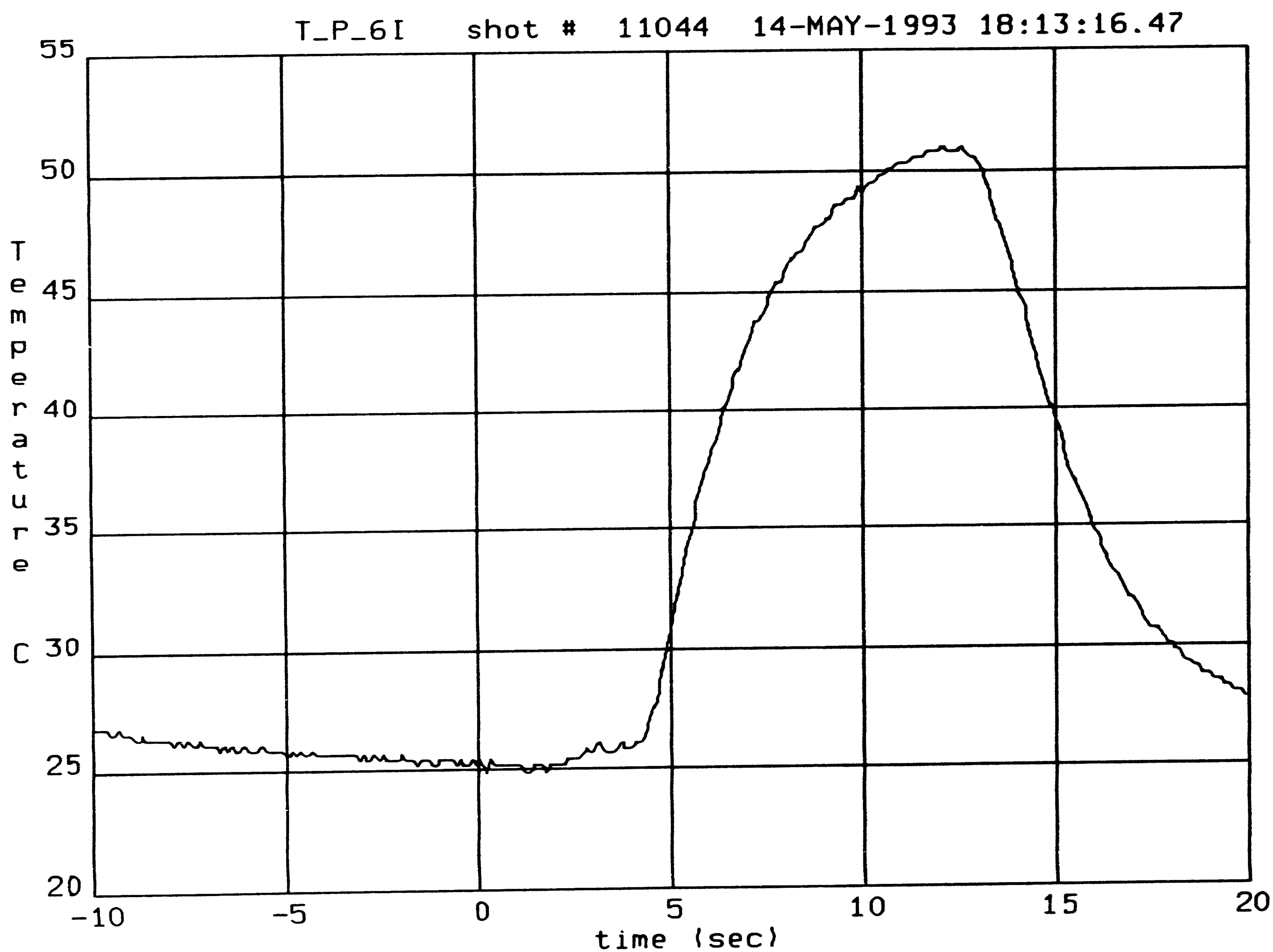
FL_7E shot # 11044 14-MAY-1993 18:13:16.47
Flow gpm
6.5
6.4
6.3
6.2
6.1
6
5.9
5.8
time (sec)
-10
-5
0
5
10
15
20


T_P_ILE shot # 11044 14-MAY-1993 18:13:16.47
35
30
25
20
15
10
5
0
Temperature
C
-10
-5
0
5
10
15
20
time (sec)


T_P_ICTR shot # 11044 14-MAY-1993 18:13:16.47
50
40
30
20
10
0
Temperature C
-10
-5
0
5
10
15
20
time (sec)

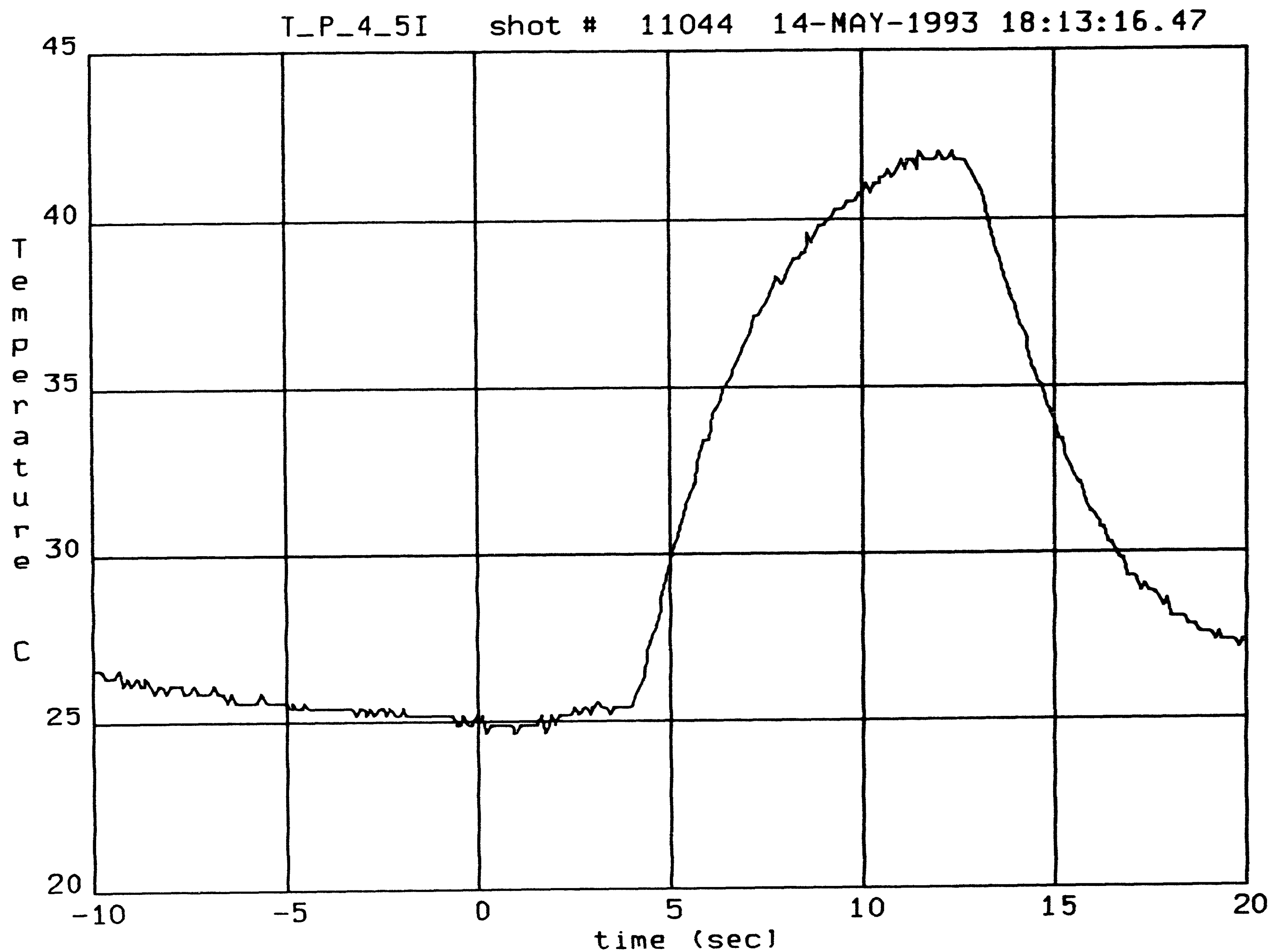
B15


T_P_7I shot # 11044 14-MAY-1993 18:13:16.47
Temperature C
time (sec)
120
100
80
60
40
20
-10
-5
0
5
10
15
20

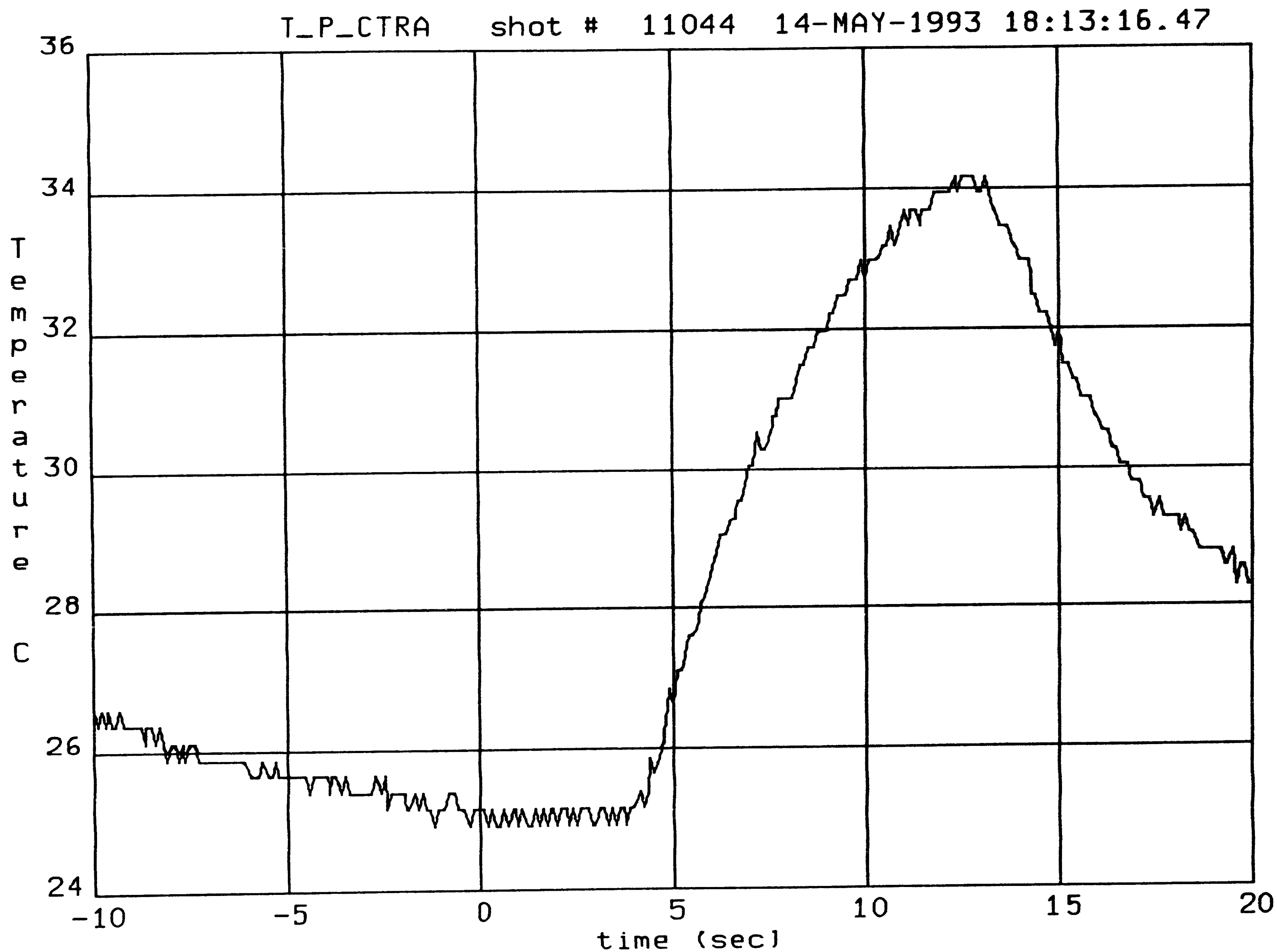


T_P_6I shot # 11044 14-MAY-1993 18:13:16.47
55
50
45
40
35
30
25
20
Temperature C
-10
-5
0
5
10
15
20
time (sec)

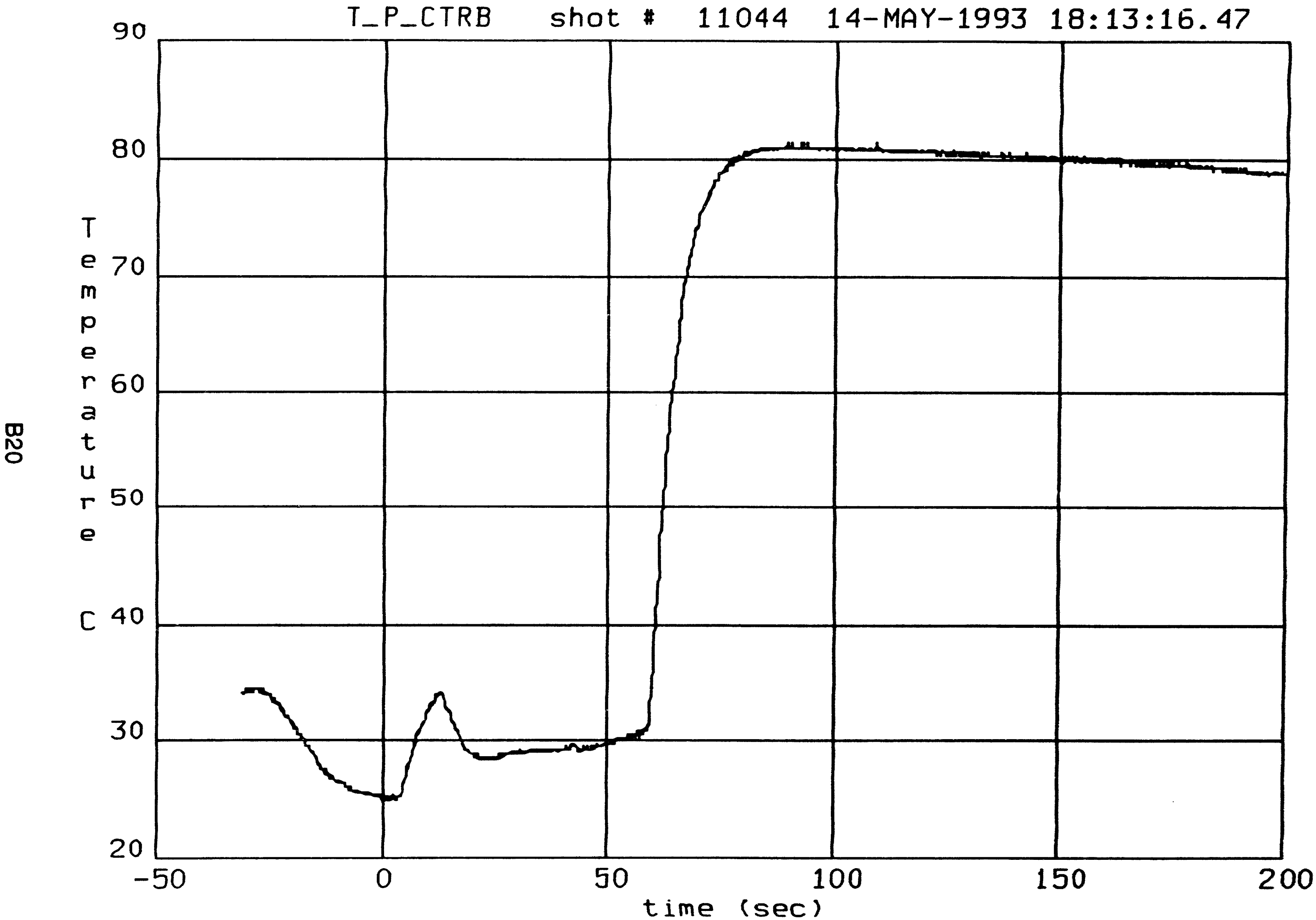
B17

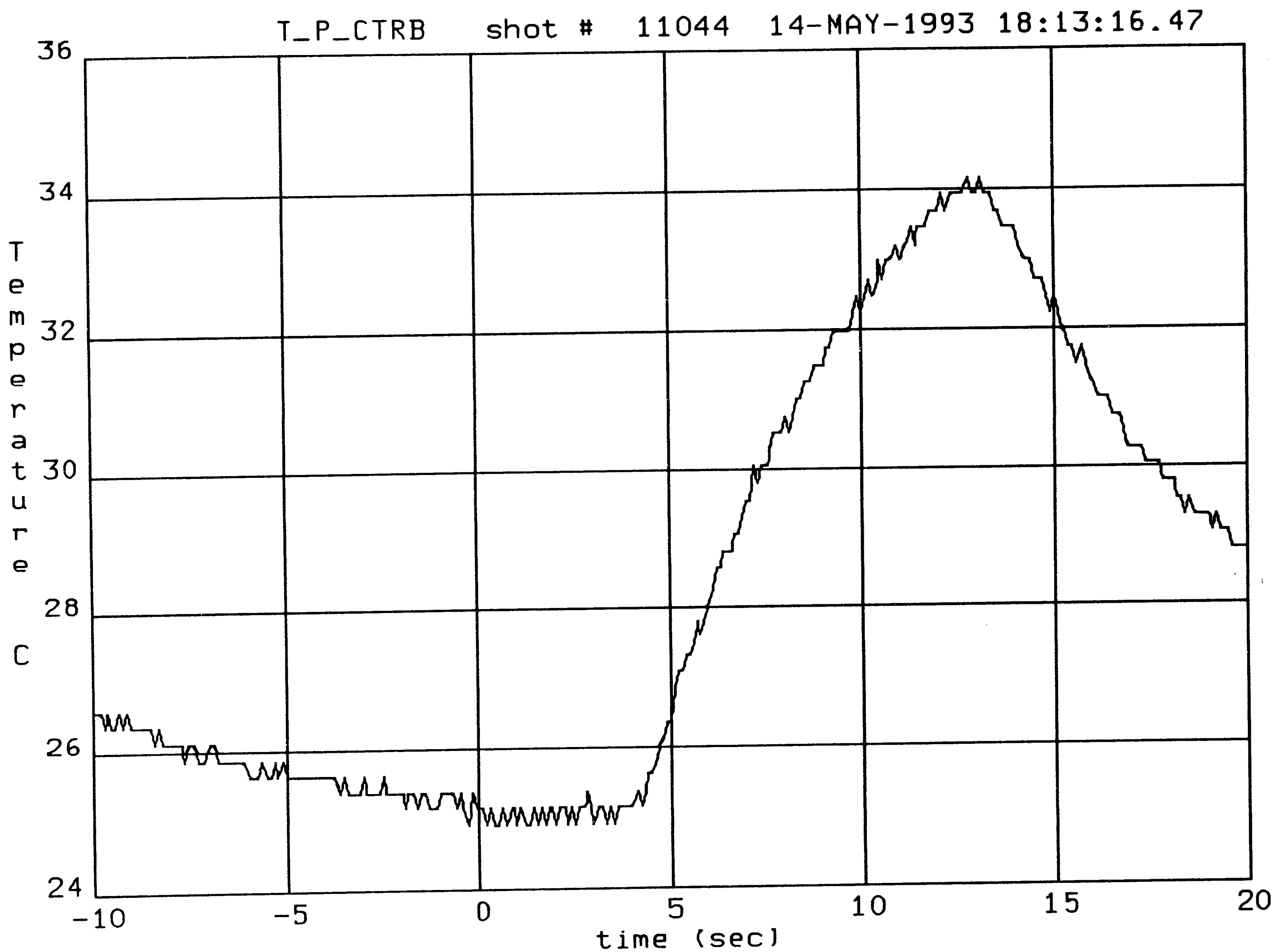

T_P_4_5I shot # 11044 14-MAY-1993 18:13:16.47
45
40
35
30
25
20
Temperature
C
-10
-5
0
5
10
15
20
time (sec)

B18


T_P_CTRA shot # 11044 14-MAY-1993 18:13:16.47
Temperature C
36
34
32
30
28
26
24
-10
-5
0
5
10
15
20
time (sec)

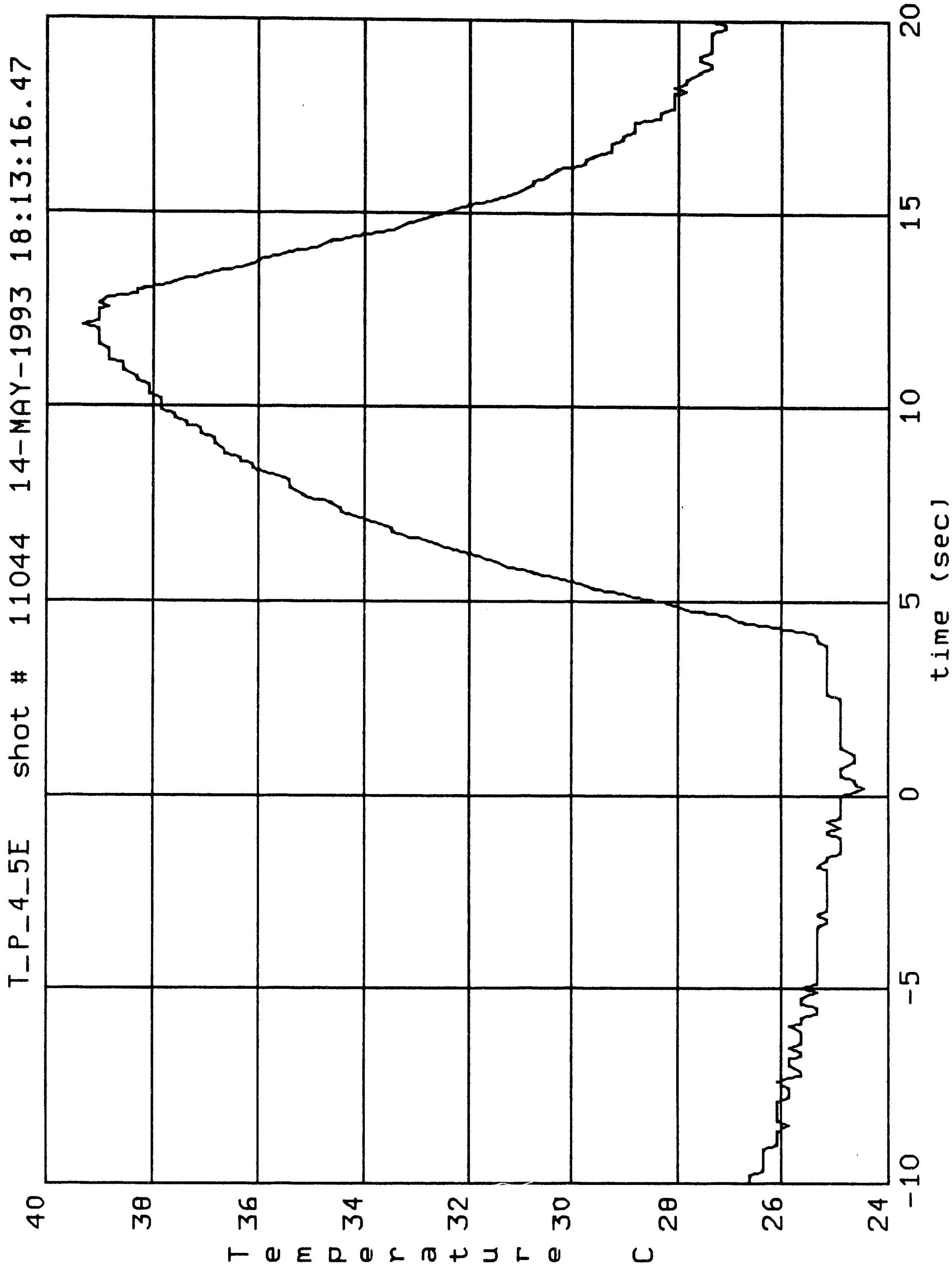
B19

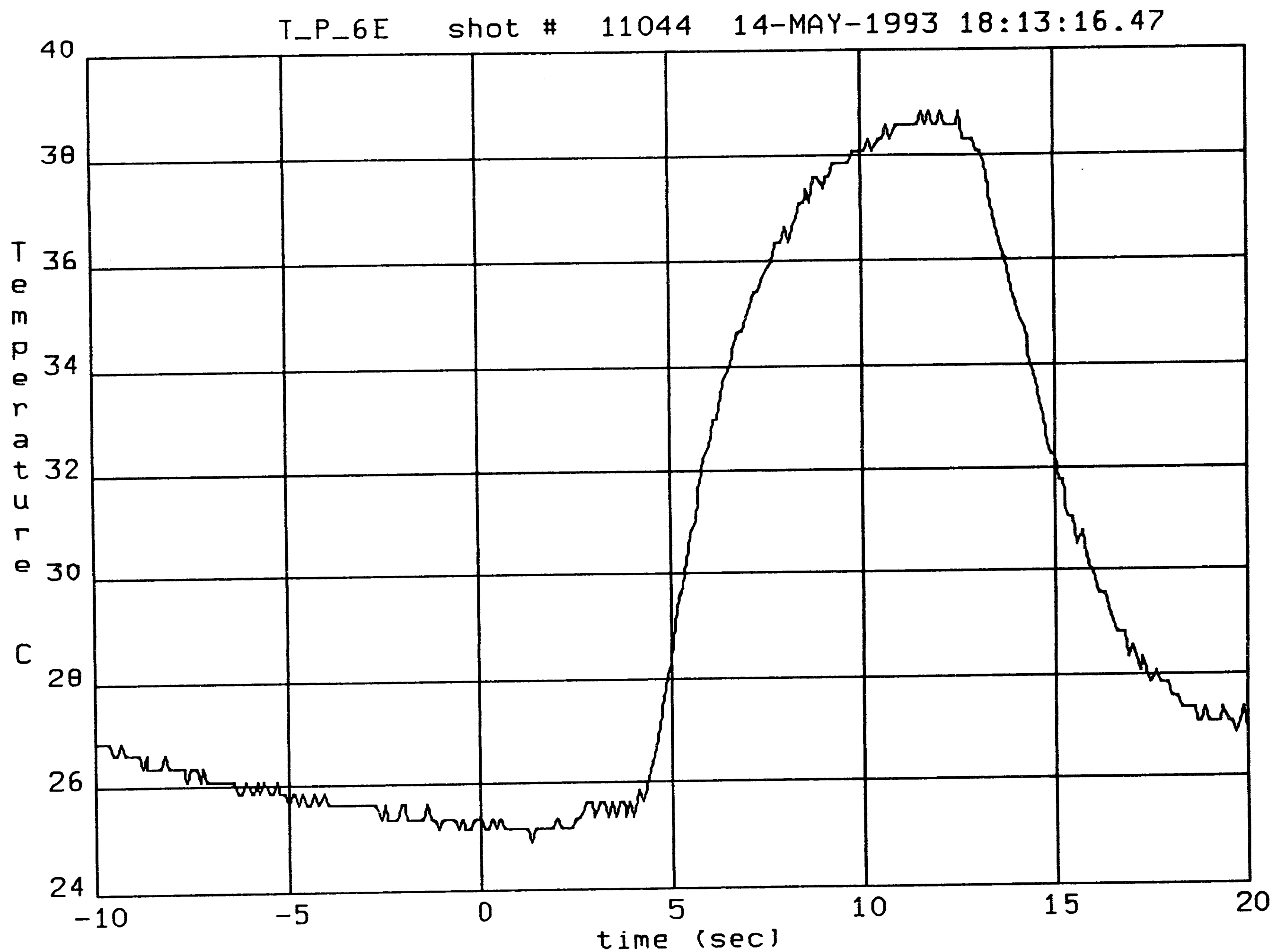

T_P_CTRB shot # 11044 14-MAY-1993 18:13:16.47
Temperature C
90
80
70
60
50
40
30
20
-50
0
50
100
150
200
time (sec)
B20

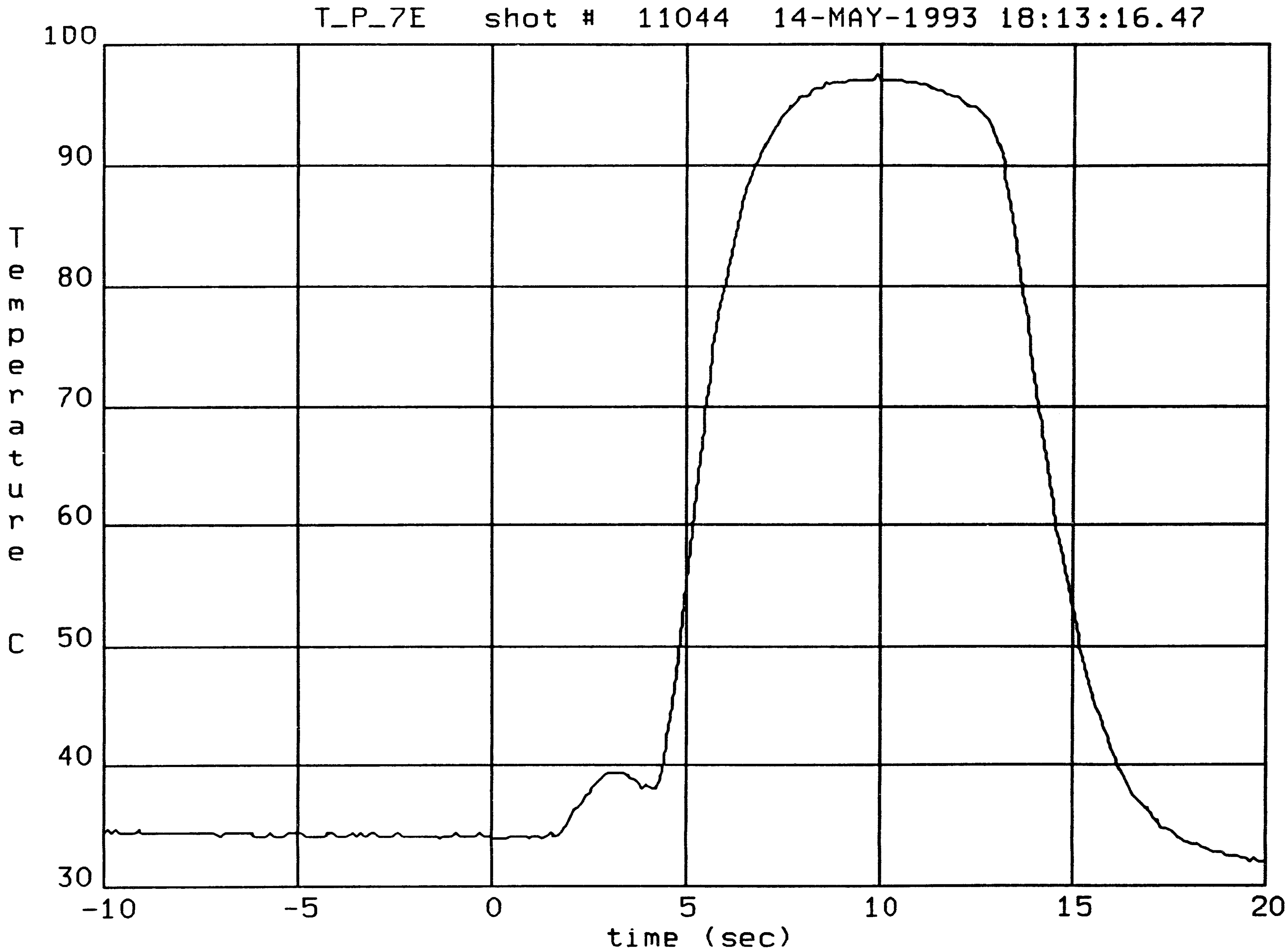


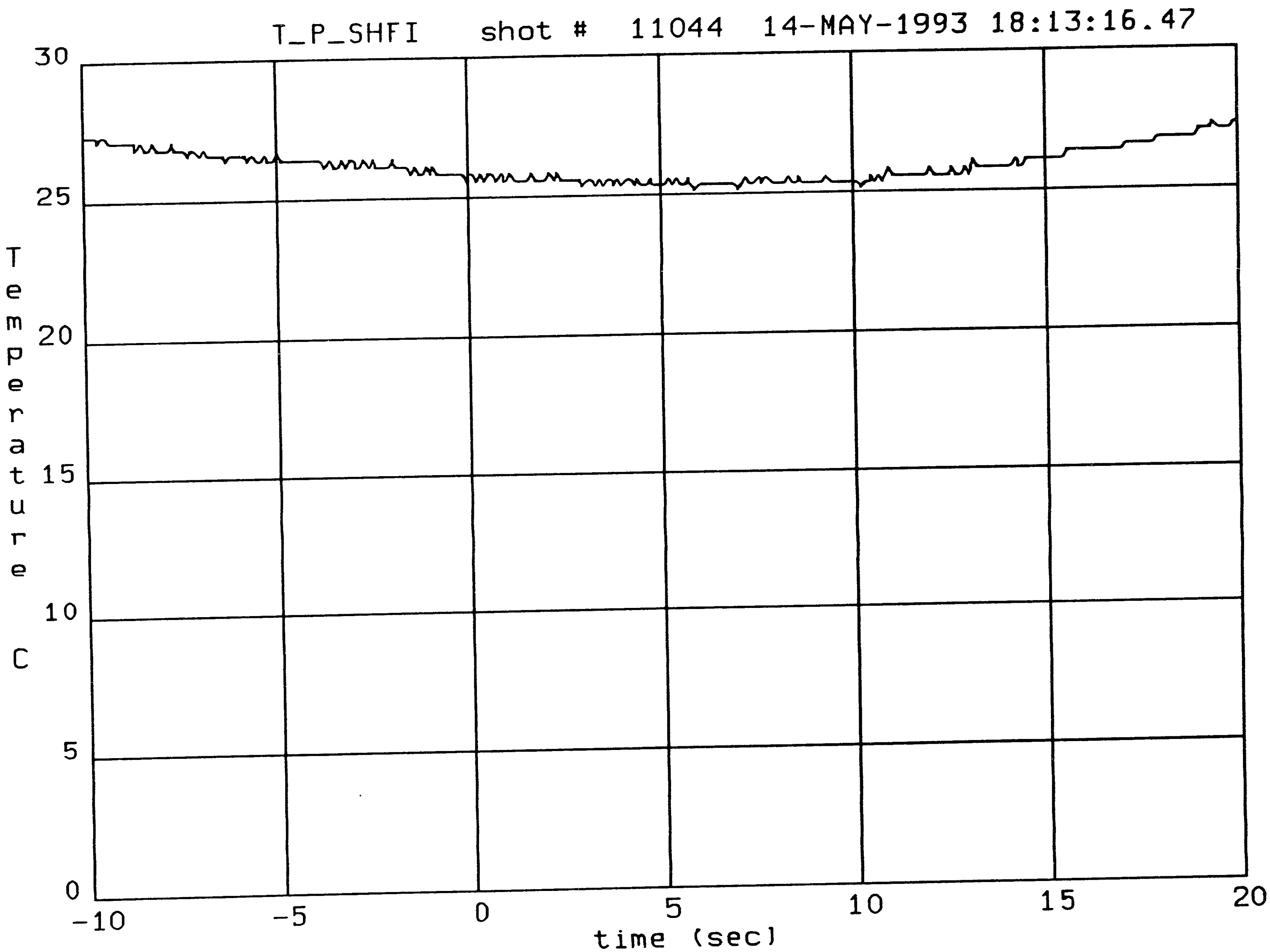
T_P_CTRB shot # 11044 14-MAY-1993 18:13:16.47
Temperature C
time (sec)
36
34
32
30
28
26
24
-10
-5
0
5
10
15
20

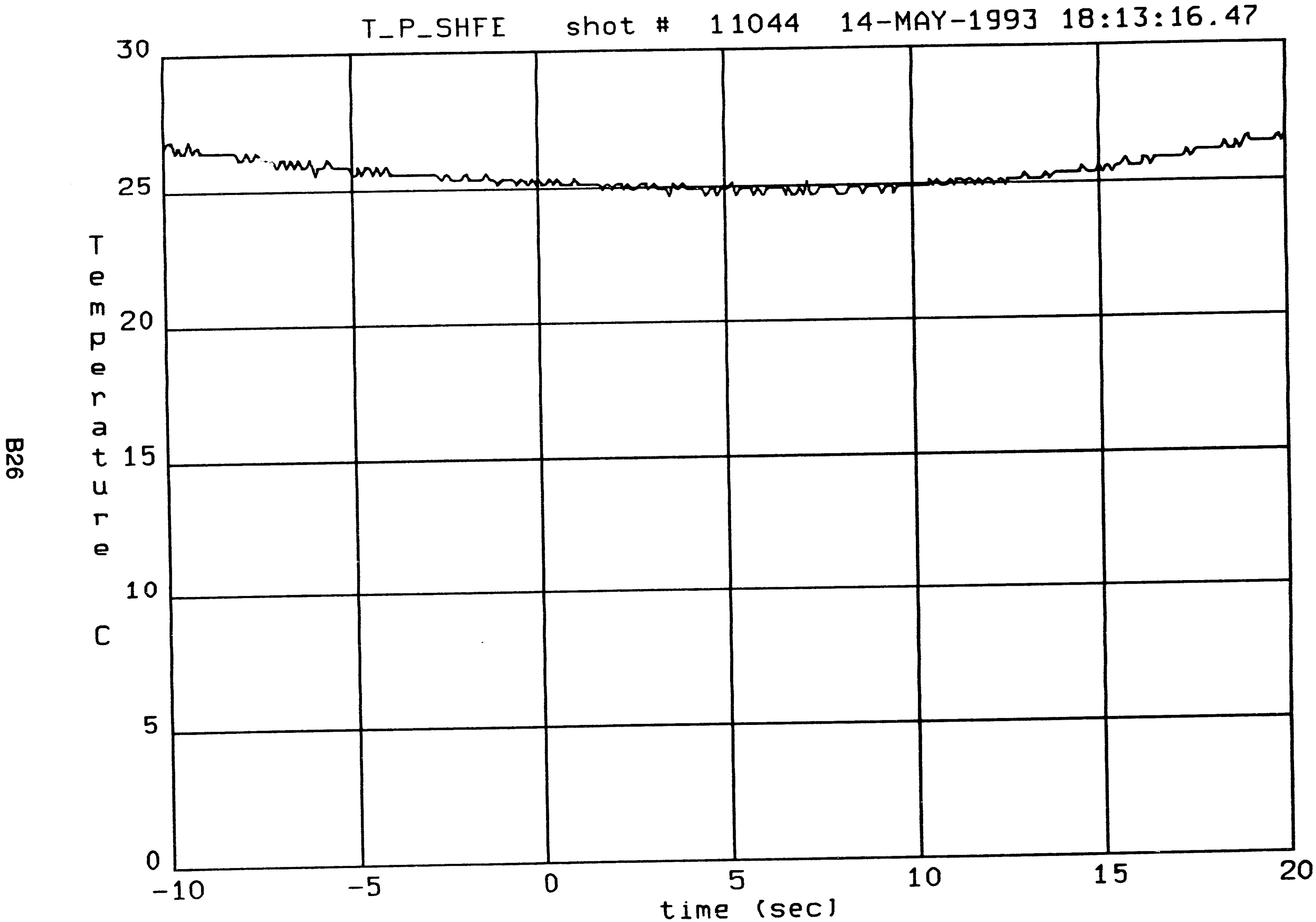
B21

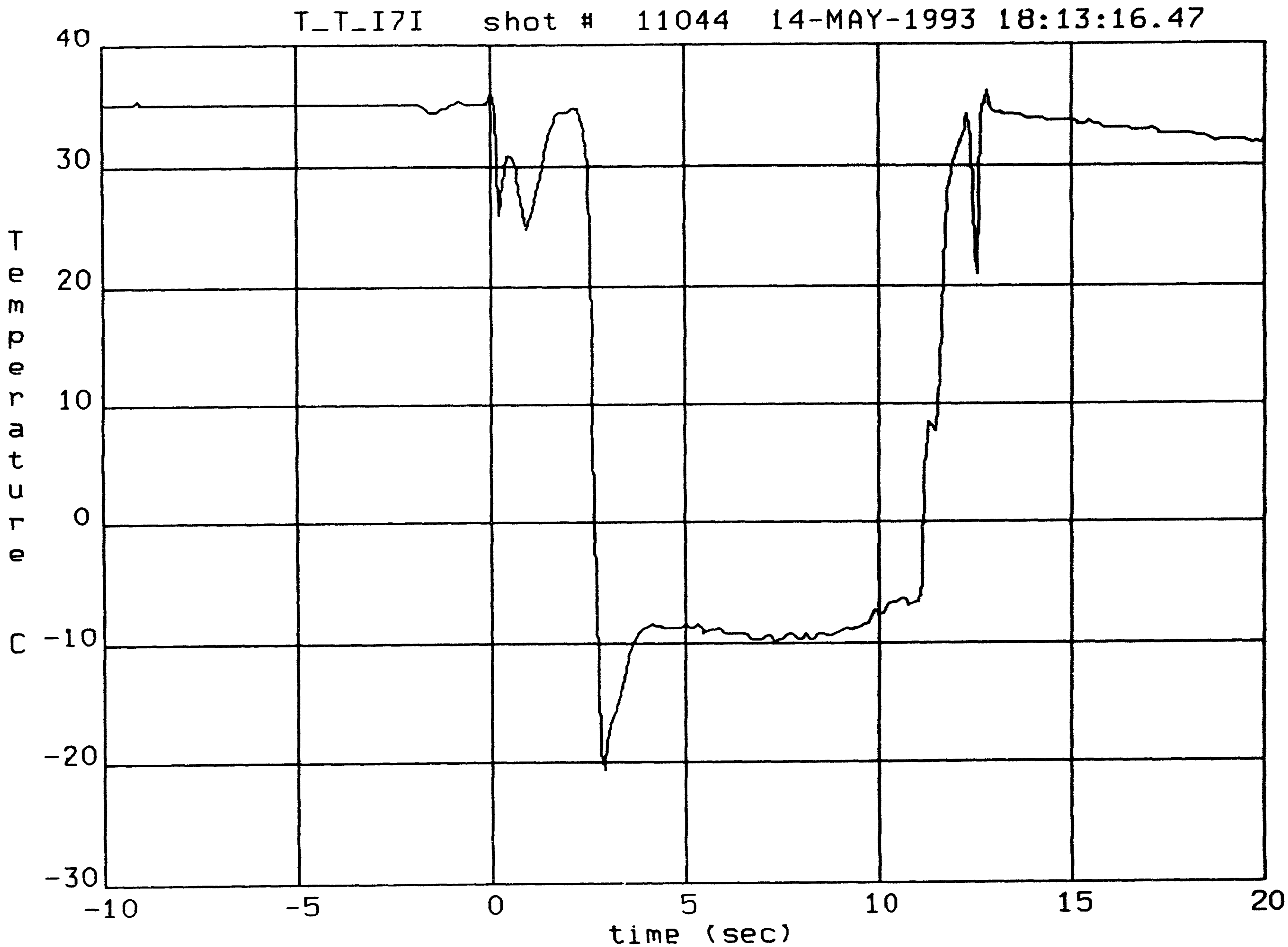

T_P_4_5E shot # 11044 14-MAY-1993 18:13:16.47
Temperature C
40
38
36
34
32
30
28
26
24
-10
-5
0
5
10
15
20
time (sec)


T_P_6E shot # 11044 14-MAY-1993 18:13:16.47
Temperature C
40
38
36
34
32
30
28
26
24
-10
-5
0
5
10
15
20
time (sec)


T_P_7E shot # 11044 14-MAY-1993 18:13:16.47
Temperature C
100
90
80
70
60
50
40
30
-10
-5
0
5
10
15
20
time (sec)

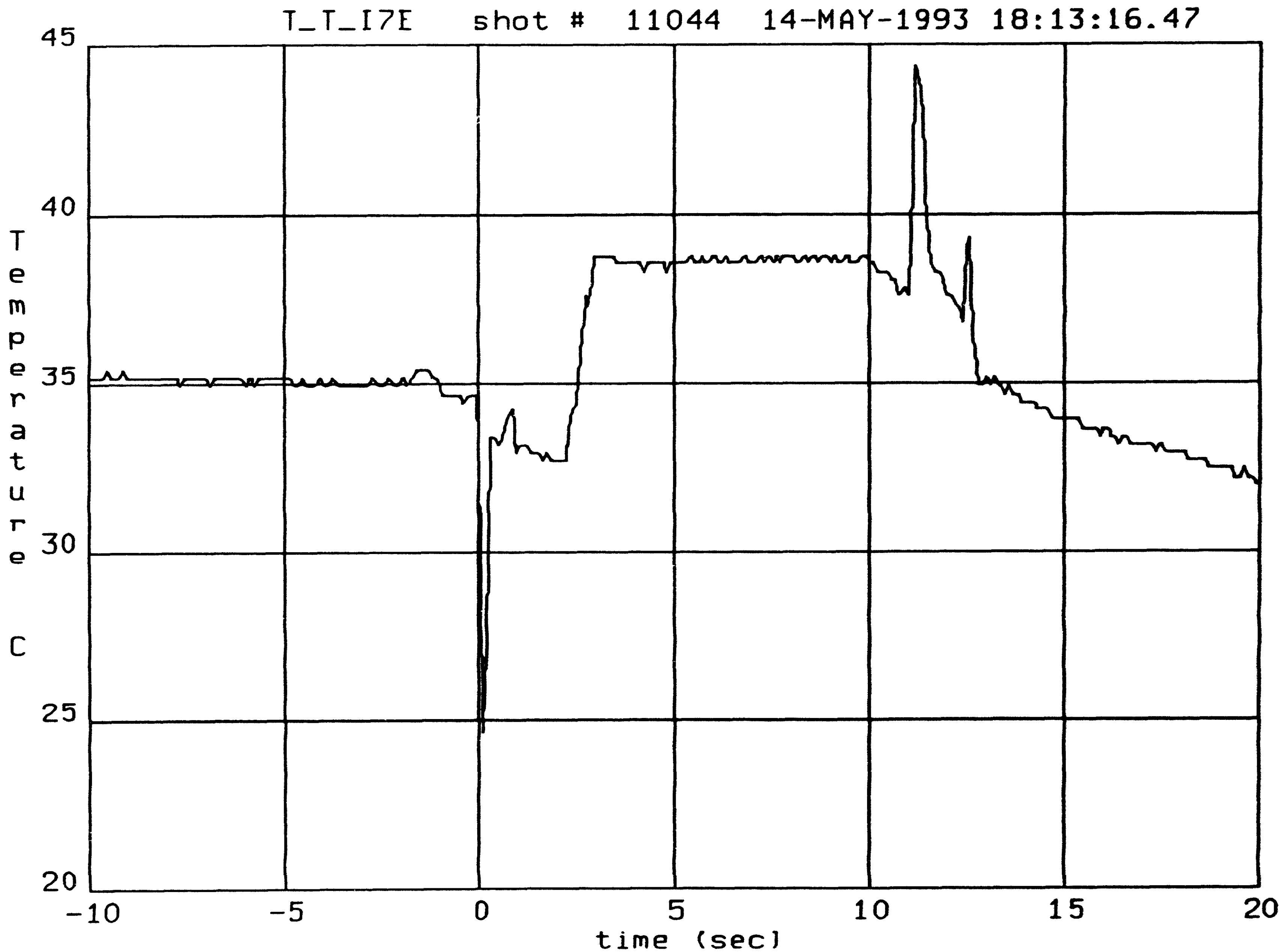

T_P_SHFI shot # 11044 14-MAY-1993 18:13:16.47
30
25
20
15
10
5
0
Temperature C
-10
-5
0
5
10
15
20
time (sec)
B25


T_P_SHFE shot # 11044 14-MAY-1993 18:13:16.47
Temperature C
30
25
20
15
10
5
0
-10
-5
0
5
10
15
20
time (sec)
B26

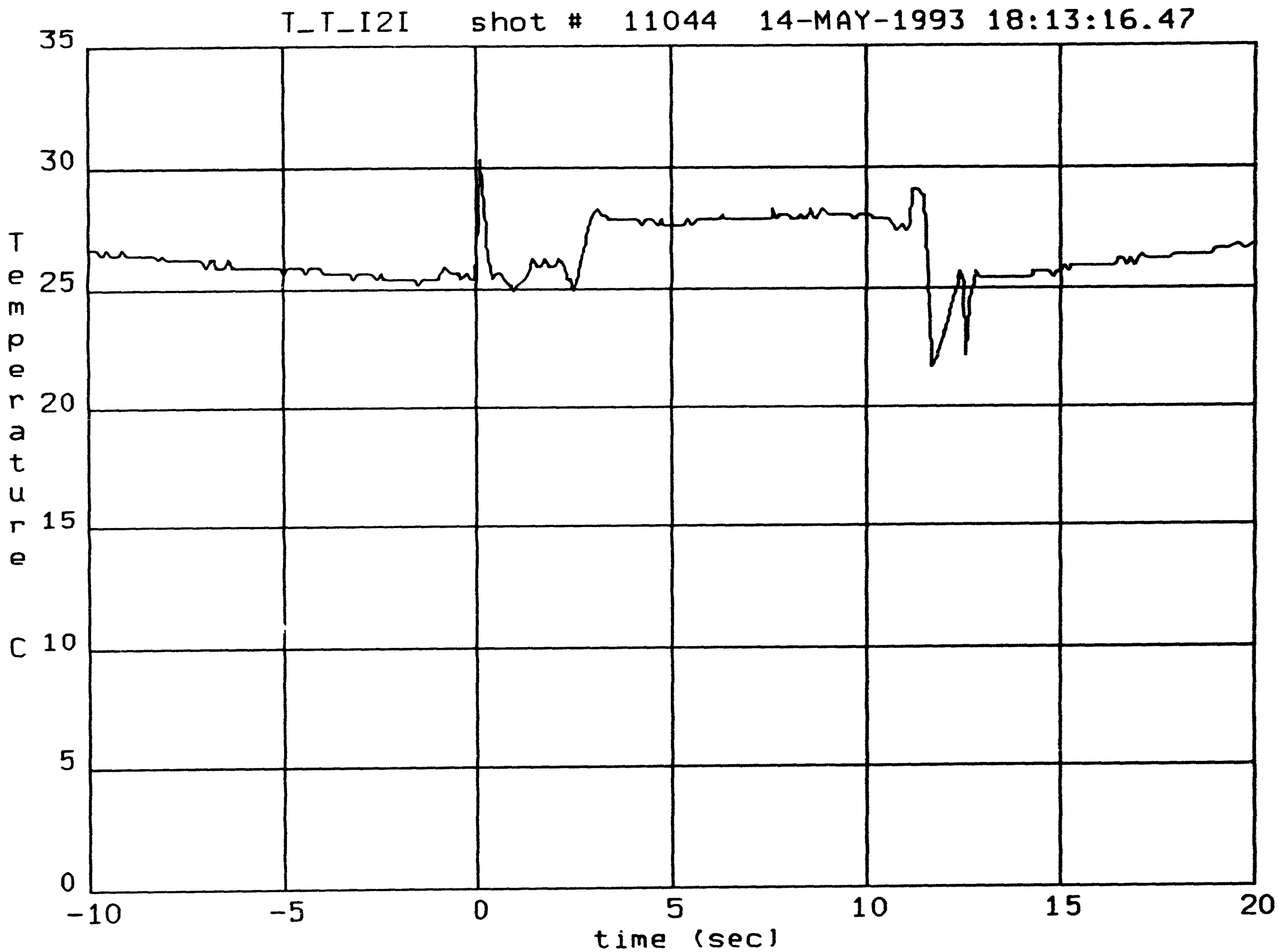


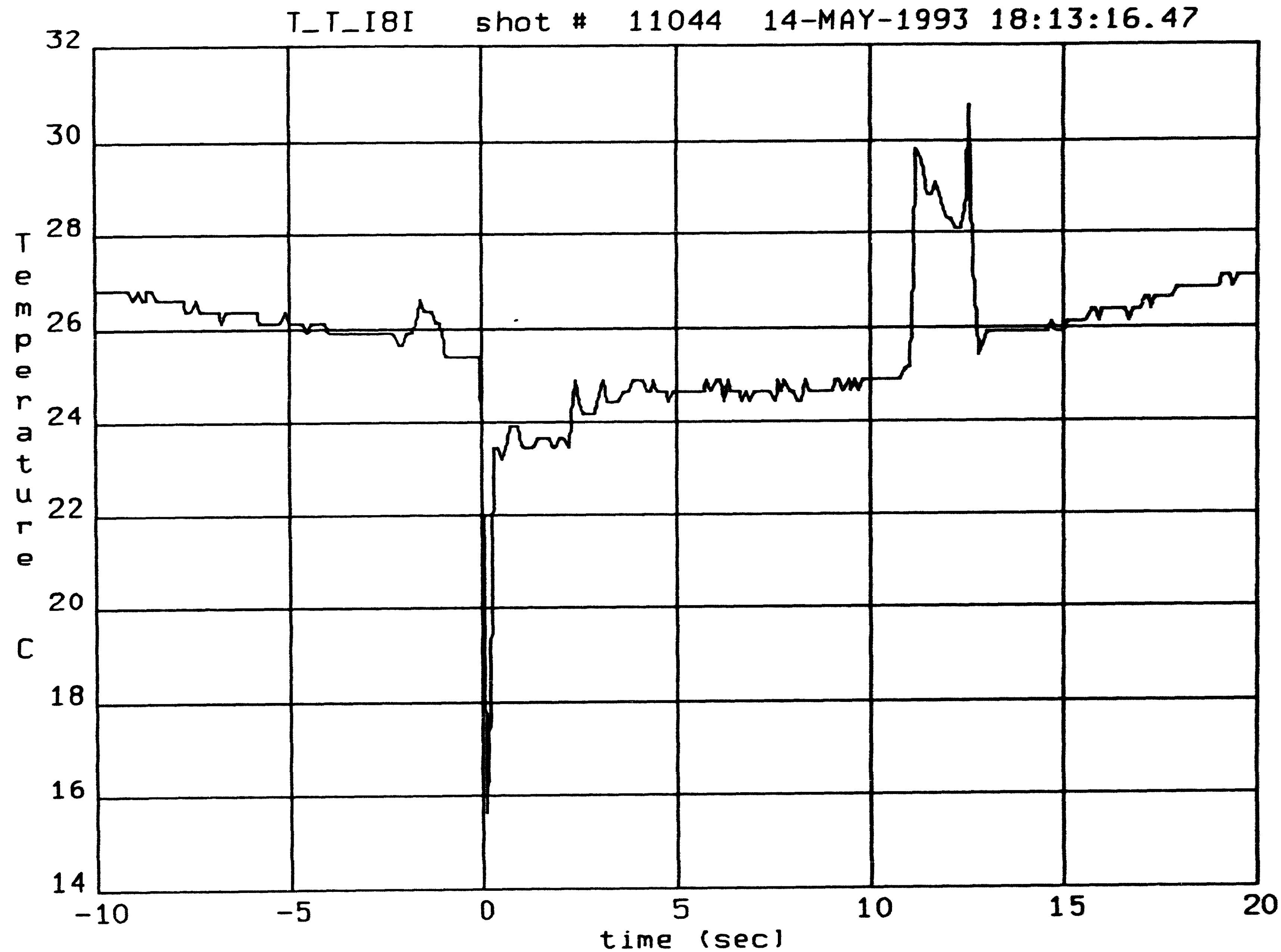
T_T_I7I shot # 11044 14-MAY-1993 18:13:16.47
Temperature C
time (sec)
40
30
20
10
0
-10
-20
-30
-10
-5
0
5
10
15
20

B27

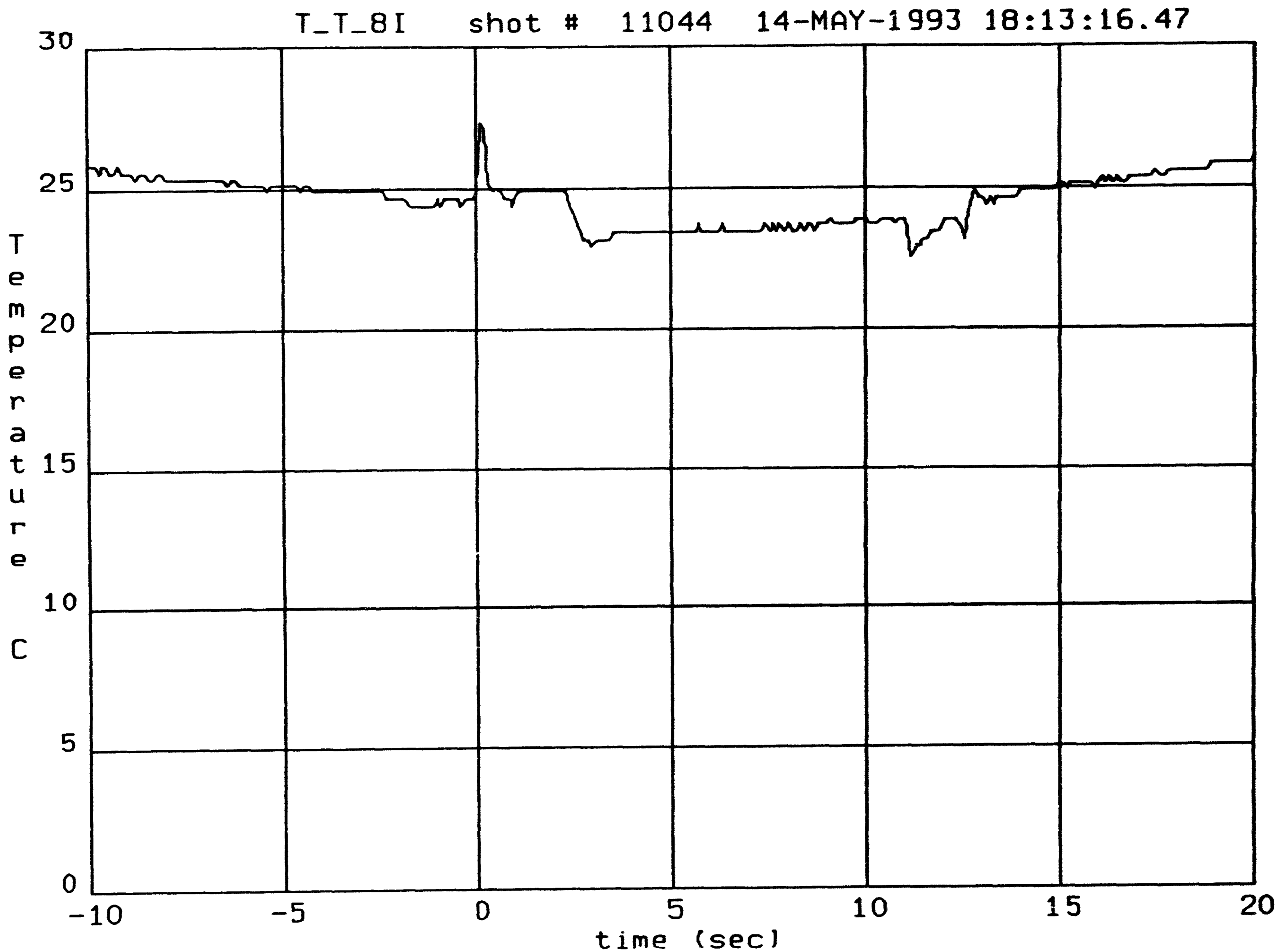

T_T_I7E shot # 11044 14-MAY-1993 18:13:16.47
Temperature C
45
40
35
30
25
20
-10
-5
0
5
10
15
20
time (sec)

B28

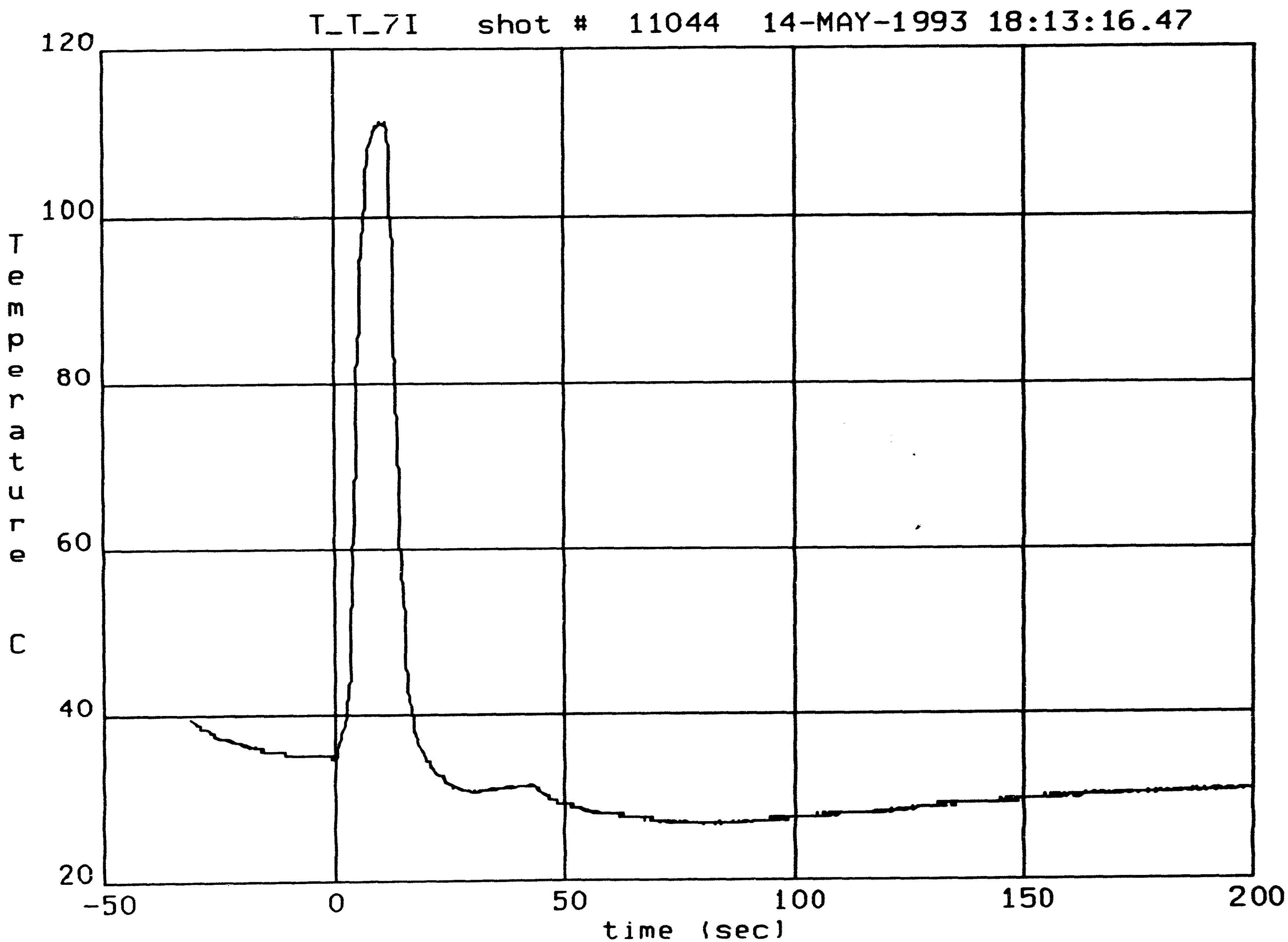

T_T_I2I shot # 11044 14-MAY-1993 18:13:16.47
Temperature C
35
30
25
20
15
10
5
0
-10
-5
0
5
10
15
20
time (sec)


T_T_I8I shot # 11044 14-MAY-1993 18:13:16.47
32
30
28
26
24
22
20
18
16
14
Temperature
C
-10
-5
0
5
10
15
20
time (sec)

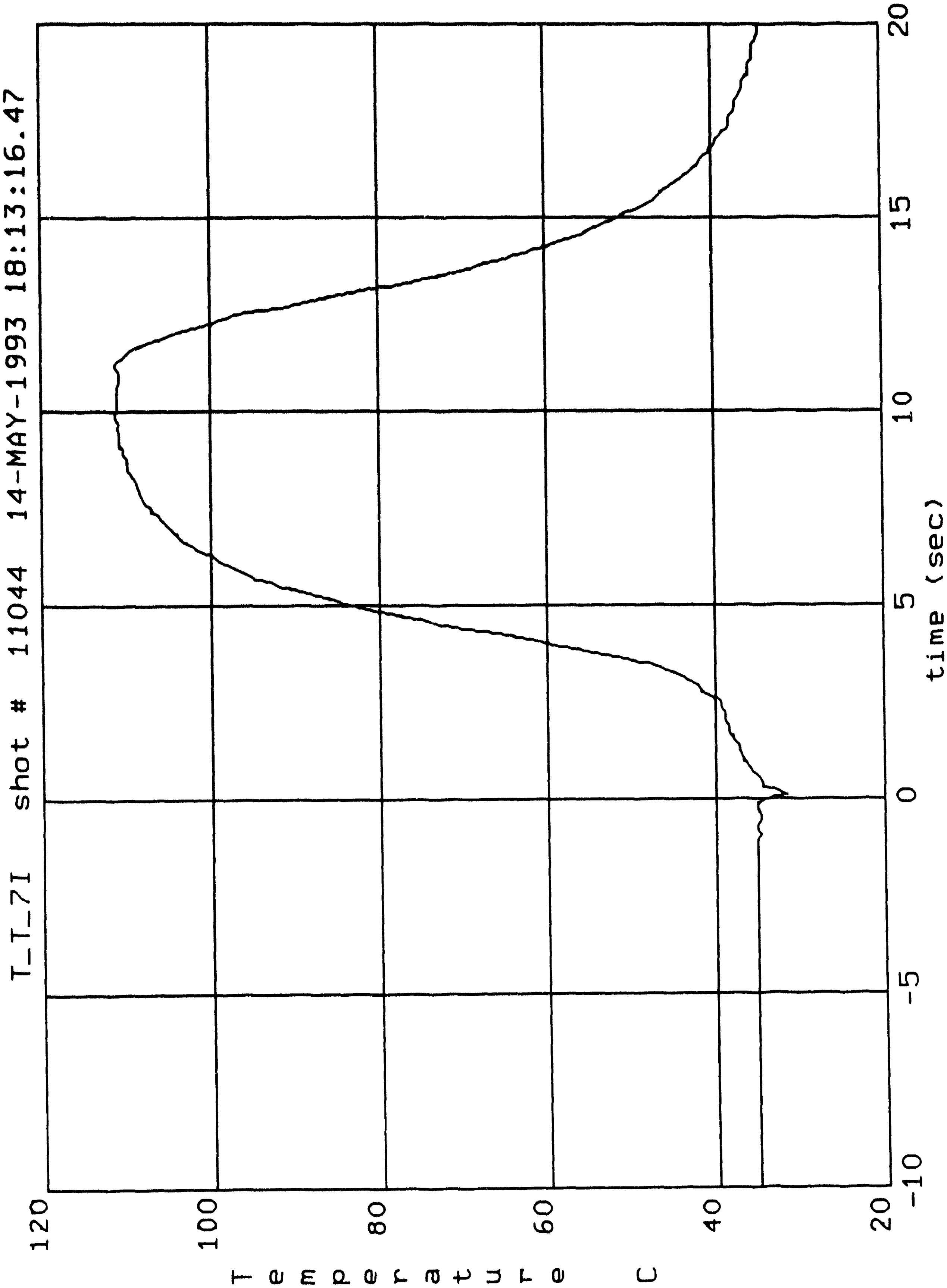
B30


T_T_8I shot # 11044 14-MAY-1993 18:13:16.47
30
25
20
15
10
5
0
Temperature C
-10
-5
0
5
10
15
20
time (sec)

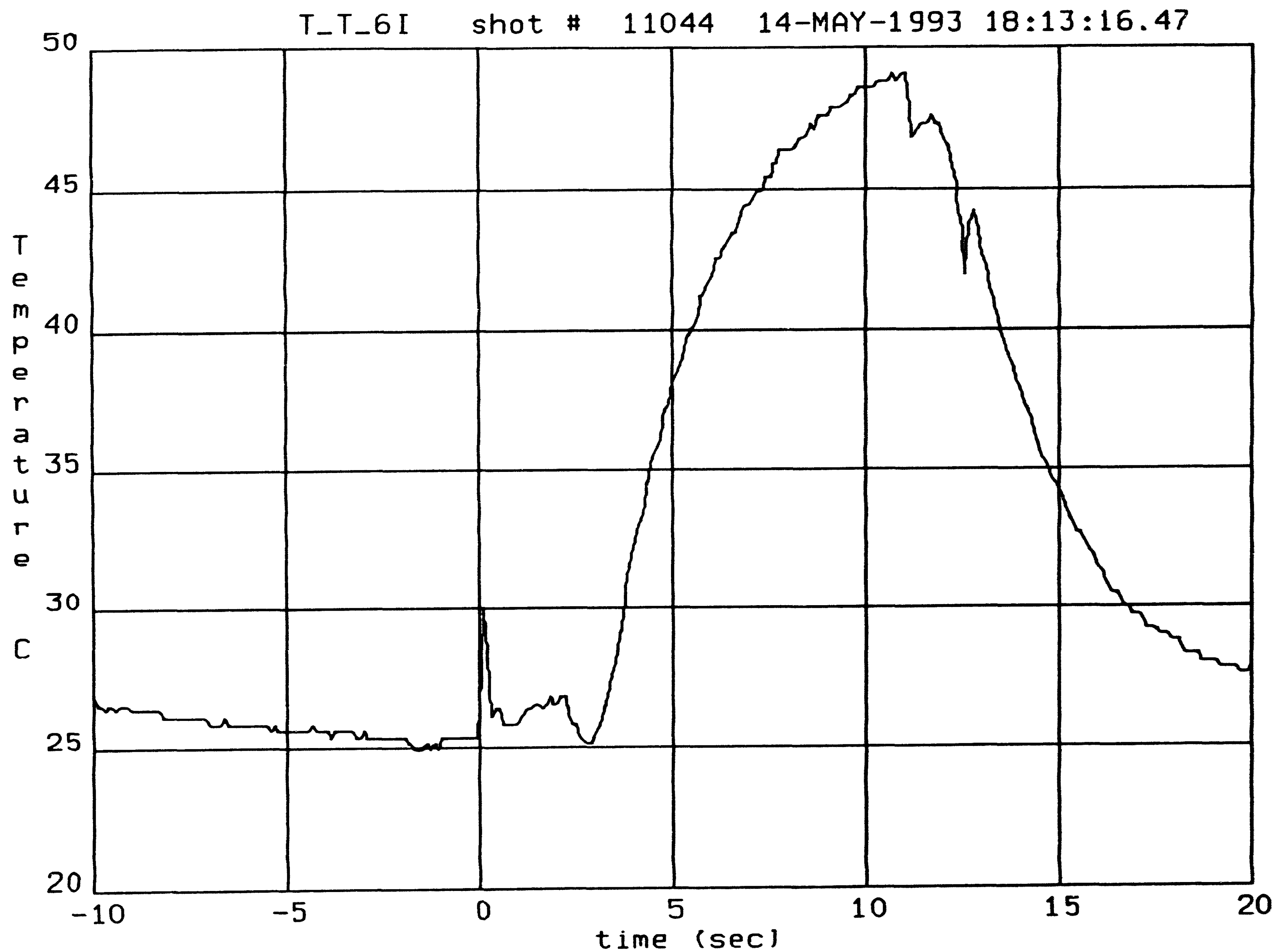
B31


T_T_7I shot # 11044 14-MAY-1993 18:13:16.47
120
100
80
60
40
20
Temperature C
-50
0
50
100
150
200
time (sec)

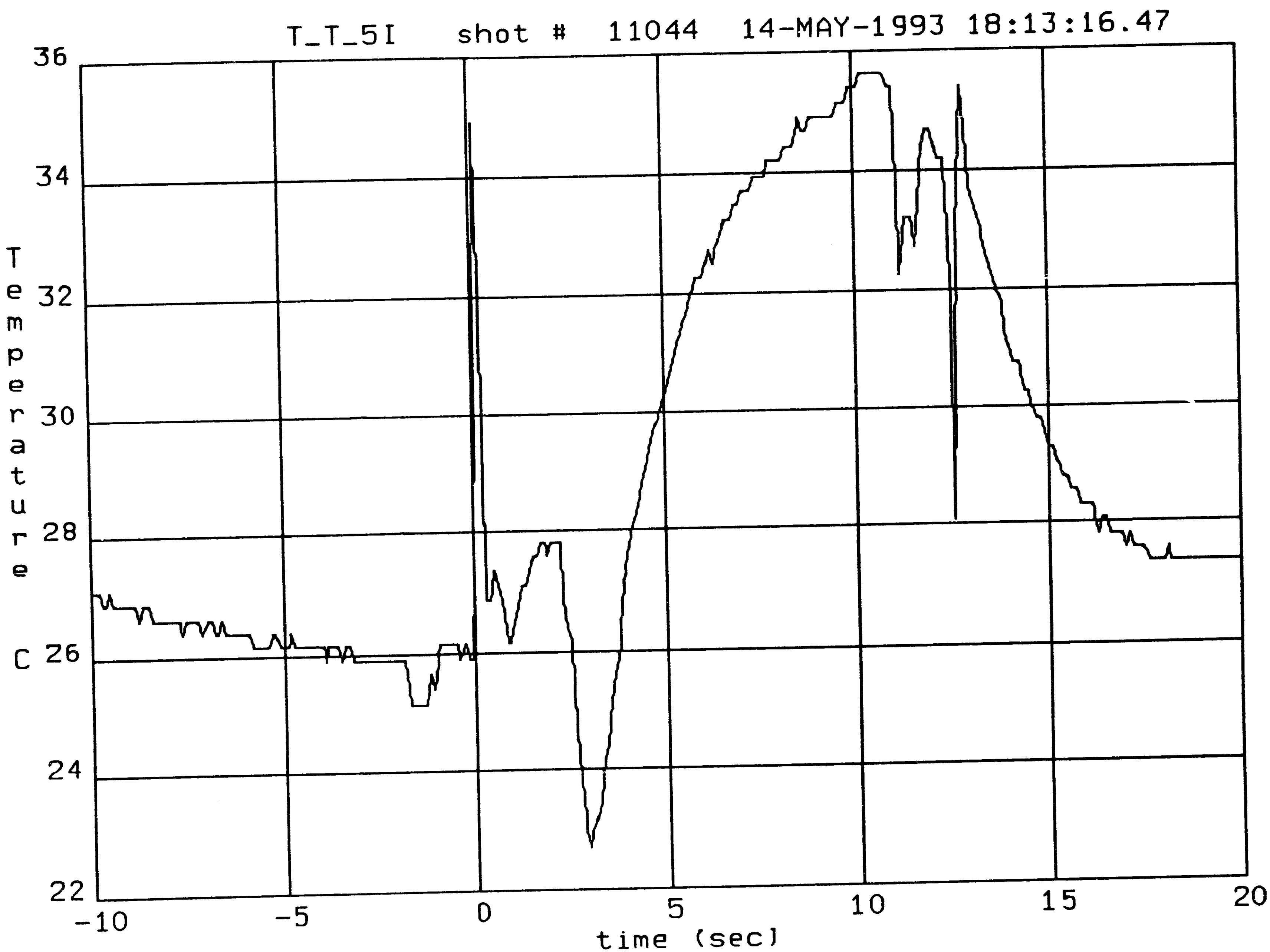
B32



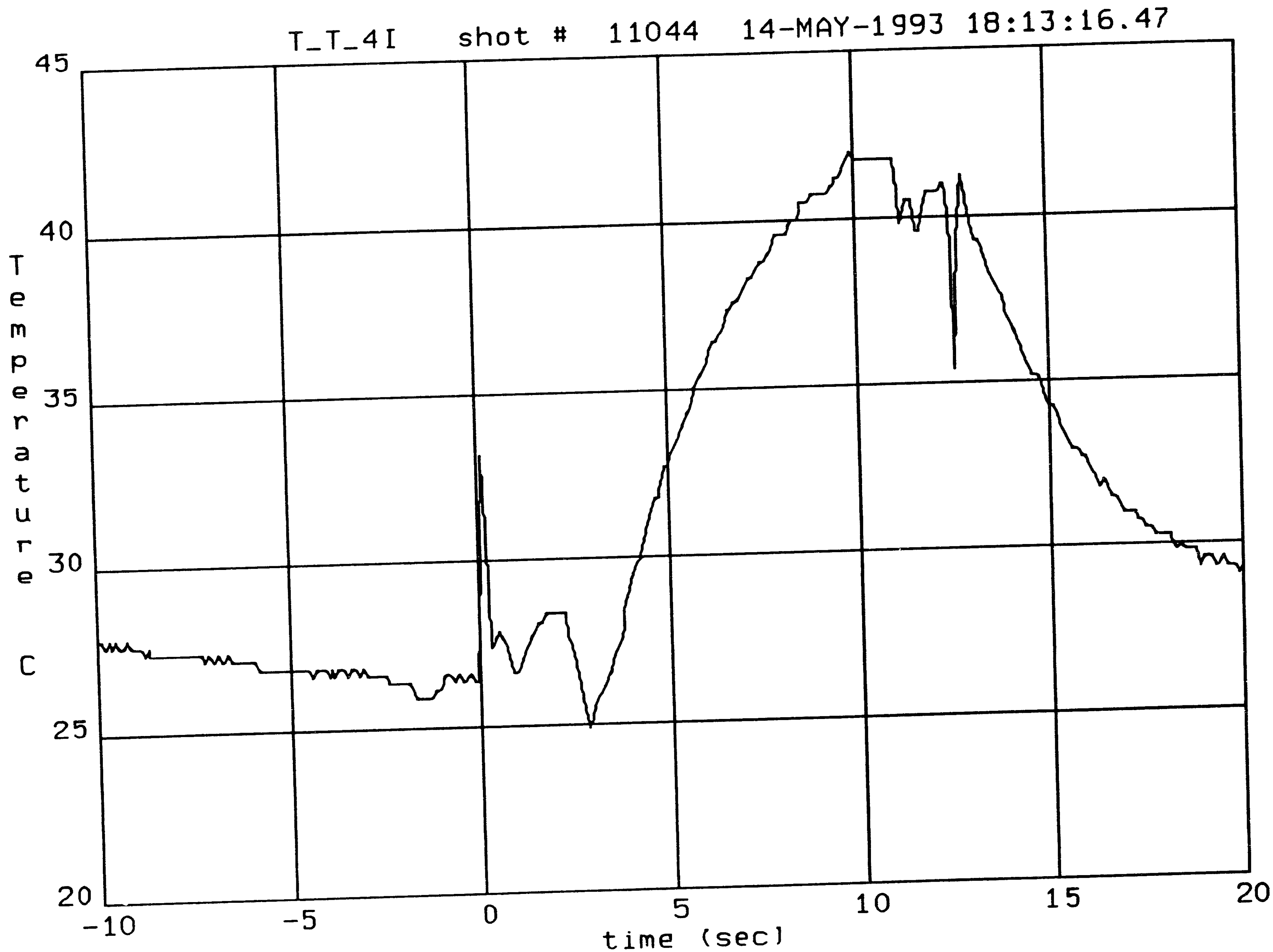
T_T_71 shot # 11044 14-MAY-1993 18:13:16.47
120
100
80
60
40
20
Temperature C
-10
-5
0
5
10
15
20
time (sec)



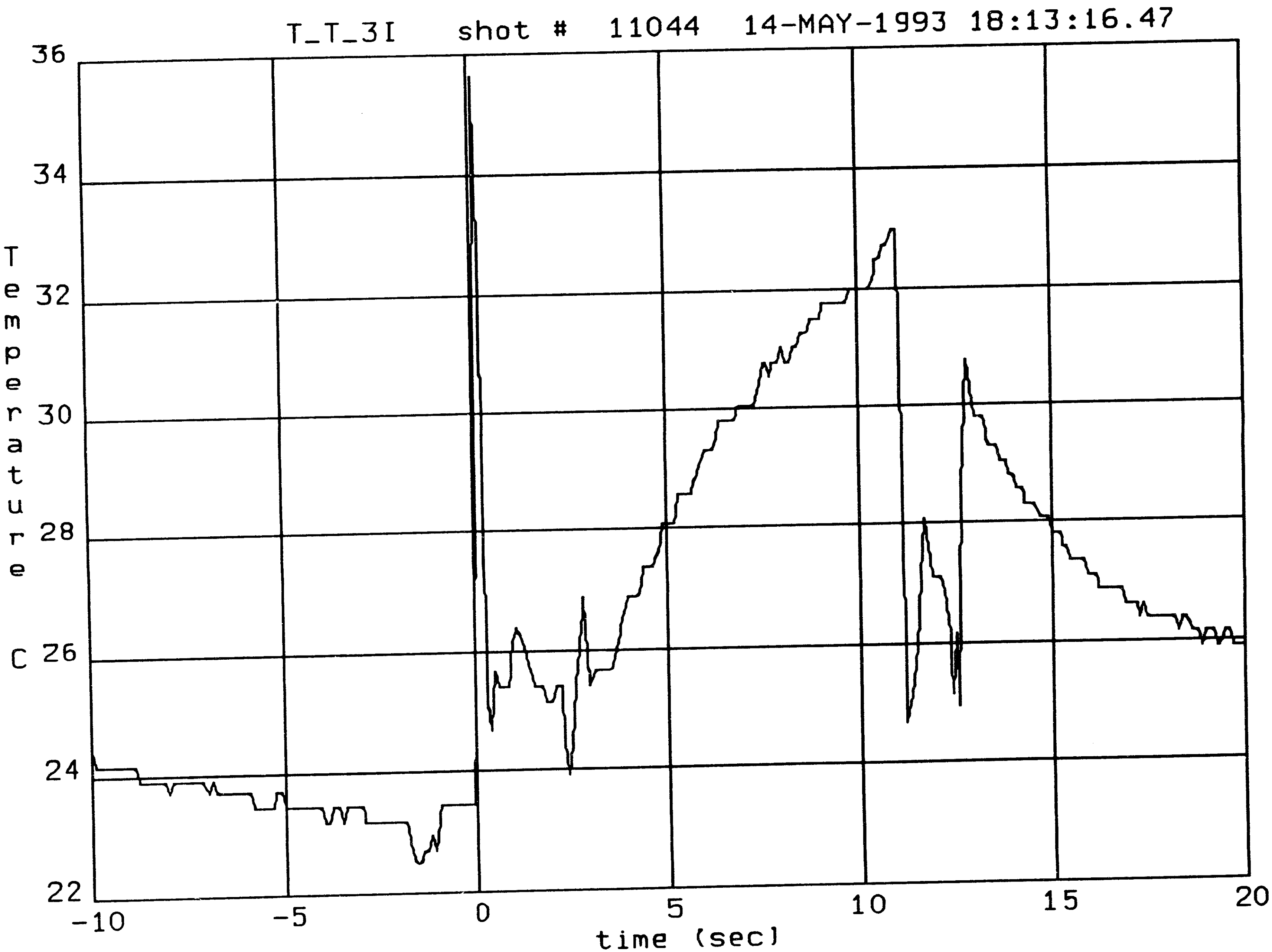
T_T_6I shot # 11044 14-MAY-1993 18:13:16.47
50
45
40
35
30
25
20
Temperature C
-10
-5
0
5
10
15
20
time (sec)


T_T_5I shot # 11044 14-MAY-1993 18:13:16.47
Temperature C
36
34
32
30
28
26
24
22
-10
-5
0
5
10
15
20
time (sec)

B35

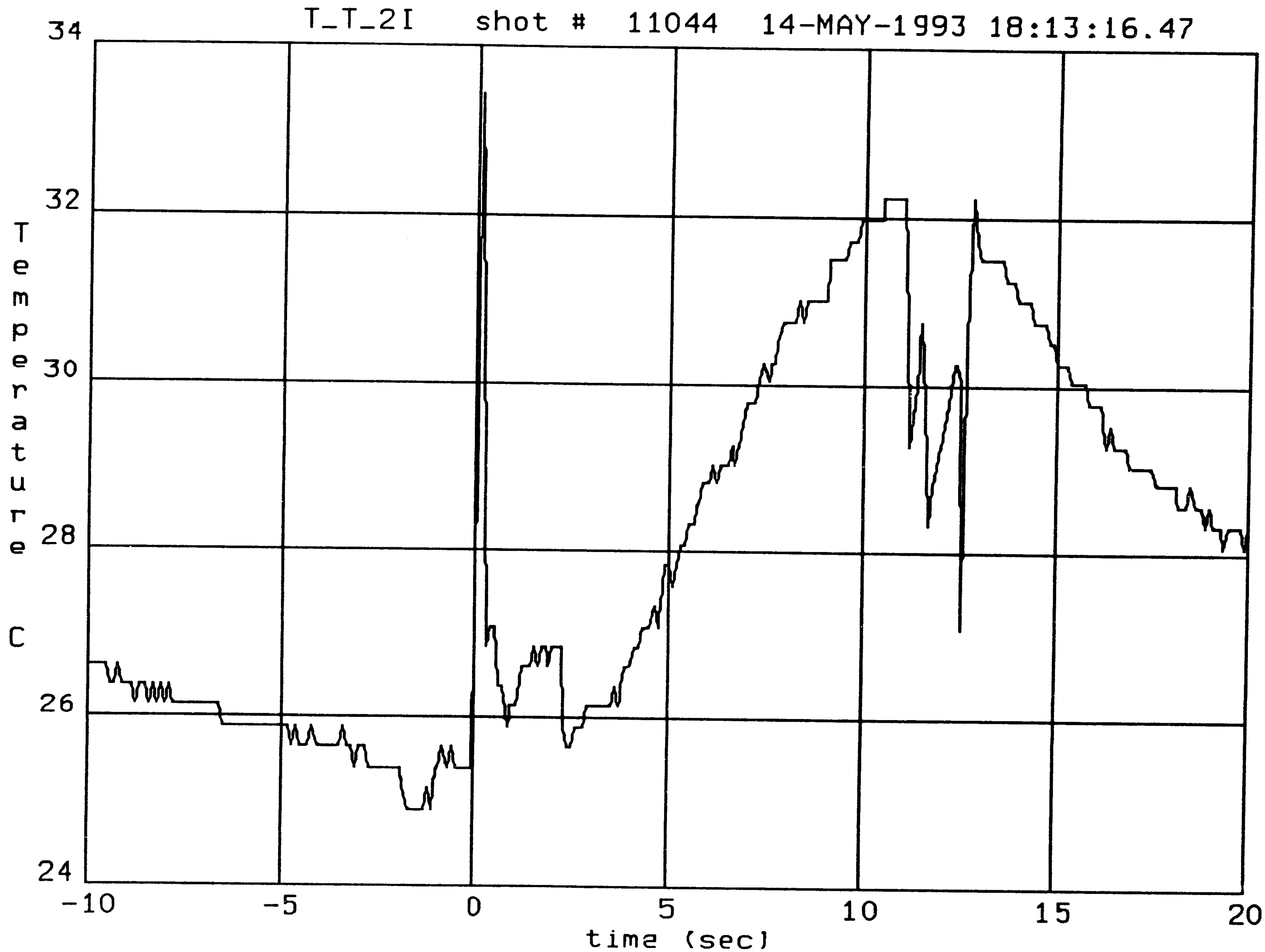

T_T_4I shot # 11044 14-MAY-1993 18:13:16.47
45
40
35
30
25
20
Temperature
C
-10
-5
0
5
10
15
20
time (sec)

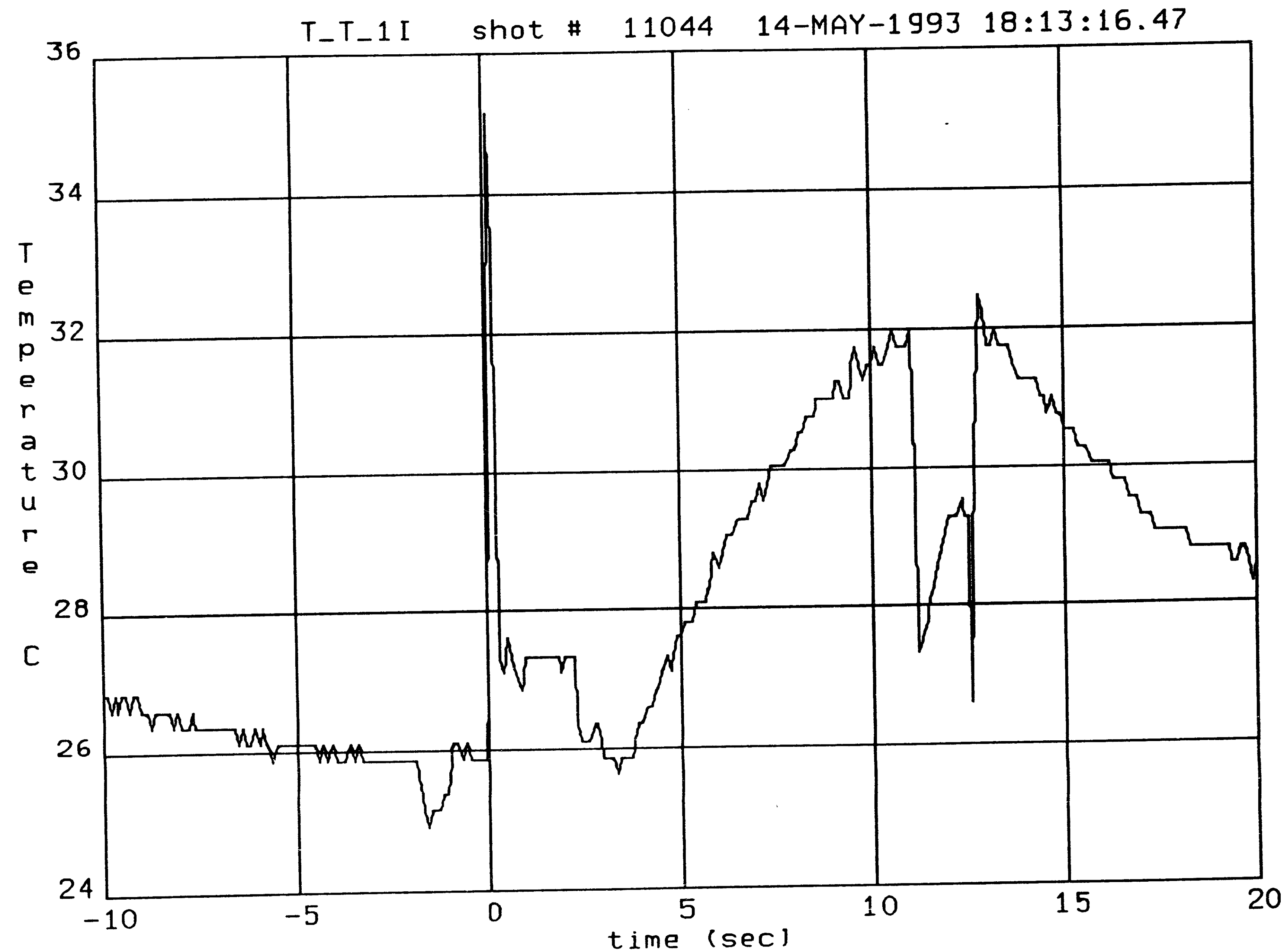
B36



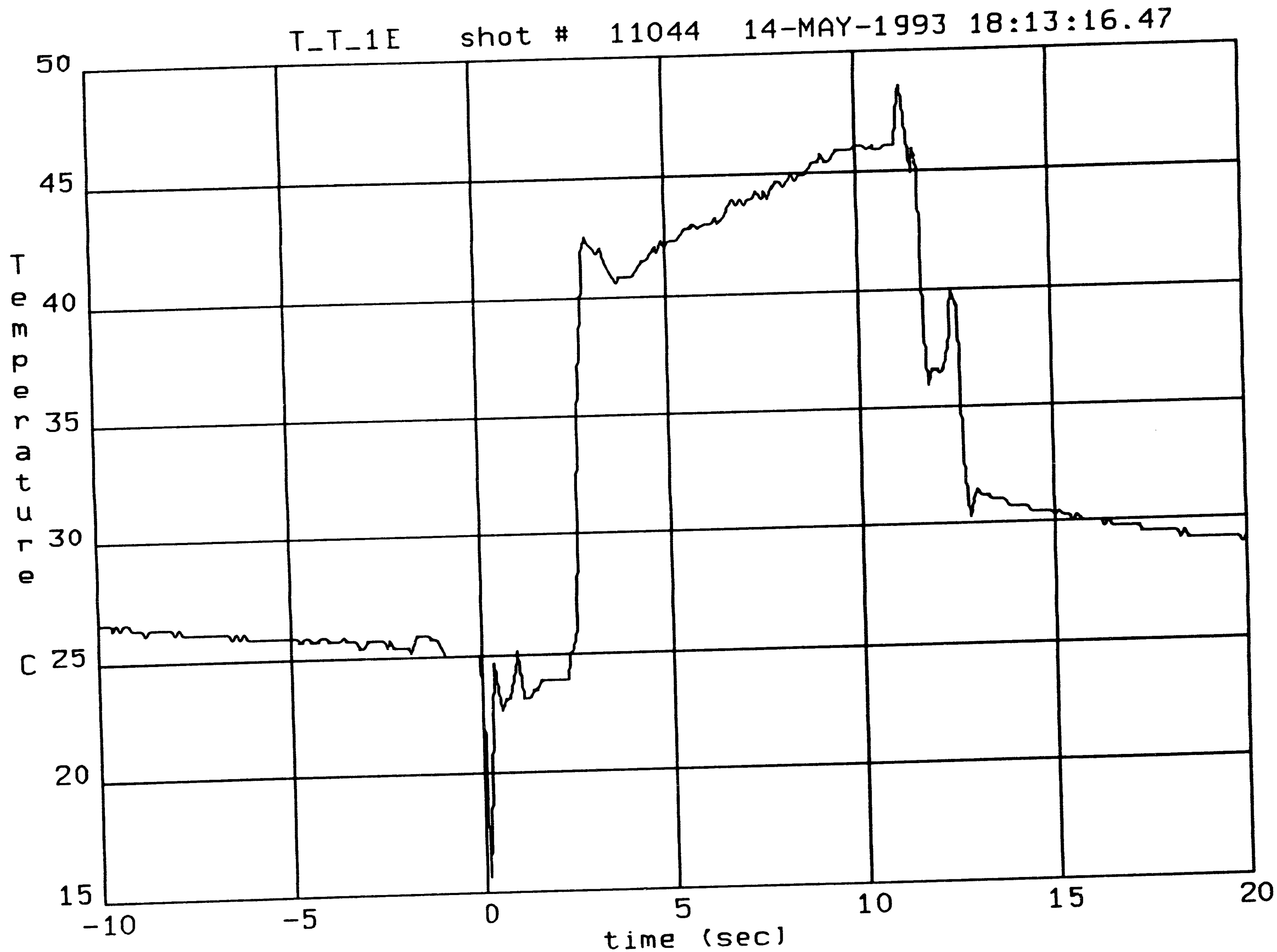
T_T_3I shot # 11044 14-MAY-1993 18:13:16.47
36
34
32
30
28
26
24
22
Temperature C
-10
-5
0
5
10
15
20
time (sec)

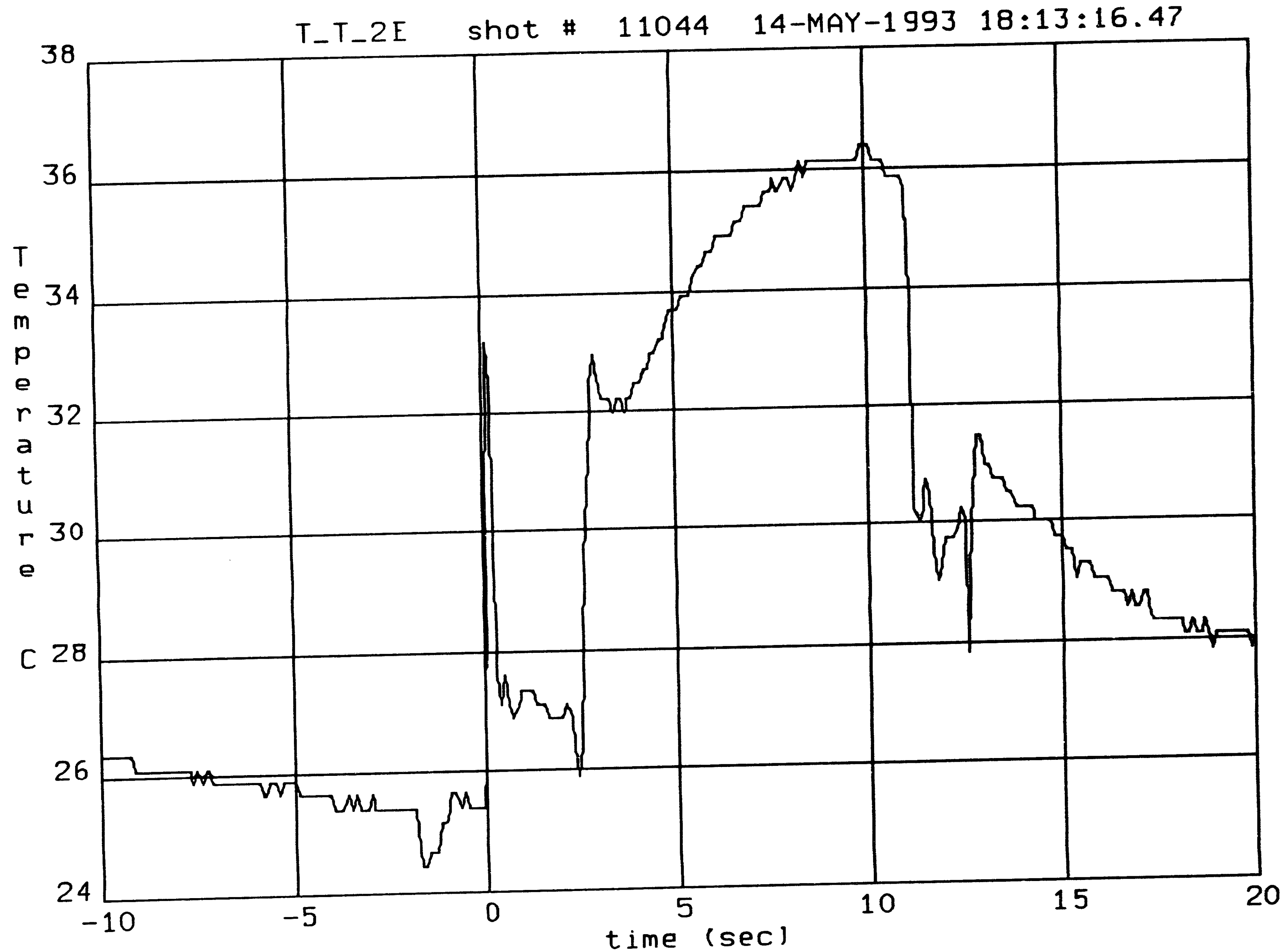
B37


T_T_2I shot # 11044 14-MAY-1993 18:13:16.47
34
32
30
28
26
24
Temperature C
-10
-5
0
5
10
15
20
time (sec)


T_T_1I shot # 11044 14-MAY-1993 18:13:16.47
36
34
32
30
28
26
24
Temperature C
-10
-5
0
5
10
15
20
time (sec)

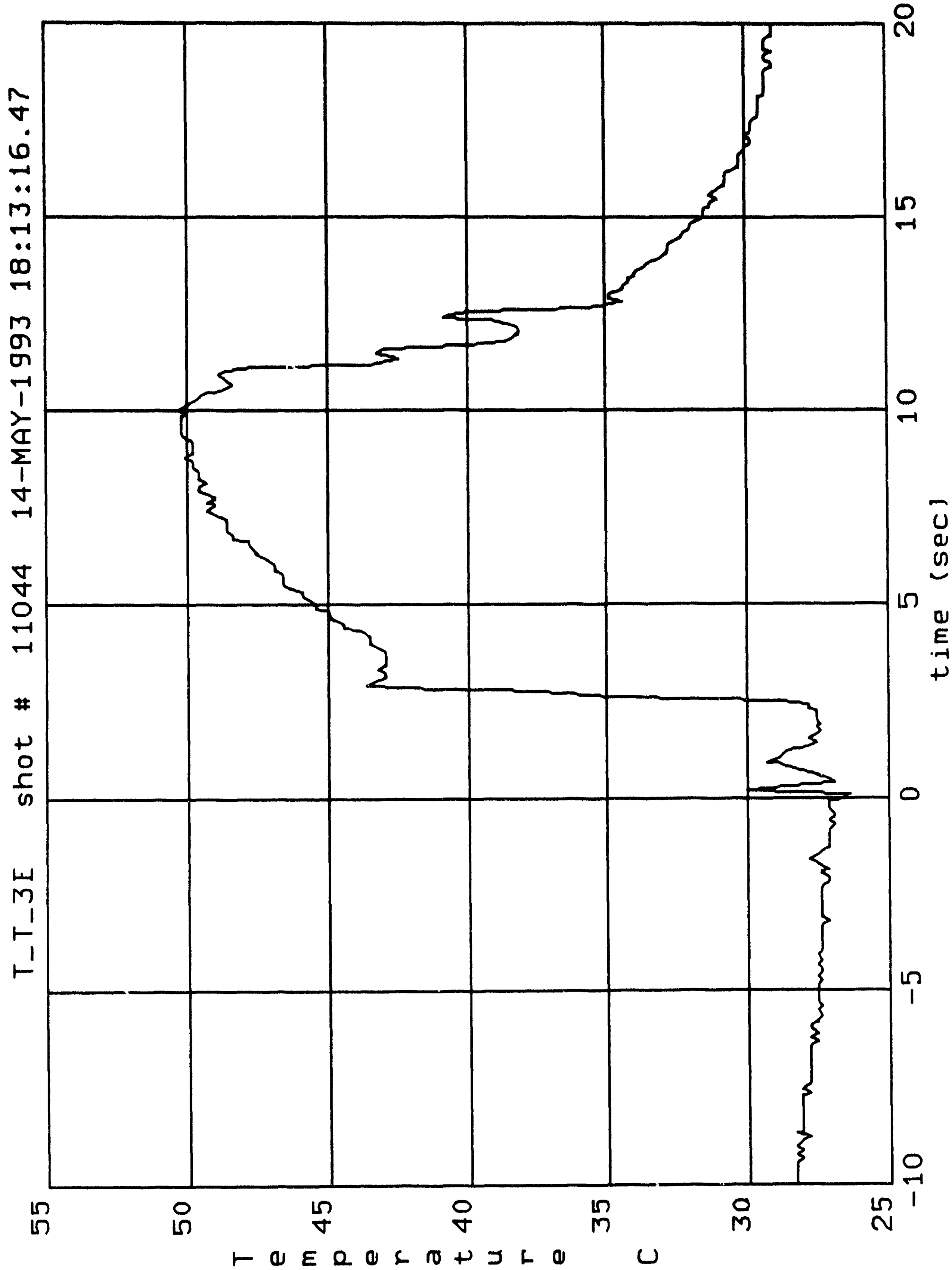
B40

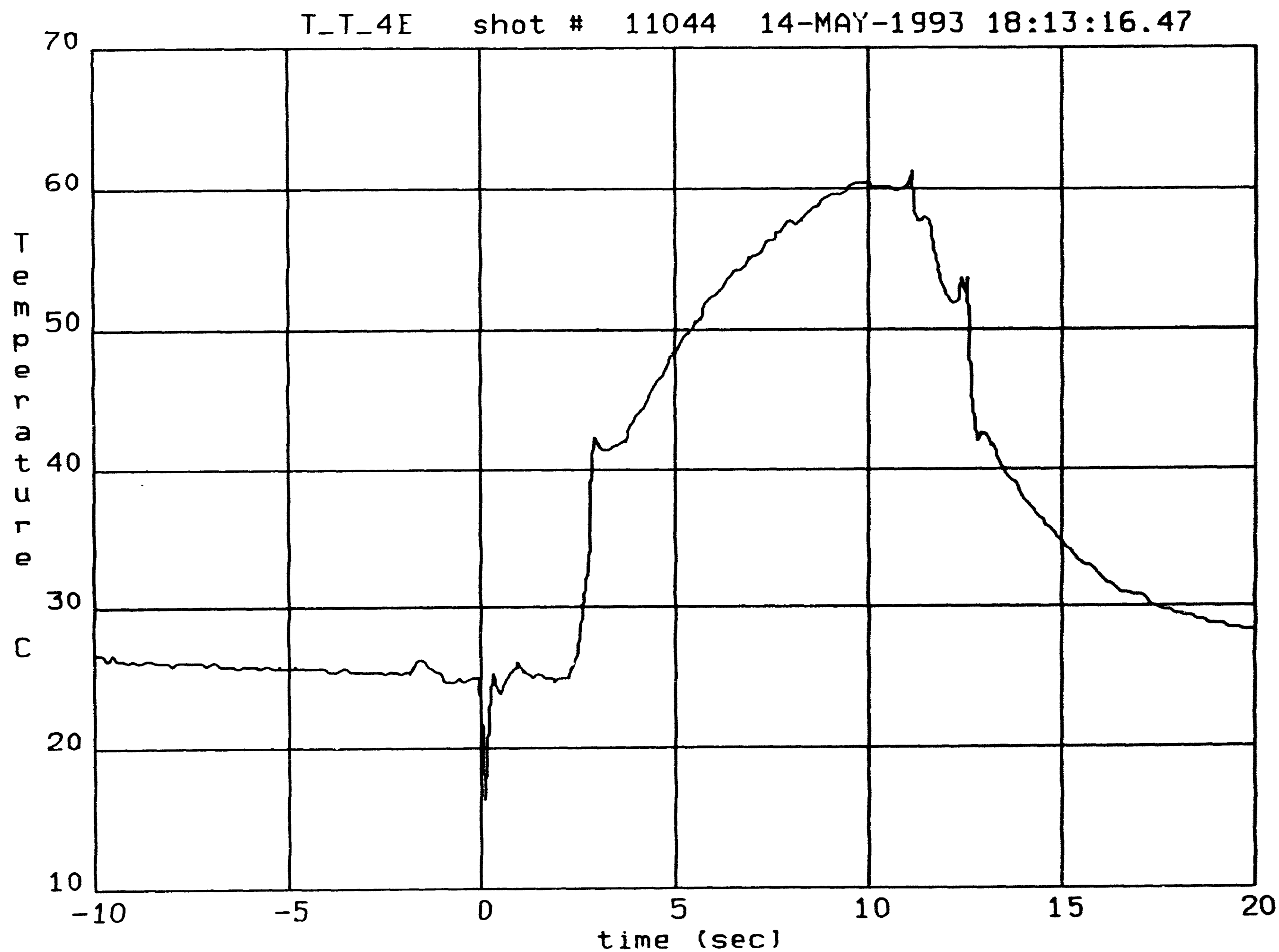

T_T_1E shot # 11044 14-MAY-1993 18:13:16.47
Temperature C
time (sec)
50
45
40
35
30
25
20
15
-10
-5
0
5
10
15
20



T_T_2E shot # 11044 14-MAY-1993 18:13:16.47
Temperature C
38
36
34
32
30
28
26
24
-10
-5
0
5
10
15
20
time (sec)

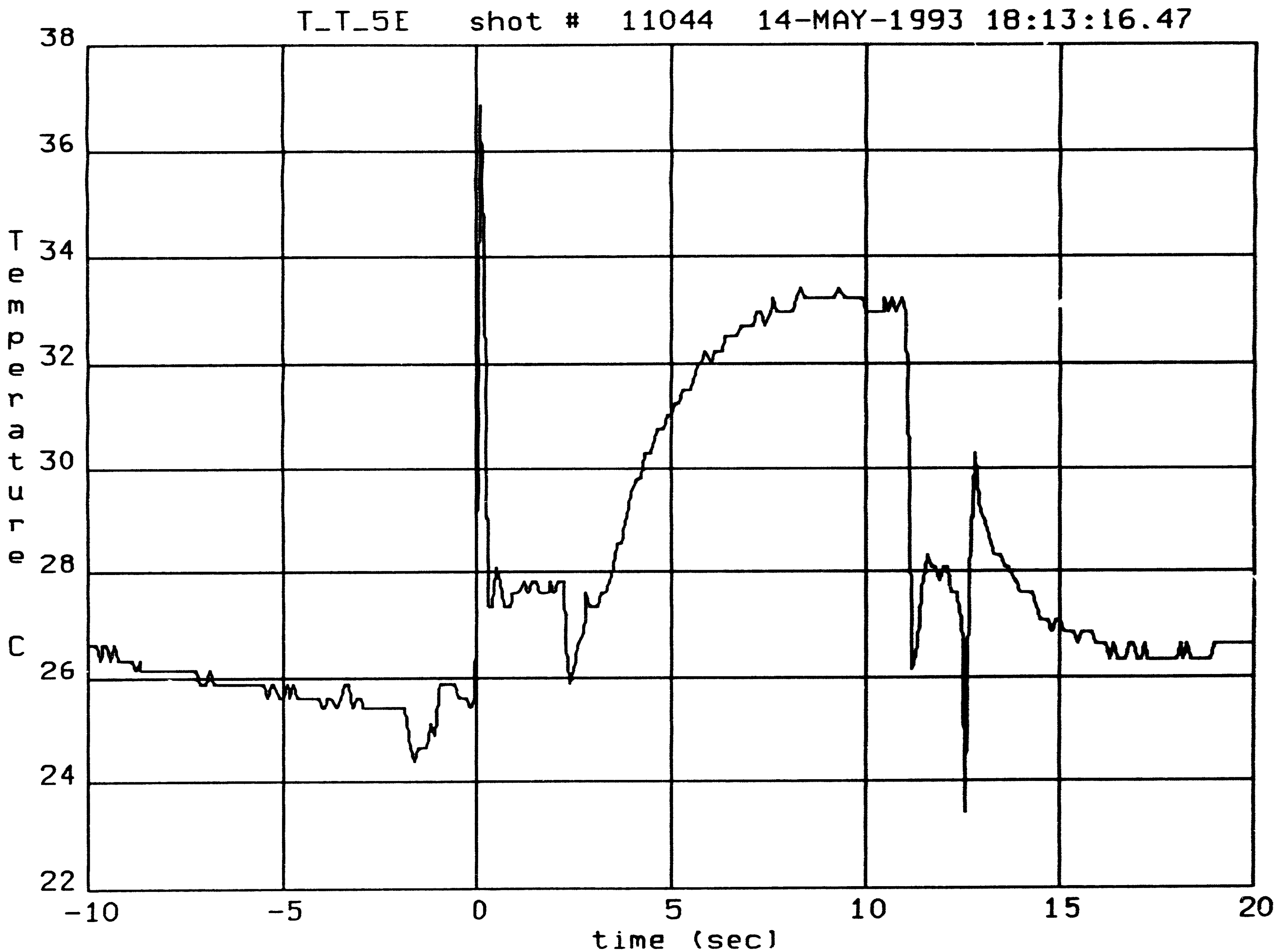
B41


T_T_3E shot # 11044 14-MAY-1993 18:13:16.47
Temperature C
55
50
45
40
35
30
25
-10
-5
0
5
10
15
20
time (sec)

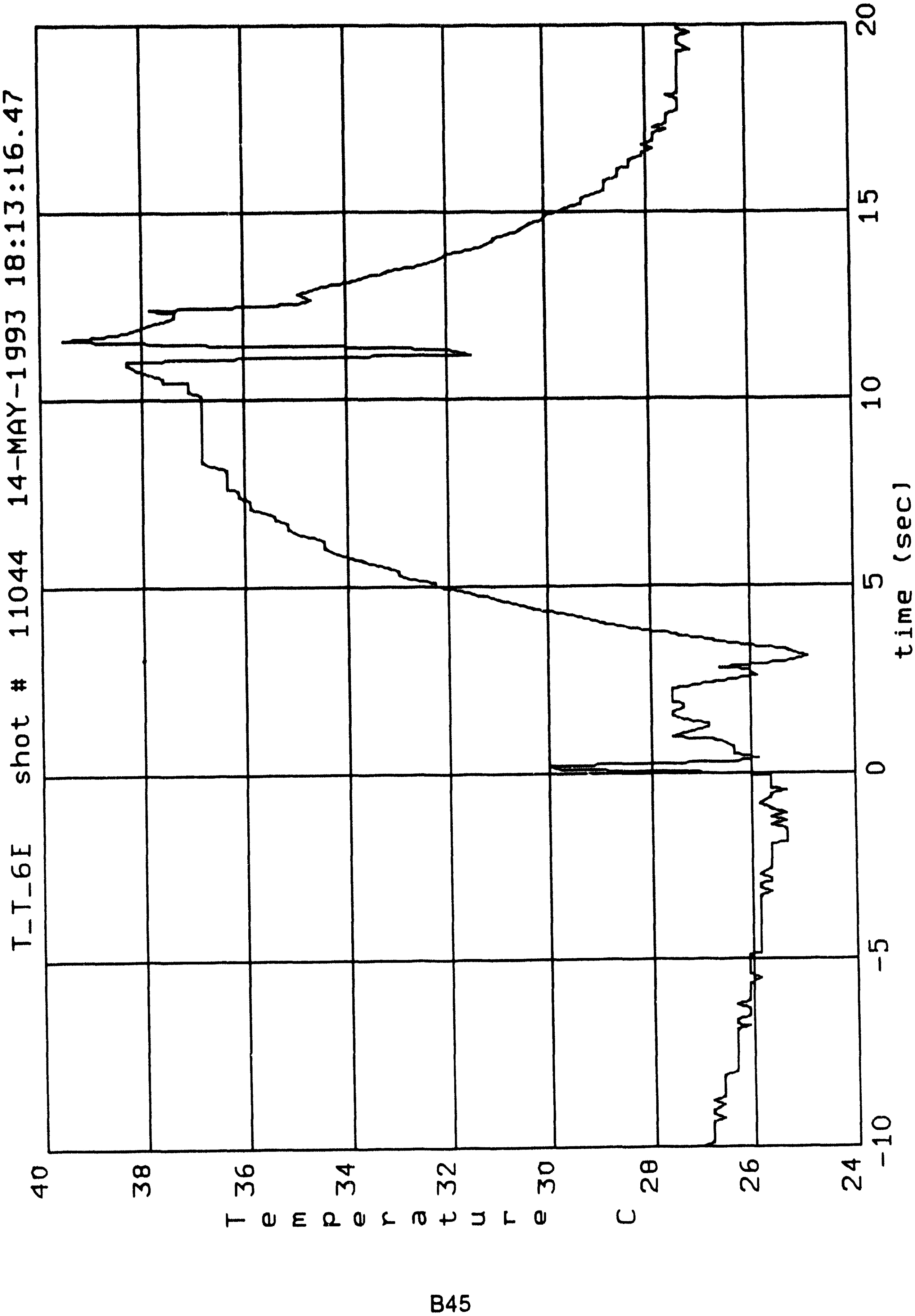


T_T_4E shot # 11044 14-MAY-1993 18:13:16.47
Temperature C
70
60
50
40
30
20
10
-10
-5
0
5
10
15
20
time (sec)

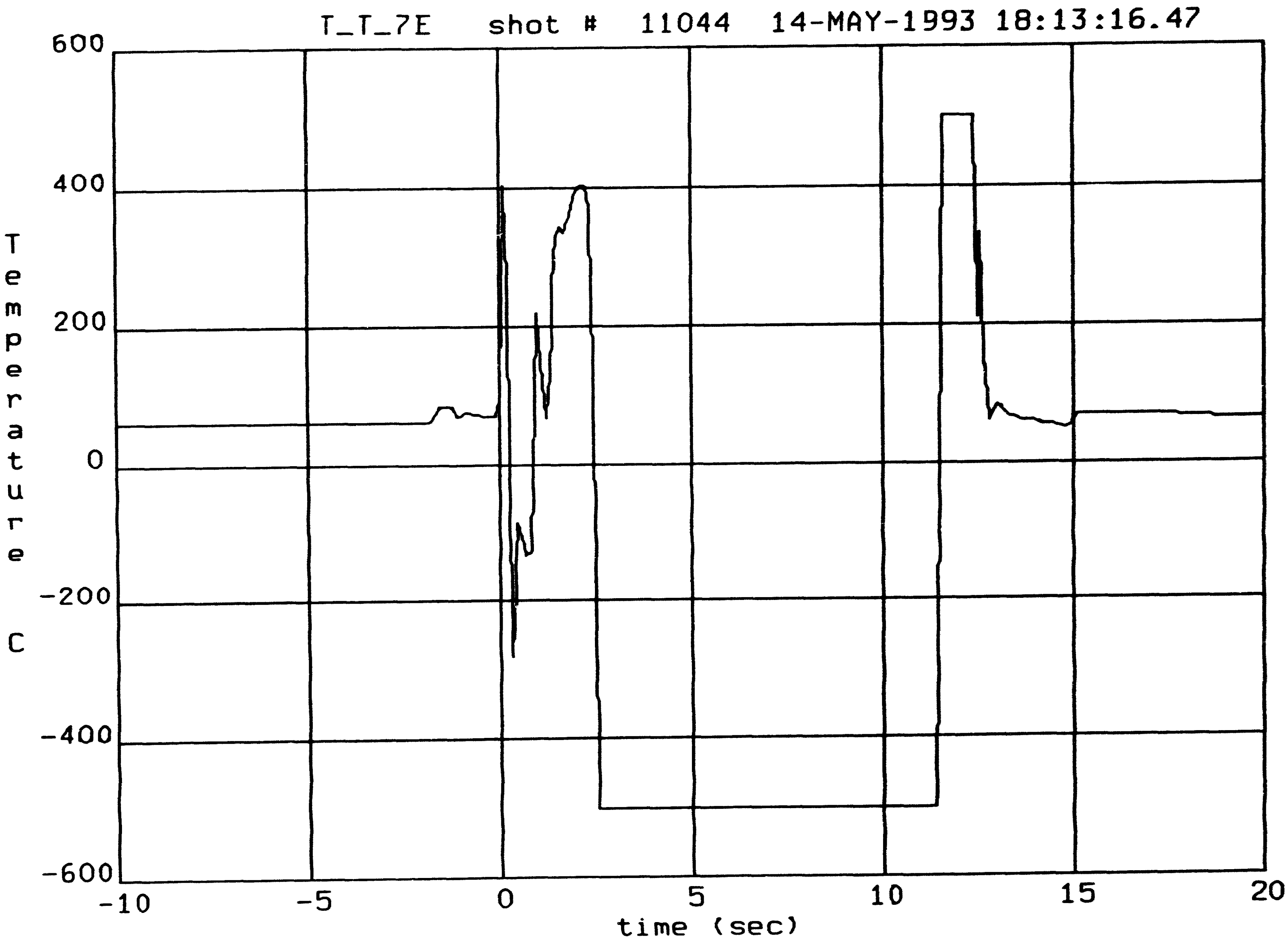
B43

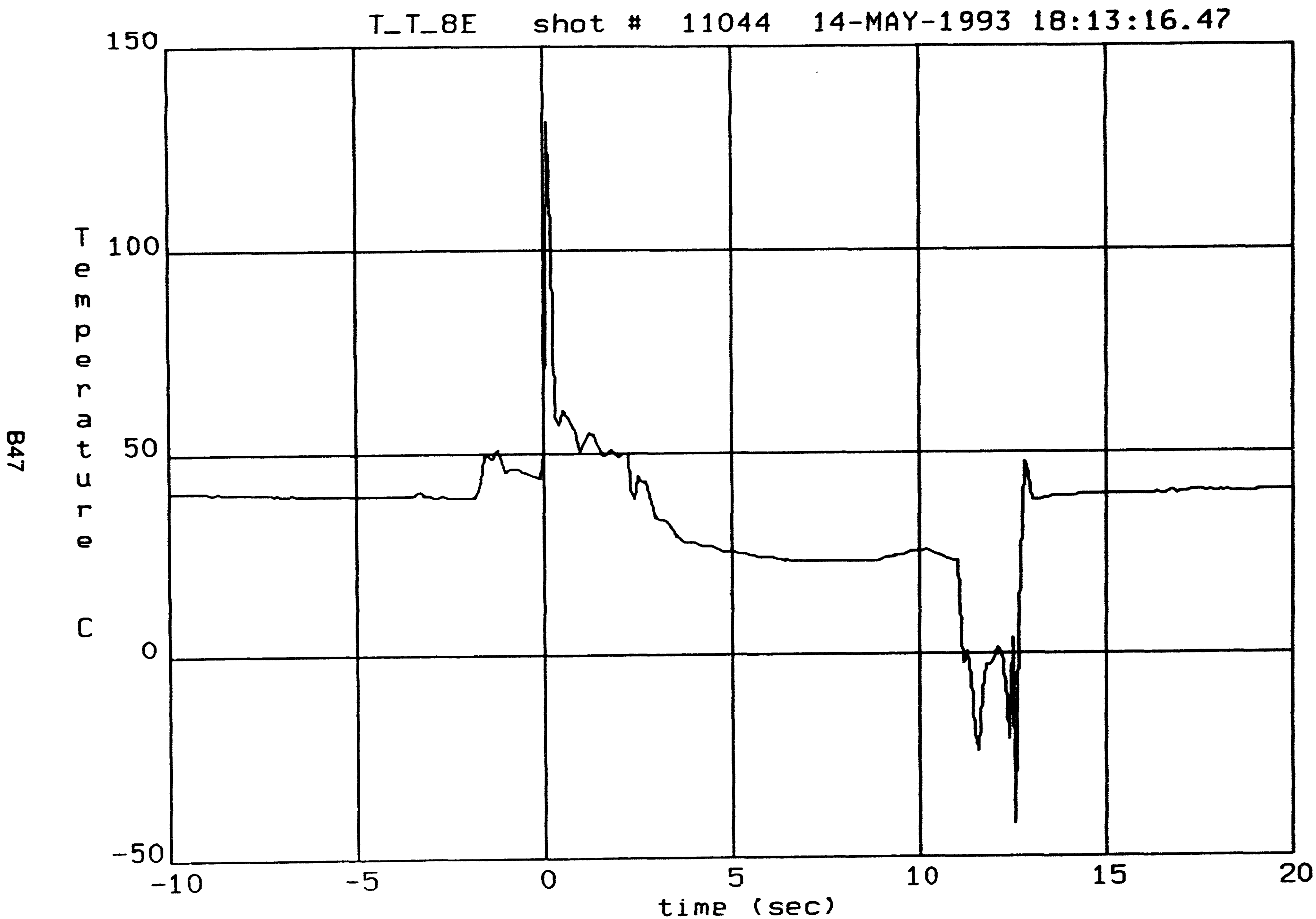


T_T_5E shot # 11044 14-MAY-1993 18:13:16.47
Temperature C
38
36
34
32
30
28
26
24
22
-10
-5
0
5
10
15
20
time (sec)



T_T_6E shot # 11044 14-MAY-1993 18:13:16.47
Temperature C
40
38
36
34
32
30
28
26
24
-10
-5
0
5
10
15
20
time (sec)


T_T_7E shot # 11044 14-MAY-1993 18:13:16.47
Temperature C
600
400
200
0
-200
-400
-600
-10
-5
0
5
10
15
20
time (sec)


T_T_8E shot # 11044 14-MAY-1993 18:13:16.47
150
100
50
0
-50
Temperature C
-10
-5
0
5
10
15
20
time (sec)
B47

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