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AIRCRAFT CARGO BAY FIRE PROTECTION BY WATER SPRAYS: A FEASIBILITY STUDY FOR THE CAA UNDER CONTRACT № 7D/S/951

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SUMMARY

Large quantities of combustibles are contained in the cargo compartments of civil aircraft, thereby presenting a significant fire hazard. In order to control such fires in relatively large Class C cargo bays, Halons are usually deployed. As a result of the Montreal Protocol and its later amendments, however, the production of Halons is to be discontinued by the year 2000, if not sooner, and so more environmentally friendly means of fire control should be evaluated as a matter of urgency.

The objective of this latest study, commissioned and funded by the CAA under contract number 7D/S/951 (August 1991), was to determine the feasibility of using fine water spray for the control of fires in a simulated Class C cargo compartment of internal volume 28 m^3. The combustible fire load was a 10% fill of cardboard boxes containing assorted rags; in most of the tests, concrete blocks were added as inert fire load, bringing the total fill to 50%.

For the three hour duration of the tests, temperatures were measured at 15 locations within or on the surface of the test chamber. Concentrations of the gases CO, CO_2 and O_2 were monitored continuously, with the detection of other gaseous species being determined using 'grab' samples taken at suitable time intervals and analysed by infrared spectrometry and gas chromatography. Measurements were also taken of infrared radiation, chamber pressure and smoke obscuration. In addition, video recordings were made of all the tests.

The unsprayed event for a 50% total fill was characterised by a series of significant but short-lived temperature excursions due to the onset of flaming combustion which appear to be oxygen-concentration controlled. These fires were found to be generally reproducible and comparable in severity to those generated during earlier trials in 1987 involving the control of Class C and D cargo bay fires by Halon 1301. For 10% total fill fires, temperature profiles were more even, although average temperatures were similar to the 50% fill case.

During the experimental programme, four types of water spray nozzle were employed in a variety of temporal regimes. A single operation system in which the spray was discharged for 10 minutes only was relatively ineffective in controlling the fire under the defined spray

conditions. More successful were so-called 'pulsed' sprays in which an initial discharge was followed by a series of relatively short discharges at regular intervals throughout the test. In these cases, there was generally good correlation between the degree of fire control and the total quantity of water consumed. 'Reactive' sprays were initiated when a designated threshold temperature, T_r, was reached and these systems were found to maintain temperatures at or below the assigned value of T_r; the higher the T_r, the less water was required for successful fire control. Two types of continuous spray were also demonstrated to be effective. The first was a sustained low flow fine spray, while the second was a twin spray system comprising an initial higher flow spray followed by a continuous lower flow fine mist.

In conclusion, therefore, water sprays, when suitably deployed, have been found to offer control of Class C cargo bay fires comparable to that provided by current Halon 1301 systems. The amount of water required will depend on the defined safety criteria. In common with Halon 1301, however, water spray is unable to extinguish fully the deep-seated fires encountered in this study.

CONTENTS

1. Introduction

The cargo compartments of civil aircraft often contain large quantities of combustible materials, thereby presenting a significant fire hazard. In one notable example from August 1980, a Saudia L-1011 TriStar experienced a cargo bay fire shortly after take off from Riyadh[1]. Although the aircraft was returned safely to the ground, flames from the cargo compartment had impinged on the passenger cabin seats and begun to spread, causing combustible gases to collect at ceiling level. Before evacuation could be commenced, a flash fire occurred which produced large amounts of toxic gases and consumed most of the oxygen. The lives of all 301 passengers and crew were lost in this incident.

Fire protection measures are mandatory in cargo bays and vary according to the type of compartment[2] ; this information is summarised in Appendix A. Only Class C compartments are considered in this present study, these being widely used particularly on large twin-engined aircraft such as the Airbus 310 and the Boeing 757 and 767. Compartments of this class range in volume from around 21 m^3 to 176 m^3 and are equipped with smoke detectors and a fire suppression system.

Typical crew procedure in the event of an alarm is to shut off forced ventilation to the compartment in question and to discharge the suppressant manually; a Halon extinguishant is usually used in Class C bays[3]. However, since these systems were first developed, Halons have been shown to be responsible for a considerable part of the damage to the ozone layer observed since 1978[4,5,6]. As a result, they were included in the list of compounds whose production is to be controlled, and ultimately phased out under the Montreal Protocol and its later amendments[7,8]. These production controls come into effect in 1992 and, unless amended by subsequent meetings of the signatory countries, production will be phased out by the year 2000. Recent scientific findings, however, indicate that ozone depletion is twice that previously measured[6,9], and this will almost certainly result in earlier phase out of production. Indeed, the UK government, in a policy statement issued on 19th December 1991, has said that Halon production should cease, subject to certain provisions for essential uses, at the end of 1994[10]. Clearly, there is therefore an urgent need to examine other, more environmentally acceptable, means of fire suppression and control in aircraft cargo compartments.

The possibility of using water spray was included among the recommendations featured in reference 3. A further development has been the recent interest shown in the use of a fine water spray for aircraft passenger protection in the event of a post-crash fire. Studies pioneered by the Civil Aviation Authority (CAA) and later carried out by the Federal Aviation Administration (FAA) as well as by private industry have confirmed that such systems enhance survivability time in the passenger cabin in the face of an external fire[11]. If water sprays can be demonstrated to be effective for cargo compartment protection also, the same dedicated water supply could be used for either purpose, thereby enabling an important weight saving to be achieved.

The objective of this study, commissioned and funded by the CAA (Contract No. 7D/S/951), was to determine the feasibility of using fine water sprays for the control and suppression of fires in a simulated Class C cargo compartment of internal volume 28 m^3. Furthermore, the results of this study may be compared with earlier data on cargo bay fire control using Halon 1301[3]. During these experimental trials, a range of spray regimes was tested with variations in the type of nozzle used, the geometry of the spray array and the temporal regime of the spray.

2. Experimental Considerations

2.1 Test Rig

The rig used in this work was originally built for use on an earlier project on cargo compartment fire suppression employing Halon 1301[3]. It was designed to simulate a small Class C or a large Class D type compartment in accordance with the requirements of JAR/FAR 25.857[2]. The rig and associated instrumentation are shown in figure 2.1

The walls, ceiling and floor of the chamber were constructed from 3 mm mild steel sheet on a framework of 40 mm angle iron. The rig dimensions are 3.5 m x 4 m x 2 m height, giving an internal volume of 28 m^3 (1000 ft^3). The chamber was accessed by a door in one wall, while small glass windows in the other three other walls enabled lighting and a video camera to provide surveillance of the inside of the rig. The edges of the walls and windows were sealed with high temperature self-adhesive aluminium tape to prevent excessive air leakage although, given that forced ventilation was applied during the tests, some small apertures were retained throughout the rig to permit the desired air flow.

In order to reduce the internal volume for most of the tests by 40% to 16.8 m^3, thereby reducing the required fire load, 1057 concrete blocks of dimensions 46 cm x 23 cm x 10 cm were placed approximately symmetrically on the floor and along the walls of the chamber (figure 2.2).

2.2 Ventilation System

The test chamber was supplied with forced air ventilation at two air flow rates, 7.4 m^3 min^{-1} and 0.47 m^3 min^{-1}. These rates simulate, respectively, the "pet air" ventilation for the transport of animals and the estimated leakage rate into a sealed cargo compartment of 28 m^3 volume.

The air flow was generated by a centrifugal fan which fed the test chamber via a length of 200mm diameter flexible PVC tube. To permit metering of the air flow, the air was drawn through an orifice plate mounted in the duct leading to the fan inlet. The orifice plate was of square-edged design and was manufactured and installed in accordance with BS 1042 Pt. 1[12]. The pressure difference across this plate was measured using an Airflow Developments Mk 5 inclined manometer. Appendix B shows the calculations employed to obtain the pressure differentials required for the 7.4. and 0.47 m^3 min^{-1} flows.

2.3 Fire Load and Ignition Source

The fire load was selected to be equal in weight and volume to those of the Class C tests detailed in reference 3. The aim, as before, was to simulate as closely as possible real aircraft passenger luggage while ensuring that a reproducible fire could be generated for each test. It was also ensured that the fire threat was comparable to that generated in the previous test series.

The load consisted of 34 corrugated cardboard boxes of dimensions 44 x 44 x 42 cm^3, giving a total fill of 2.8 m^3 or 10% of the initial test volume. They were placed in a 6 x 3 x 2 boxes high arrangement (minus two boxes) on the floor of the chamber. Each of the boxes contained 4.1 kg of rags composed of miscellaneous items of clothing to give a total load of 140 kg.

A reliable and reproducible method of ignition was established during preliminary tests conducted outside the test rig. The fire was initiated by means of an electrically-fired pyrotechnic match-head fuse placed near the top of a central box containing a normal load of rags. Large holes were cut in two opposite sides of the box to improve ventilation. In tests 1-9, the upper surface of the rags was then sprinkled with 50 mL of a 9:1 mixture of petrol and diethyl ether and the test initiated within two minutes to prevent excessive evaporation of the liquid fuel. In later tests, 30 mL of petrol was contained in a small metal cup placed on the surface of the rags. No significant differences were noted arising from these variations in ignition procedure.

2.4 Suppression System

Water for the suppressed tests was supplied from three 227 L plastic tanks using a Grundfos type CR2 electric pump via a 0-6 bar pressure regulator. The water was initially contained in 22 mm pipe which fed four 15 mm pipes comprising the spray manifolds, each fitted with nozzle ports at 0.33 m intervals. This arrangement is shown in figure 2.3 with dimensions given in figure 2.4.

2.5 Radiation Measurement

An infrared flame detector was positioned outside the test rig as shown in figure 2.1, viewing the fire load through a sapphire window in the side of the rig. The detector comprised a thermopile fitted with a 4.4 μm filter, with the signal produced being amplified and recorded by the data acquisition system (see section 2.10).

2.6 Temperature Measurement

A total of 15 mineral insulated type K (nickel chromium alloy/nickel aluminium alloy) thermocouples were deployed in the test rig as shown in figures 2.5 and 2.6. Thermocouples 1-9 and 12-13 measured the air temperature at either 10 cm or 60 cm from ceiling height; the ends of these sensors were turned upward to prevent water from the spray collecting on the tips. Thermocouples 10 and 11 were positioned in the box containing the ignition source and in an adjacent box respectively. Thermocouples 14 and 15 were fixed to the outside of the chamber roof in order to measure surface temperatures at two locations. The response of all these sensors was checked immediately prior to use with a small gas flame.

2.7 Smoke Measurement

The obscuration equipment, shown in figure 2.7, was a two part system comprising a remote optical head unit linked to an amplifier/driver unit, the former being mounted within a smoke measurement box on the roof of the test chamber. A 4 Hz light signal generated from a 2 V, 340 mA filament lamp was passed through a collimating lens and directed across a 30 cm path length to a collecting lens. The path length was chosen to comply with FAA Standard TSO C1B[13]. The light was then focused onto a BPW 21 photodiode and the resulting signal amplified and passed to the amplifier/driver unit via a 20 m cable. Signals to the 4 Hz lamp and from the amplified photodiode were fed into an AD 630 phase detector integrated circuit in order to enhance the smoke obscuration signal, thereby enabling the unit to operate in high and variable ambient light conditions. The analogue voltage produced was then passed to the Orion data acquisition system (see section 2.10) where it was continuously displayed in order that fire suppression could be initiated at the appropriate smoke obscuration level.

Reference 13 defines a smoke obscuration alarm level in the range 4-16% ft^{-1} (4% ft^{-1} = 13.1% m^{-1}), although modern detectors operate at much lower obscuration levels, e.g. 0.1-0.2 % m^{-1}. Alarm levels of either 2% ft^{-1} or 7% ft^{-1} were selected.

2.8 Pressure Measurement

The pressure within the test chamber was monitored at a position in the roof (see figure 2.1) using a Kistler piezoresistive pressure transducer type 4045 A2. The 0-2 bar output was amplified by a Kistler type 4601 unit and recorded by the data acquisition system.

2.9 Gas Analysis

Concentrations of several gases were monitored during the tests with samples taken using the manifold illustrated schematically in figure 2.8.

Gases from the test chamber were continuously withdrawn by a diaphragm pump, drawing through glass wool and paper tube filters and a condenser to remove solid particulates and excess water vapour respectively. The gases were then drawn into a Rosemount Binos 100/Oxynos 100 gas analyser unit where concentrations of CO and CO_2 were measured in the range 0-2% by non-dispersive infrared photometry, and the concentration of O_2 in the range of 0-25% by paramagnetic susceptibility.

A 'tee' in the main gas sampling line enabled a PVF film gas 'grab' sample bag to be filled using a second diaphragm pump. Samples were taken at timed intervals and returned to the site laboratory for later analysis using a Perkin Elmer 1710 Fourier transform infrared (FTIR) spectrometer equipped with a gas cell having a variable path length of up to 20 m. From test 9, additional analysis of H_2 concentration was carried out using a Perkin Elmer 8500 gas chromatograph, with gases being separated on either a Carbosphere (6 ft, ⅛" diameter stainless steel) or molecular sieve (5 ft, ¼" diameter glass) column.

2.10 Data Capture

All data were recorded on a Schlumberger Technologies Orion 3531 D data acquisition system which was powered via a 1.5 kW constant voltage transformer to prevent loss of data due to mains supply transients and noise. The instrument was located within a small cabin close to the cargo bay test rig and is shown schematically in figure 2.9.

The Orion is a stand-alone software-controlled unit which was programmed to scan the 24 sensor outputs at 10 second intervals, storing these data values to a 720 kbyte 3.5 inch diskette. A 2 line alpha-numeric display was used to continuously monitor any 4 of the 24 data inputs.

At the end of each test, information on the diskette was converted into a Lotus 123 V2.2 worksheet for subsequent data analysis.

3. Test Procedures

3.1 Unsprayed Tests

Four tests were conducted in which no active fire suppression measures were taken. These were carried out in order to identify the characteristics of the unsuppressed event such that the performance of the water spray system could then be reliably evaluated. The duplication of these tests enabled the reproducibility of notionally identical fires to be determined.

The test chamber was loaded with the combustible fire load and the ignition system prepared as described in Section 2.3. The chamber door was then closed and the 'pet air' supply established at 7.4 m^3 min^{-1}. Data capture was initiated and a 1 minute countdown observed before ignition of the fire load by the means stated in section 2.3. Given that a successful ignition had been accomplished, the fire was allowed to develop until a 7% ft^{-1} smoke obscuration level was reached, whereupon a 1 minute 'reaction time' delay was observed before the forced ventilation was reduced to 0.47 m^3 min^{-1}. The 1 minute 'reaction time' was estimated to be the time taken for an airline pilot to engage the fire protection system having received and confirmed the smoke alarm. The fire was then allowed to burn for a further three hours before the test was ended, the test chamber opened and any continuing fire extinguished with a hose water supply. In later tests, the ventilation was reduced to 0.47 m^3 min^{-1} immediately upon reaching 2% ft^{-1} smoke obscuration in order to simulate more immediate response.

3.2 Sprayed Tests

The initial procedure for the water sprayed tests was identical to that of the unsprayed tests. When the forced air supply was reduced to 0.47 m^3 min^{-1} however, either upon reaching 2% ft^{-1} smoke obscuration (tests 13-18) or 1 minute after reaching 7% ft^{-1} smoke obscuration (tests 3-6, 9-12), the water spray system was initiated simultaneously and continued as prescribed. The test was again allowed to run for a period of three hours.

3.3 Spray Nozzles

Four types of spray nozzles were used during this test programme, all being supplied by Lurmark plc.

An array of DC 23.05 nozzles was employed for the majority of the experiments. The body of the DC nozzle is a threaded cylinder available in various materials and terminating in male or female threads; a male body in brass was used in these tests.

When in operation, water passes down the body, optionally via a suitable filter, and meets a slotted swirl core which imparts a circular motion to the fluid. The water then passes through a single circular orifice in a domed disc from whence the spray issues. The droplet size distribution, flow rate and spray discharge angle are varied by the interchange of various discs and cores. The 23.05 core/disc combination was that used by SAVE Ltd in 1988[14] to demonstrate the effectiveness of an aircraft cabin spray system in preventing the ingress of an external fuel fire, and its effects, into the cabin of a Trident II aircraft. The same nozzle array has since been tested by a number of other workers including the FAA and the Fire Research Station under the direction of the CAA[11], as well as by ourselves. It produces a relatively fine hollow cone-type spray of discharge angle 90° and flow rates of 0.71 to 1.00 L min^{-1} in the 3-6 bar range quoted by the manufacturers.

DC 13.02 nozzles were used in tests 14 and 15. It is of the same basic design as the DC 23.05 but produces a somewhat finer spray of discharge angle 70°. Flow rates range from 0.107 L min^{-1} at 2 bar to 0.24 L min^{-1} at 10 bar, from which it is apparent that water consumption is relatively low.

The KES 260 nozzles employed in test 6 are manufactured from moulded Kematal and produce a very fine spray of discharge angle 90°. Flow rates for this nozzle range from 0.17 L min^{-1} at 2 bar to 0.24 L min^{-1} at 10 bar, from which it is noted that water consumption is relatively low.

The KES 180 nozzles used in test 18 are of similar design to the 260 type. They have very low flow rates of 0.07 L min^{-1} to 0.16 L min^{-1} in the 2-10 bar range and give a fine spray of discharge angle 90°.

Flow rates in the 2-10 bar pressure range for the four nozzles used in this study are shown in figure 3.1.

4. Results

4.1 Presentation of Data

A full library of temperature profiles is given in figures 4.1 to 4.72. There are four figures associated with each test, showing thermocouple numbers 1,10,11; 4,5,8,9; 6,7,12,13; and 2,3,14,15. A plot of spray pressure vs time (marked W/P) is also shown on each figure to enable the spray regime to be easily identified. For reasons of clarity, temperature profiles are offset as follows:-

Thermocouples 1, 2, 4, 6 no offset
Thermocouples 3, 5, 7 offset 300 °C
Thermocouple 10 offset 400 °C
Thermocouples 8, 12, 14 offset 600 °C
Thermocouple 11 offset 800 °C
Thermocouples 9, 13, 15 offset 900 °C

Average temperatures at thermocouple positions 1-15 have been calculated for each test and are given in table 4.1. In addition to an average temperature over the three hours duration of the test, it is useful to quantify the periodic or occasional temperature excursions which are characteristic of many of the experiments. In order to do this, tables 4.2 and 4.3 feature the time in seconds spent at above 100°C (i.e. $T > 100$ °C) and above 200°C (i.e. $T > 200$ °C) respectively for each test and thermocouple position.

Gas concentrations in volume terms obtained using 'grab' samples at suitable time intervals are given in tables 4.4 to 4.21. All values were found by FTIR spectrometry, except those for H_2 (tests 9-18) which were obtained by gas chromatography. Oxygen concentrations were estimated from the Oxynos data (see section 2.9).

4.2 Test Commentary

Tests 1,2

A repeated unsprayed test was conducted with a 'standard' 10% fill of combustible materials with an additional 40% fill of 'inert fire load'. The purpose of these initial experiments was to establish the characteristics of the unimpeded fire and, in duplicating the tests, to determine the reproducibility of these notionally identical events. It was also necessary to ensure that the unsprayed fires in this work were comparable in severity to the uncontrolled Class C fires described in reference 3.

As indicated by the response of the 4.4 μm infrared detector shown in figure 4.73, the unsprayed fire is typified by a number of discrete combustion events. These give rise to corresponding temperature peaks of 200-600 °C recorded at central ceiling height by thermocouple 1 (TC 1) as seen in figures 4.1 and 4.5, as well as more modest increases in other parts of the test chamber (figures 4.1 - 4.8).

Again with reference to figures 4.1 and 4.5, it is seen that there are fewer temperature excursions in test 2 than in test 1, resulting in lower average temperatures for the second test. Performing a simple summation over the 11 air temperature thermocouples returns an average air temperature of 119 $\pm$ 23 °C for test 1 compared with 102 $\pm$ 19 °C for test 2.

Figure 4.74 shows dramatic decreases in oxygen concentrations below ambient values to as little as $\sim$2% in the early stages of the fires. By comparison with figure 4.1, the major troughs in the oxygen concentration are found to correspond to the several combustion events occurring in the chamber.

Carbon monoxide concentrations obtained using the Rosemount instrument are given in figures 4.75 and 4.76, from which a number of peaks in excess of 2% are apparent. 'Grab' samples analysed by FTIR (tables 4.4 and 4.5) return average concentrations for tests 1 and 2 of 0.66 and 0.85% respectively.

The 'grab' samples were also analysed for concentrations of the species hydrogen cyanide (HCN), methane (CH_4), ethyne (C_2H_2) and ethene (C_2H_4); combined average concentrations for the two tests are 0.0037, 0.056, 0.0056 and 0.018% by volume respectively.

Based on the results of tests 1 and 2, the unsprayed fires produced in this present study were essentially identical to those for Class C fires found in reference 3.

Test 3

A 1 m spaced array of SAVE-type DC 23.05 nozzles was operated at 3 bar for the first 10 minutes of the test, returning a very low water consumption of 89 L. This single operation spray regime reduced temperatures relative to the unsprayed event but, as illustrated in figures 4.9 to 4.12, failed to prevent a series of temperature excursions, some giving temperatures in excess of 500 °C after the spray was terminated.

Test 4

In order to achieve improved temperature control, the same 'standard' DC 23.05 array was operated initially for 10 minutes and then for 5 minutes in every 15 minutes. This temporal regime resulted in a high water consumption of 688 L. Good control of the fire was achieved except for two minor temperature peaks occurring at about 1.3 and 2.4 hours (figures 4.13 - 4.16); the oxygen concentration shown in figure 4.77 reflects these events.

Test 5

In order to reduce markedly the water requirement, the DC 23.05 array was operated for only 5 minutes initially and then for 2 minutes in every 15 minutes. Although a 65% reduction in water use was achieved over test 4, only a moderate control of the fire was maintained, with a number of temperature excursions being noted during the first half of the test (figures 4.17 - 4.20).

Test 6

A 0.67 m spaced array of fine spray KES 260 nozzles was operated continuously at 3 bar to give a total water consumption of 528 L. As shown in figures 4.21 to 4.24, good control of the fire was achieved except for two temperature excursions within the first 30 minutes, one of which gave a peak temperature in excess of 600 °C at TC 1.

Tests 7, 8

Two unsprayed tests were carried out in which the effects of increasing the free volume of the test rig were examined; the 40% fill of inert fire load was removed, leaving only a 10% fill of combustible material. From figures 4.25 to 4.32, it is noted that, except in the first 30 minutes, flat temperature profiles were obtained relative to 50% total fill tests 1 and 2. Average temperatures at each of the thermocouple positions were, however, broadly similar to those of the earlier unsprayed fires.

Test 9

With the 10% fill retained, a 1 m spaced array of DC 23.05 nozzles was operated at 3 bar for 10 minutes initially and then for 5 minutes in every 15 minutes. Good control of the fire was achieved using 602 L of water.

Test 10

The same DC 23.05 array was operated for 5 minutes initially and then for 2 minutes in every 15 minutes, giving a reduced water consumption, relative to test 9, of 252 L.

Less successful control of the fire was maintained, however, with a number of temperature excursions occurring during the test.

Test 11

For this and subsequent tests, the 40% inert fire load was returned to the test chamber. A 1 m spaced array of DC 23.05 nozzles was operated at 5.25 bar in a 'reactive' system, the spray being initiated at temperatures in excess of 100 °C at thermocouple 1 and subsequently disengaged when the temperature at thermocouple 1 fell below 90 °C. As shown in figure 4.41, the temperature at TC 1 was maintained at or below 100 °C except in the very early stages of the experiment. Figure 4.78 shows that oxygen concentration did not fall below around 12%. During the test, the spray was operated on some 50 occasions, consuming 299 L of water.

Test 12

A 'reactive' DC 23.05 system was again employed, this time at 3 bar, with the spray being initiated when TC 1 reached 100 °C and discontinued 1 minute after TC 1 fell below 100 °C. During the 3 hour test, the spray was operated 15 times. Successful control of the fire was achieved at the expense of 265 L of water, representing a modest 11% saving over the previous test.

Test 13

This was a repeat of the previous test except that the spray was activated immediately upon reaching 2% ft^{-1} smoke obscuration (in previous tests, sprays were engaged 1 minute after 7% ft^{-1} smoke obscuration was reached); all subsequent tests were conducted in this manner. Apart from two minor excursions in the first hour, temperatures were maintained at or below 100 °C. Total water consumption was 232 L during 18 operations of the spray.

Test 14

The spray regime was as test 4 except that lower flow rate DC 13.02 nozzles were used in place of the DC 23.05 type, resulting in a reduced water consumption of 252 L. A moderate control of the fire was maintained in this case.

Test 15

DC 13.02 nozzles were employed in a 'reactive' regime of the type employed in tests 12 and 13. Moderate control of the fire was achieved using 189 L of water.

Test 16

A repeat of test 12 was carried out except that 150 °C and not 100 °C was taken as the reaction temperature threshold. Except for one brief excursion at around 0.4 hr, the temperature at thermocouple 1 was maintained at around 150 °C or below using only 127 L of water.

Test 17

A 'standard' DC 23.05 spray was operated for 15 minutes initially and then for 1 minute in every 15 minutes, resulting in a water consumption of 207 L. This yielded moderate control of the fire, with several temperature excursions occurring between 0.5 and 2.5 hr.

Test 18

A twin spray manifold was installed in the chamber for this test in which a DC 23.05 array at 1 m spacing and 3 bar was operated for 10 minutes initially. This was immediately followed by a continuous fine spray from an array of KES 180 nozzles at 0.67 m spacing and 3 bar. Successful control of the fire was maintained at a consumption of 334 L of water.

5. Discussion

5.1 Unsprayed Tests

For the 'standard' 50% total fill case (tests 1,2), the unsprayed event is characterised by a number of temperature excursions occurring during the three hour duration of the test. These significant but short-lived temperature rises are coincident with decreases in oxygen concentration in the chamber and occur due to the onset of flaming combustion. In fact, these intermittent flare-ups appear to be largely controlled by the oxygen concentration, with these events occurring only when the O_2 level in the test chamber is sufficiently high to enable gas phase combustion to take place. The oxygen concentration during combustion then declines rapidly, leading to a dormant phase in which the O_2 level again rises, owing to forced air input, to a concentration able to support a further flaming combustion event. The sharpness of the temperature peaks indicates that after hot gases are expelled from the chamber during a combustion event as a result of overpressure, air is rapidly drawn into the rig, reducing the air temperature and increasing the oxygen concentration. Clearly, portions of the fire load continue to smoulder throughout the test.

In the case of the 10% total fill tests 7 and 8, the temperature excursions are fewer and less pronounced than for the 50% fill tests. This is perhaps a surprising result given the greater amount of oxygen present in the larger free volume of the test chamber. It is noted, however, that this outcome may be influenced by the position of the fire load relative to the forced air inlet, since the cardboard boxes are raised on the inert fire load towards the ventilation inlet for the 50% fill tests.

5.2 Sprayed Tests

5.2.1 Single Operation Sprays

The first sprayed test of the current research programme involved the use of a DC 23.05 array at 1 m spacing and 3 bar operating pressure (described subsequently as a 'standard' DC 23.05 array) for a period of 10 minutes only. The spray was initiated 1 minute after 7% ft^{-1} smoke obscuration was reached. The characteristics of the fire were little different from those of the unsprayed events and it is concluded, therefore, that such a spray regime does not provide effective control of these fires at the given water consumption rate. Clearly, the fire load is not sufficiently wetted to prevent deep-seated combustion spreading from the ignition zone during the remainder of the test.

5.2.2 'Pulsed' Operation Sprays

Tests 4 and 5 illustrate the use of 'standard' DC 23.05 arrays in pulsed type spray regimes. In test 5, operation of the spray for 5 minutes initially and then for 2 minutes in every 15 minutes resulted in improved control of the fire relative to the single 10 minute spray of test 3, at the expense of 230 L of water. In test 4, the total spray duration was greater still and resulted in the use of 688 L of water; this provided successful control of the fire except for two minor temperature excursions. On the basis of these results, good control of the fire can be achieved by means of a standard DC 23.05 array. Greater control of the fire is afforded by a longer total spray time and, therefore, a higher overall water consumption.

Test 14 is analogous to test 4 except that DC 23.05 nozzles were replaced by DC 13.02 nozzles. Control of the fire was not as successful as the earlier test however. The most likely explanation is that DC 13.02 nozzles have a considerably lower flow rate that the DC 23.05 type, giving a total water consumption of only 252 L compared with 688 L for test 4. A further factor is the 70° spray discharge angle of the DC 13.02 nozzle, resulting in a less homogeneous distribution of spray than given by the 90° discharge angle DC 23.05 nozzles.

5.2.3 Continuous Fine Sprays

Low flow fine continuous sprays provide a further means of cargo bay fire control, although there is some evidence to suggest that these sprays cannot cope adequately with the severe combustion processes occurring early in the test.

5.2.4 'Reactive' Sprays

Systems responding at a designated reaction temperature, T_r, have proved to be a most effective means of fire control in a cargo bay. With reference to tests 11-13, it is seen that the higher the reaction temperature, the less water is required to maintain the temperature at or below the selected value.

All 'reactive' sprays were 'standard' DC 23.05 arrays except for test 15 where DC 13.02 nozzles were employed. As was true for the 'pulsed' sprays, the DC 13.02 array was less effective in controlling the fire than the DC 23.05 array.

5.2.5 Twin Sprays

The twin spray system examined in test 18 proved the most effective means of fire control of all the sprays studied. It appears to provide a dual means of protection, with the initial spray dealing with the early stages of the fire and the finer continuous spray then maintaining control through the remainder of the test.

5.2.6 A Comparison of Spray Regimes

The sprays examined in this present study may be classed as having single operation (test 3), continuous (tests 6, 18), pulsed (tests 4, 5, 9, 10, 14, 17) or reactive (tests 11, 12, 13, 15, 16) regimes. For all the spray systems studied, there is generally good correlation between the total water consumption and, for example, the average temperature recorded at thermocouple 1. There exists, therefore, no clear benefit of one spray regime type over another at equivalent water consumptions.

A feature common to all the tests was that a significant proportion of the sprayed water ran from the test rig rather than becoming soaked into the fire load. No quantitative measurement of this potentially recyclable water was carried out.

It is worth noting here that although the relative efficiency of the sprays has been determined in this work, the choice of spray system to be used in a real application depends on defined safety criteria and on system weight. For example, if air temperatures in the cargo bay must be maintained below an average of 100 °C, all the sprays except for that of test 3 would be acceptable. If average temperatures must be below 60 °C, only the sprays of tests 4, 6, 9, 17 and 18 would suffice. In addition, the total amount of water required would also be a primary determinant of system selection.

5.2.7 A Comparison With Halon 1301 Systems

The results of reference 3 indicate that, in common with water sprays, Halon 1301 systems do not extinguish the deep-seated fires encountered in these studies. It was found, however, that an initial fast discharge of Halon 1301 to achieve a concentration of 5 vol % followed by a continuous bleed to maintain 3 vol% limits combustion and controls air temperatures for up to 2 hours. In one such test under these conditions, air temperatures rose from around 40 °C at the start of the bleed period to about 80 °C at the end. Rig surface temperatures were 50-60 °C at the end of the test.

6. Conclusions

1. A reliable ignition method has been developed to enable reproducible fires to be generated using cardboard boxes filled with rags. These fires are equal in severity to those encountered in earlier CAA-funded studies on the control of cargo bay fires by Halon 1301.

2. For the 'standard' 50% total fill case, the unsprayed fire is characterised by a number of temperature excursions occurring throughout the three hour duration of the test. These transient temperature excursions occur due to flaming combustion events controlled by oxygen concentration.

3. Fires involving a 10% total fill of the test chamber gave more even temperatures through the test than those for which a 50% total fill was employed. This difference may be due, at least in part, to a change in position of the combustible fire load relative to the forced air supply inlet.

4. Sprayed water, however deployed during the tests, does not fully extinguish the deep-seated fires encountered in this experimental programme. In this way, finely divided water behaves similarly to Halon 1301, exerting control over the fire in the gas phase rather than accomplishing complete suppression.

5. The degree of control of the fire is determined principally by the total water deployed rather than by the temporal regime of the spray. The following specific points were noted, however:

    a. A single 10 minute spray from an array of DC 23.05 nozzles at 1 m spacing and 3 bar operating pressure failed to control adequately a fire in a Class C cargo compartment.

    b. So-called 'pulsed' sprays of DC 23.05 arrays, in which spray is deployed at regular intervals throughout the 3 hour test, are effective in controlling such fires. In general, the greater the total spraying time, and therefore the greater the total water consumption, the more control over the fire is effected by the spray.

    c. 'Pulsed' sprays from DC 13.02 arrays are less effective in fire control that those from analogous DC 23.05 arrays. This is due to the lower overall flow rate and less homogeneous spray distribution of the DC 13.02 system.

2. The effects of containing the fire load within realistic cargo containers should be identified.

3. Tests to date have been carried out under ambient conditions of around 10 °C. It would be useful to examine fires and their control at reduced and elevated temperatures.

4. Only a limited number of spray nozzles were tested in this current work. The study should be extended to cover other nozzles having a variety of water flow rates, average droplet sizes and spray discharge angles.

5. The influence of wetting agents, fire retardants and anti-freeze agents in the water should be investigated.

6. Modern smoke detectors can alarm at smoke obscuration values of as little as 0.1% m^{-1}. The possible benefits of such early fire detection in cargo bays should be evaluated.

7. The extent of the water run-off and the feasibility of filtering and recycling this excess water should be examined. There exists an important potential saving in water requirement and, consequently, in system weight by this means.

References

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3. P C Cooke, P C Howell and D J Spring, 'Cargo Bay Fire Suppression', CAA Paper 91003, March 1991.

4. S O Anderson, 'Halons and the Stratospheric Ozone Issue', Fire Journal, May/June, 56, 1987.

5. 'The Ozone Layer', booklet published by UK Department of the Environment, Global Atmosphere Division, September 1991.

6. 'The Use of Halons in the United Kingdom and the Scope For Substitution', report by C S Todd and Associates for the UK Department of the Environment, HMSO, 1991.

7. 'The Montreal Protocol on Substances that Deplete the Ozone Layer', Final Act, United Nations Environment Programme, September 1987 (HMSO, CM977).

8. Second Meeting of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer, London, June 1990.

9. 'Scientific Assessment of Stratospheric Ozone, 1991', executive summary of report issued 22nd October 1991 by the US National Aeronautics and Space Administration.

10. Announcement by David Trippier, Minister of State for the Environment, 18th December 1991.

11. Several papers presented at the CAA Cabin Water Spray Systems Industry Consultative Conference, Gatwick Hilton Hotel, May 1991.

12. British Standard BS 1042, 1984

13. TSO C1B, Federal Aviation Administration, Technical Standards Order, Cargo and Baggage Compartment Smoke Detection Instruments.

14. R T Whitfield, Q d'A Whitfield and J Steel, CAA Paper 88014, 'Aircraft Cabin Fire Suppression by Means of an Interior Water Spray System, July 1988.

Appendix A

CARGO COMPARTMENT CLASSIFICATION JAR/FAR 25.857

Class A

A Class A cargo or baggage compartment is one in which the presence of fire would be easily discovered by a crew member while at his station, and each part of the compartment is easily accessible in flight.

Class B

A Class B cargo or baggage compartment is one in which (1) there is sufficient access in flight to enable a crew member to reach any part of the compartment effectively with the contents of a hand-held fire extinguisher; (2) when the access provisions are being used, no hazardous quantity of smoke, flame, or extinguishing agent will enter any compartment occupied by the crew and passengers; and (3) there is a separate approved smoke detector or fire detector system to give warning at the pilot's or flight engineer's station.

Class C

A Class C cargo or baggage compartment is one not meeting the requirements for either a Class A or B compartment but in which (1) there is a separate approved smoke detector or fire detector system to give warning at the pilot's or flight engineer's station; (2) there is an approved built-in fire extinguishing system controllable from the pilot's or flight engineer's station; (3) there are means to exclude hazardous quantities of smoke, flames, or extinguishing agent from any compartment occupied by crew or passengers; and (4) there are means to control ventilation and draughts within the compartment so that the extinguishing agent used can control any fire that may start within the compartment.

Class D

A Class D cargo or baggage compartment is one in which (1) a fire occurring in it will be completely confined without endangering the safety of the aircraft or the occupants; (2) there are means to exclude hazardous quantities of smoke, flames or other noxious gases, from any compartment occupied by the crew or passengers; (3) ventilation and draughts are controlled within each compartment so that any fire likely to occur in the compartment will not progress beyond safe limits; and (4) consideration is given to the effect of heat within the compartment on adjacent critical parts of the aeroplane. For compartments of 500 cubic feet or less, an airflow of 1500 cubic feet per hour is acceptable.

Class E

A Class E cargo compartment is one on aeroplanes used only for the carriage of cargo and in which (1) there is a separate approved smoke or fire detector system to give warning at the pilot's or flight engineer's station; (2) there are means to shut off the ventilation airflow to or within the compartment, and the control of these means are accessible to the flight crew in the crew compartment; (3) there are means to exclude hazardous quantities of smoke, flames, or noxious gases, from the flight crew compartment; and (4) the required crew emergency exits are accessible under any cargo loading conditions

Appendix B

The following formula for determining the mass flow through an orifice plate is given in Section 1:1 of BS 1042:

$$q_m = C\ E\ \epsilon\ \frac{\pi}{4}\ d^2\ \sqrt{2\Delta p \times \rho}$$

q_m	=	mass flow through the orifice plate / kg s^{-1}
C	=	coefficient of discharge, dimensionless
E	=	velocity of approach factor, dimensionless
ϵ	=	expansibility factor, dimensionless
d	=	diameter of orifice / m
Δp	=	pressure differential across orifice / Pa
p_1	=	standard atmospheric pressure
ρ	=	mass density of air/ kg m^{-3}
β	=	ratio of orifice: pipe diameters, dimensionless
κ	=	ratio of specific heats C_p/C_v, dimensionless

We have $\beta = \dfrac{0.090}{0.1575} = 0.5714$

$C = 0.604$ initially based on above value of β

$$E = \frac{1}{\sqrt{1 - \beta^4}} = 1.0579$$

$$\epsilon = 1 - (0.41 + 0.35\ \beta^4)\ \frac{\Delta p}{\kappa\ p_1}$$

where κ = 1.401

p_1 = 101325 Pa (standard atmospheric pressure)

ρ = 1.24 kg m^{-3} at ambient temperature of 10 °C

The requirement was for volume flows of 7.4 m^3 min^{-1} and 0.47 m^3 min^{-1} which correspond to 0.153 kg s^{-1} and 0.0097 kg s^{-1} respectively.

At a Δp of 565 Pa,

$$q_m = C \times E \times \epsilon \times \frac{\Pi}{4} \times d^2 \times \sqrt{2 \Delta p \times \rho}$$

$$= 0.60826^* \times 1.0579 \times 0.9982 \times 0.7854 \times 0.0081 \times 37.43$$

$$= 0.15295 \text{ kg s}^{-1}$$

At a Δp of 2 Pa, q_m = 0.00966 kg s^{-1}

* corrected value of C based on the true Reynolds number, R_e.

Table 3.1 Test Programme

Test No.	Nozzle	P/bar	Spray Regime	Total Water Consumption/L	Remarks
1					No Spray
2					No Spray
3	DC 23.05, 1 m	3	Spray on for 10 minutes	89	
4	DC 23.05, 1 m	3	Spray on for 10 minutes then for 5 minutes in every 15 minutes	688	
5	DC 23.05, 1 m	3	Spray on for 5 minutes then for 2 minutes in every 15 minutes	230	
6	KES 260, 67 cm	3	Continuous Spray	528	
7					No Spray 10% Fill
8					No Spray 10% Fill
9	DC 23.05, 1 m	3	Spray on for 10 minutes then for 5 minutes in every 15 minutes	602	10% Fill

Table 3.1 Cont.

Test No.	Nozzle	P/bar	Spray Regime	Total Water Consumption/L	Remarks
10	DC 23.05, 1 m	3	as test 5	252	10% fill
11	DC 23.05, 1 m	5.25	"reactive"system ON at TC1 > 100°C OFF at TC1 < 90°C	299	
12	DC 23.05, 1 m	3	10 mins initially then "reactive" ON at TC1 > 100°C OFF 1 min after TC1 < 100°C	265	
13	DC 23.05, 1 m	3	as test 12	232	Immediate response at 2% ft^{-1} smoke obscuration
14	DC 13.02, 1 m	3	as test 4	252	Immediate response at 2% ft^{-1} smoke obscuration
15	DC 13.02, 1 m	3	as tests 12, 13	189	Immediate response at 2% ft^{-1} smoke obscuration

Table 3.1 Cont.

Test No.	Nozzle	P/bar	Spray Regime	Total Water Consumption/L	Remarks
16	DC 23.05, 1 m	3	10 mins initially then "reactive". ON at TC1 > 150°C OFF 1 min after TC1 < 150°C	127	Immediate response at 2% ft^{-1} smoke obscuration
17	DC 23.05, 1 m	3	Spray on for 15 minutes then for 1 minute in every 15 minutes	207	Immediate response at 2% ft^{-1} smoke obscuration
18	DC 23.05, 1 m ---------- KES 180, 0.67 m	3	DC 23.05 for 10 minutes then KES 180 continuously	334	Immediate response at 2% ft^{-1} smoke obscuration

Table 4.1 Average Temperatures in °C at Thermocouple Positions 1-15

Test Number	Thermocouple Number														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	161	153	102	130	98	140	98	113	95	109	318	121	94	96	71
2	132	129	92	113	84	125	85	98	83	-	126	105	81	84	72
3	106	98	72	89	71	88	72	78	70	230	280	79	68	64	52
4	46	48	33	40	33	42	33	37	34	91	85	37	31	34	31
5	78	75	47	62	43	65	51	54	50	555	196	58	45	50	30
6	52	50	36	43	36	47	37	39	35	188	-	40	36	39	34
7	145	136	113	137	114	140	123	118	119	366	138	123	118	92	91
8	150	143	114	131	109	139	111	113	111	302	170	121	113	87	59
9	47	45	36	41	35	42	36	38	34	128	73	40	35	34	26
10	65	61	46	55	45	58	46	50	45	273	51	53	46	47	37
11	76	72	48	63	50	66	50	58	52	303	55	59	50	51	42
12	64	53	39	51	41	48	41	48	40	96	113	43	39	38	32
13	76	61	43	58	46	57	47	55	46	360	278	50	44	43	37
14	74	68	52	61	45	63	45	53	47	83	34	53	46	44	37
15	83	70	44	64	45	64	47	57	45	135	78	52	44	54	38
16	83	77	50	70	52	73	51	60	51	222	285	61	51	37	36
17	55	55	39	47	37	49	35	41	37	110	42	44	36	33	29
18	40	39	28	37	31	37	30	34	31	268	56	33	31	32	30

Table 4.2 Time at T > 100°C in seconds for Thermocouples 1-15

Test Number	Thermocouple Number														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	10360	10460	4570	9330	3830	9770	3870	6670	3120	4340	8250	8690	3270	2900	100
2	7480	8020	3390	6180	1840	7310	2360	4480	1680	-	5370	6190	1370	2040	580
3	4810	3360	730	2540	610	2700	630	1340	500	10650	10450	1510	370	100	0
4	480	540	0	380	0	450	0	40	10	2340	1780	180	0	0	0
5	2600	2340	260	830	0	1590	200	340	140	10690	9200	710	0	0	0
6	500	90	0	100	0	90	30	80	0	10790	-	60	0	0	0
7	10180	10040	9400	10070	9340	10090	957	9270	9500	10770	10580	9750	9450	170	3610
8	10540	9980	7420	9840	7370	10010	7650	8170	8000	9660	10090	9340	7870	3270	0
9	390	61	0	250	0	330	0	0	0	3170	0	300	0	0	0
10	1440	1160	500	850	340	990	390	540	240	9280	780	810	32	31	0
11	790	720	20	50	20	50	30	70	40	10520	0	50	30	0	0
12	500	0	20	20	0	0	0	0	0	4220	3160	0	0	0	0
13	200	40	0	30	0	0	0	0	0	10650	6460	0	0	0	0
14	1740	1310	420	630	100	940	80	400	90	2020	0	220	90	0	0
15	1540	940	0	690	30	730	0	270	0	4240	1520	240	0	0	0
16	2170	1420	80	800	0	1300	0	60	0	8380	10550	1400	0	0	0
17	1040	1150	120	590	6	760	80	40	0	1680	420	320	0	0	0
18	160	0	0	0	0	0	0	0	0	6820	0	0	0	0	0

Table 4.3 Time at T > 200°C in seconds for Thermocouples 1-15

Test Number	Thermocouple Number														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	1680	1410	40	790	0	970	0	330	0	1900	6240	440	0	0	0
2	770	650	160	440	40	820	40	260	30	-	660	360	0	0	0
3	440	350	0	140	0	110	0	60	0	6290	5350	70	0	0	0
4	200	0	0	0	0	0	0	0	0	180	1230	0	0	0	0
5	110	60	0	0	0	0	0	0	0	10670	5110	0	0	0	0
6	50	30	0	50	0	40	0	30	0	330	-	0	0	0	0
7	340	370	130	220	80	320	90	140	90	10720	790	170	100	0	0
8	590	450	190	370	120	390	120	190	110	4730	1680	210	120	0	0
9	0	0	0	0	0	0	0	0	0	2160	0	0	0	0	0
10	240	170	40	80	40	180	0	60	40	5100	160	70	0	0	0
11	20	10	0	0	0	0	0	0	0	5910	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	470	1640	0	0	0	0
13	0	0	0	0	0	0	0	0	0	844	6000	0	0	0	0
14	210	140	0	80	0	120	0	0	0	760	0	30	0	0	0
15	310	170	0	160	0	130	0	50	0	2190	360	0	0	0	0
16	30	30	0	0	0	20	0	0	0	3590	1040	0	0	0	0
17	40	100	0	0	0	0	0	0	0	1260	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	5420	0	0	0	0	0

Test 1 Gas Analysis Results
Table 4.4

Time/ min	CO/ %	CO_2/ %	HCN/ %	CH_4/ %	C_2H_2/ %	C_2H_4/ %	O_2/ %
1	0.14	1.99	d	0.02	d	0.01	-
20	1.07	5.17	d	0.06	0.01	0.01	12.0
40	2.01	5.25	0.01	0.18	0.01	0.05	11.4
60	0.83	2.65	0.01	0.11	d	0.03	10.1
80	0.27	1.13	d	0.03	d	0.01	13.5
100	0.57	2.84	d	0.06	d	0.02	11.5
120	0.46	2.49	d	0.05	d	0.02	13.1
140	0.24	1.32	d	0.03	d	0.03	13.3
160	0.41	3.58	d	0.03	0.01	0.01	9.0
180	0.56	2.32	d	0.03	d	0.03	13.5

d = detected
all concentrations quoted are in % by volume

Test 2 Gas Analysis Results
Table 4.5

Time/ min	CO/ %	CO_2/ %	HCN/ %	CH_4/ %	C_2H_2/ %	C_2H_4/ %	O_2/ %
1	0.07	0.41	0	0.01	d	d	-
20	0.67	3.87	d	0.03	0.01	0.01	13.4
40	0.82	3.72	0.01	0.05	0.01	0.01	13.9
60	1.03	5.37	0.01	0.09	0.01	0.02	5.4
80	0.73	2.10	d	0.06	d	0.01	15.5
100	0.66	1.41	d	0.05	d	0.01	16.8
120	1.20	5.94	d	0.06	0.01	0.01	10.2
140	1.25	3.86	d	0.07	0.01	0.02	12.9
160	1.20	5.67	d	0.06	0.01	0.02	11.0
180	0.88	4.10	d	0.05	0.01	0.02	12.4

d = detected
all concentrations quoted are in % by volume

Test 3 Gas Analysis Results
Table 4.6

Time/ min	CO/ %	CO_2/ %	HCN/ %	CH_4/ %	C_2H_4/ %	O_2/ %
0.5	0.02	0.02	0	0	0	-
4.5	2.29	6.10	0.01	0.19	0.04	-
7.5	2.02	5.16	0.01	0.17	0.03	-
10.5	2.10	4.99	0.01	0.18	0.04	12.8
20	2.32	5.08	0.01	0.21	0.04	11.2
40	1.46	3.45	0.01	0.14	0.03	14.0
60	1.02	4.33	d	0.08	0.02	12.2
80	0.99	3.74	d	0.08	0.02	-
100	0.90	4.85	d	0.06	0.01	-
120	1.10	3.57	0.01	0.08	0.01	-
140	1.05	3.41	0.01	0.09	0.02	-
160	0.78	2.30	d	0.06	0.01	-
180	0.55	2.29	d	0.05	0.01	-

d = detected
all concentrations quoted are in % by volume

Test 4 Gas Analysis Results
Table 4.7

Time/ min	CO/ %	CO_2/ %	HCN/ %	CH_4/ %	O_2/ %
1	0.03	0.07	0	0	-
5	1.60	4.72	0.02	0.18	-
8	1.52	4.45	0.02	0.16	-
11	1.40	4.05	0.02	0.13	14.6
20	1.30	4.36	0.02	0.12	15.4
40	0.65	2.01	0.01	0.07	16.6
60	0.35	1.13	0.01	0.04	18.5
80	0.69	3.31	0.01	0.06	14.5
100	0.31	1.53	0.01	0.04	18.0
120	0.24	1.38	d	0.04	18.1
140	0.54	4.57	0.01	0.05	17.0
160	0.23	1.40	d	0.03	18.0
180	0.15	0.79	d	0.02	19.2

d = detected
all concentrations quoted are in % by volume

Test 5 Gas Analysis Results
Table 4.8

Time/ min	CO/ %	CO_2/ %	HCN/ %	CH_4/ %	C_2H_4/ %	O_2/ %
1	0.04	0.34	d	d	d	-
7	1.90	5.17	0.02	0.20	0.05	-
20	1.38	3.82	0.02	0.12	0.03	14.0
33	0.81	3.13	0.01	0.07	0.02	-
40	0.83	4.83	0.01	0.07	0.01	13.3
48	0.73	3.56	0.01	0.11	0.01	-
60	0.70	3.45	0.01	0.13	0.01	14.0
80	0.76	3.41	0.01	0.12	0.01	14.5
100	0.61	2.78	0.01	0.09	0.01	15.5
120	0.62	2.70	0.01	0.06	0.01	16.2
140	0.48	2.16	0.01	0.05	0.01	17.0
160	0.36	1.47	0.01	0.03	d	18.2
180	0.35	1.46	0.01	0.04	0.01	18.3

d = detected
all concentrations quoted are in % by volume

Test 6 Gas Analysis Results
Table 4.9

Time/ min	CO/ %	CO_2/ %	HCN/ %	CH_4/ %	C_2H_4/ %	O_2/ %
1	0.03	0.05	d	d	d	-
5	2.64	11.47	0.03	0.08	0.02	-
10	1.57	5.33	0.02	0.15	0.03	12.0
15	1.21	3.65	0.02	0.11	0.02	-
20	0.83	2.42	0.01	0.08	0.02	16.0
40	1.58	5.18	0.02	0.19	0.03	12.0
60	0.57	1.93	0.01	0.09	0.01	16.9
80	0.48	2.07	0.01	0.07	0.01	17.2
100	0.61	2.46	0.01	0.09	0.01	16.5
120	0.66	2.76	0.01	0.11	0.01	16.3
140	0.42	2.40	0.01	0.04	0.01	16.8
160	0.38	2.14	0.01	0.03	0.01	17.4
180	0.25	1.31	d	0.01	0.01	18.5

d = detected
all concentrations quoted are in % by volume

Test 7 Gas Analysis Results
Table 4.10

Time/ min	CO/ %	CO_2/ %	HCN/ %	CH_4/ %	C_2H_4/ %	O_2/ %
1.5	0.07	0.80	d	0.01	d	-
5	1.08	9.75	0.01	0.08	0.02	-
10	1.69	7.34	0.02	0.18	0.04	7.3
15	1.13	4.95	0.02	0.12	0.03	-
20	1.14	4.38	0.02	0.12	0.03	13.9
40	2.02	5.67	0.02	0.24	0.05	11.0
60	1.99	5.82	0.02	0.35	0.05	10.3
80	1.58	5.43	0.02	0.30	0.04	10.4
100	1.41	5.41	0.02	0.30	0.04	9.8
120	1.19	4.65	0.02	0.24	0.03	10.9
140	1.22	4.99	0.02	0.16	0.02	11.5
160	0.92	4.19	0.01	0.08	0.01	11.2
180	0.91	4.00	0.01	0.08	0.01	12.2

d = detected
all concentrations quoted are in % by volume

Test 8 Gas Analysis Results
Table 4.11

Time/ min	CO/ %	CO_2/ %	HCN/ %	CH_4/ %	C_2H_4/ %	O_2/ %
1	0.04	0.15	d	0.01	d	-
5	1.40	8.81	0.02	0.10	0.03	-
10	2.56	7.45	0.03	0.30	0.07	8.7
15	2.51	7.04	0.03	0.26	0.06	-
20	2.54	7.13	0.03	0.28	0.07	8.2
40	1.73	6.67	0.02	0.23	0.05	9.6
60	1.76	5.97	0.02	0.26	0.04	11.1
80	1.68	5.28	0.02	0.29	0.04	10.4
100	1.08	4.16	0.02	0.14	0.02	11.6
120	0.65	3.17	0.01	0.06	0.01	12.9
140	0.28	1.51	d	0.03	0.01	12.5
160	0.12	0.61	d	0.02	0.01	13.8
180	0.14	0.75	d	0.02	d	14.0

d = detected
all concentrations quoted are in % by volume

Test 9 Gas Analysis Results
Table 4.12

Time/ min	CO/ %	CO_2/ %	HCN/ %	CH_4/ %	C_2H_4/ %	O_2/ %	H_2/ %
1	0.05	0.12	d	0.01	d	20.7	0.00
7	1.47	4.83	0.02	0.19	0.04	15.4	0.10
10	2.26	6.39	0.03	0.27	0.06	12.4	0.19
15	1.81	5.75	0.02	0.19	0.05	13.7	0.14
20	1.86	5.80	0.01	0.19	0.05	12.0	0.11
40	0.72	2.47	0.01	0.08	0.02	16.8	0.08
60	0.33	1.15	0.01	0.04	0.01	17.7	0.03
80	0.25	0.84	d	0.03	0.01	20.0	0.06
100	0.73	2.91	0.01	0.08	0.02	14.8	0.05
120	0.39	1.92	0.01	0.05	0.02	20.6	0.08
140	0.31	1.59	0.01	0.05	0.01	19.4	0.04
160	0.50	3.56	0.01	0.07	0.02	16.6	0.08
180	0.33	2.07	0.01	0.05	0.01	16.6	0.04

d = detected
all concentrations quoted are in % by volume

Test 10 Gas Analysis Results
Table 4.13

Time/ min	CO/ %	CO_2/ %	HCN/ %	CH_4/ %	C_2H_4/ %	O_2/ %	H_2/ %
1	0.03	0.06	d	0.01	d	20.6	0.00
7	0.71	1.91	0.01	0.11	0.03	17.9	0.08
10	1.16	6.89	0.02	0.08	0.02	8.9	0.08
15	1.08	5.19	0.02	0.08	0.02	12.8	0.06
20	1.01	4.33	0.01	0.07	0.02	14.1	0.08
40	0.32	1.64	0.01	0.03	0.01	17.3	0.01
60	0.21	1.02	d	0.02	0.01	19.0	0.05
80	0.18	0.76	d	0.02	0.01	19.6	0.02
100	0.19	0.71	d	0.03	0.01	19.7	0.01
120	0.96	3.98	0.01	0.13	0.03	13.9	0.06
140	0.83	3.96	0.01	0.11	0.02	14.6	0.14
160	0.80	3.78	0.01	0.09	0.02	15.7	0.11
180	0.50	2.67	0.01	0.06	0.01	16.4	0.10

d = detected
all concentrations quoted are in % by volume

Test 11 Gas Analysis Results
Table 4.14

Time/ min	CO/ %	CO_2/ %	HCN/ %	CH_4/ %	C_2H_4/ %	O_2/ %	H_2/ %
1	0.05	0.50	d	d	0.01	20.3	0.00
5	1.01	3.85	0.01	0.08	0.02	15.1	0.06
10	1.81	5.24	0.02	0.10	0.02	11.8	0.07
15	1.68	4.44	0.02	0.10	0.03	13.4	0.09
20	1.70	4.20	0.02	0.25	0.03	13.8	0.07
40	1.41	4.22	0.02	0.14	0.03	13.3	0.07
60	0.86	2.73	0.01	0.09	0.02	15.7	0.05
80	0.50	1.90	0.01	0.05	0.01	17.0	0.07
120	0.62	2.55	0.01	0.07	0.01	16.5	0.06
140	0.60	2.70	0.01	0.06	0.01	16.1	0.04
160	0.66	2.77	0.01	0.08	0.01	16.4	0.10
180	0.59	2.43	0.01	0.06	0.01	16.5	0.07

d = detected
all concentrations quoted are in % by volume

Test 12 Gas Analysis Results
Table 4.15

Time/ min	CO/ %	CO_2/ %	HCN/ %	CH_4/ %	C_2H_4/ %	O_2/ %	H_2/ %
0.5	0.04	0.14	d	d	d	20.5	0.00
5	1.19	3.82	0.02	0.14	0.03	15.1	0.08
10	1.52	4.77	0.02	0.18	0.04	13.6	0.08
15	1.52	5.16	0.02	0.17	0.04	12.8	0.11
20	1.64	5.37	0.02	0.18	0.04	12.4	0.08
40	0.83	4.03	0.01	0.09	0.02	14.5	0.07
60	0.59	2.82	0.01	0.07	0.01	15.7	0.06
80	0.55	2.24	0.01	0.06	0.01	16.7	0.03
100	0.33	1.44	0.01	0.03	0.01	18.1	0.01
120	0.20	0.94	d	0.02	0.01	18.9	0.02
140	0.17	0.78	d	0.02	d	19.3	0.06
160	0.51	2.63	0.01	0.05	0.01	16.6	0.07
180	0.27	1.43	d	0.03	0.01	18.1	0.01

d = detected
all concentrations quoted are in % by volume

Test 13 Gas Analysis Results
Table 4.16

Time/ min	CO/ %	CO_2/ %	HCN/ %	CH_4/ %	C_2H_4/ %	O_2/ %	H_2/ %
0.5	0.04	0.07	d	0.01	0.01	20.6	0.00
5	1.07	3.73	0.01	0.11	0.03	15.2	0.06
10	1.22	3.70	0.02	0.12	0.02	15.1	0.07
15	1.20	4.16	0.02	0.12	0.03	14.6	0.11
20	1.14	4.34	0.02	0.11	0.02	14.4	0.09
40	0.77	3.32	0.01	0.12	0.02	15.6	0.10
60	1.32	5.09	0.02	0.18	0.04	12.0	0.01
80	1.02	4.00	0.01	0.10	0.02	14.5	0.13
100	0.66	3.11	0.01	0.07	0.01	15.8	0.14
120	1.03	3.76	0.01	0.13	0.03	15.3	0.11
140	0.84	3.54	0.01	0.08	0.02	15.5	0.14
160	0.55	2.62	0.01	0.05	0.01	16.3	0.10
180	0.55	2.33	0.01	0.07	0.01	17.1	0.13

d = detected
all concentrations quoted are in % by volume

<u>Test 14 Gas Analysis Results</u>
<u>Table 4.17</u>

Time/ min	CO/ %	CO_2/ %	HCN/ %	CH_4/ %	C_2H_4/ %	O_2/ %	H_2/ %
1	0.00	0.03	d	d	d	20.3	0.00
5	0.70	2.35	0.01	0.07	0.02	16.8	0.14
10	1.73	7.26	0.02	0.18	0.04	13.1	0.15
15	2.33	8.00	0.03	0.20	0.04	2.5	0.18
20	1.25	4.24	0.02	0.11	0.02	12.7	0.12
40	0.49	1.37	0.01	0.06	0.01	17.7	0.09
60	0.71	2.98	0.01	0.10	0.02	16.1	0.08
80	0.89	4.07	0.01	0.11	0.02	12.5	0.12
100	0.69	3.08	0.01	0.10	0.02	14.4	0.14
120	0.85	3.34	0.01	0.13	0.02	14.5	0.20
140	1.18	4.46	0.02	0.12	0.02	12.2	0.21
160	0.84	3.48	0.01	0.07	0.01	13.9	0.18
180	0.57	2.33	0.01	0.05	0.02	15.8	0.11

d = detected
all concentrations quoted are in % by volume

Test 15 Gas Analysis Results
Table 4.18

Time/ min	CO/ %	CO_2/ %	HCN/ %	CH_4/ %	C_2H_4/ %	O_2/ %	H_2/ %
0.5	0.00	0.02	0	0	0	20.6	0.00
5	0.08	0.77	d	0.01	d	12.8	0.00
10	0.97	3.09	0.01	0.09	0.02	13.3	0.03
20	0.75	2.19	0.01	0.06	0.01	16.7	0.03
40	0.51	2.08	0.01	0.05	0.01	15.2	0.05
60	0.04	0.13	d	0.01	d	12.4	0.00
80	0.66	2.89	0.01	0.07	0.01	15.1	0.05
100	0.48	2.43	0.01	0.05	0.01	15.7	0.06
120	0.64	3.17	0.01	0.05	0.01	14.8	0.02
140	0.94	2.97	0.01	0.09	0.02	13.4	0.06
160	0.67	2.49	0.01	0.05	0.02	15.2	0.03
180	0.59	1.90	0.01	0.05	0.01	16.8	0.04

d = detected
all concentrations quoted are in % by volume

Test 16 Gas Analysis Results
Table 4.19

Time/ min	CO/ %	CO_2/ %	HCN/ %	CH_4/ %	C_2H_4/ %	O_2/ %	H_2/ %
1	0	0.03	0	0	0	20.0	0
5	0.55	1.79	0.01	0.05	0.01	17.2	0.05
10	1.47	4.13	0.02	0.20	0.05	13.0	0.20
15	1.67	4.43	0.02	0.21	0.05	11.7	0.17
20	1.57	4.02	0.02	0.20	0.05	12.6	0.16
40	1.73	4.51	0.02	0.12	0.03	11.2	0.08
60	1.22	4.20	0.02	0.09	0.02	12.4	0.09
80	1.25	3.72	0.02	0.11	0.02	13.3	0.06
100	0.99	3.26	0.01	0.09	0.02	14.0	0.06
120	0.86	3.34	0.01	0.07	0.02	13.4	0.06
160	0.03	0.05	0	0	0	19.8	0
180	0.03	0.05	0	0	0	20.0	0

d = detected
all concentrations quoted are in % by volume

Test 18 Gas Analysis Results
Table 4.21

Time/ min	CO/ %	CO_2/ %	HCN/ %	CH_4/ %	C_2H_4/ %	O_2/ %	H_2/ %
1	0.10	0.13	d	0.01	d	20.0	0.05
5	1.16	2.40	0.02	0.13	0.04	15.4	0.18
10	1.91	3.59	0.02	0.18	0.06	12.9	0.36
15	2.00	4.05	0.02	0.17	0.05	12.0	0.56
20	1.62	3.12	0.02	0.13	0.03	13.7	0.44
40	1.75	4.08	0.02	0.15	0.03	11.2	0.58
60	0.66	1.56	0.01	0.06	0.01	16.7	0.09
80	0.57	1.39	0.01	0.06	0.01	17.2	0.19
100	0.81	2.46	0.01	0.08	0.02	15.3	0.27
120	0.54	1.68	0.01	0.06	0.01	16.3	0.14
140	0.48	1.86	0.01	0.04	0.01	16.5	0.08
160	0.27	0.88	d	0.02	0.01	18.0	0.07
180	0.17	0.47	d	0.02	d	19.0	0.03

d = detected
all concentrations quoted are in % by volume

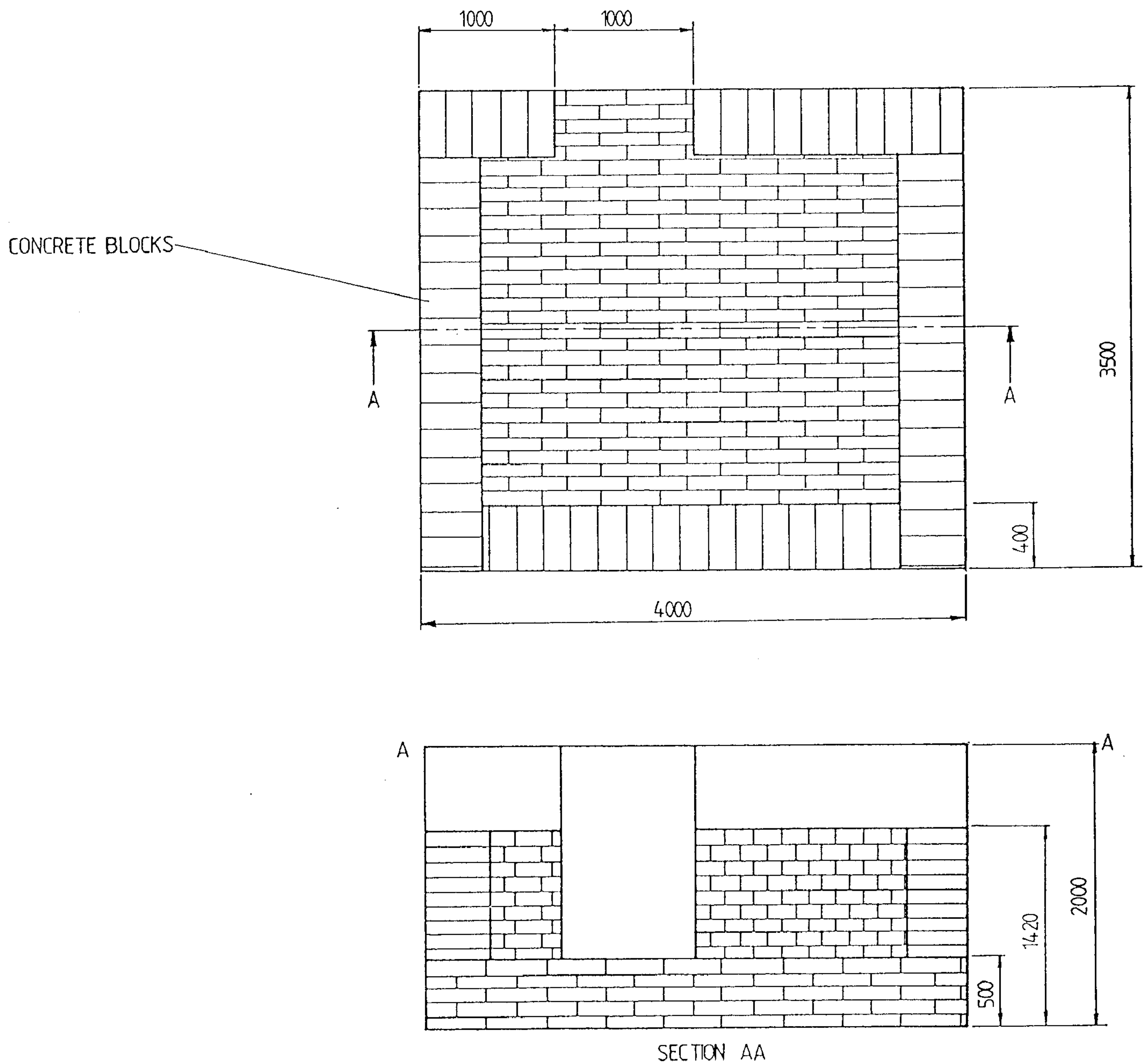


Figure 2.2 Inert Fire Load Dimensions

Figure 2.3

Spray Manifold

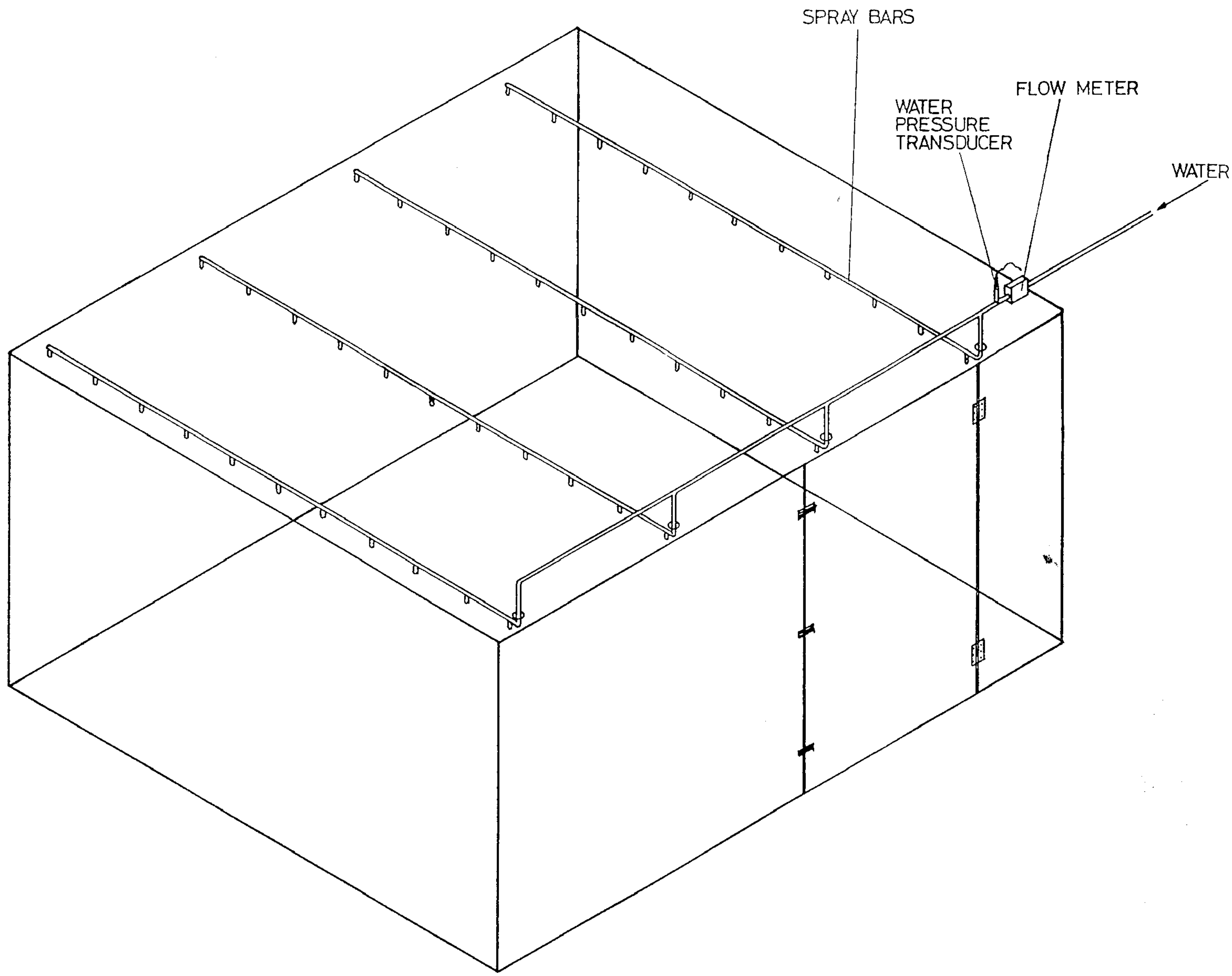


Figure 2.4
Spray Manifold
Dimensions

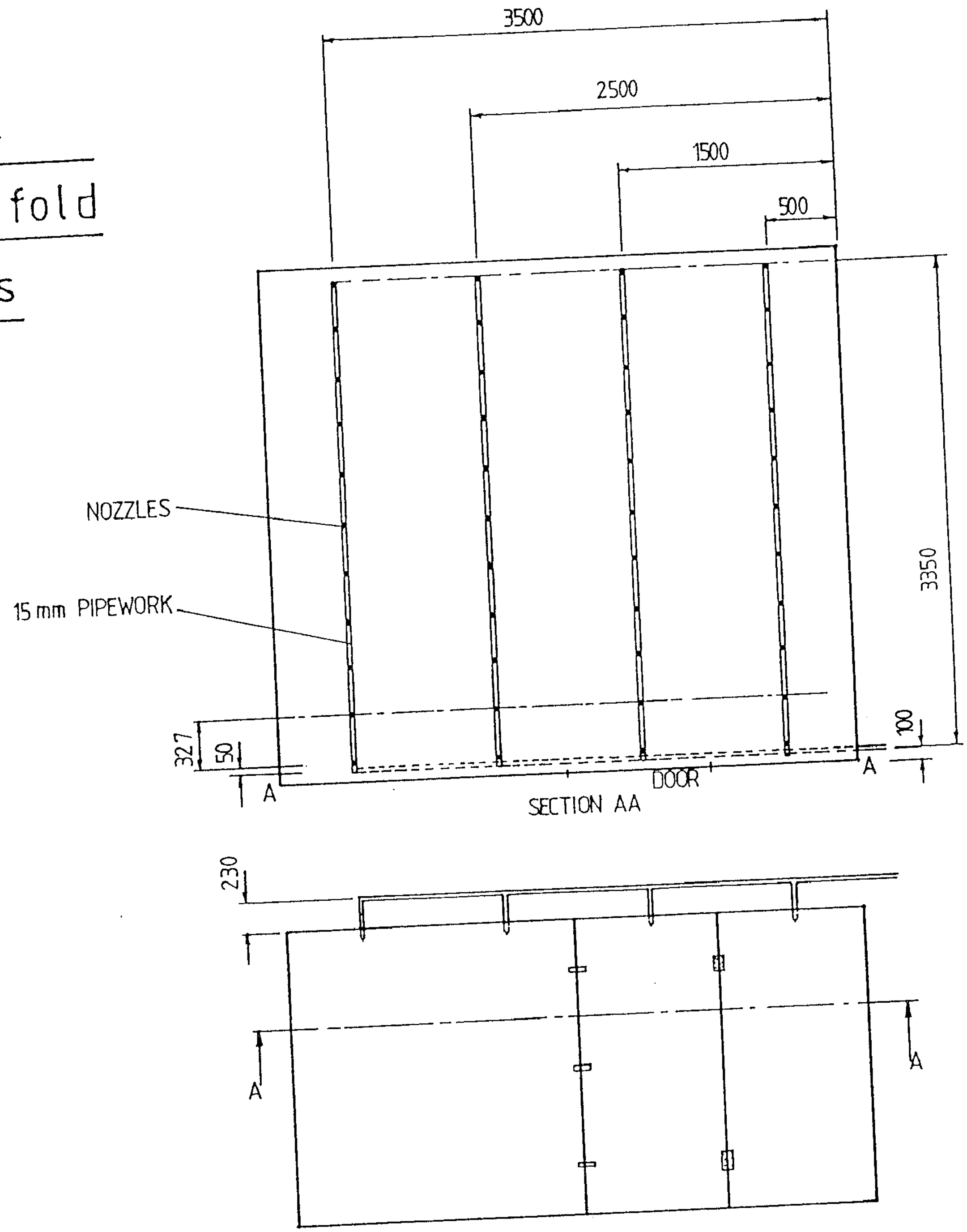
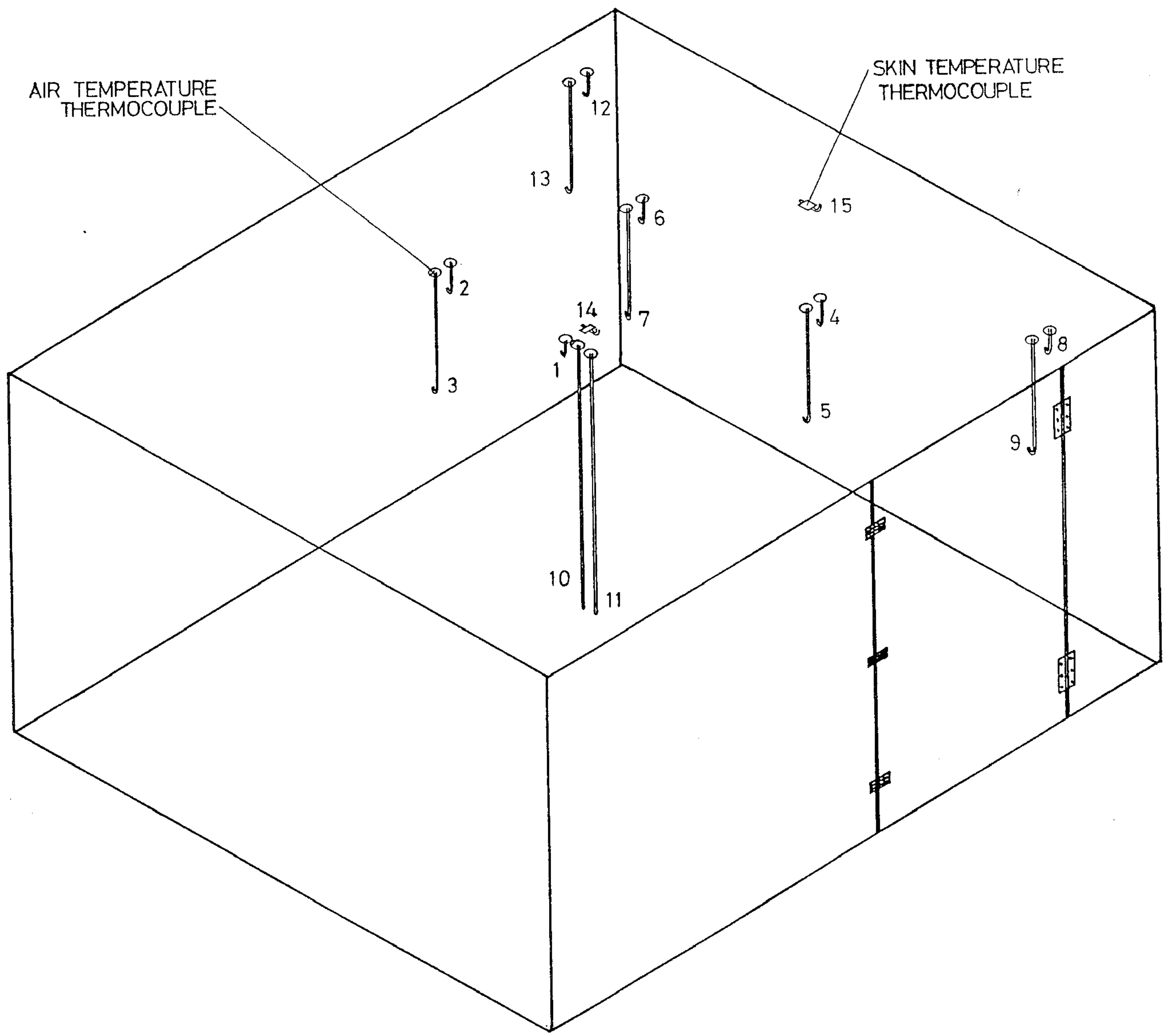


Figure 2.5 Thermocouple Locations



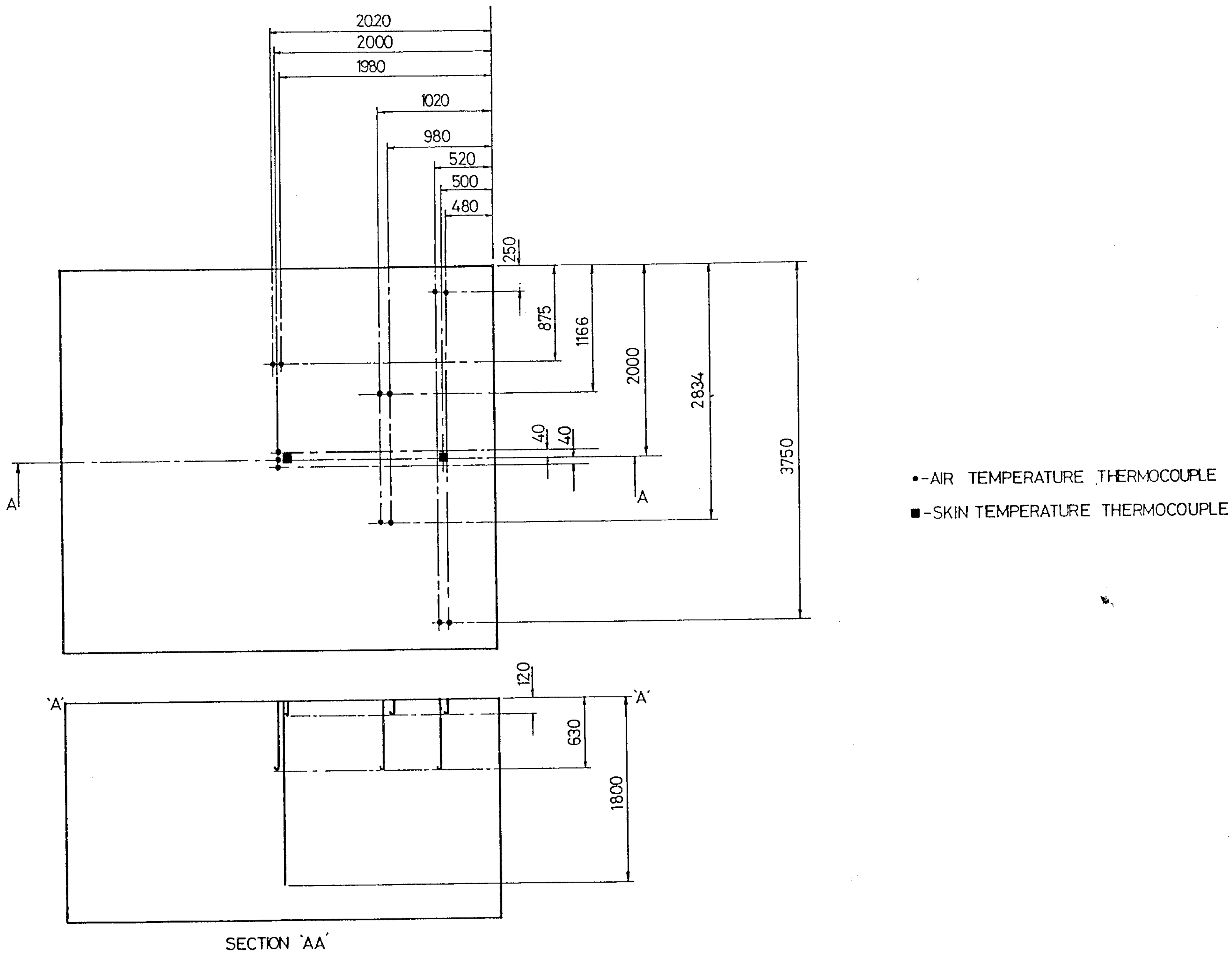


Figure 2.6 Thermocouple Location Dimensions

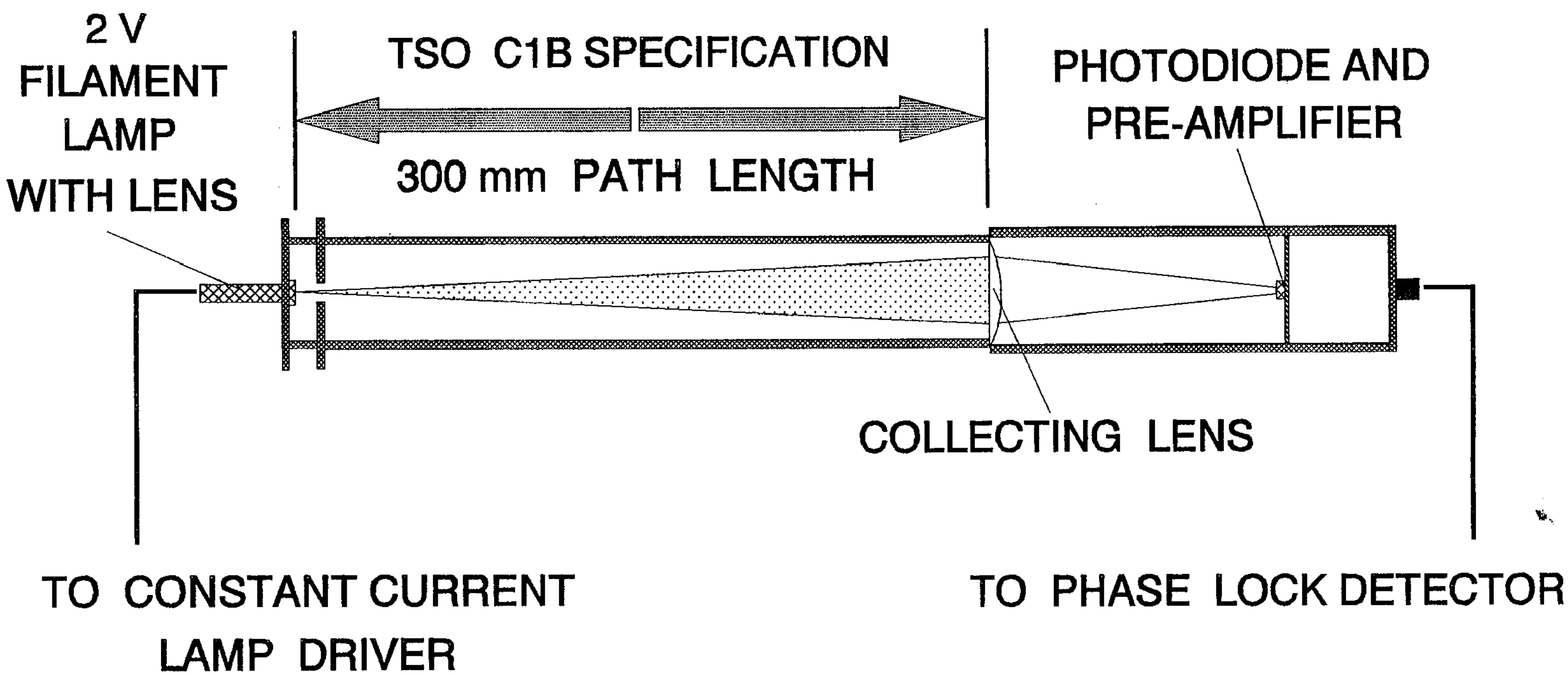


Figure 2.7 Smoke Obscuration Apparatus

Figure 2.8

GAS ANALYSIS SYSTEM

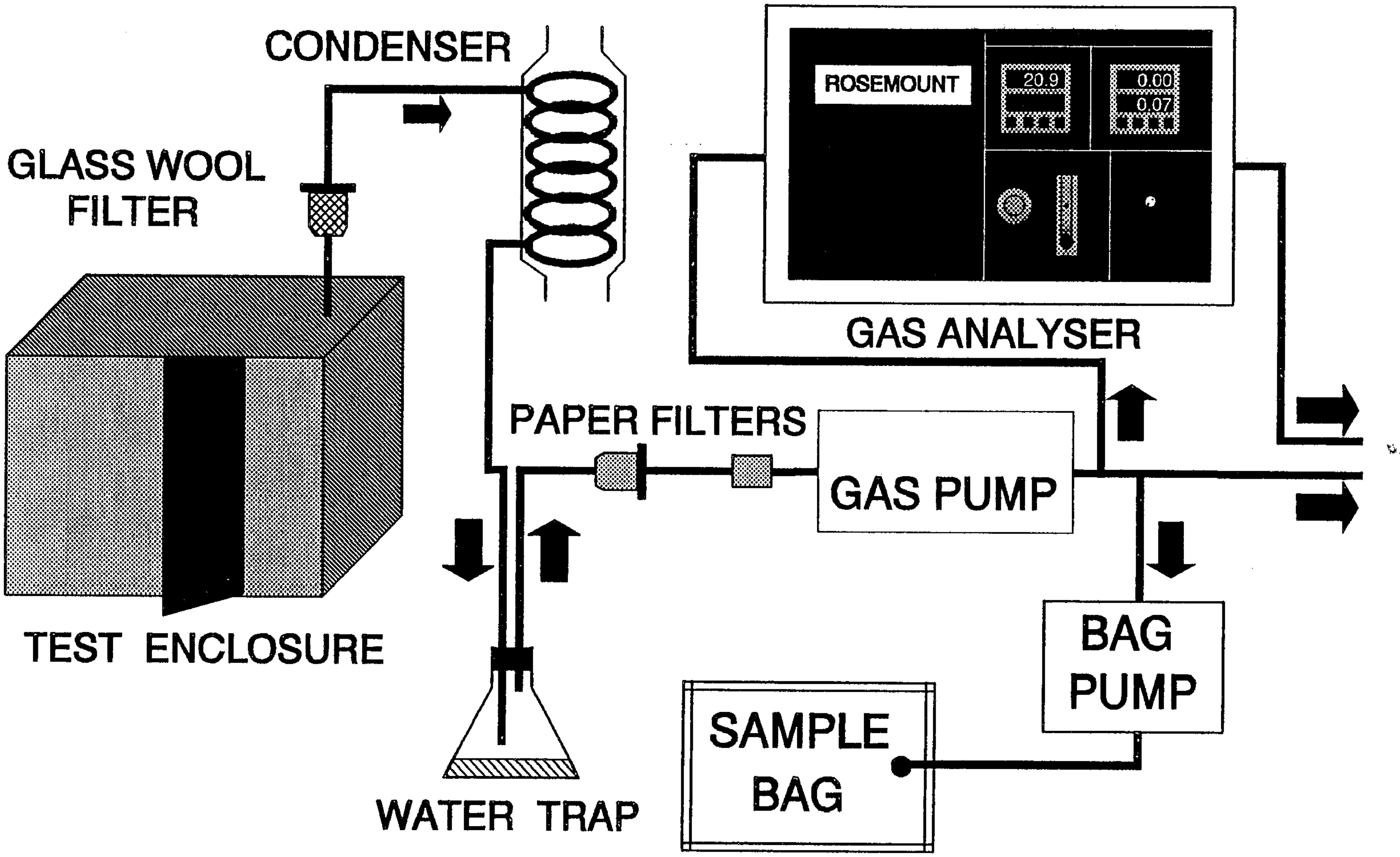


Figure 2.9

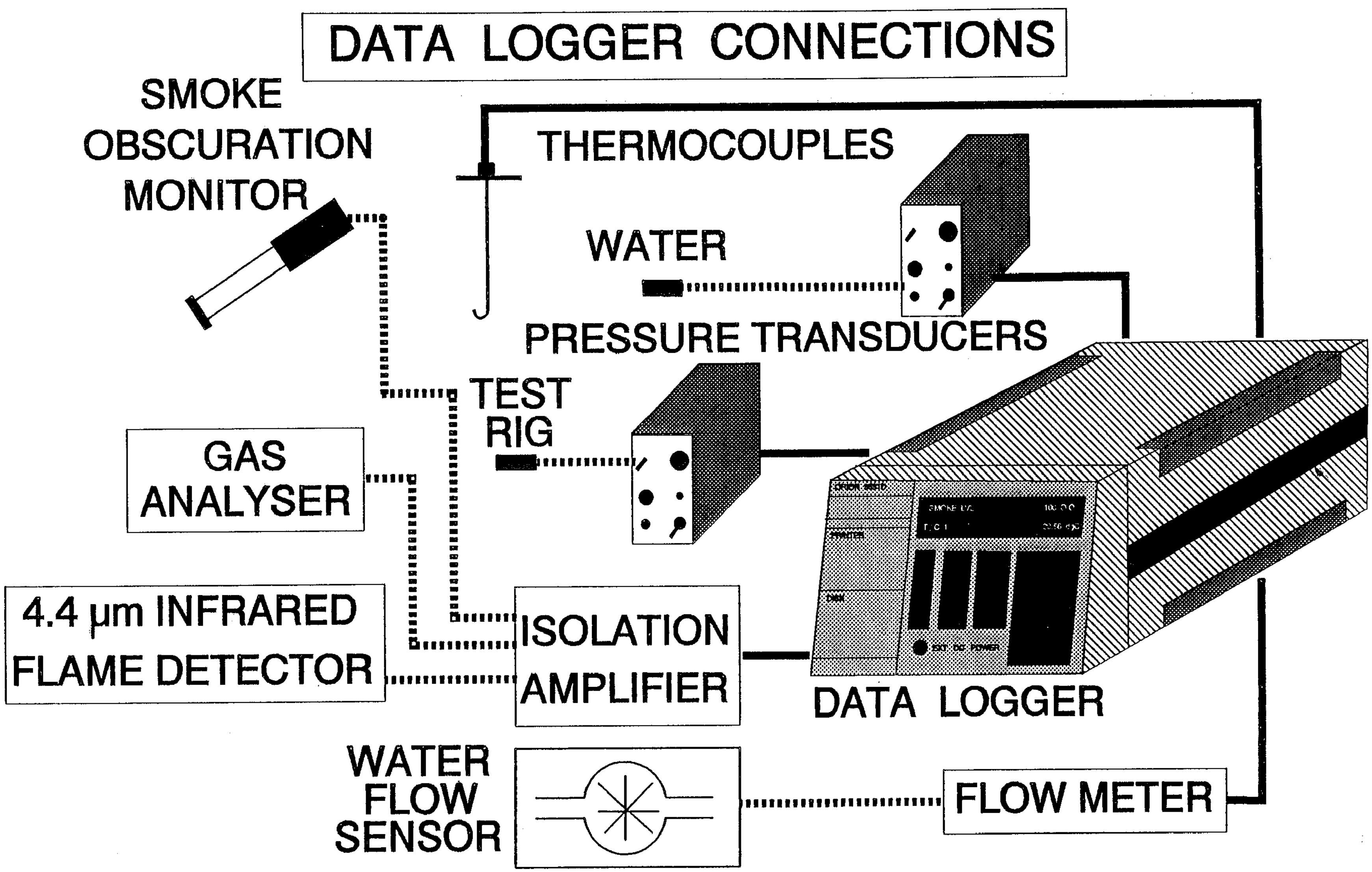

DATA LOGGER CONNECTIONS
SMOKE
OBSCURATION
MONITOR
THERMOCOUPLES
WATER
PRESSURE TRANSDUCERS
TEST
RIG
GAS
ANALYSER
4.4 μm INFRARED
FLAME DETECTOR
ISOLATION
AMPLIFIER
DATA LOGGER
WATER
FLOW
SENSOR
FLOW METER

Figure 3.1 Nozzle Flow Rates

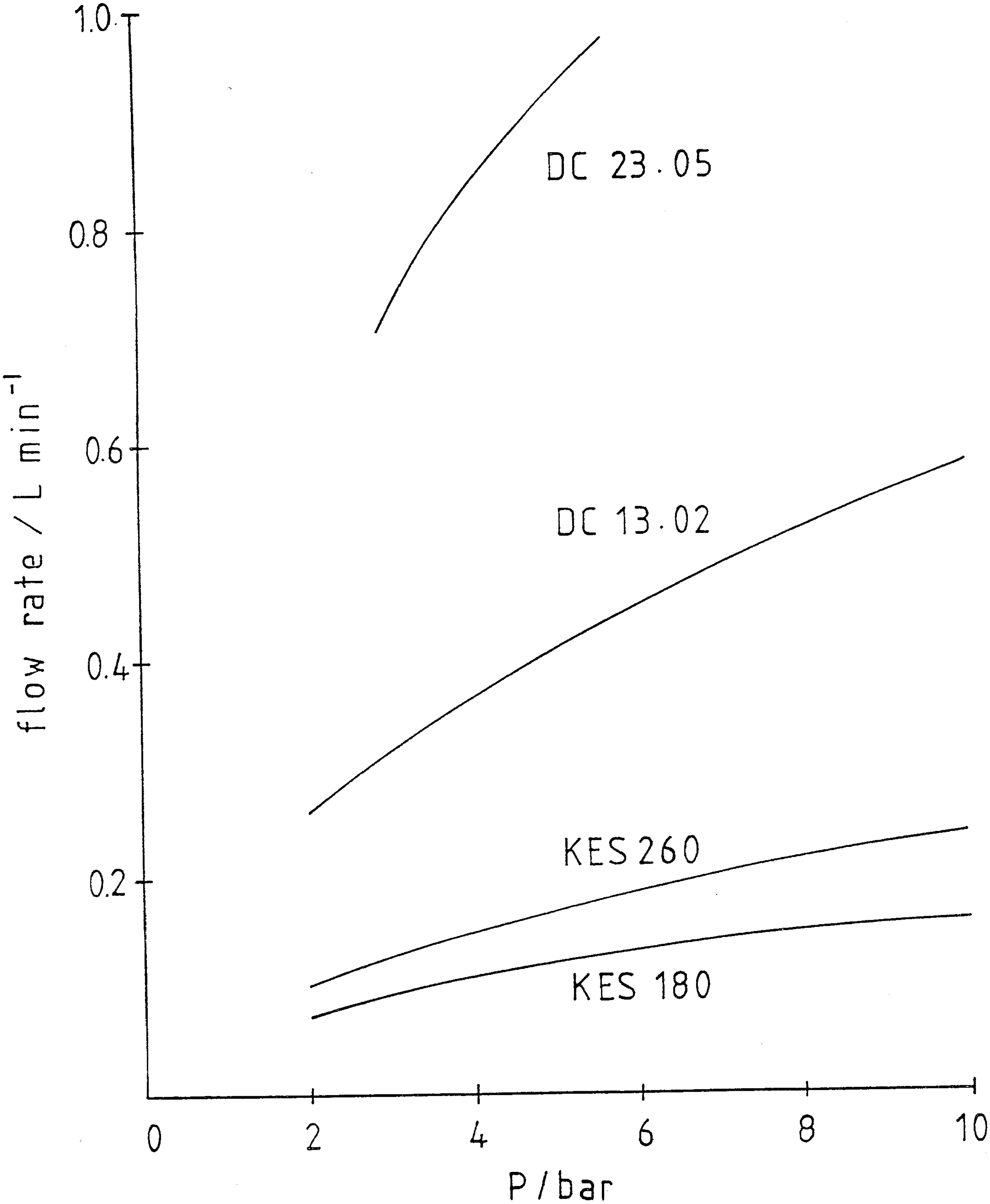


FIGURE 4.1: CAA CARGO BAY TEST NUMBER 1

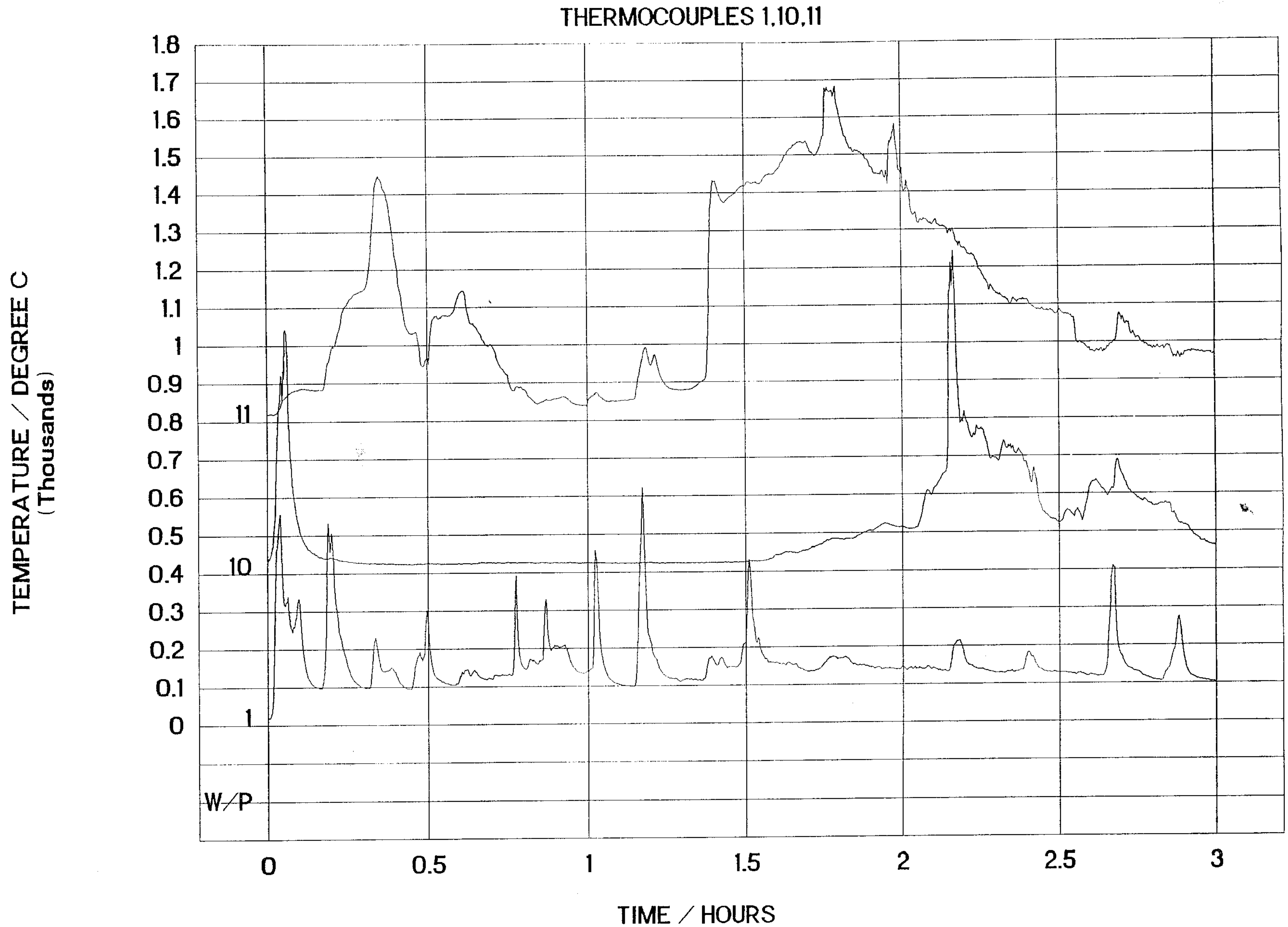


FIGURE 4.2: CAA CARGO BAY TEST NUMBER 1

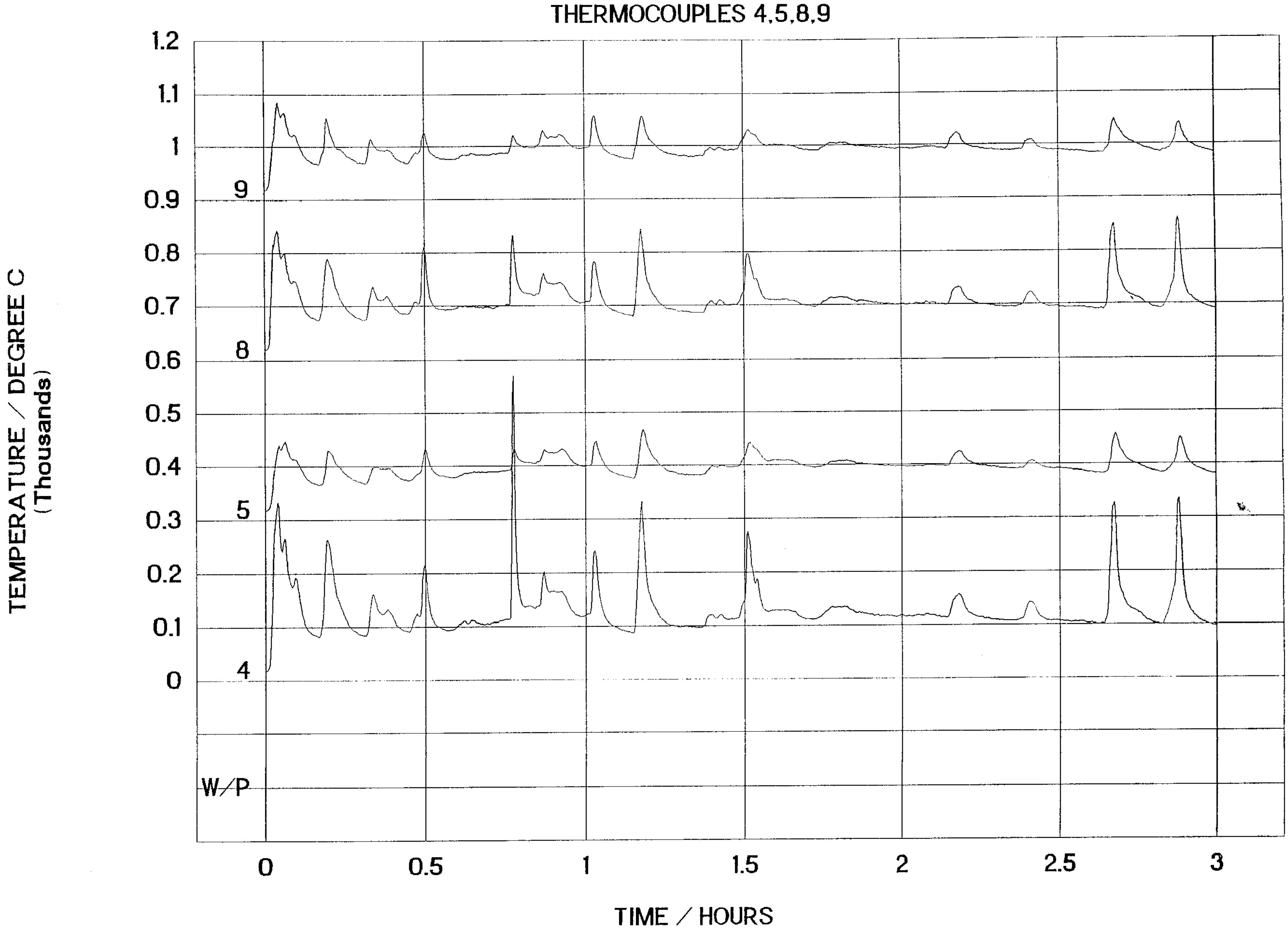


FIGURE 4.3: CAA CARGO BAY TEST NUMBER 1

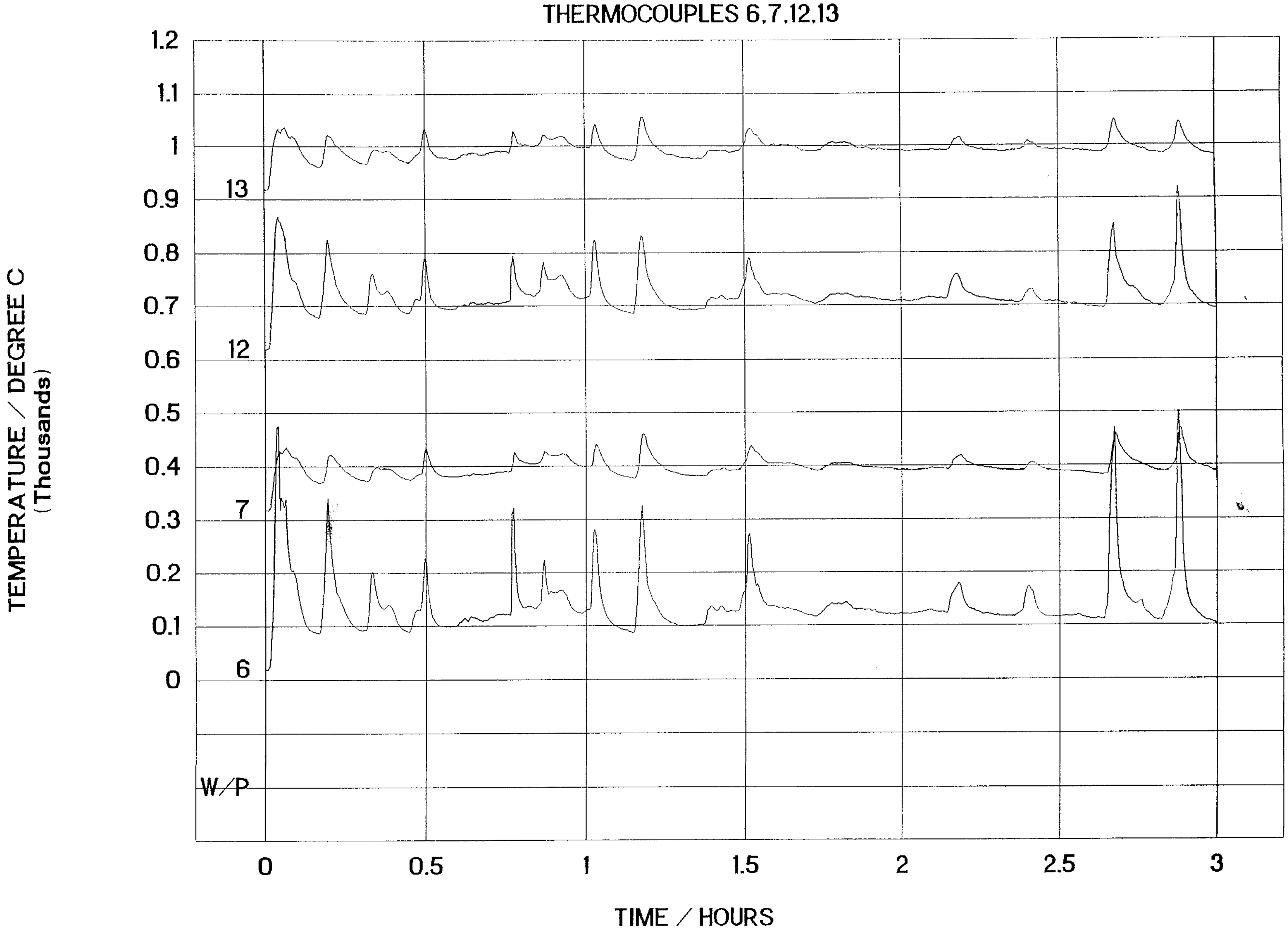


FIGURE 4.4: CAA CARGO BAY TEST NUMBER 1

THERMOCOUPLES 2,3,14,15

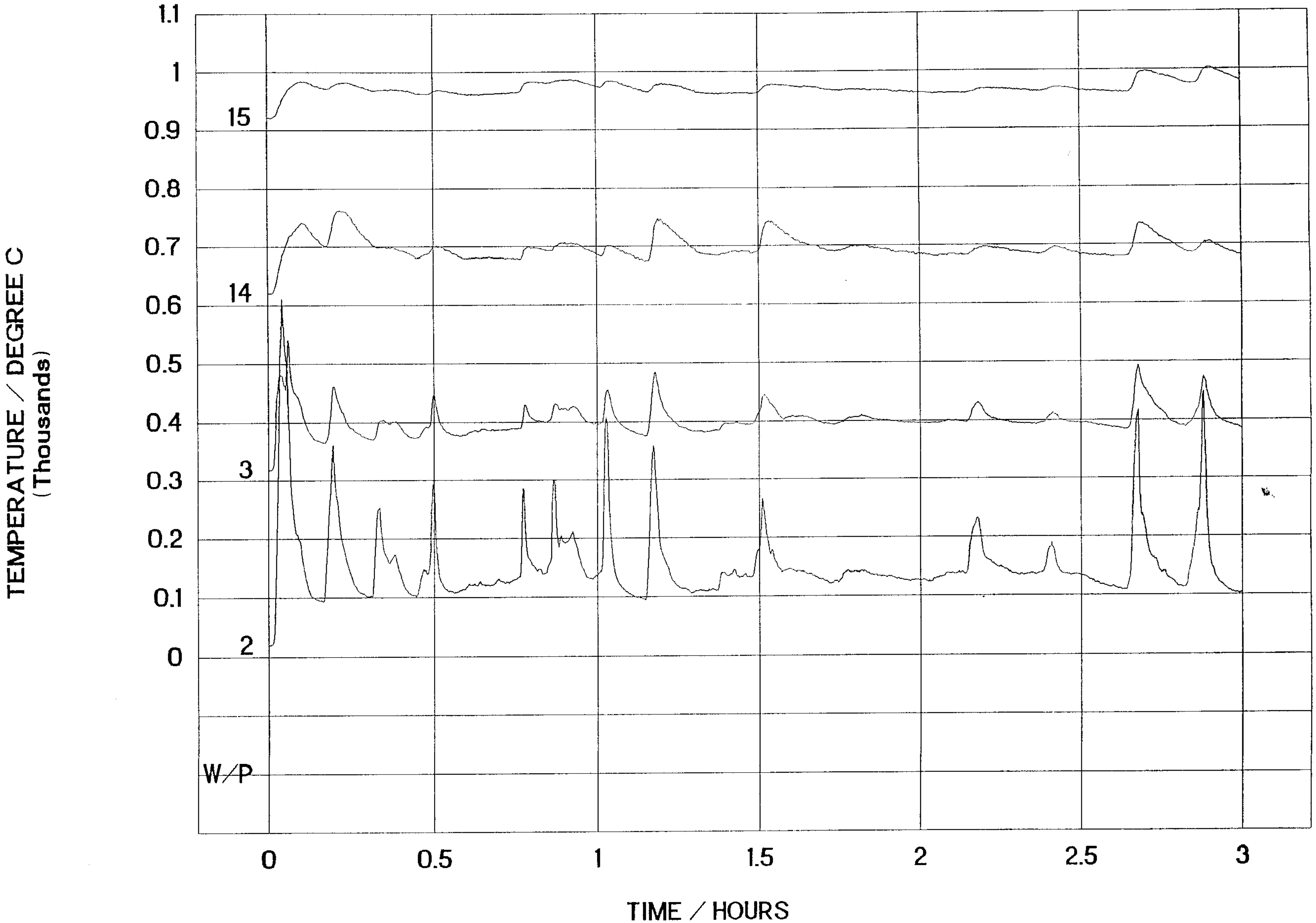


FIGURE 4.5: CAA CARGO BAY TEST NUMBER 2

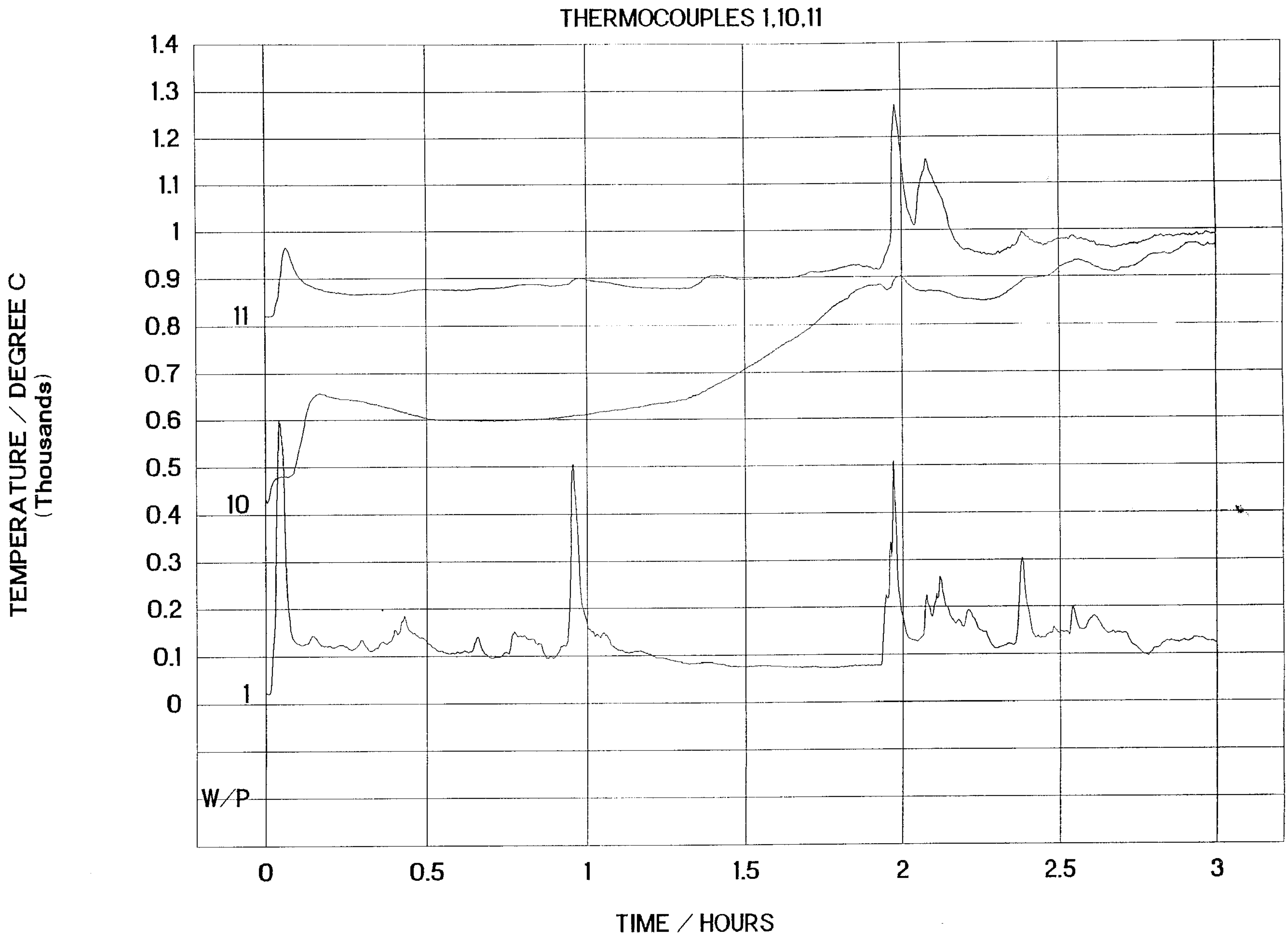


FIGURE 4.6: CAA CARGO BAY TEST NUMBER 2

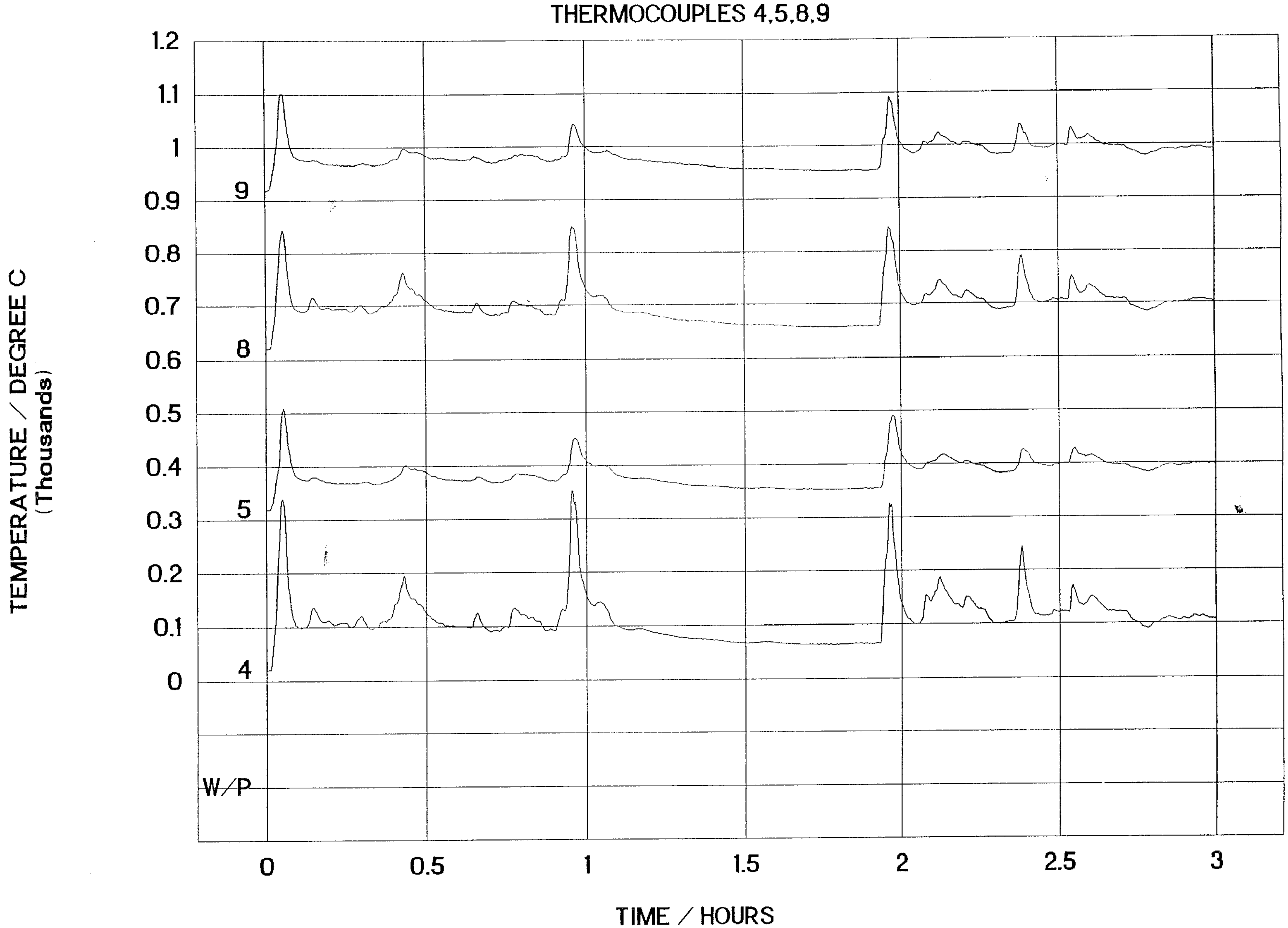


FIGURE 4.7: CAA CARGO BAY TEST NUMBER 2

FIGURE 4.8: CAA CARGO BAY TEST NUMBER 2

THERMOCOUPLES 2,3,14,15

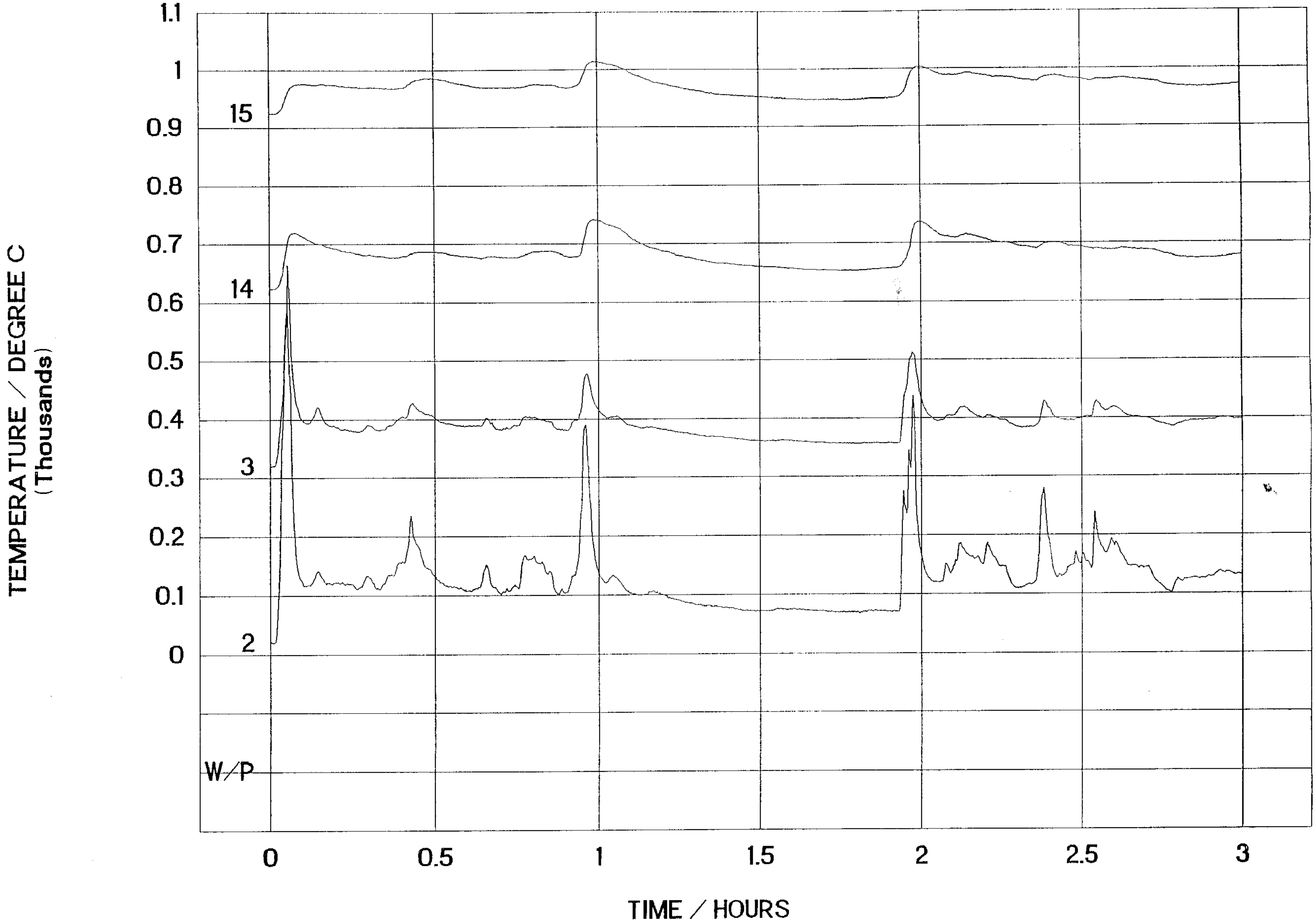


FIGURE 4.9: CAA CARGO BAY TEST NUMBER 3

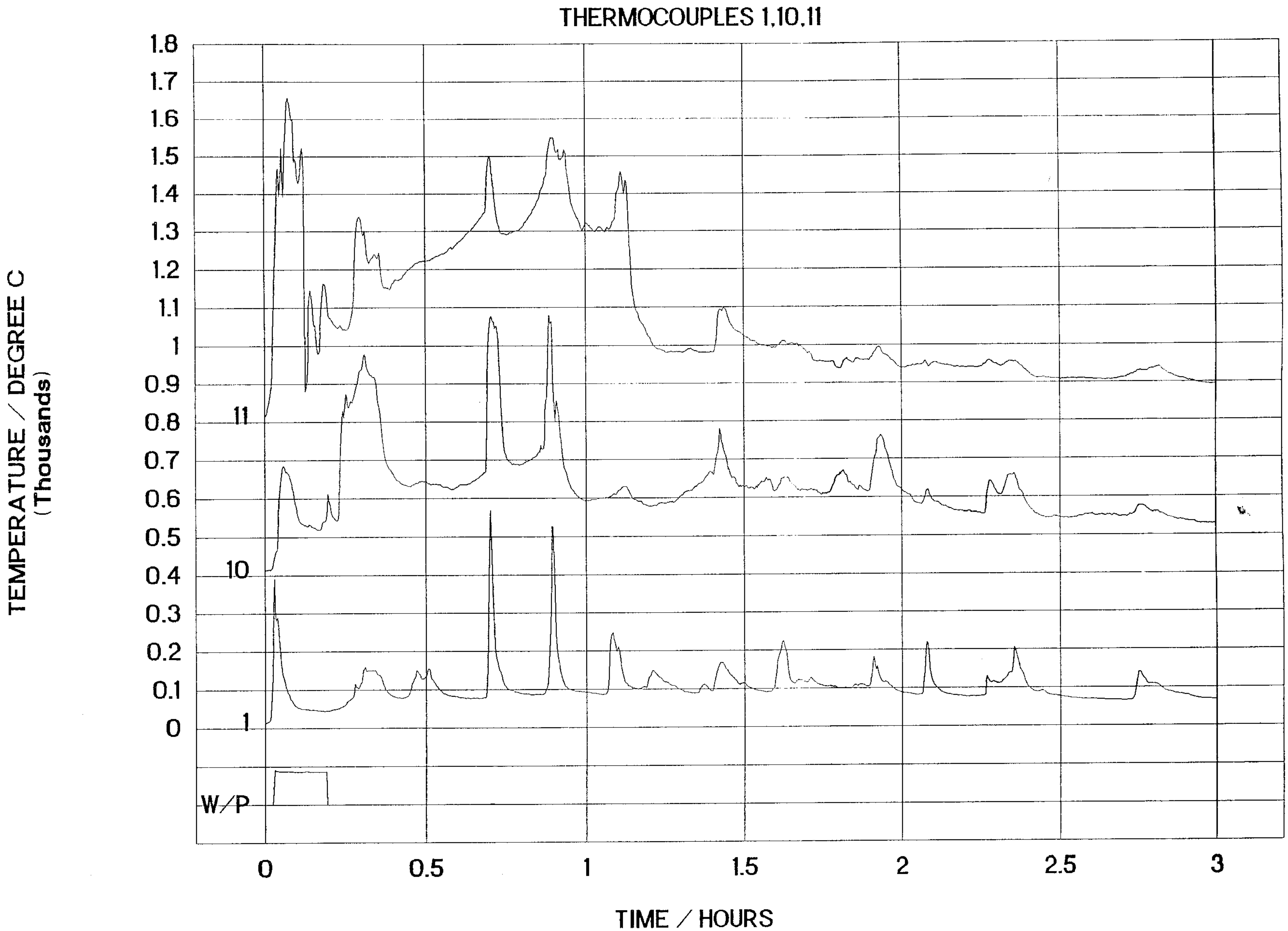


FIGURE 4.10: CAA CARGO BAY TEST NUMBER 3

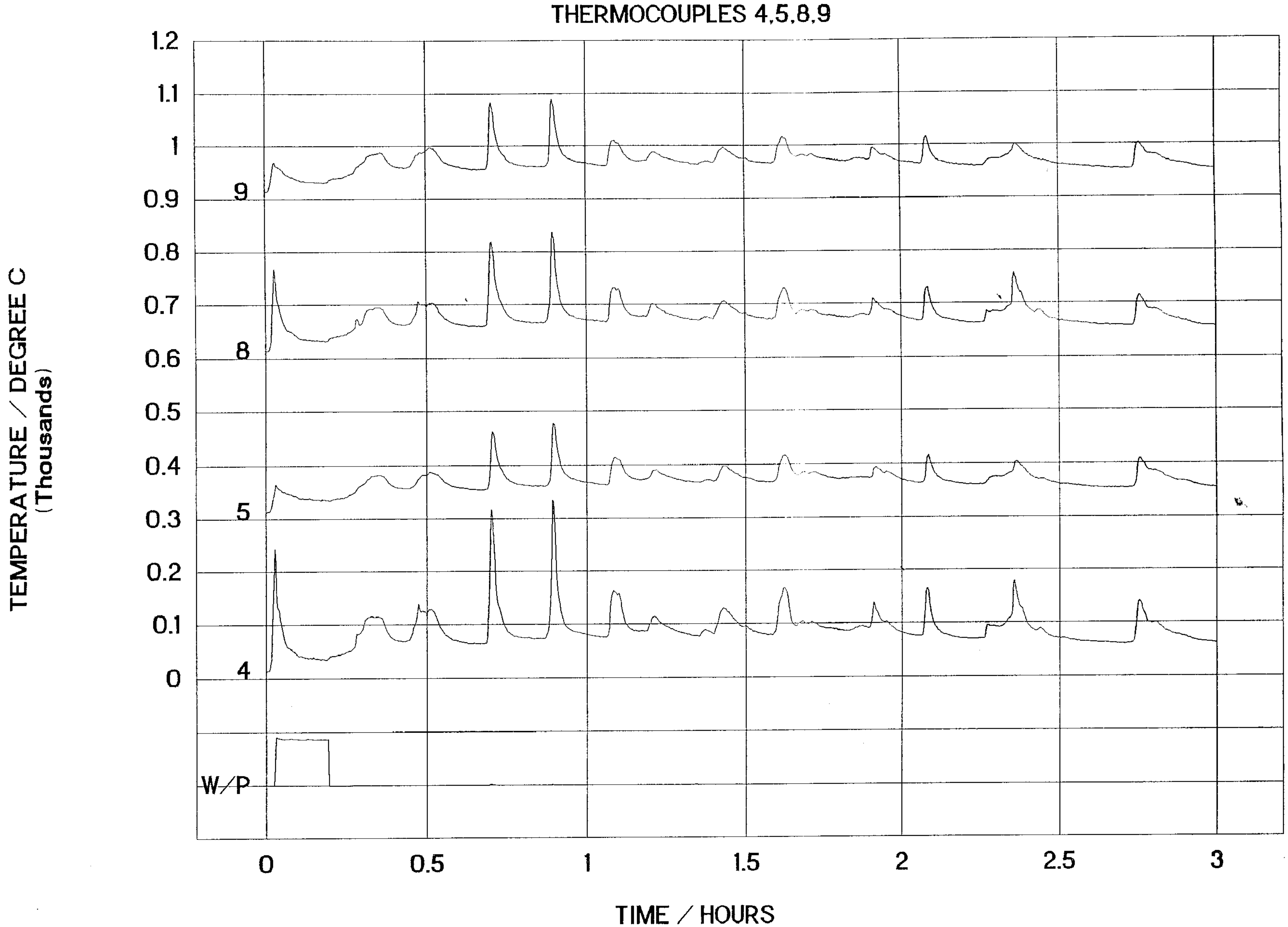


FIGURE 4.11: CAA CARGO BAY TEST NUMBER 3

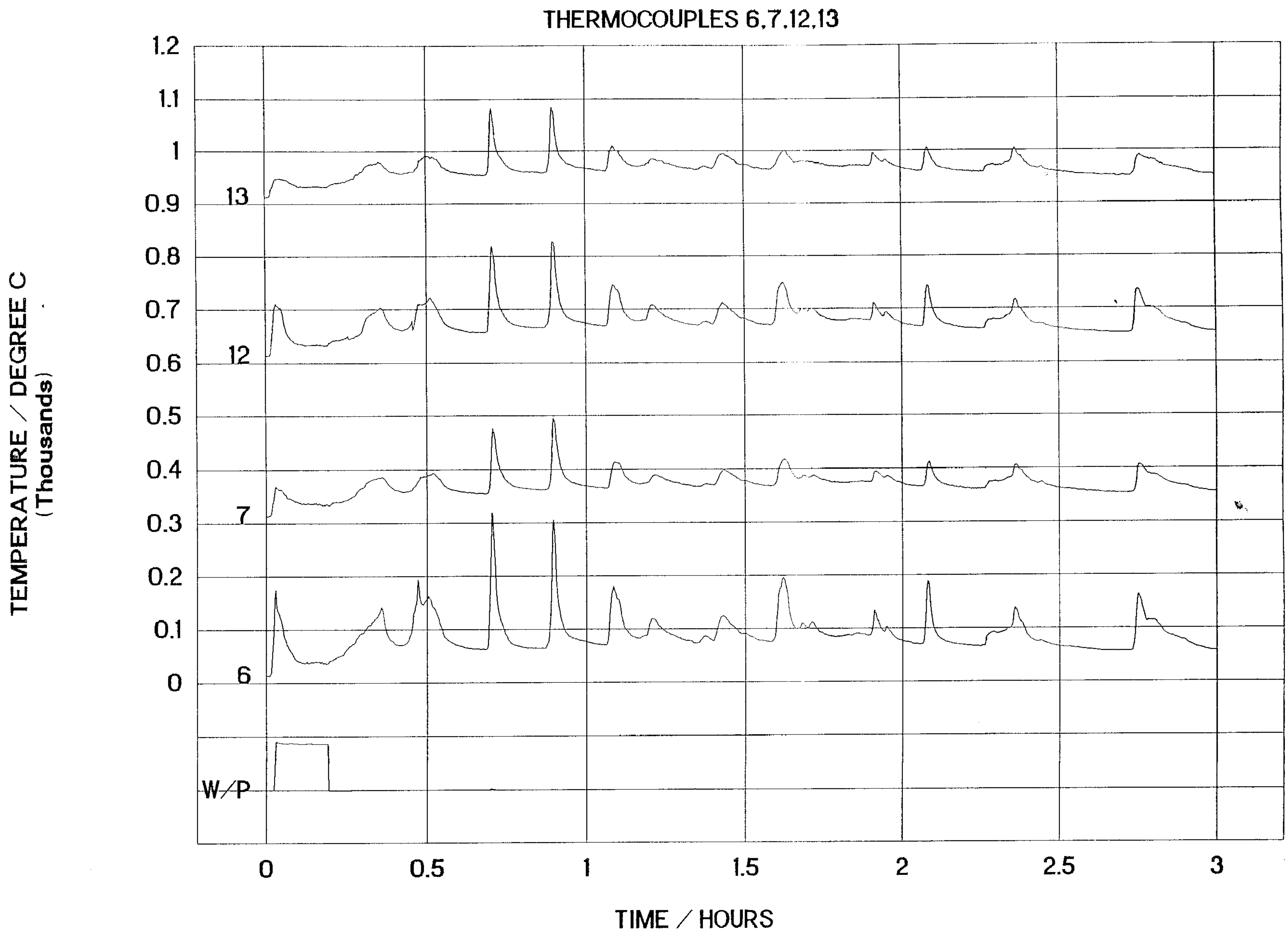


FIGURE 4.12: CAA CARGO BAY TEST NUMBER 3

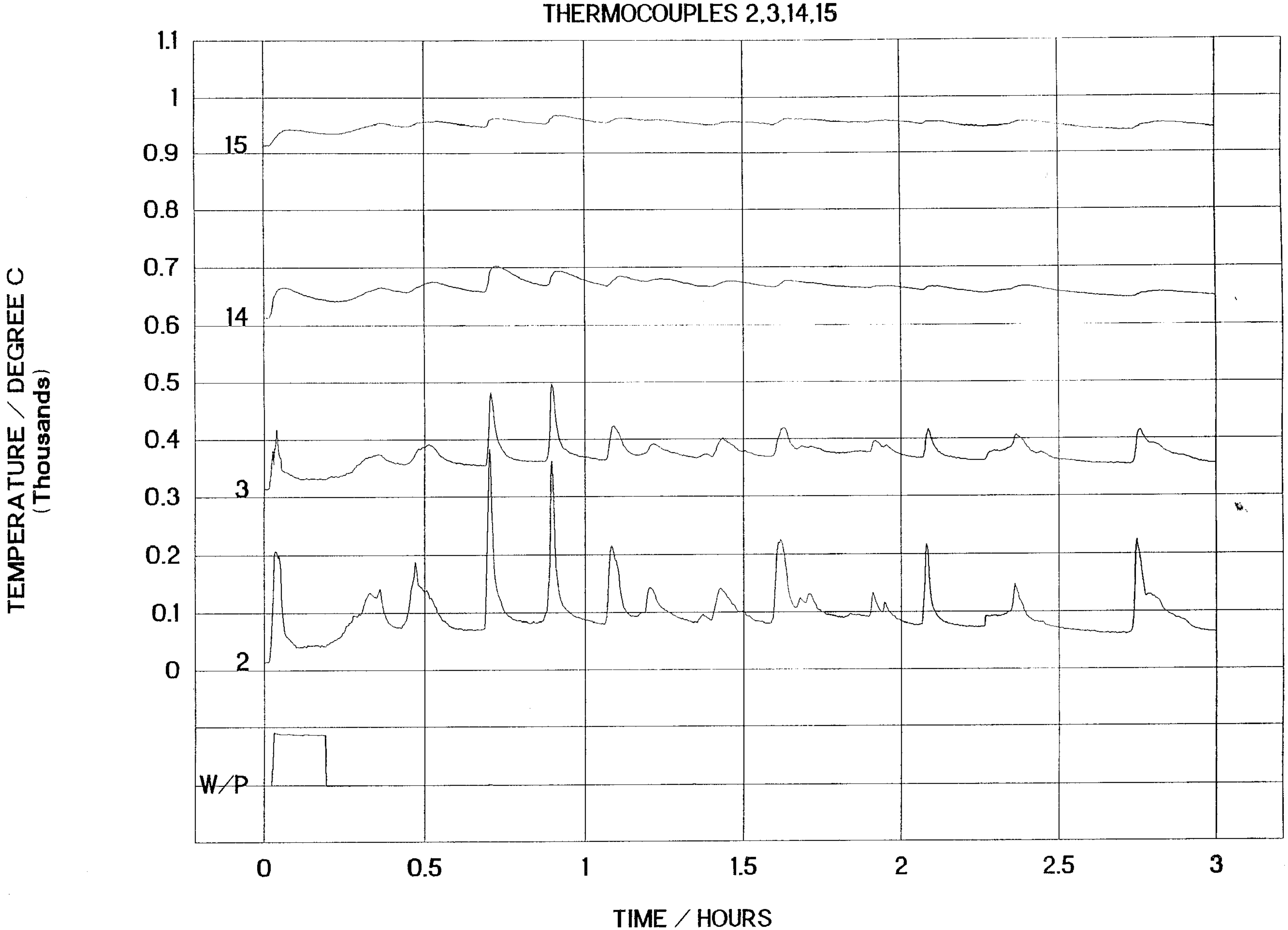


FIGURE 4.13: CAA CARGO BAY TEST NUMBER 4

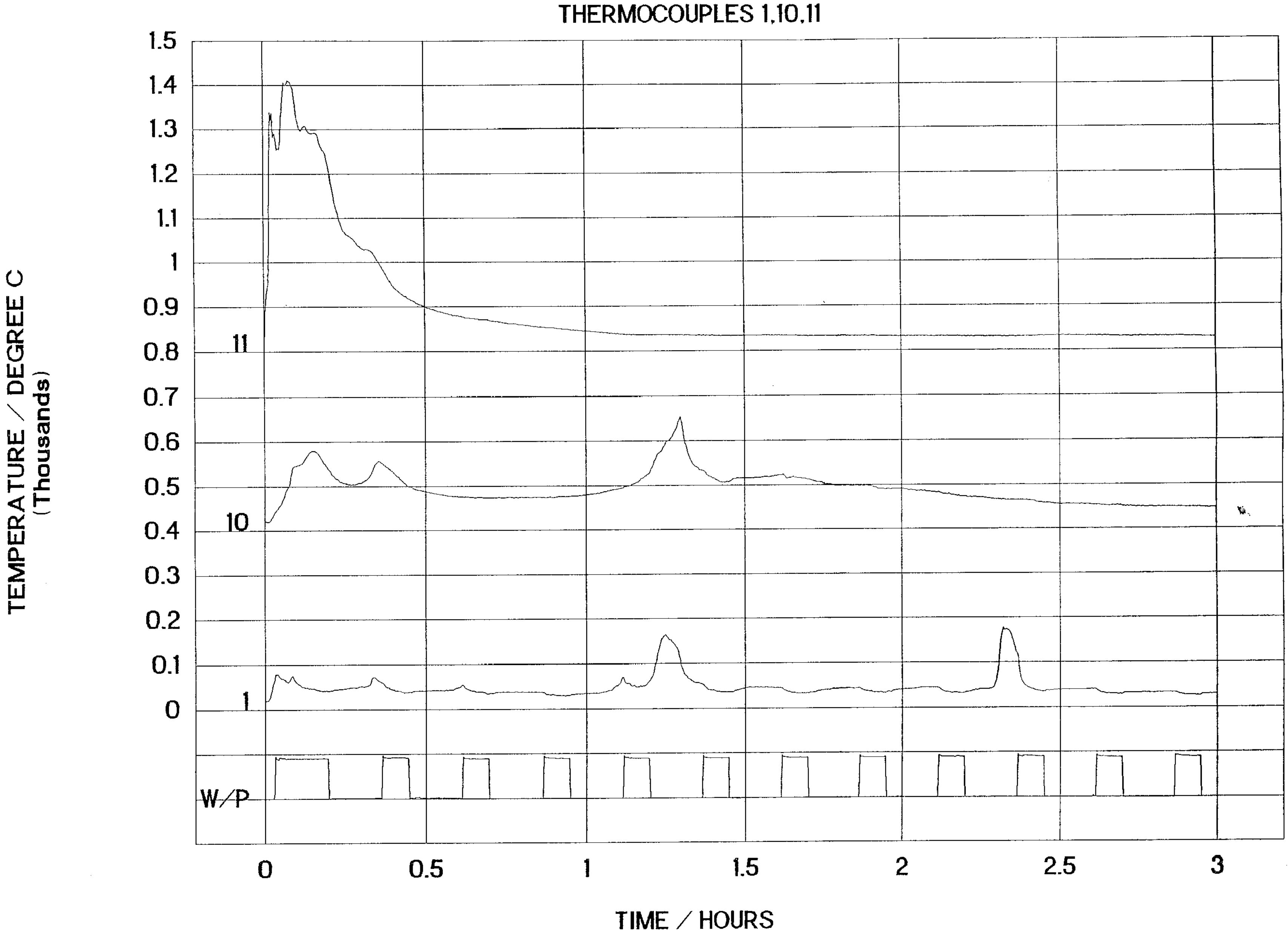


FIGURE 4.14: CAA CARGO BAY TEST NUMBER 4

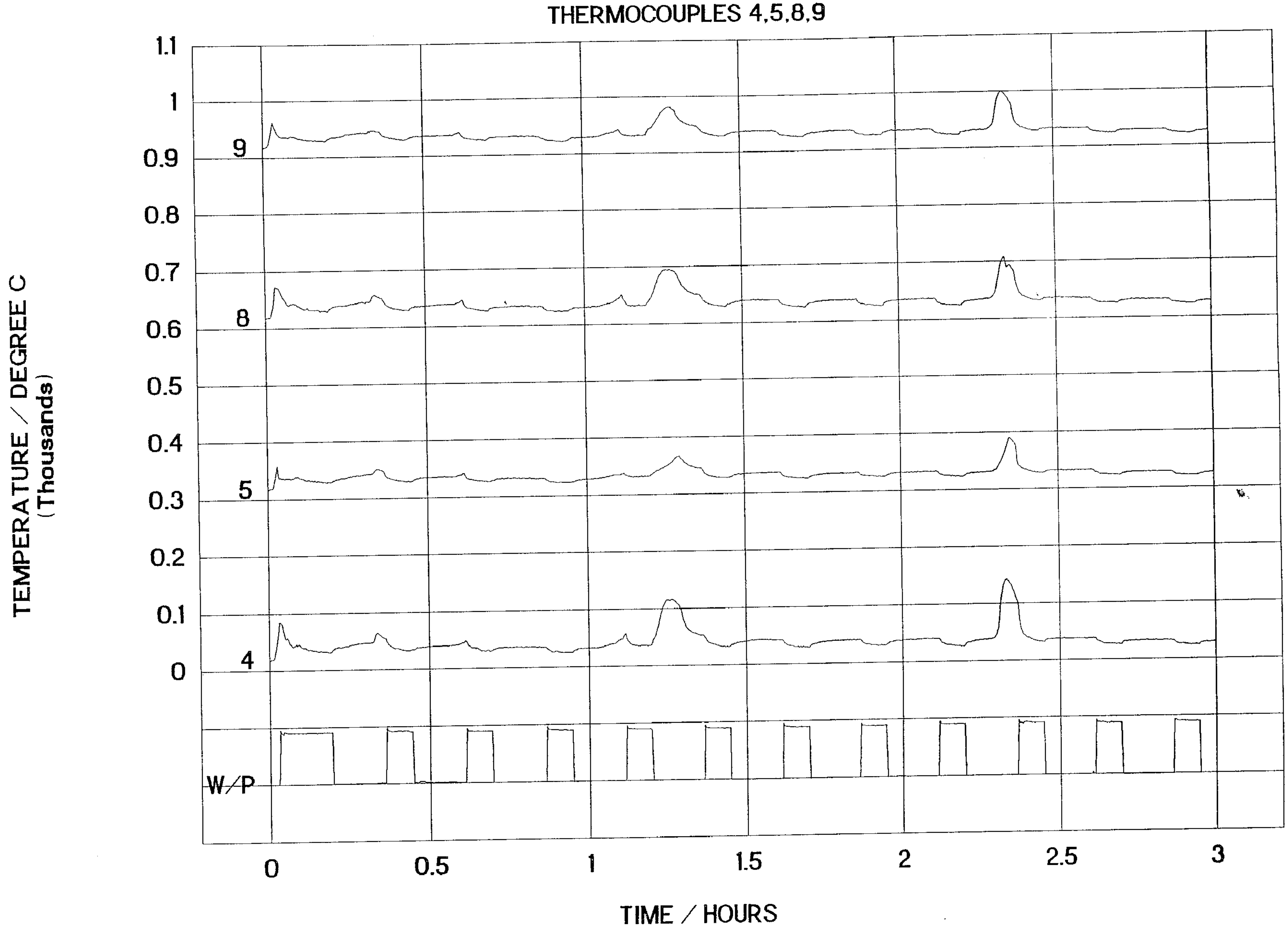


FIGURE 4.15: CAA CARGO BAY TEST NUMBER 4

THERMOCOUPLES 6,7,12,13

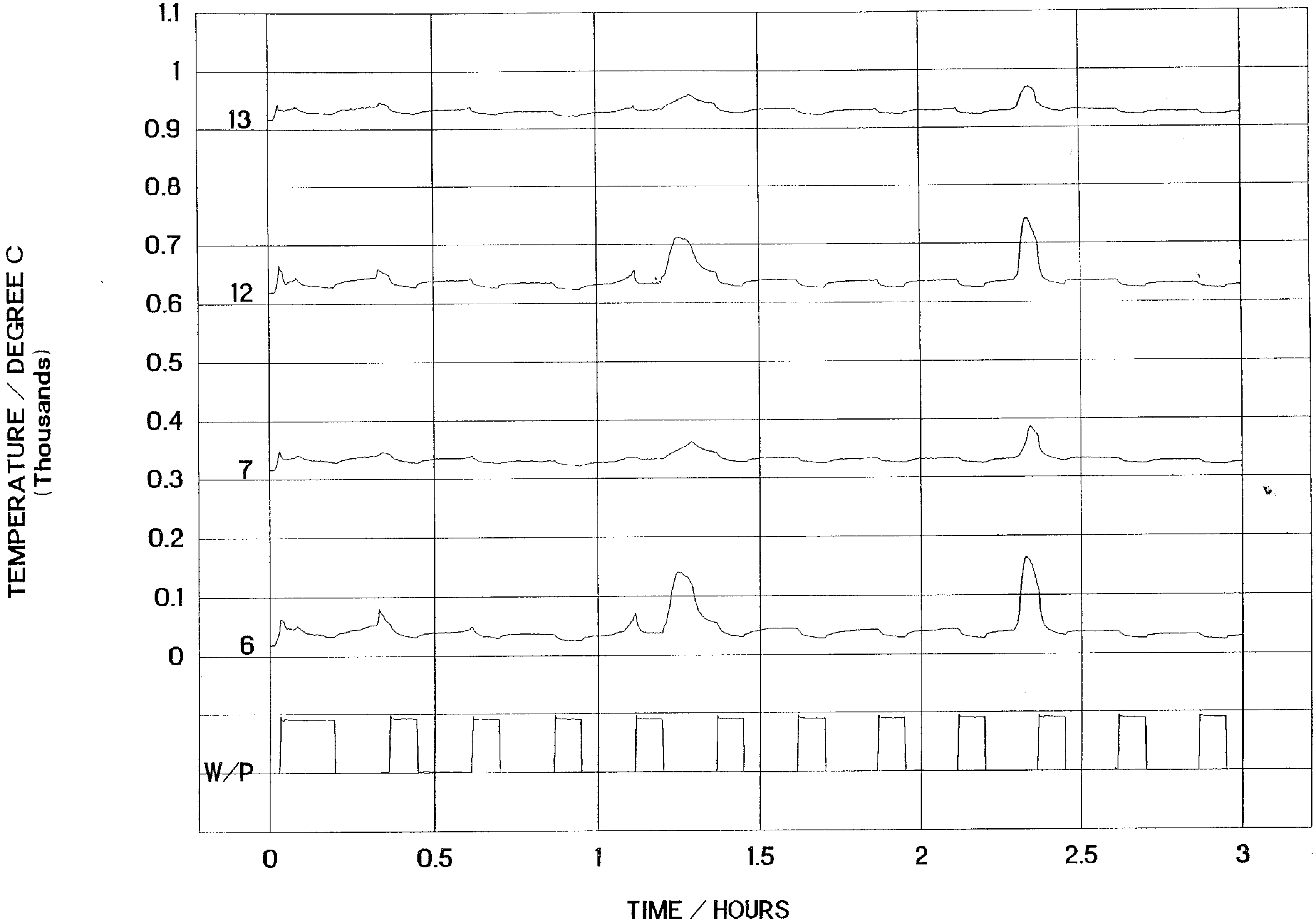


FIGURE 4.16: CAA CARGO BAY TEST NUMBER 4

THERMOCOUPLES 2,3,14,15

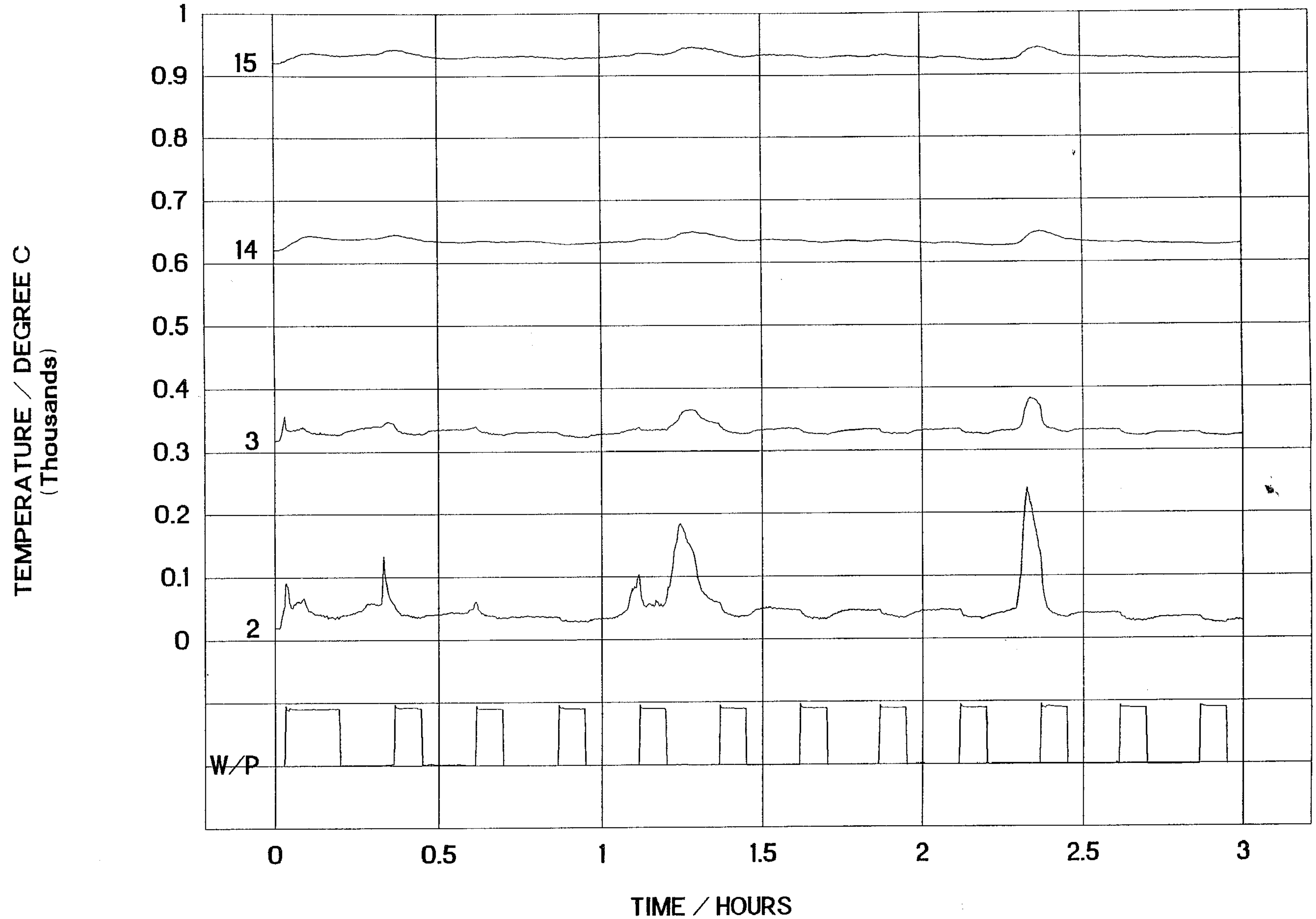


FIGURE 4.17: CAA CARGO BAY TEST NUMBER 5

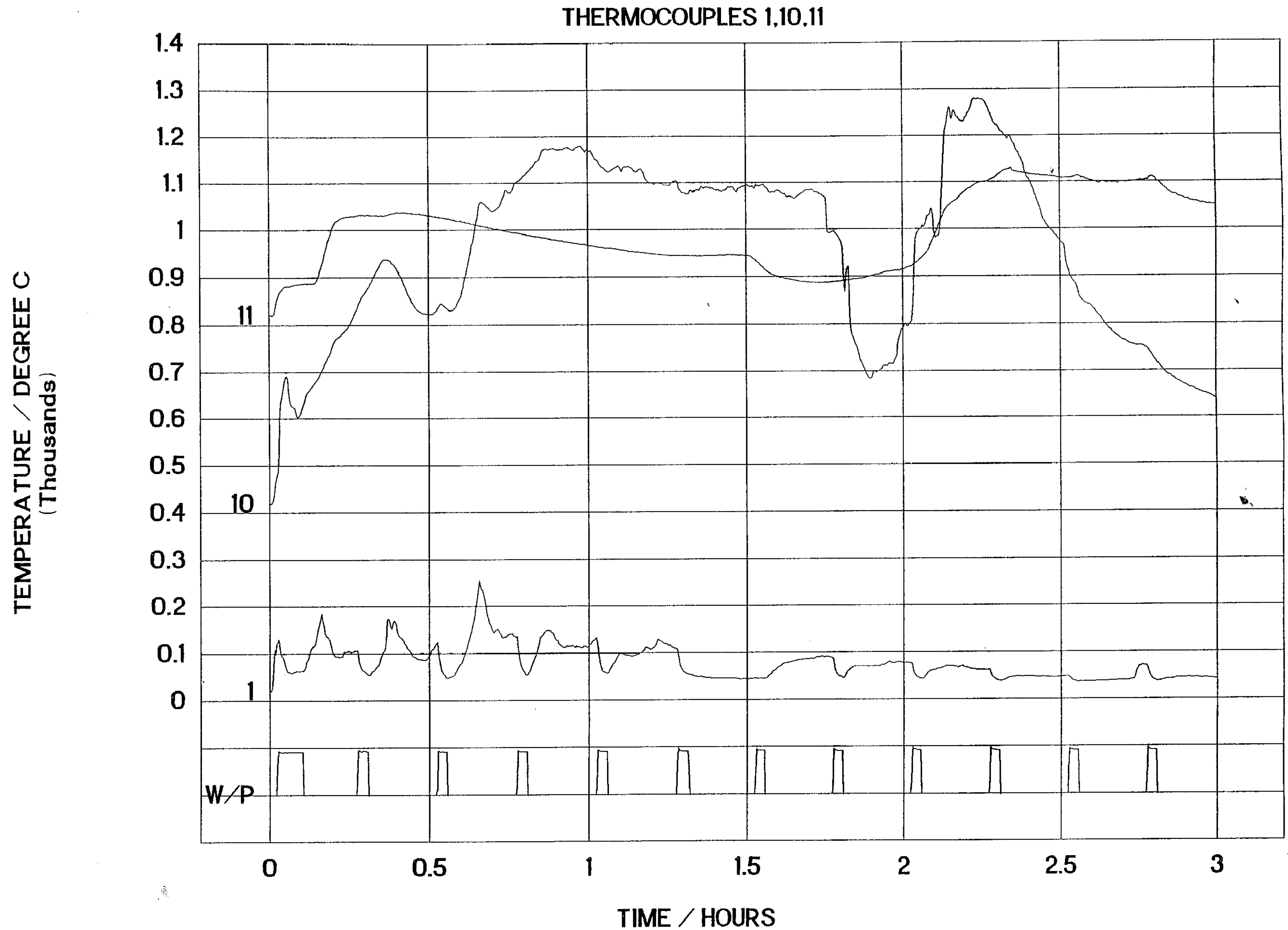


FIGURE 4.18: CAA CARGO BAY TEST NUMBER 5

THERMOCOUPLES 4,5,8,9

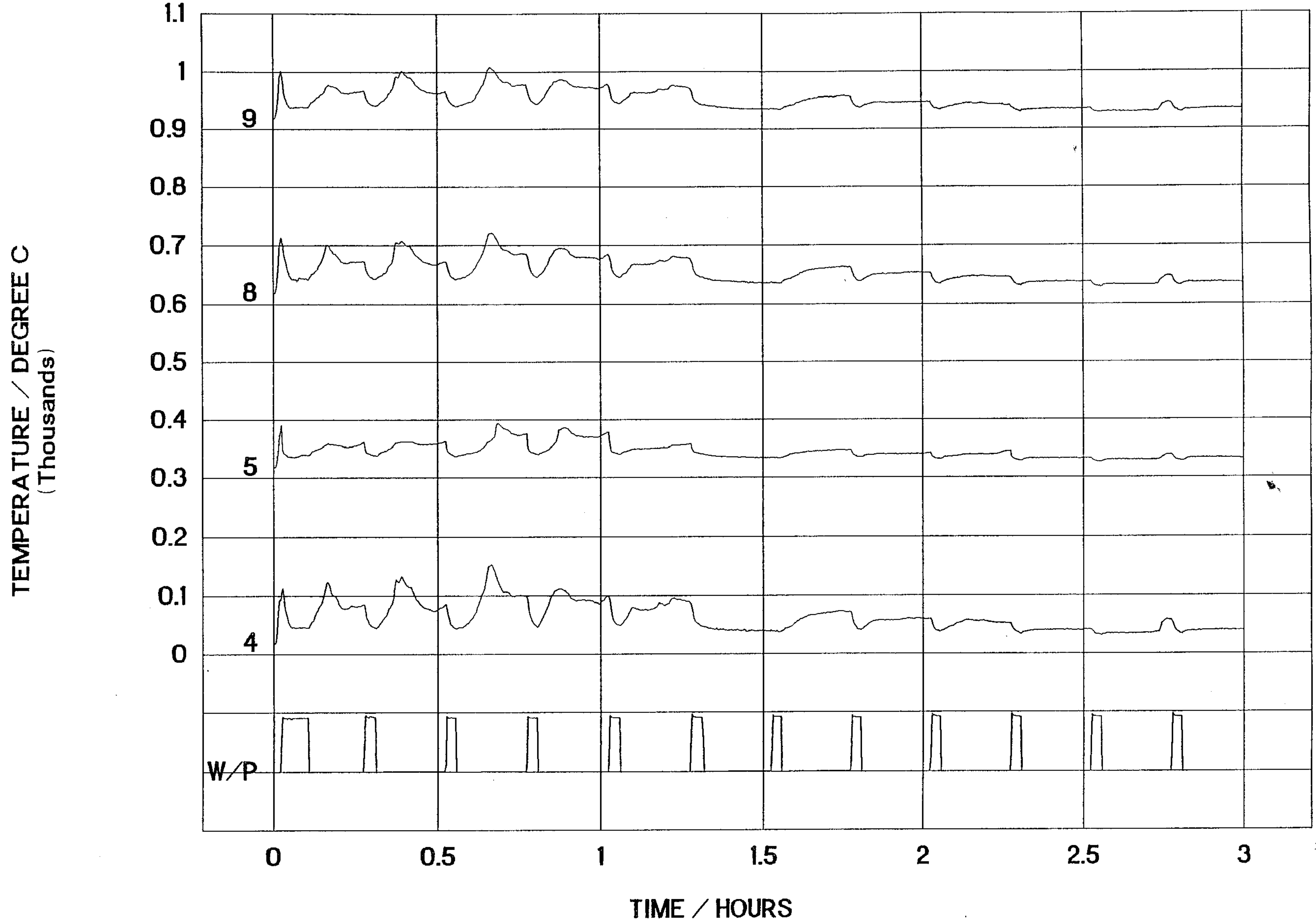


FIGURE 4.19: CAA CARGO BAY TEST NUMBER 5

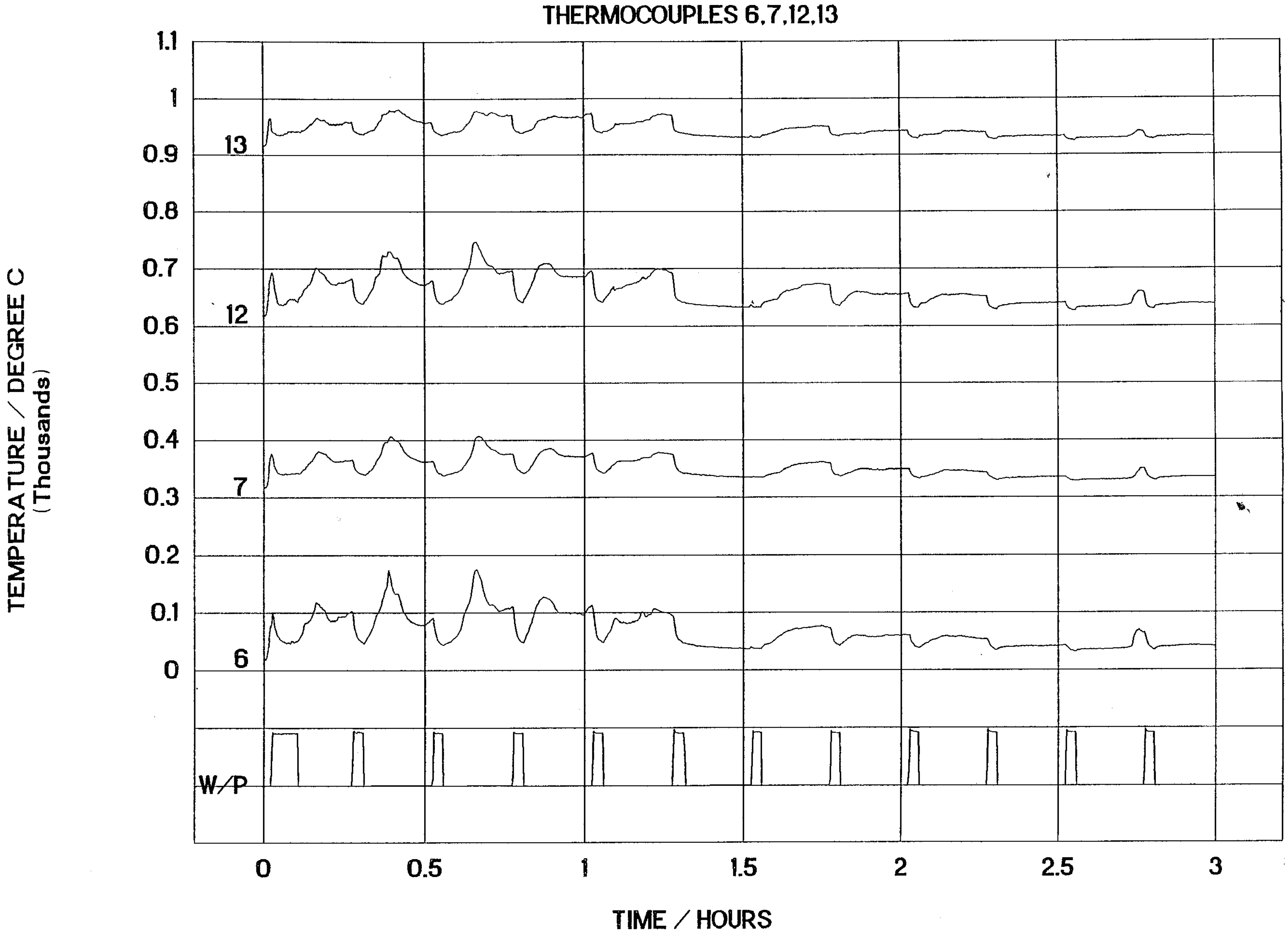


FIGURE 4.20: CAA CARGO BAY TEST NUMBER 5

THERMOCOUPLES 2,3,14,15

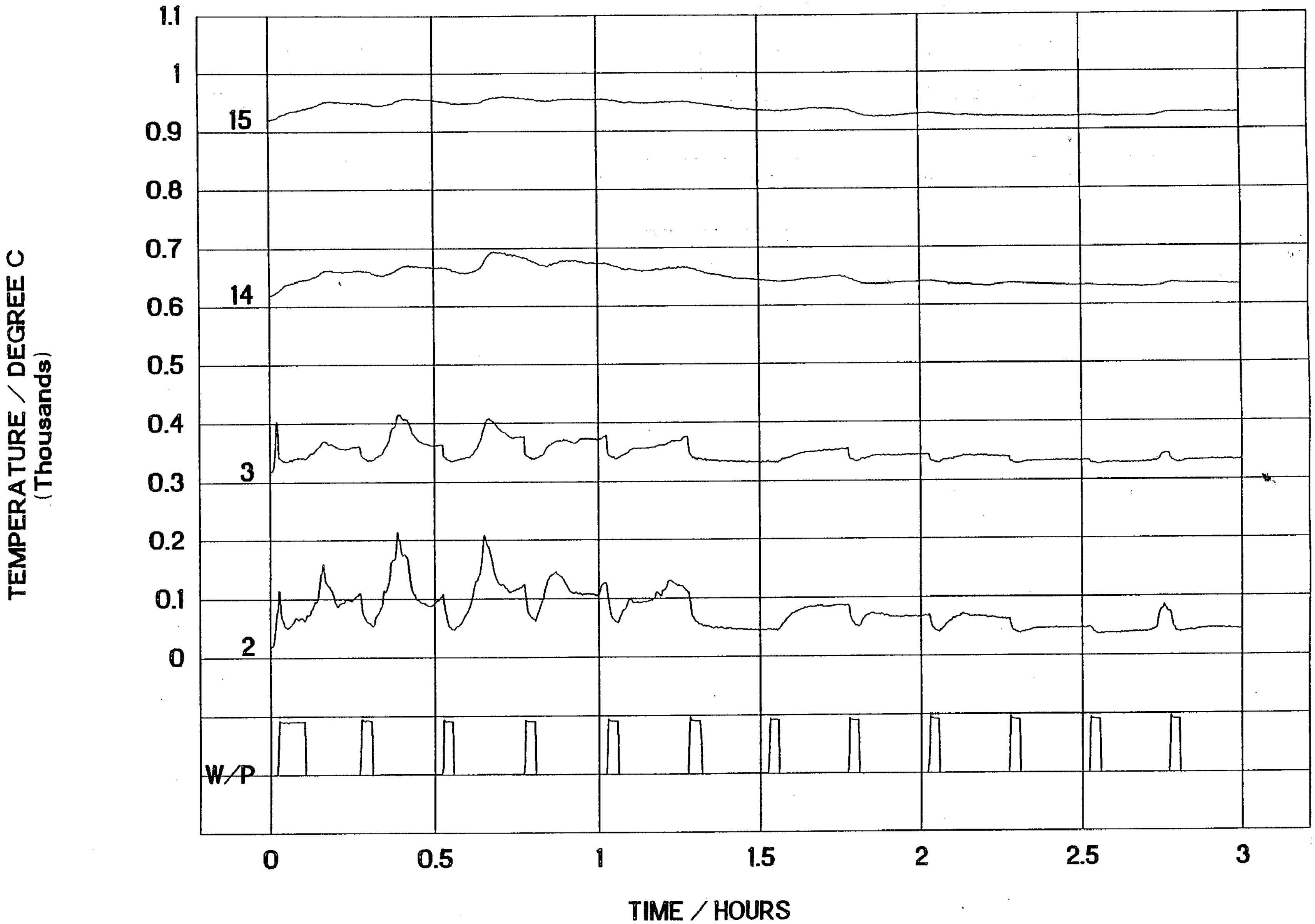


FIGURE 4.21: CAA CARGO BAY TEST NUMBER 6

THERMOCOUPLES 1,10,11

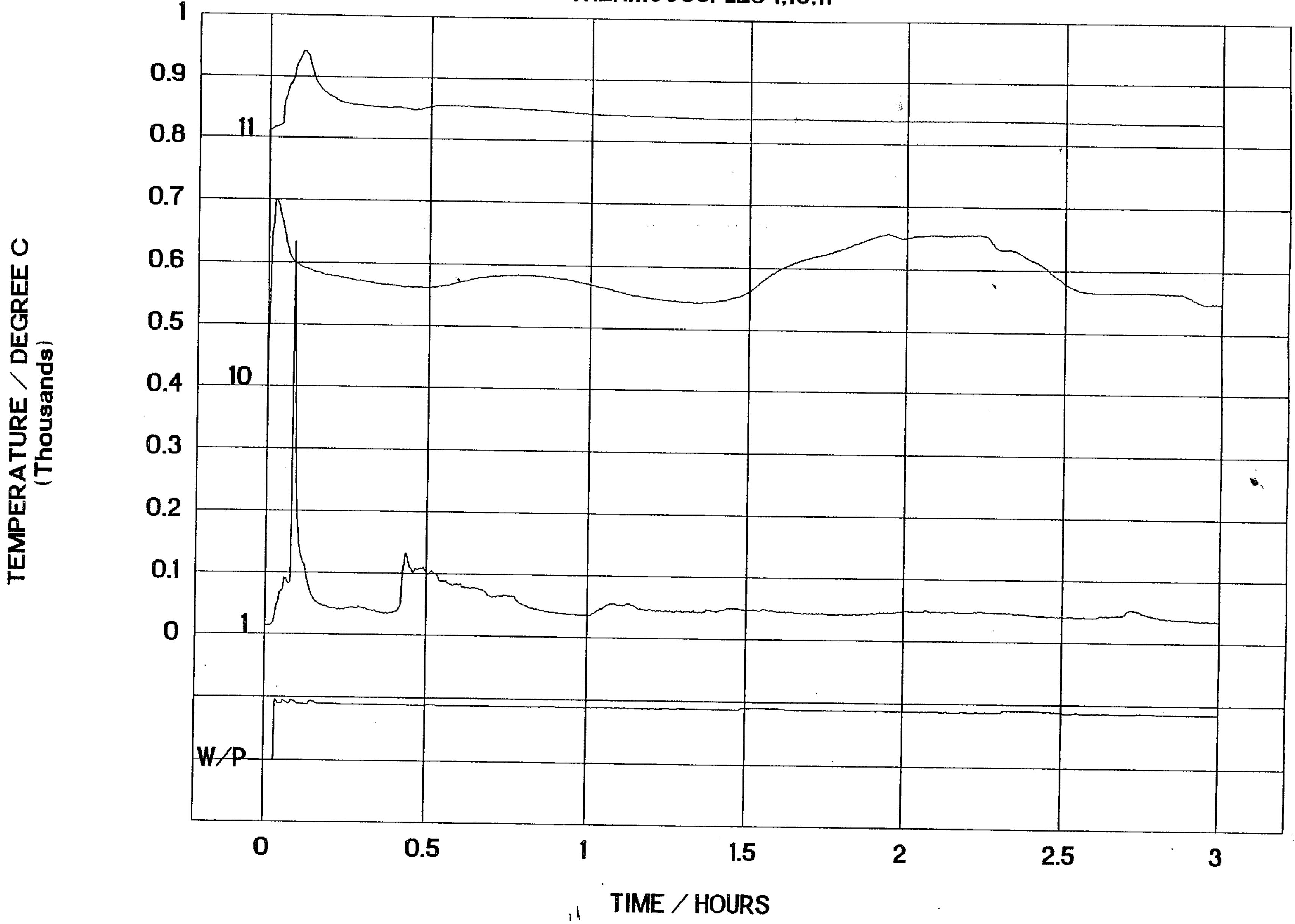


FIGURE 4.22: CAA CARGO BAY TEST NUMBER 6

THERMOCOUPLES 4,5,8,9

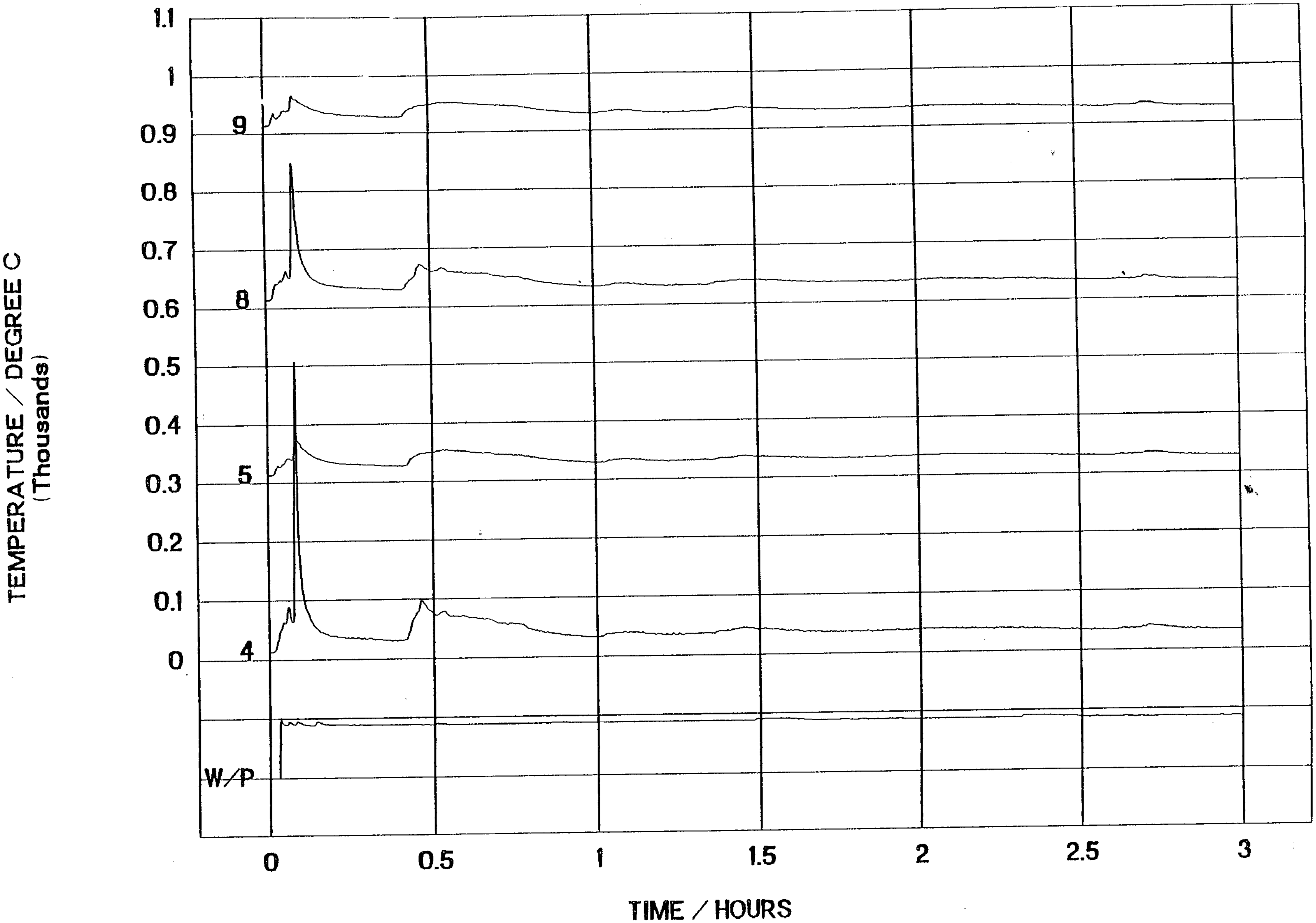


FIGURE 4.23: CAA CARGO BAY TEST NUMBER 6

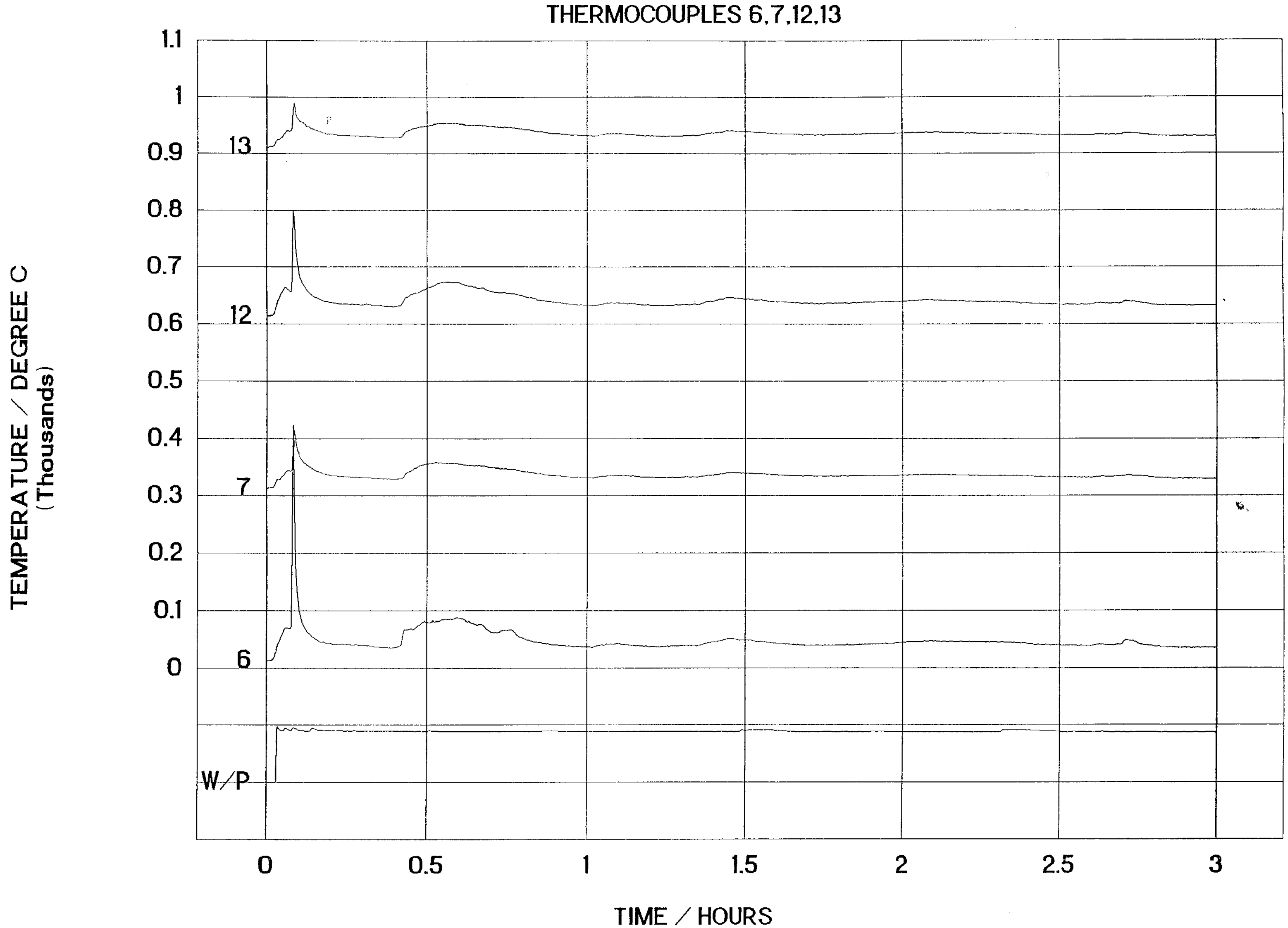


FIGURE 4.24: CAA CARGO BAY TEST NUMBER 6

THERMOCOUPLES 2,3,14,15

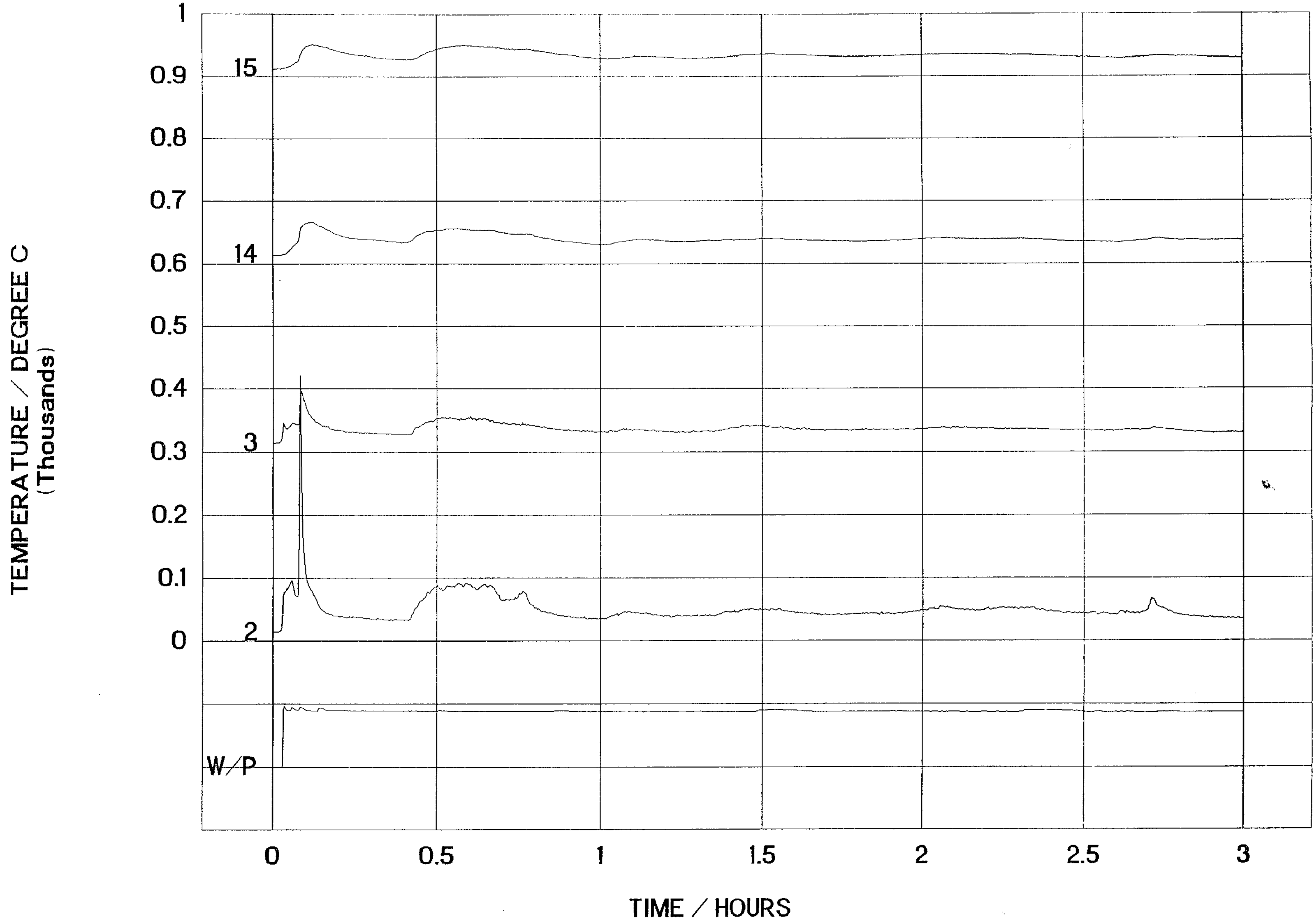


FIGURE 4.25: CAA CARGO BAY TEST NUMBER 7

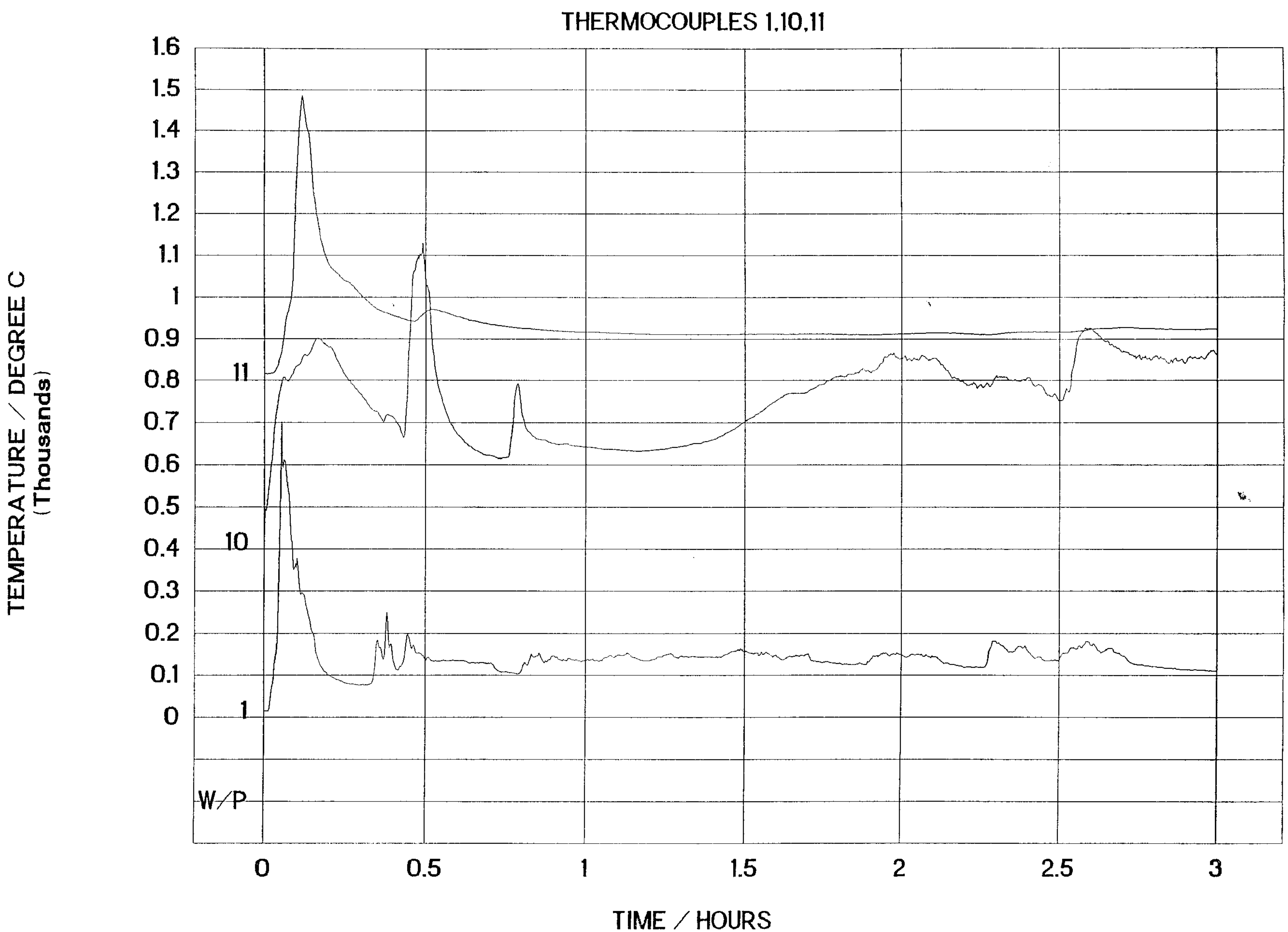


FIGURE 4.26: CAA CARGO BAY TEST NUMBER 7

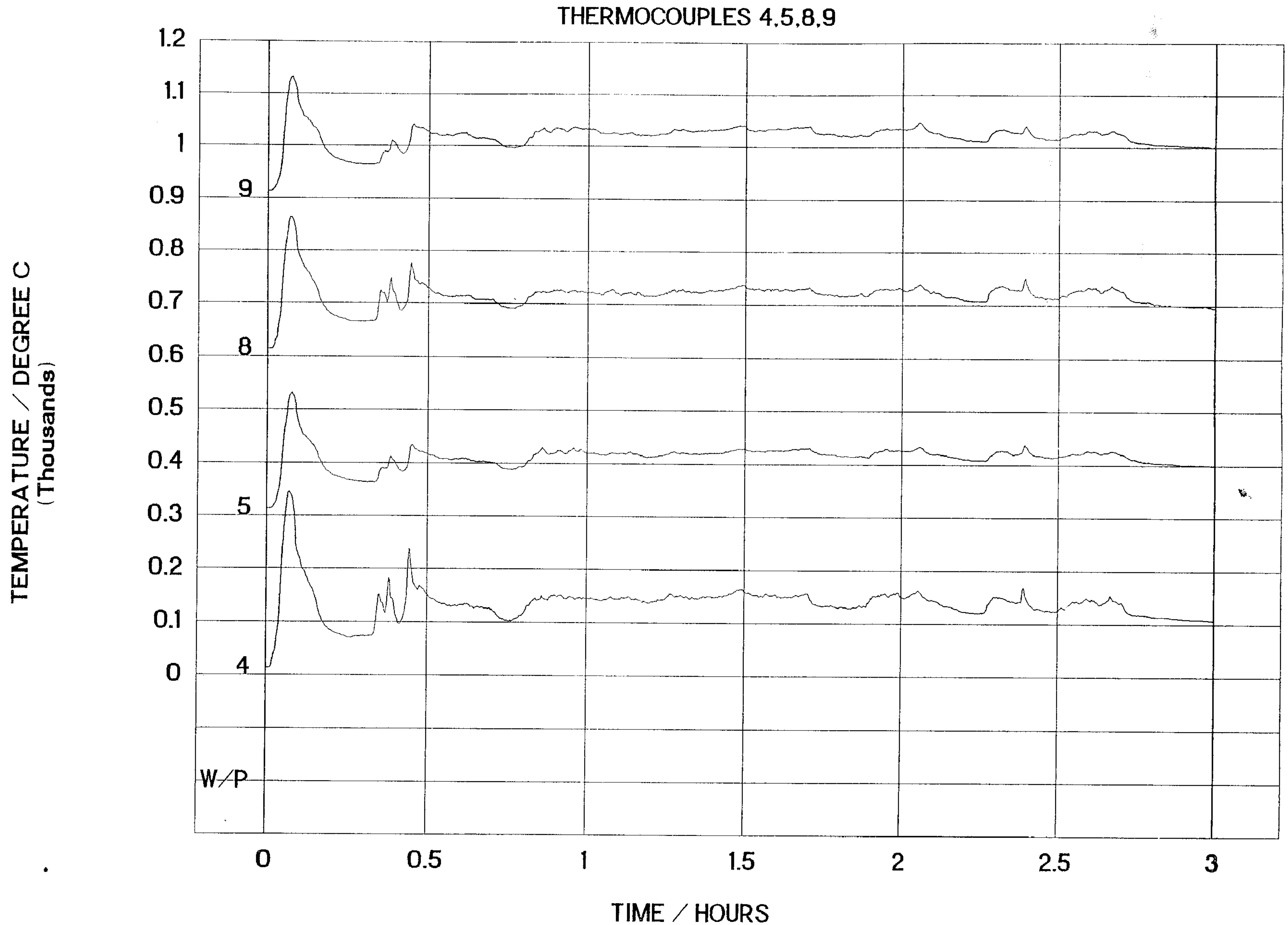


FIGURE 4.27: CAA CARGO BAY TEST NUMBER 7

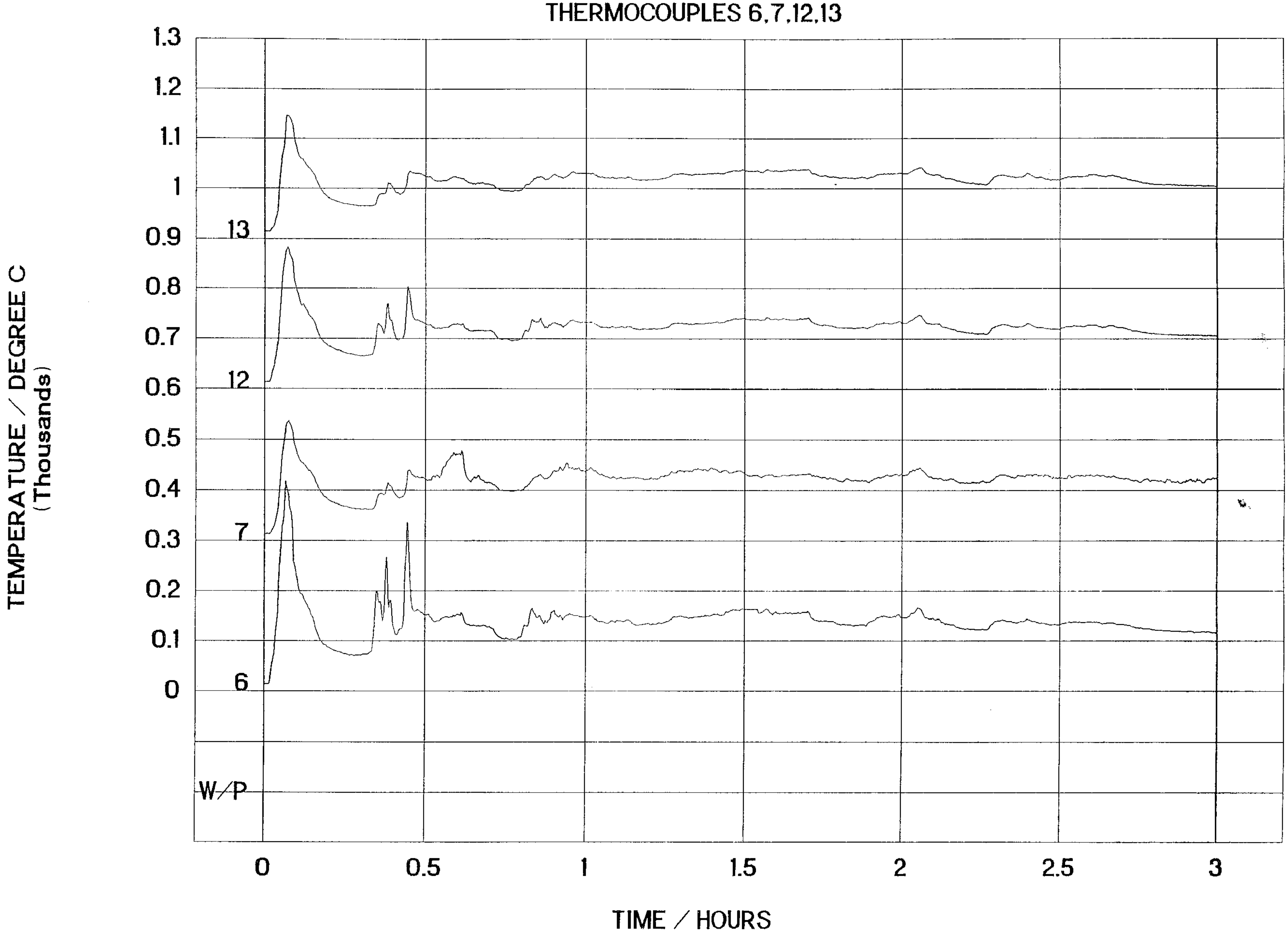


FIGURE 4.28: CAA CARGO BAY TEST NUMBER 7

THERMOCOUPLES 2,3,14,15

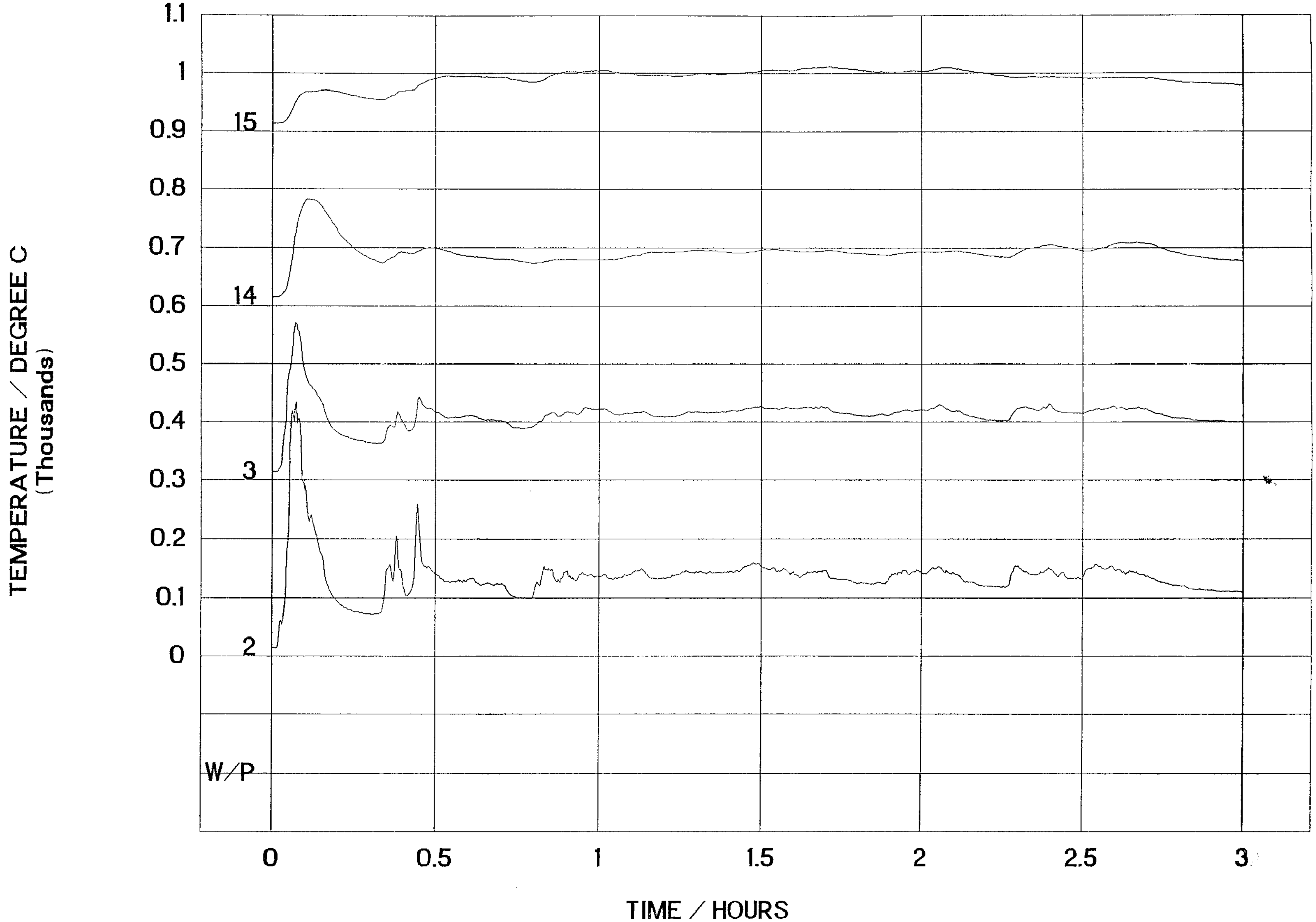


FIGURE 4.29: CAA CARGO BAY TEST NUMBER 8

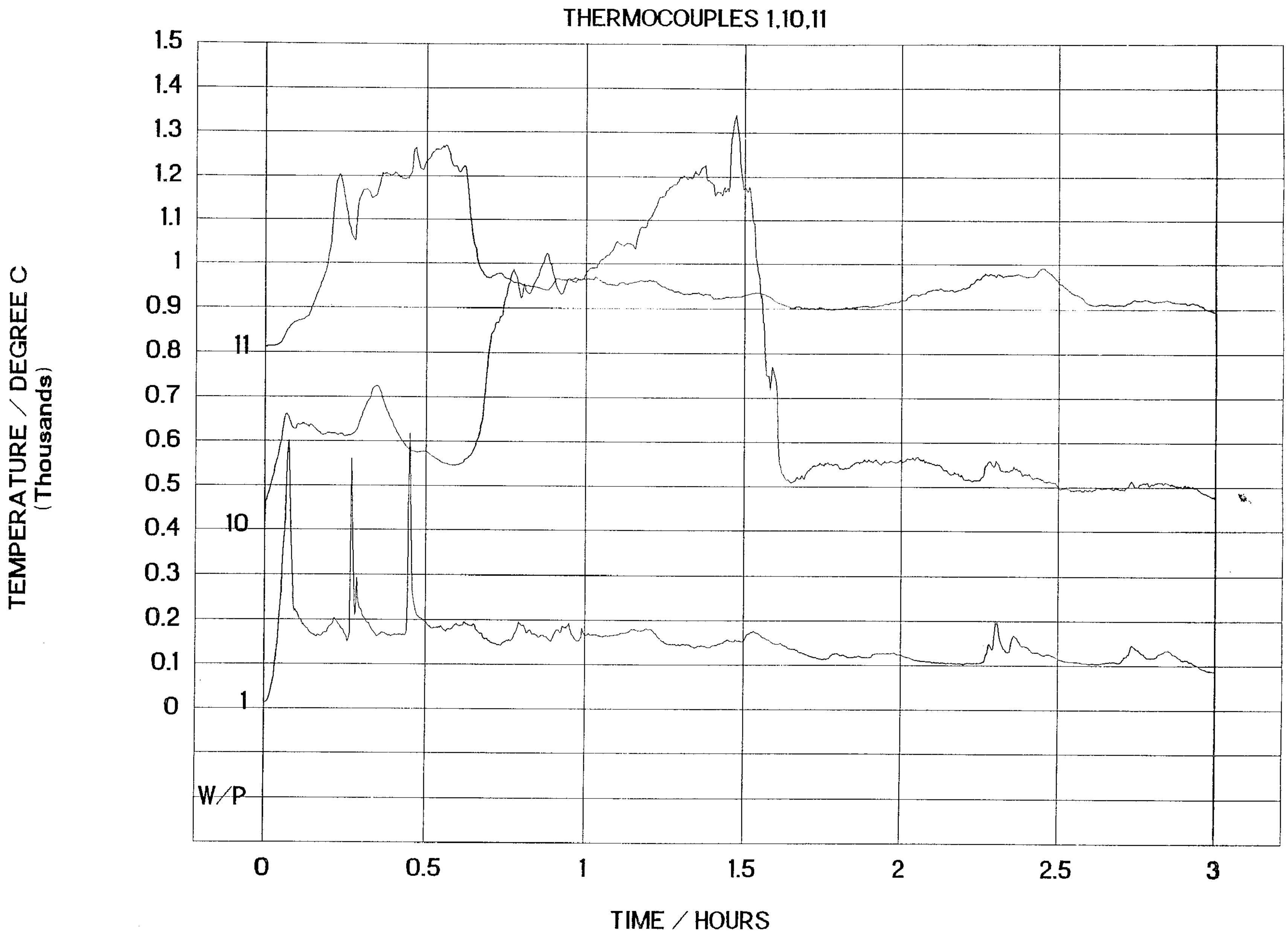


FIGURE 4.30: CAA CARGO BAY TEST NUMBER 8

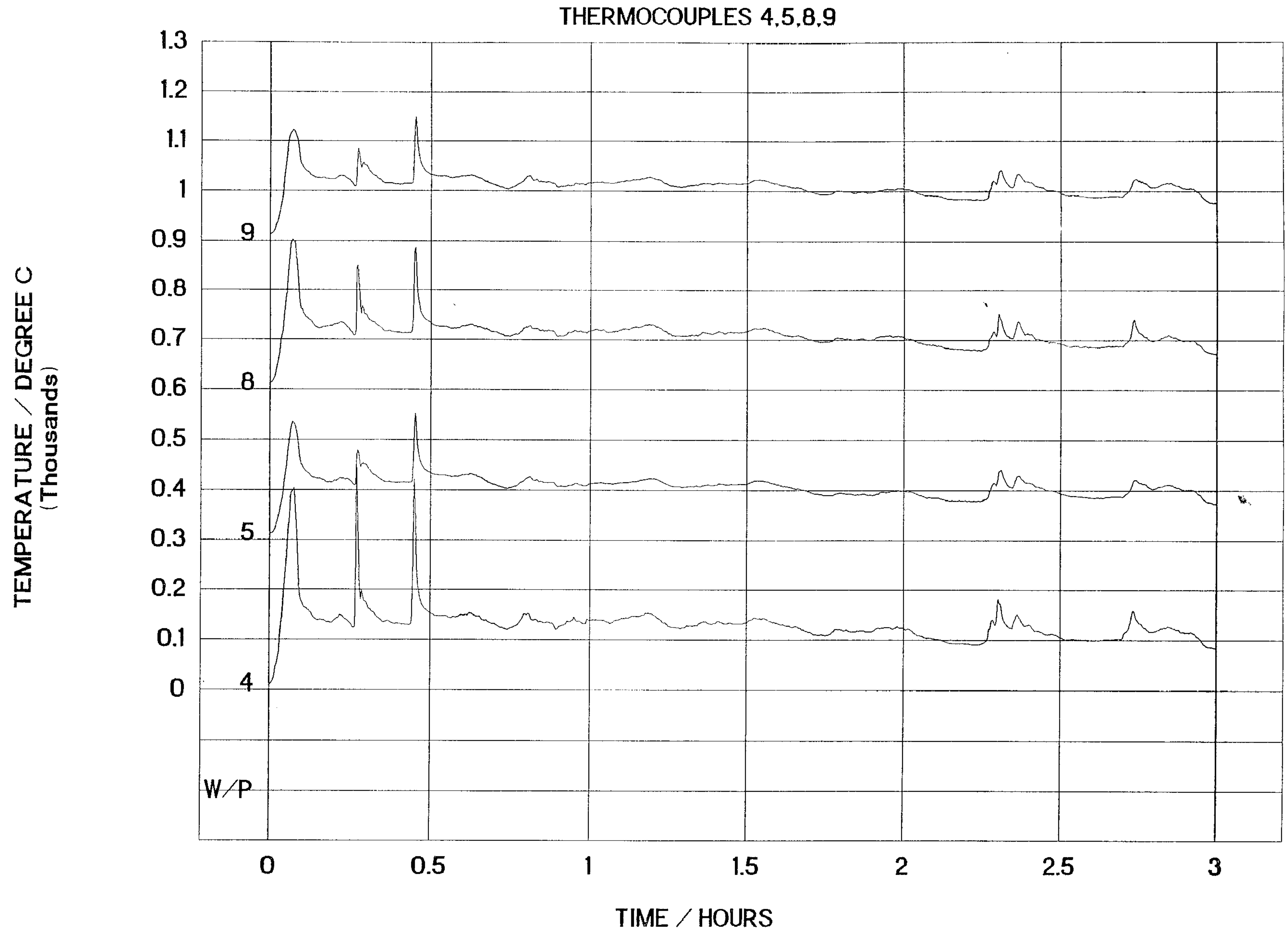


FIGURE 4.31: CAA CARGO BAY TEST NUMBER 8

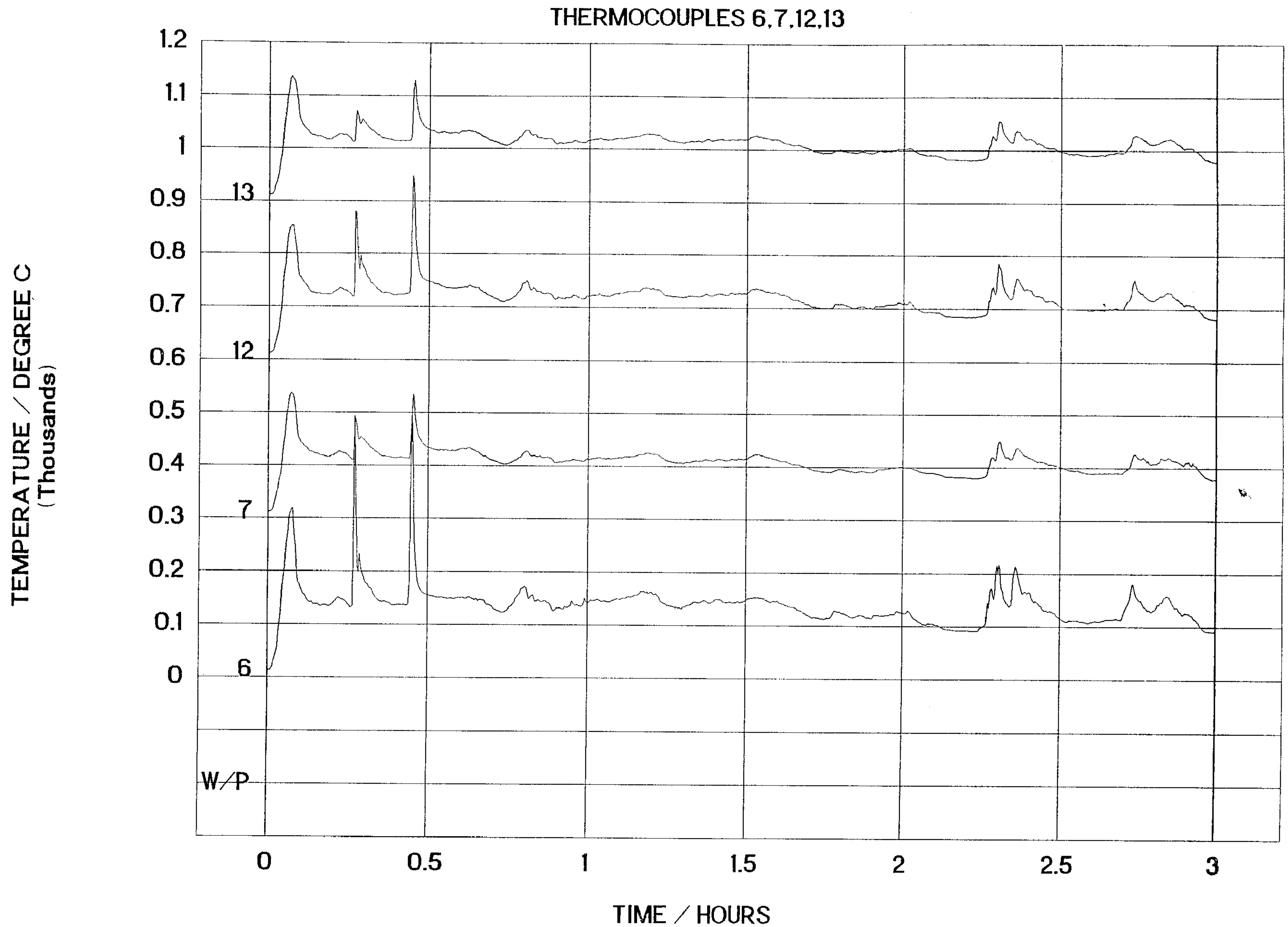


FIGURE 4.32: CAA CARGO BAY TEST NUMBER 8

THERMOCOUPLES 2,3,14,15

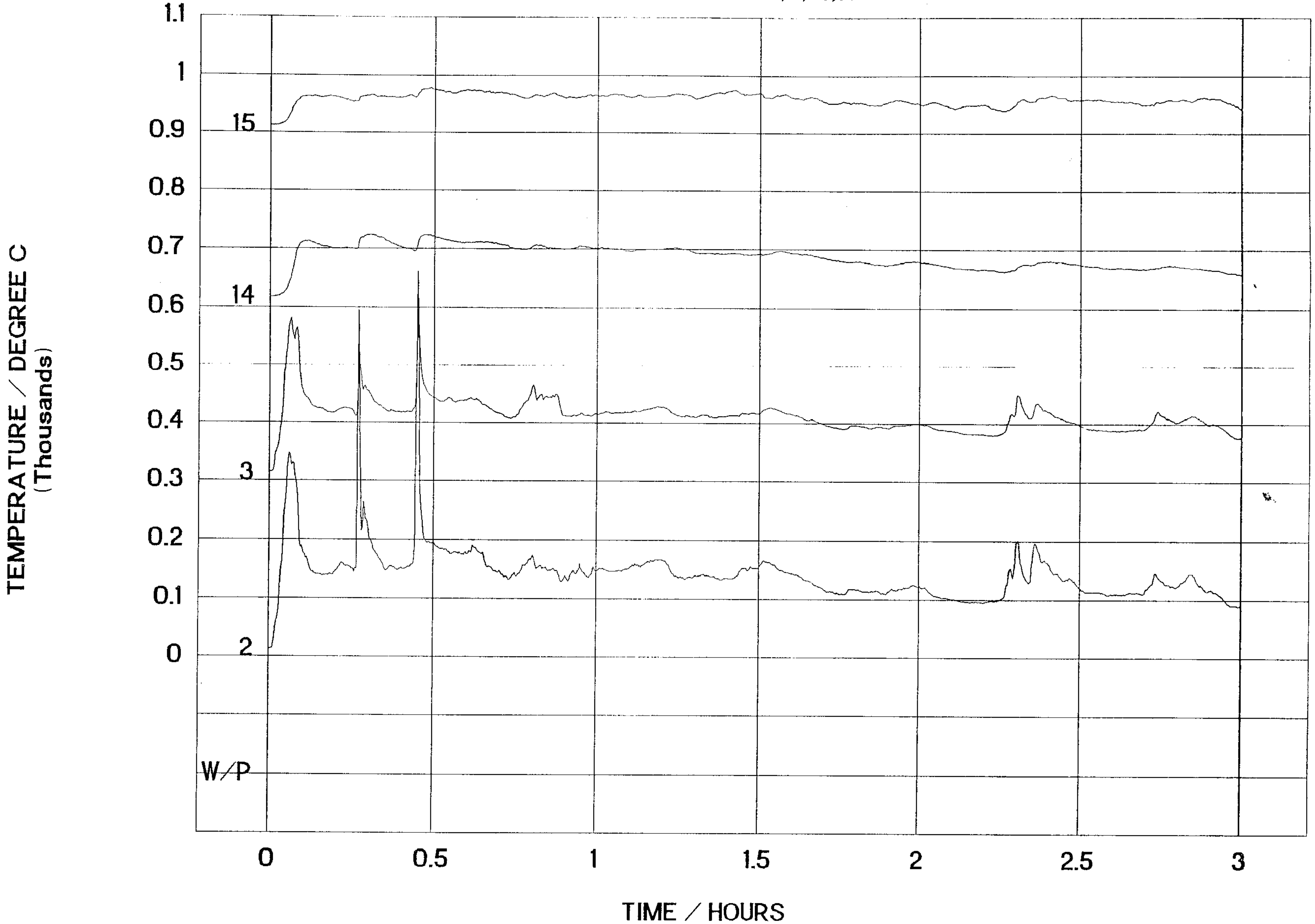


FIGURE 4.33: CAA CARGO BAY TEST NUMBER 9

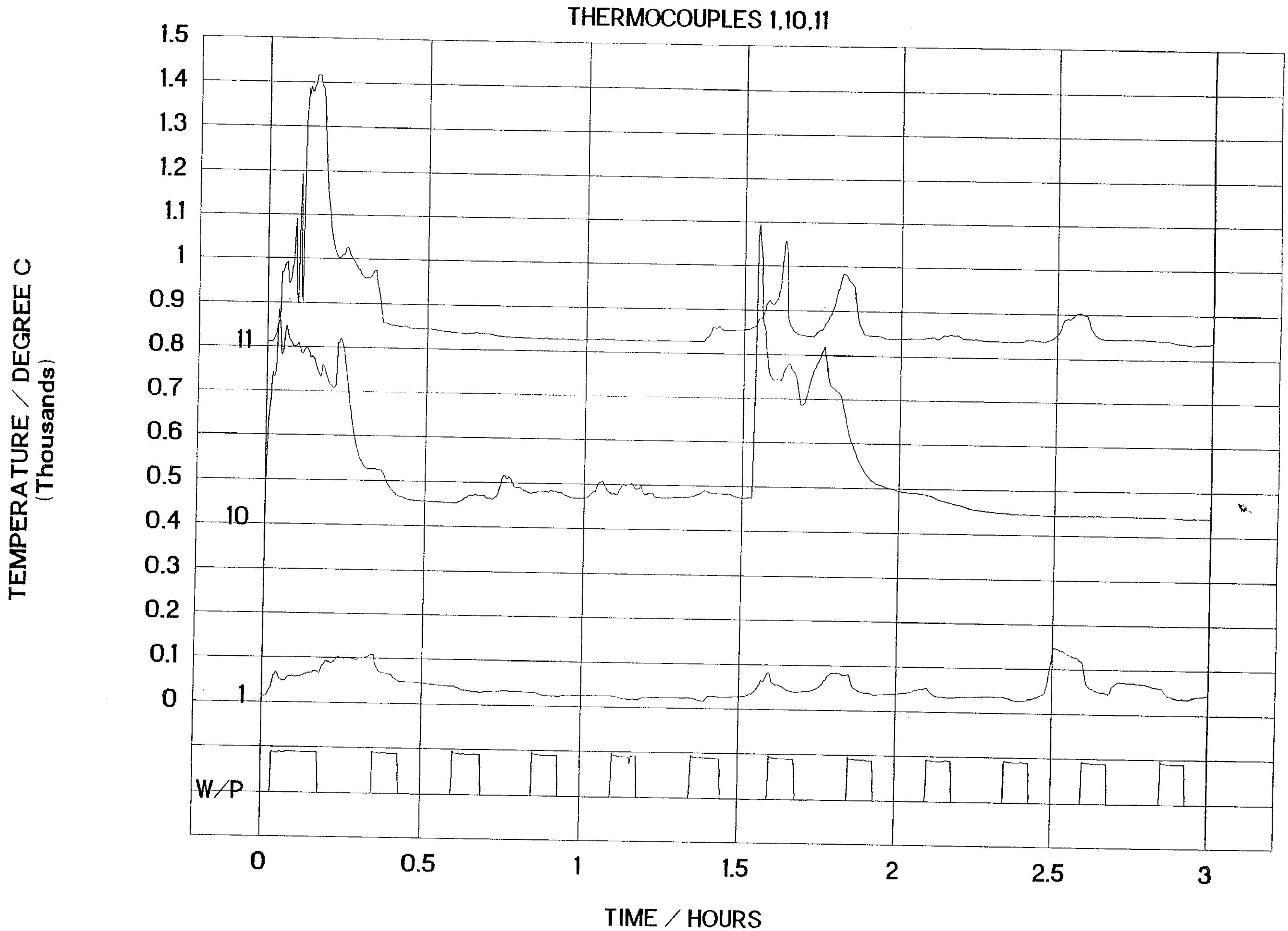


FIGURE 4.34: CAA CARGO BAY TEST NUMBER 9

THERMOCOUPLES 4,5,8,9

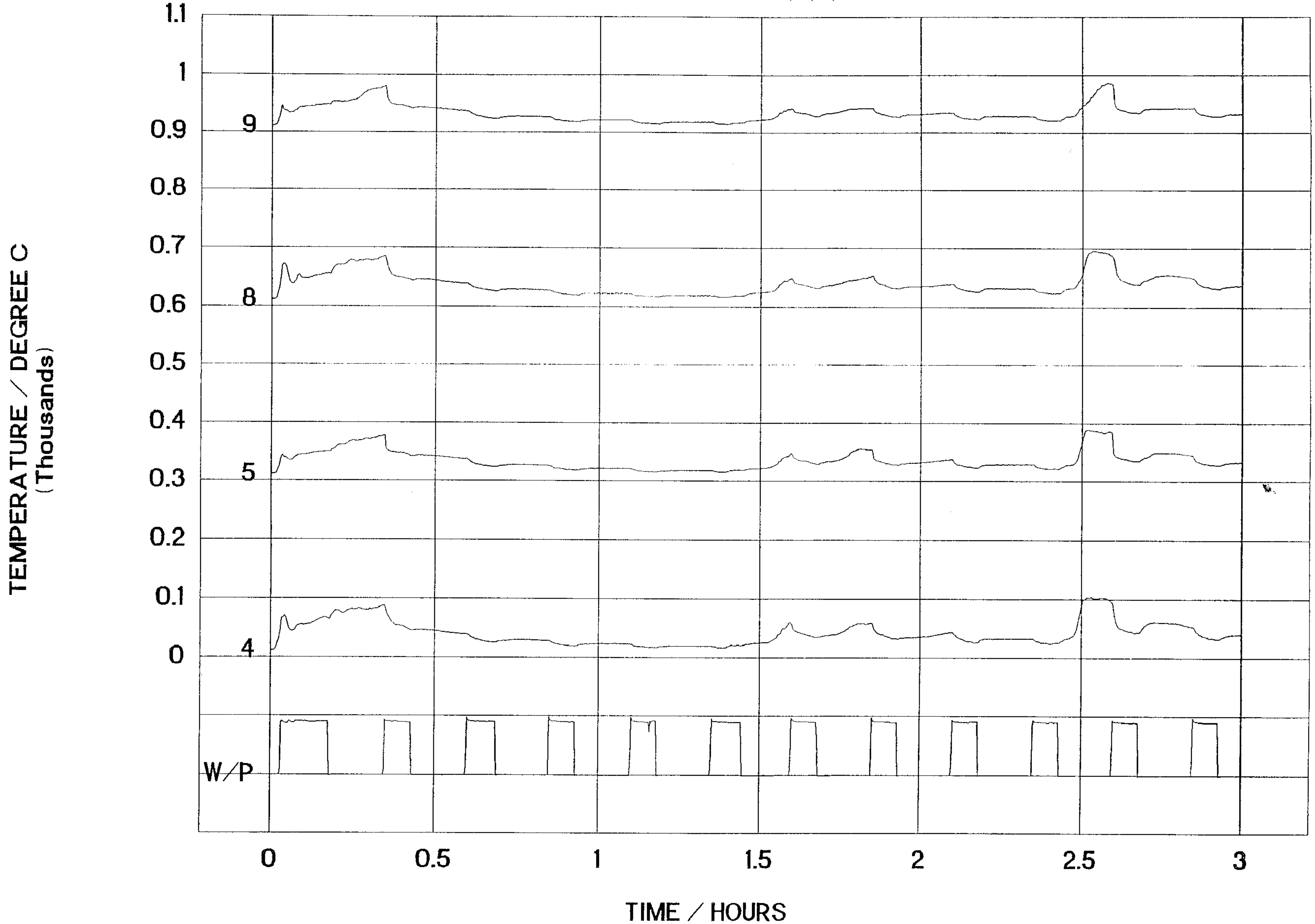


FIGURE 4.35: CAA CARGO BAY TEST NUMBER 9

THERMOCOUPLES 6,7,12,13

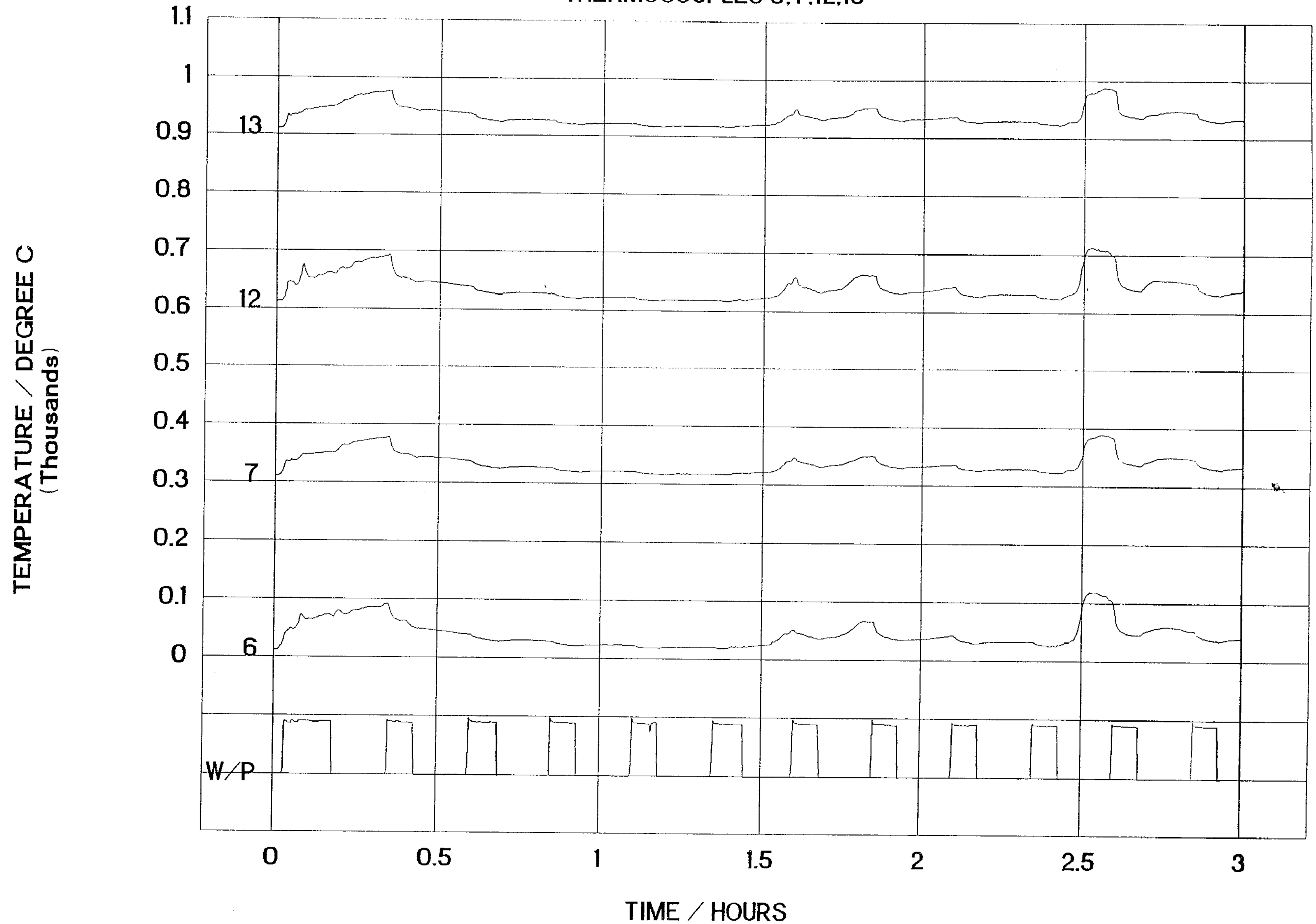


FIGURE 4.36: CAA CARGO BAY TEST NUMBER 9

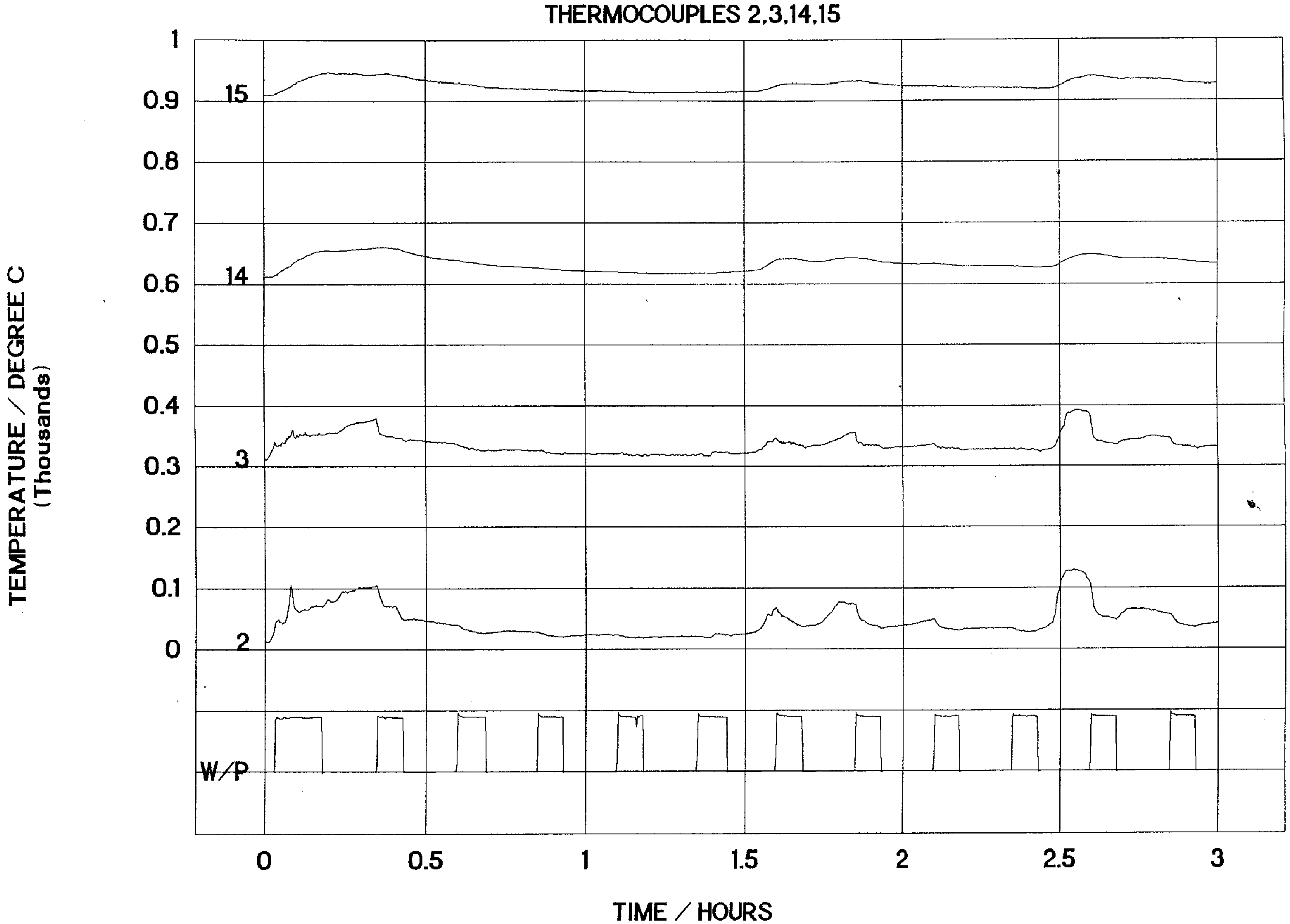


FIGURE 4.37: CAA CARGO BAY TEST NUMBER 10

THERMOCOUPLES 1,10,11

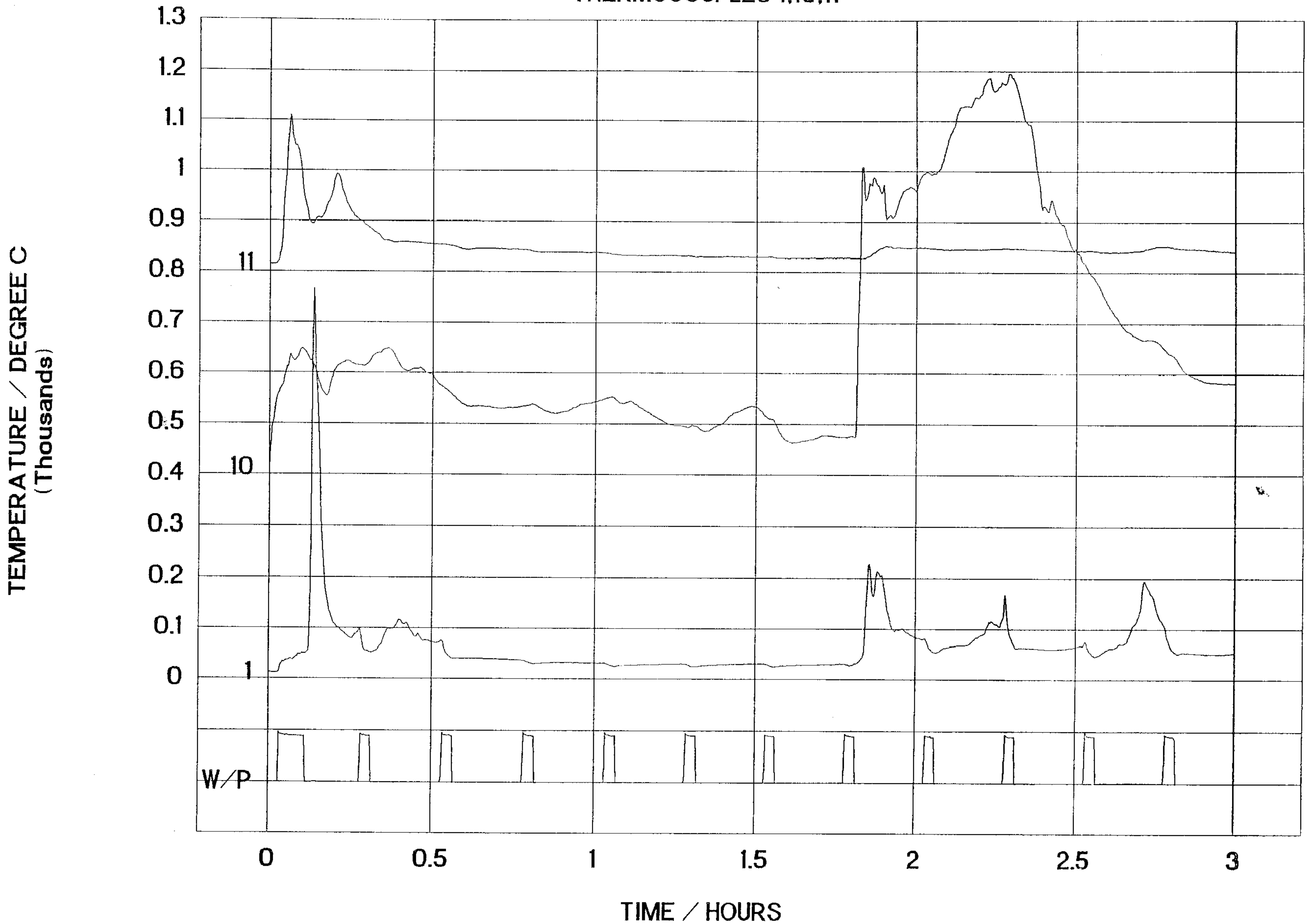


FIGURE 4.38: CAA CARGO BAY TEST NUMBER 10

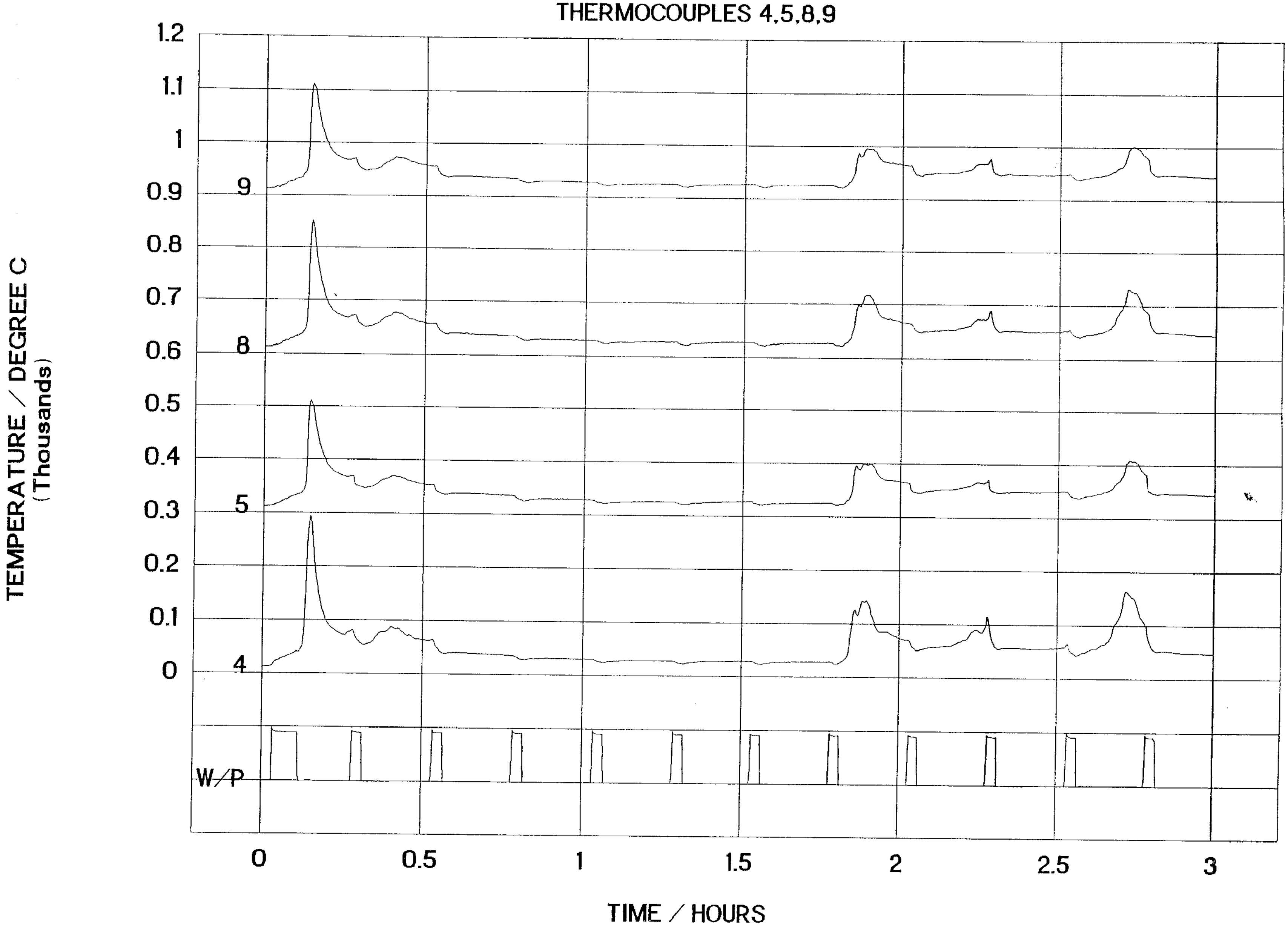


FIGURE 4.39: CAA CARGO BAY TEST NUMBER 10

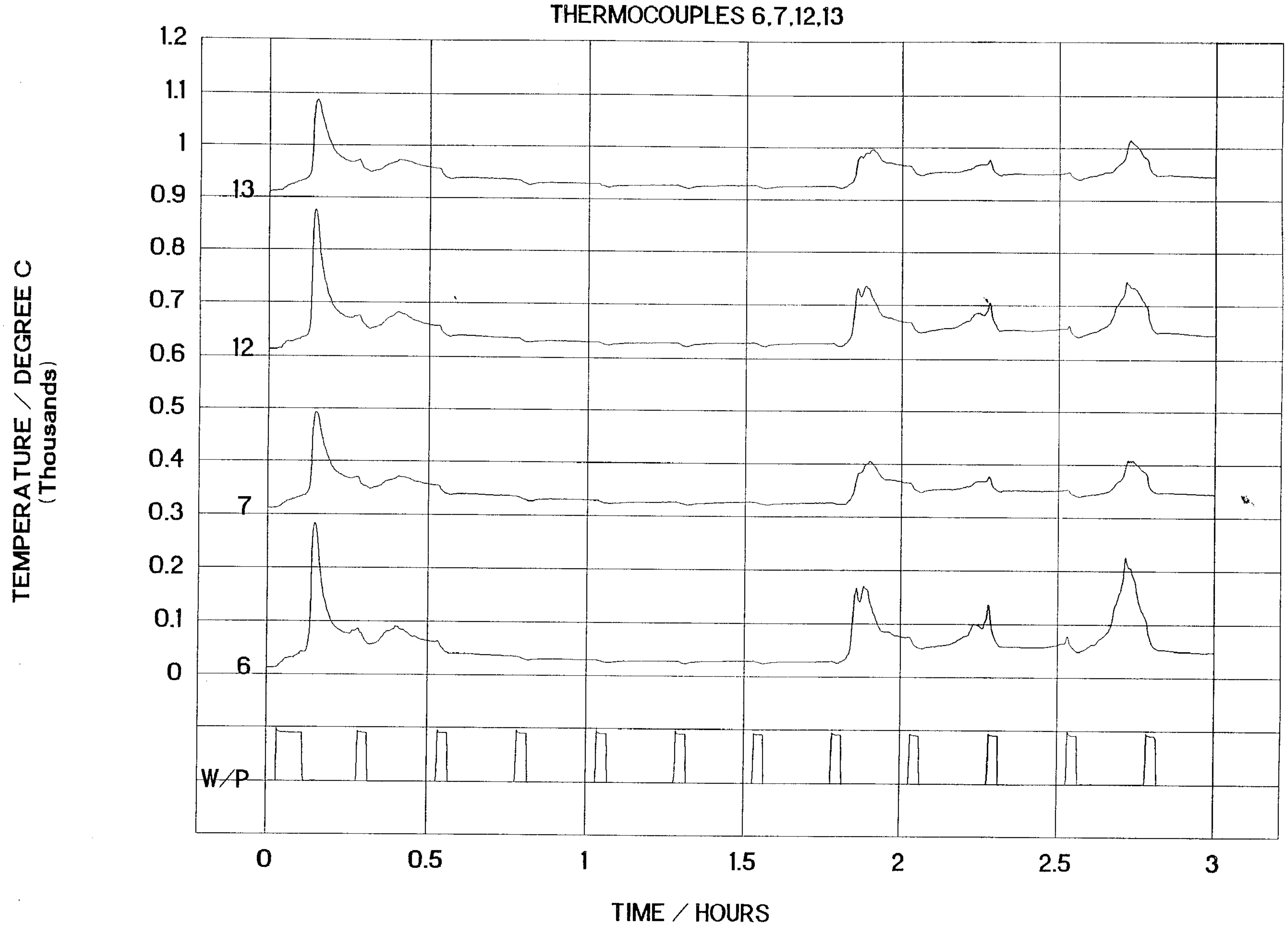


FIGURE 4.40: CAA CARGO BAY TEST NUMBER 10

THERMOCOUPLES 2,3,14,15

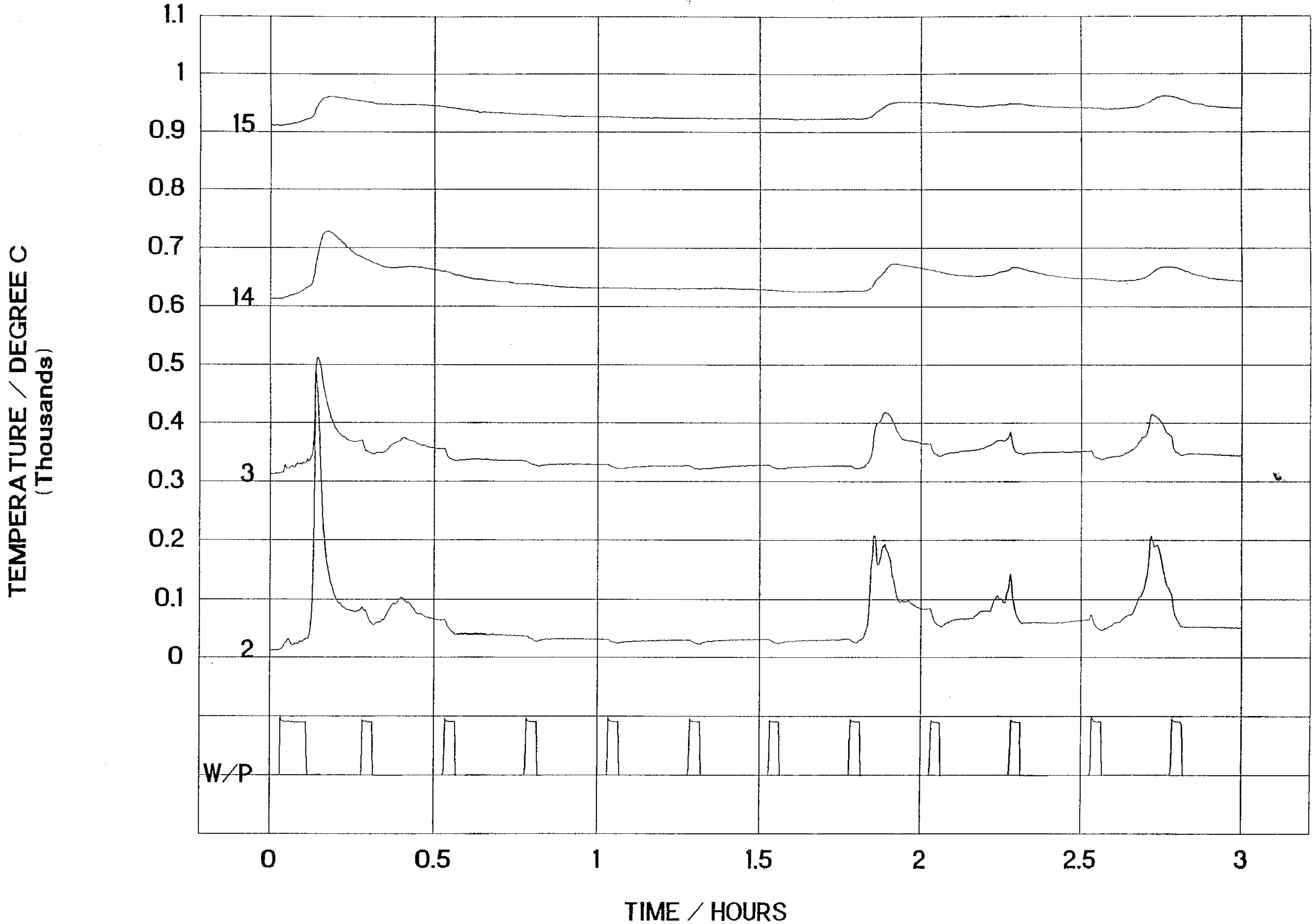


FIGURE 4.41: CAA CARGO BAY TEST NUMBER 11

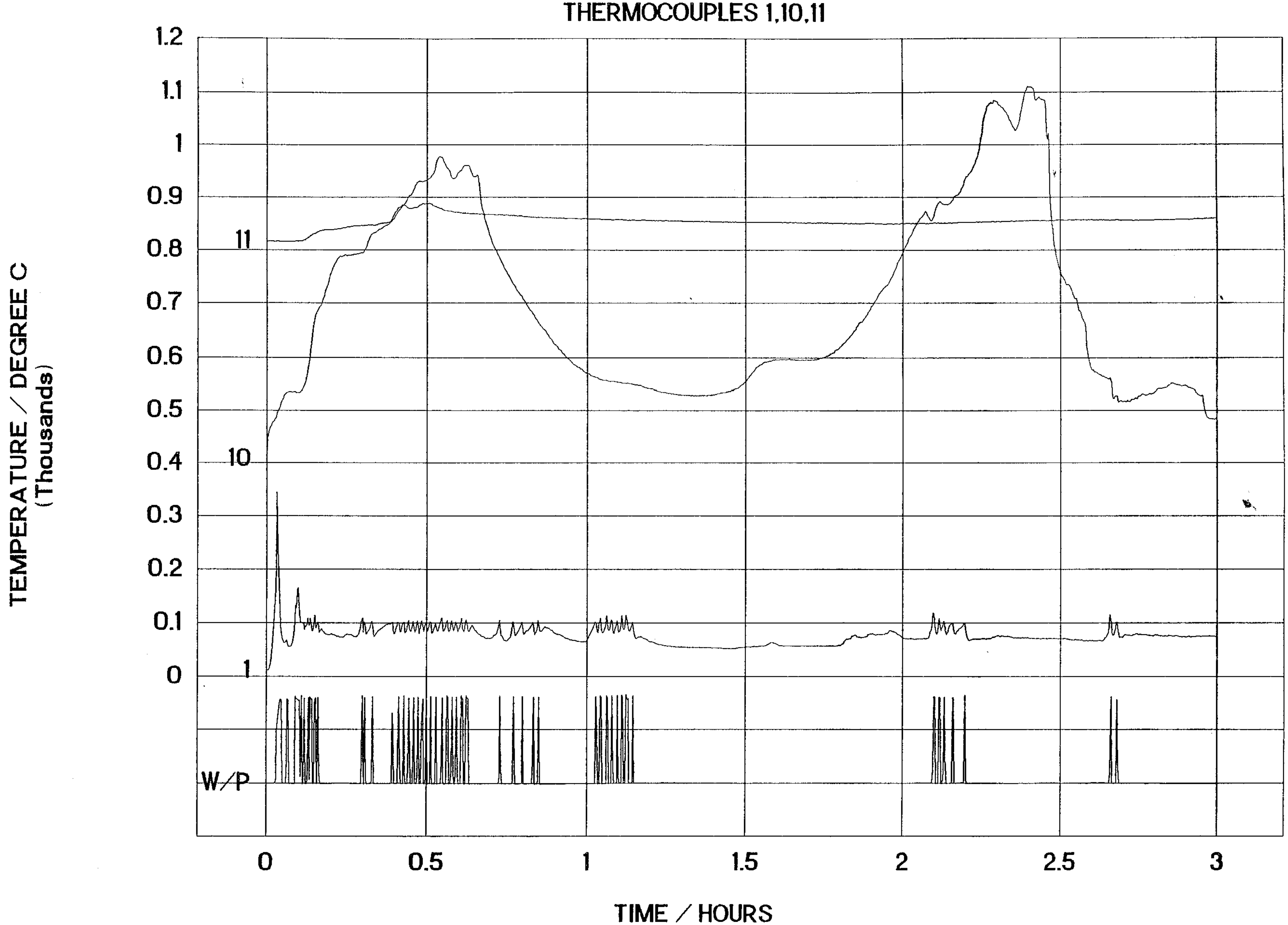


FIGURE 4.42: CAA CARGO BAY TEST NUMBER 11

THERMOCOUPLES 4,5,8,9

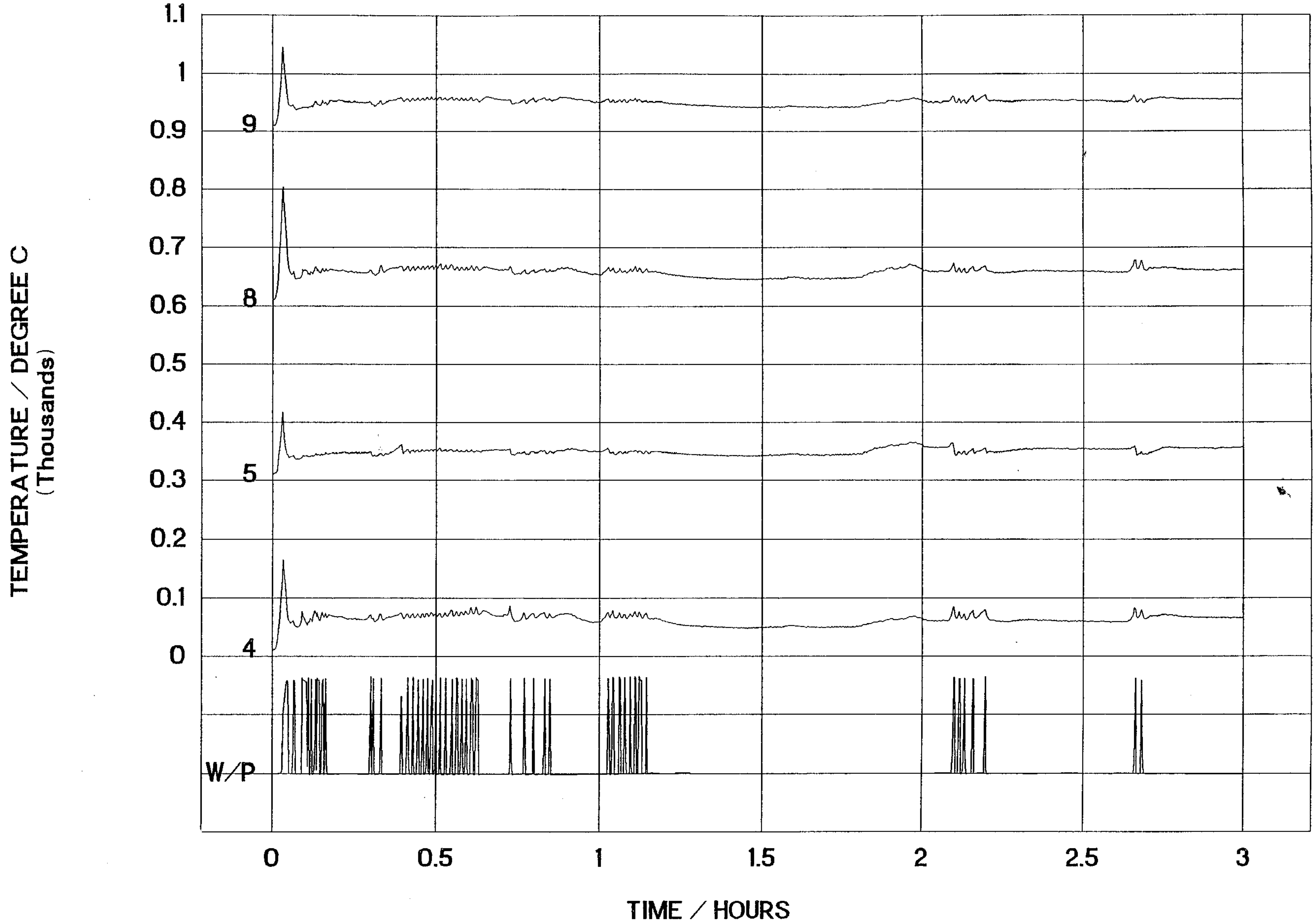


FIGURE 4.43: CAA CARGO BAY TEST NUMBER 11

THERMOCOUPLES 6,7,12,13

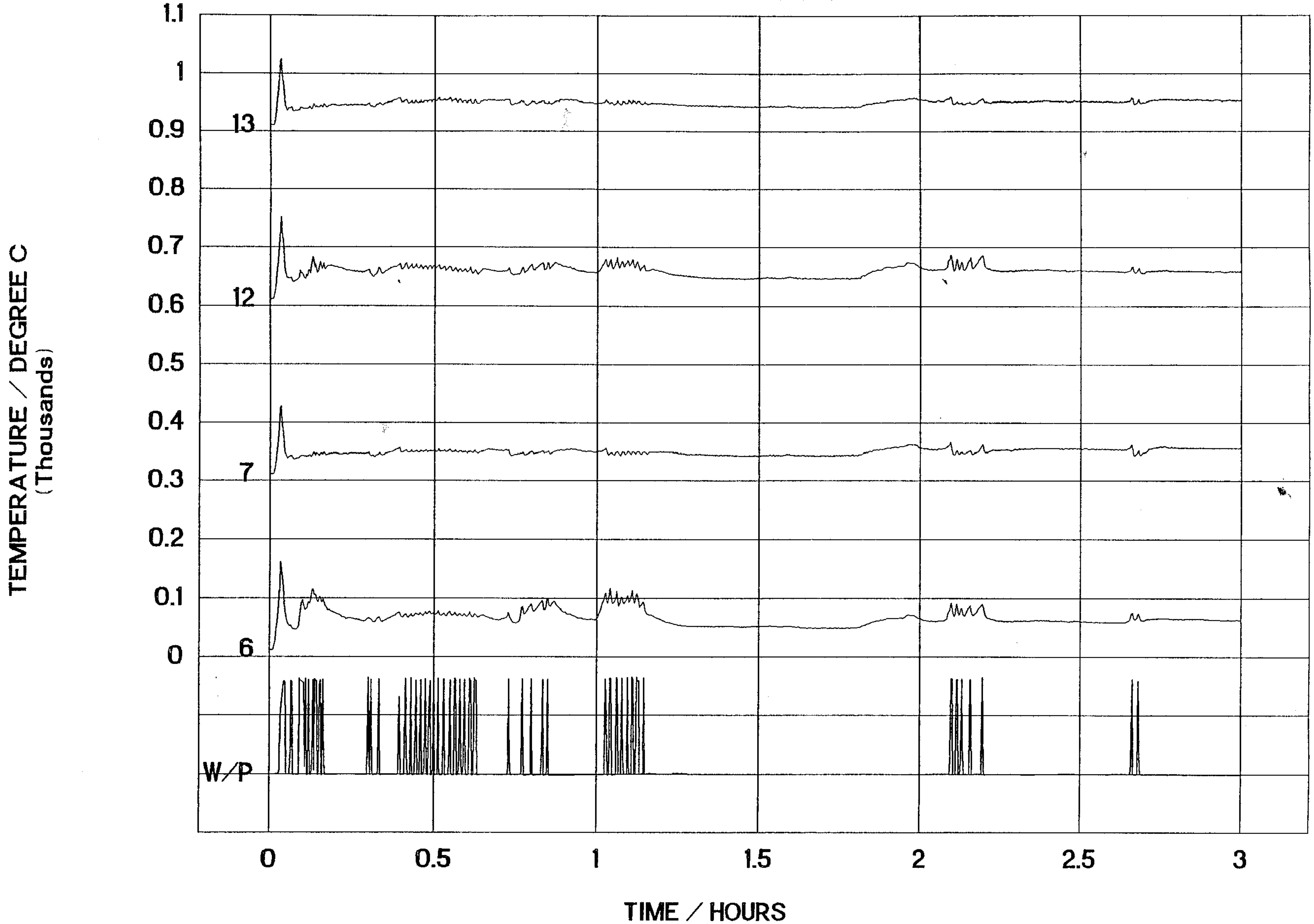


FIGURE 4.44: CAA CARGO BAY TEST NUMBER 11

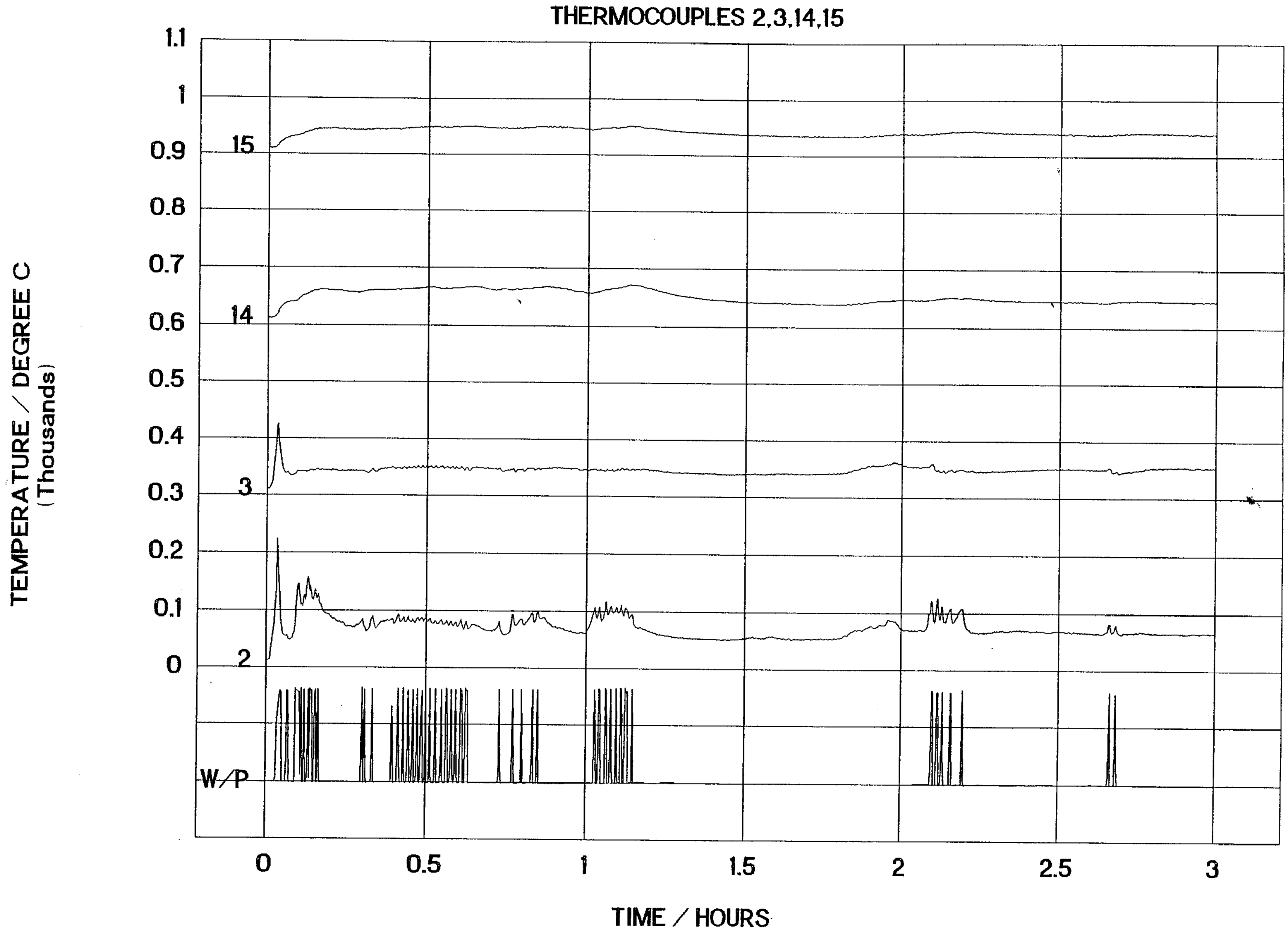


FIGURE 4.45: CAA CARGO BAY TEST NUMBER 12

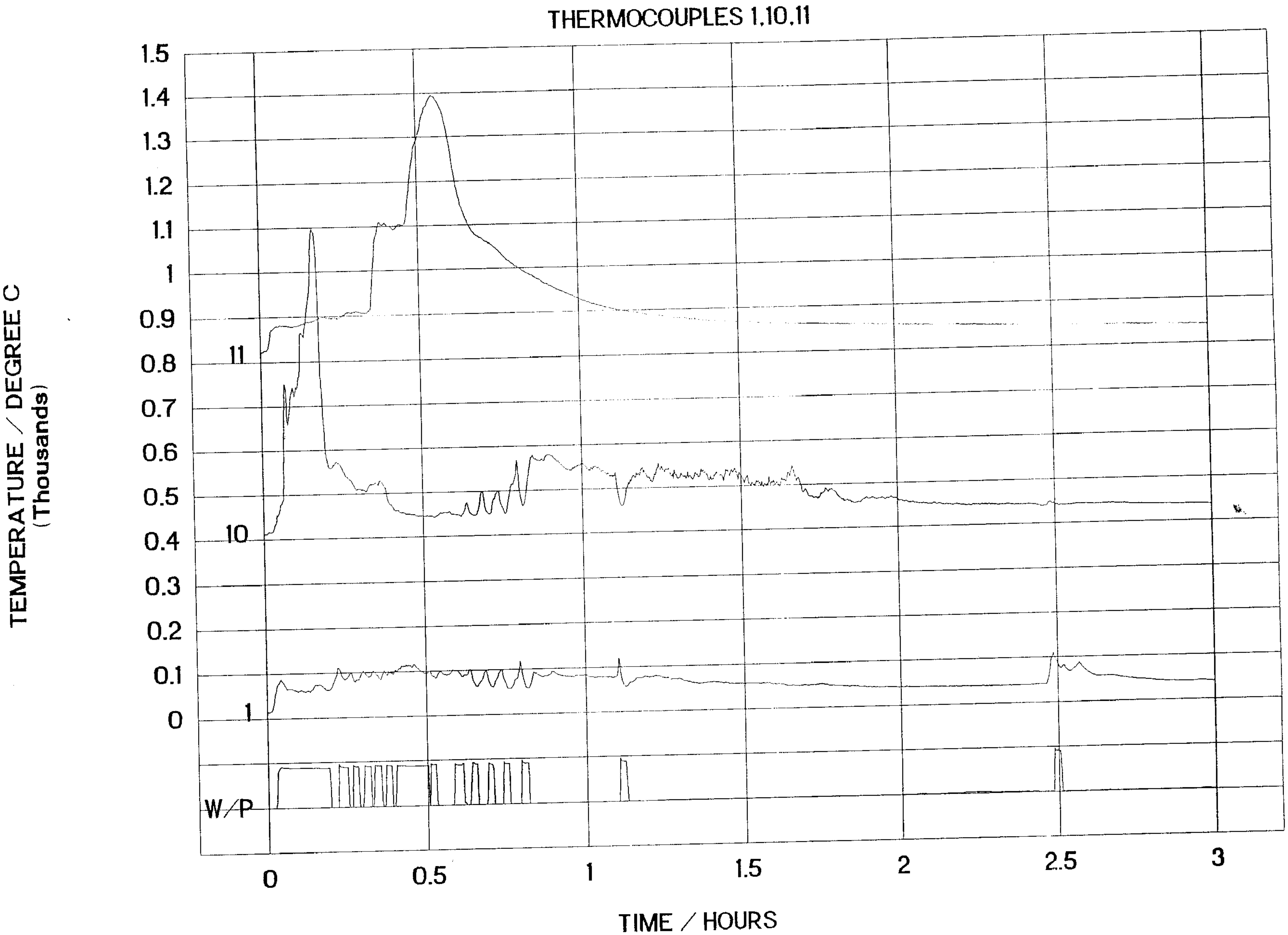


FIGURE 4.46: CAA CARGO BAY TEST NUMBER 12

THERMOCOUPLES 4.5.8.9

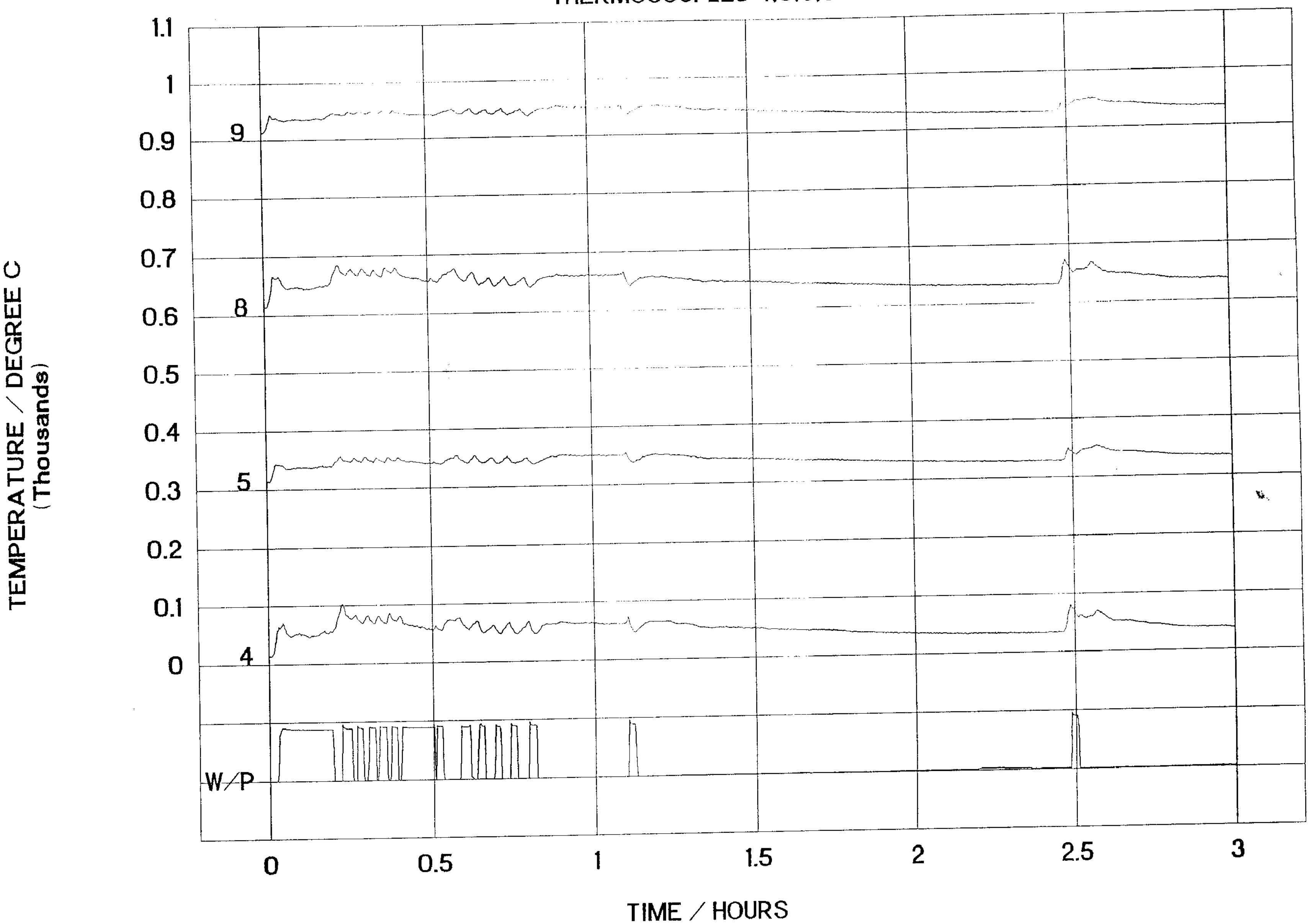


FIGURE 4.47: CAA CARGO BAY TEST NUMBER 12

THERMOCOUPLES 6,7,12,13

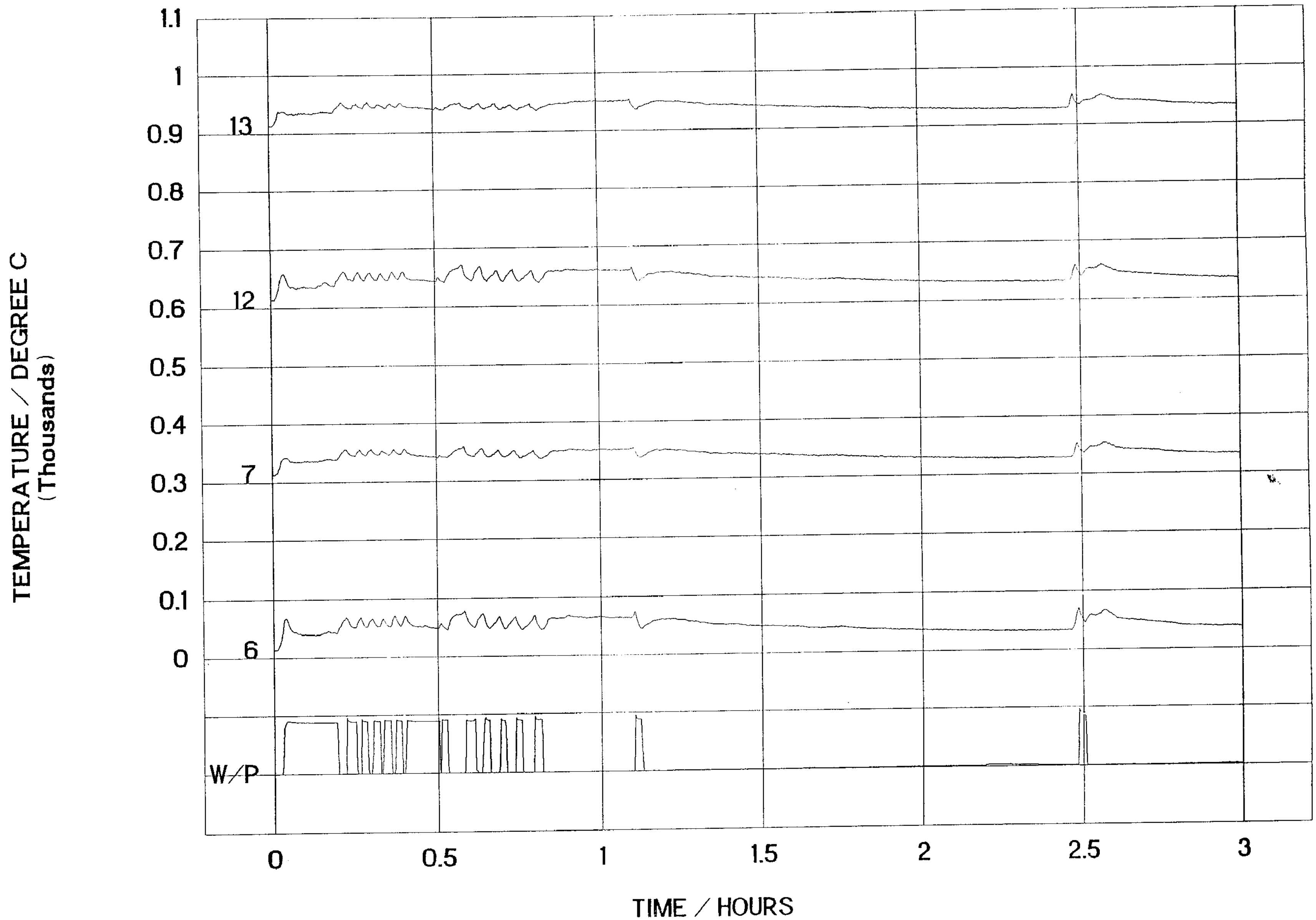


FIGURE 4.48: CAA CARGO BAY TEST NUMBER 12

THERMOCOUPLES 2,3,14,15

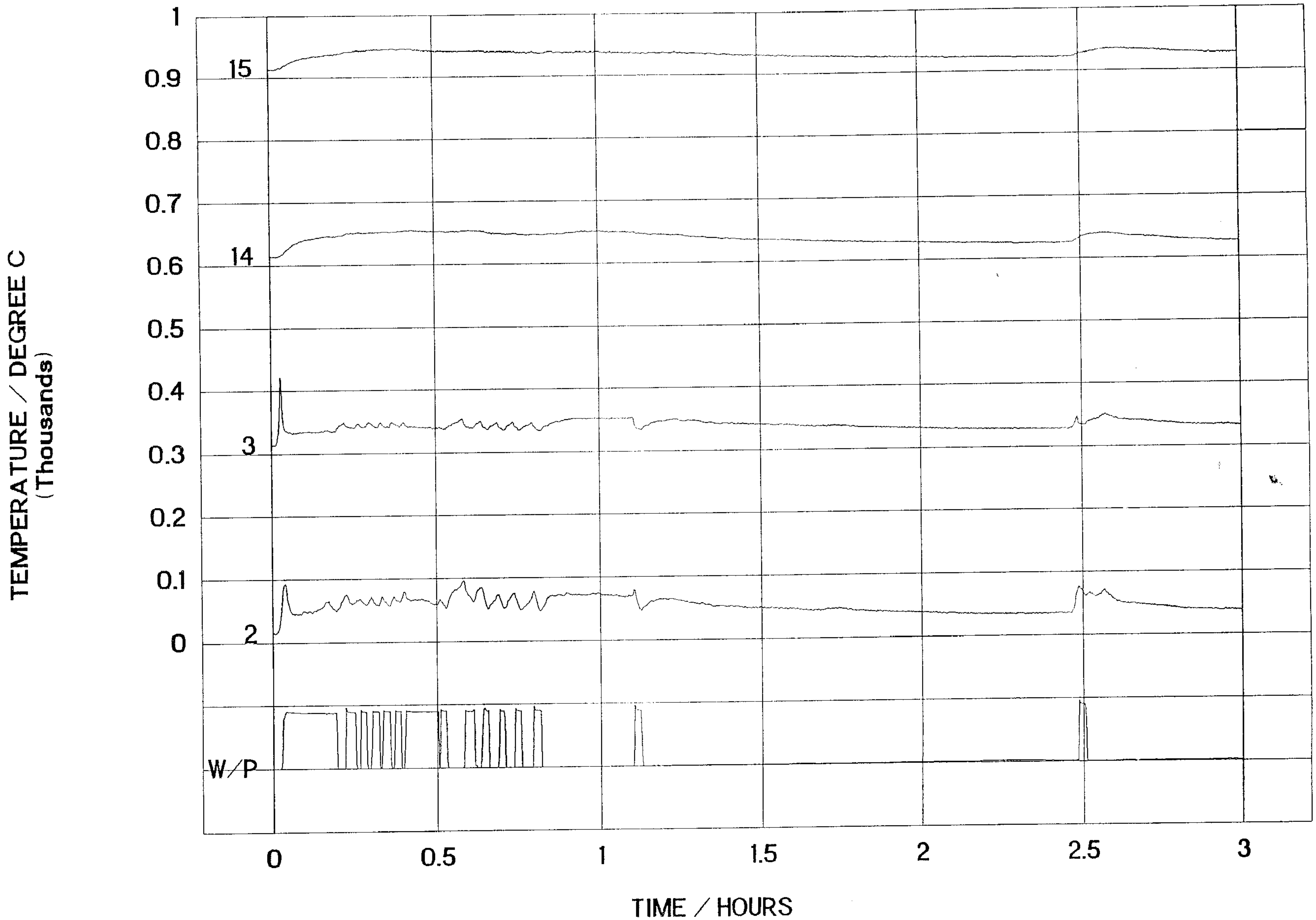


FIGURE 4.49: CAA CARGO BAY TEST NUMBER 13

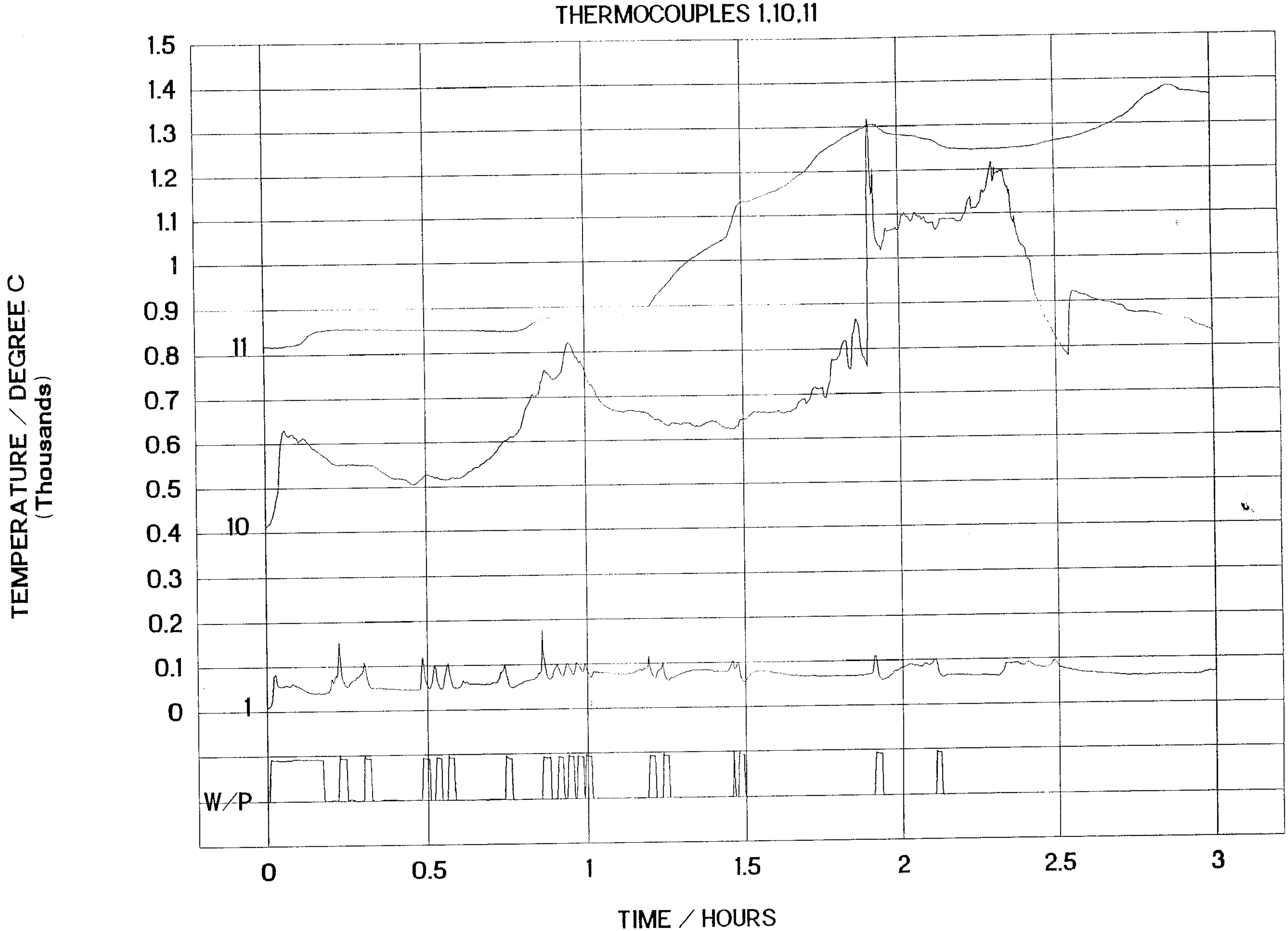


FIGURE 4.50: CAA CARGO BAY TEST NUMBER 13

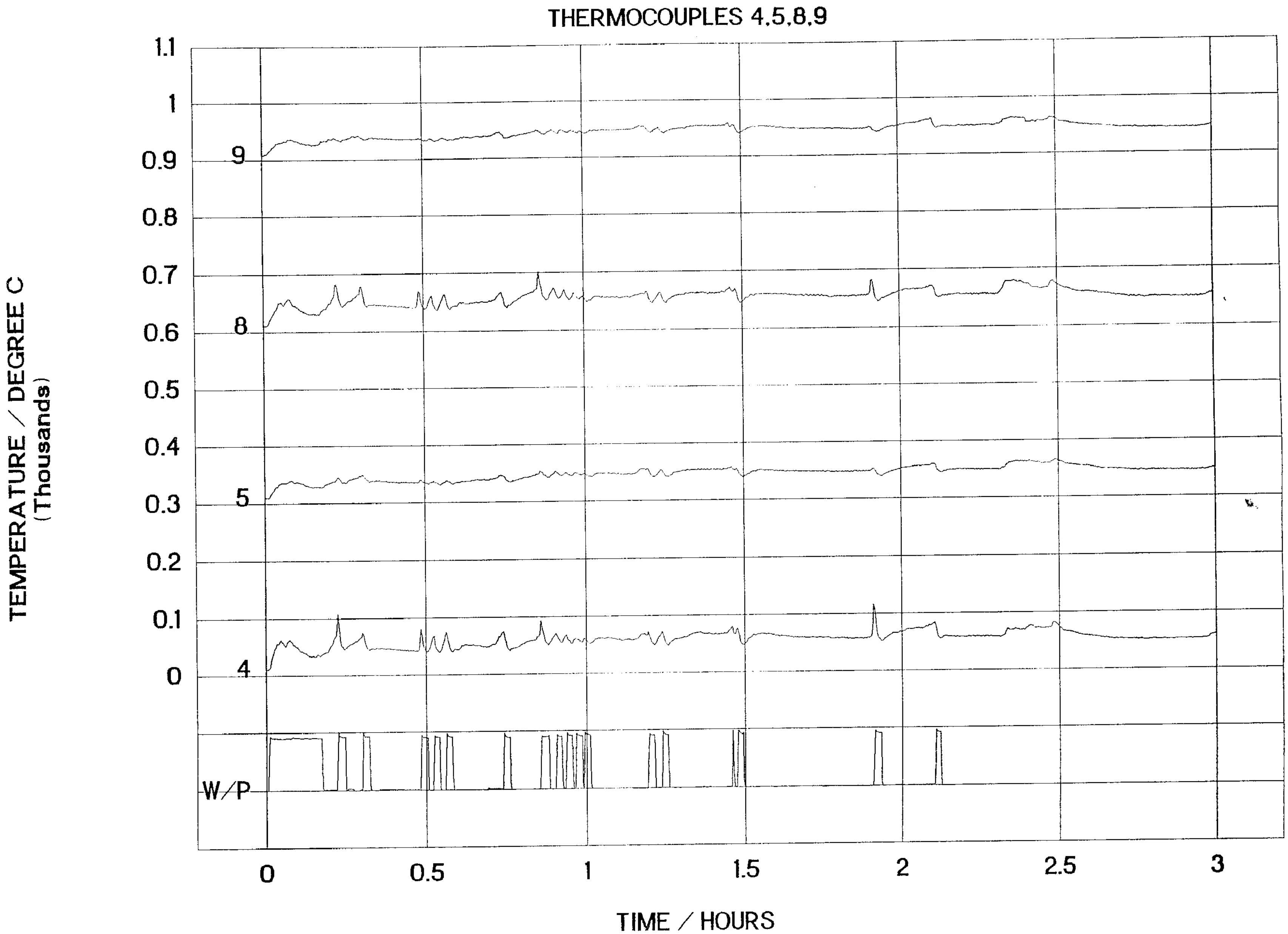


FIGURE 4.51: CAA CARGO BAY TEST NUMBER 13

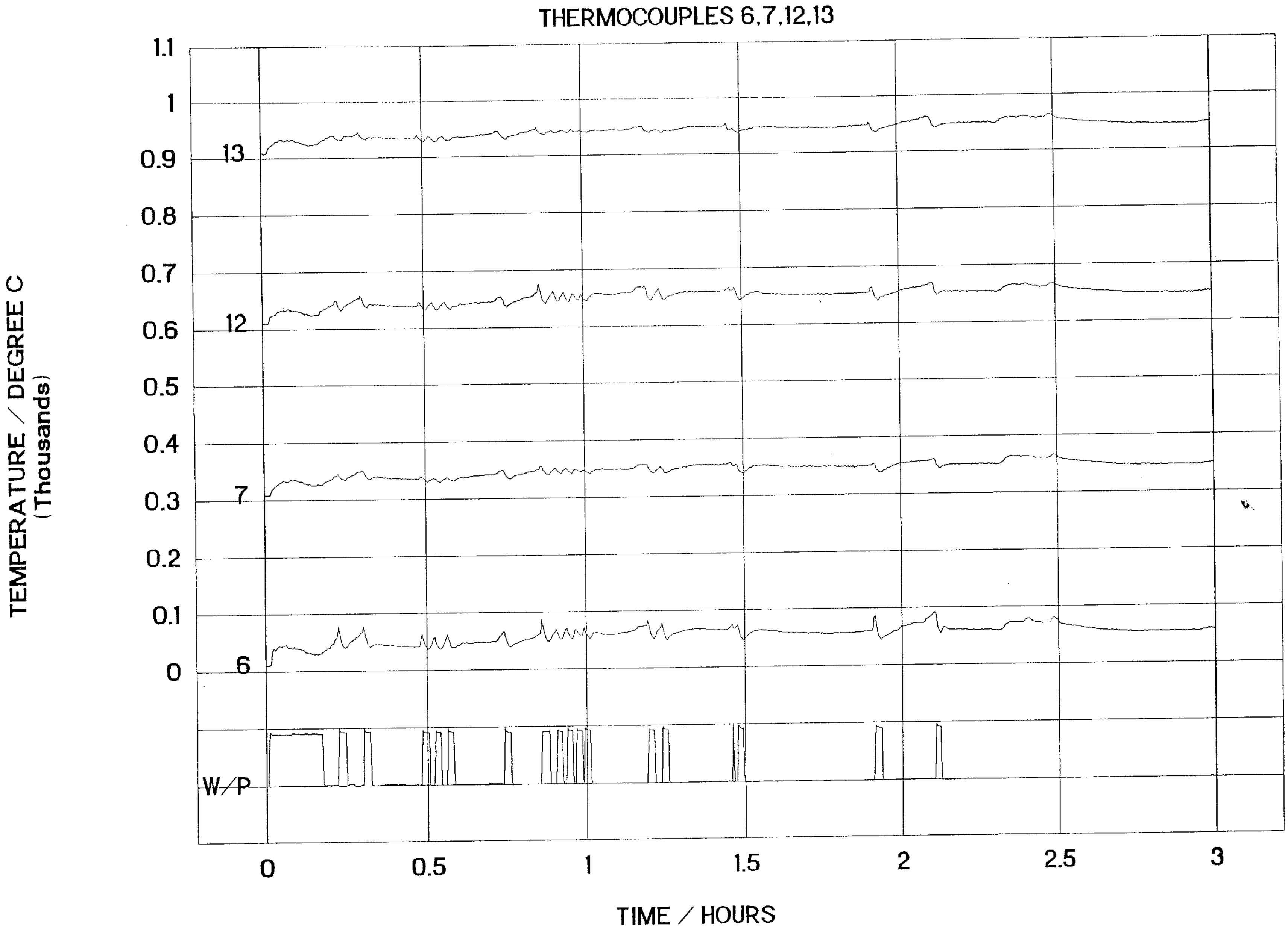


FIGURE 4.52: CAA CARGO BAY TEST NUMBER 13

THERMOCOUPLES 2,3,14,15

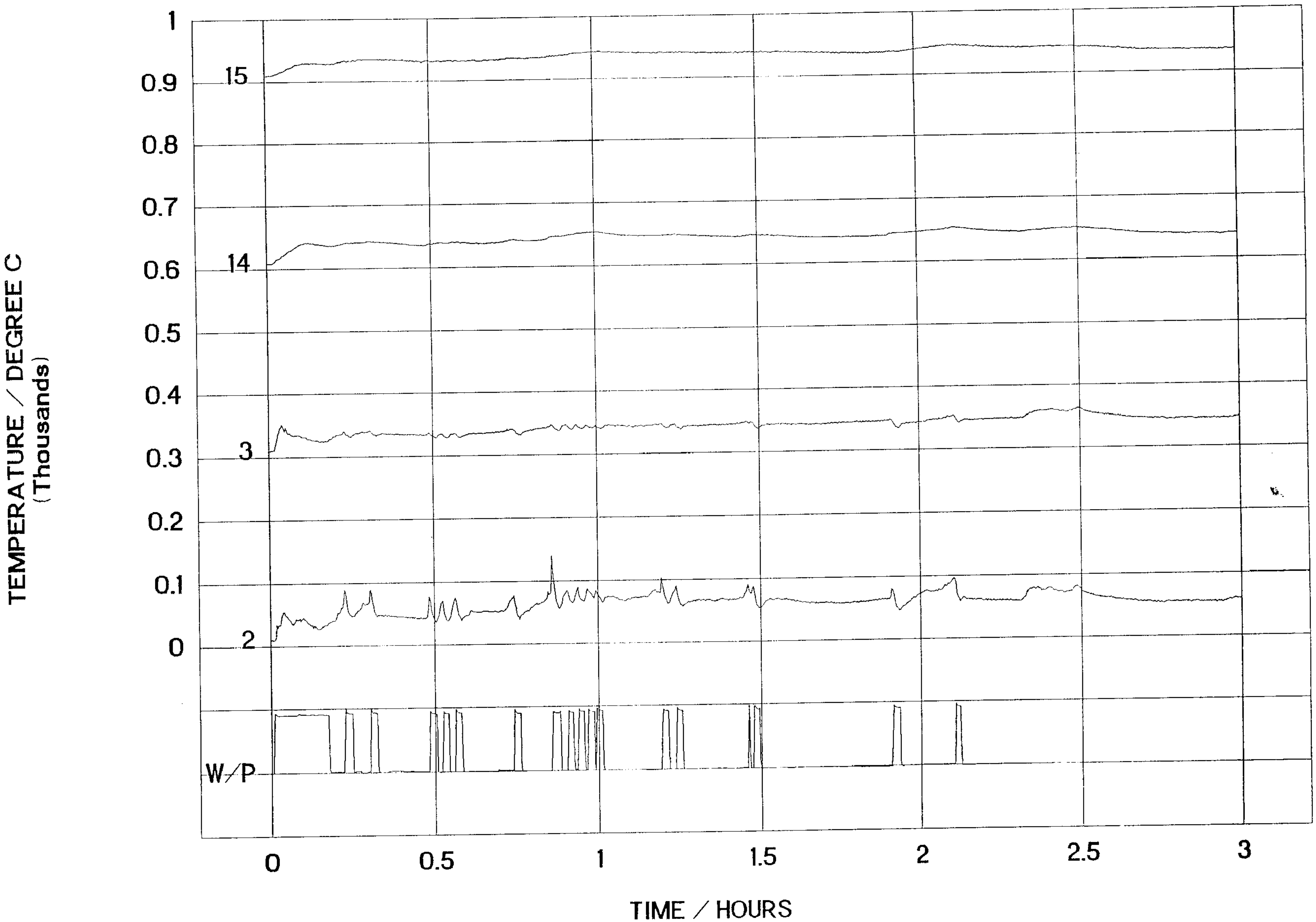


FIGURE 4.53: CAA CARGO BAY TEST NUMBER 14

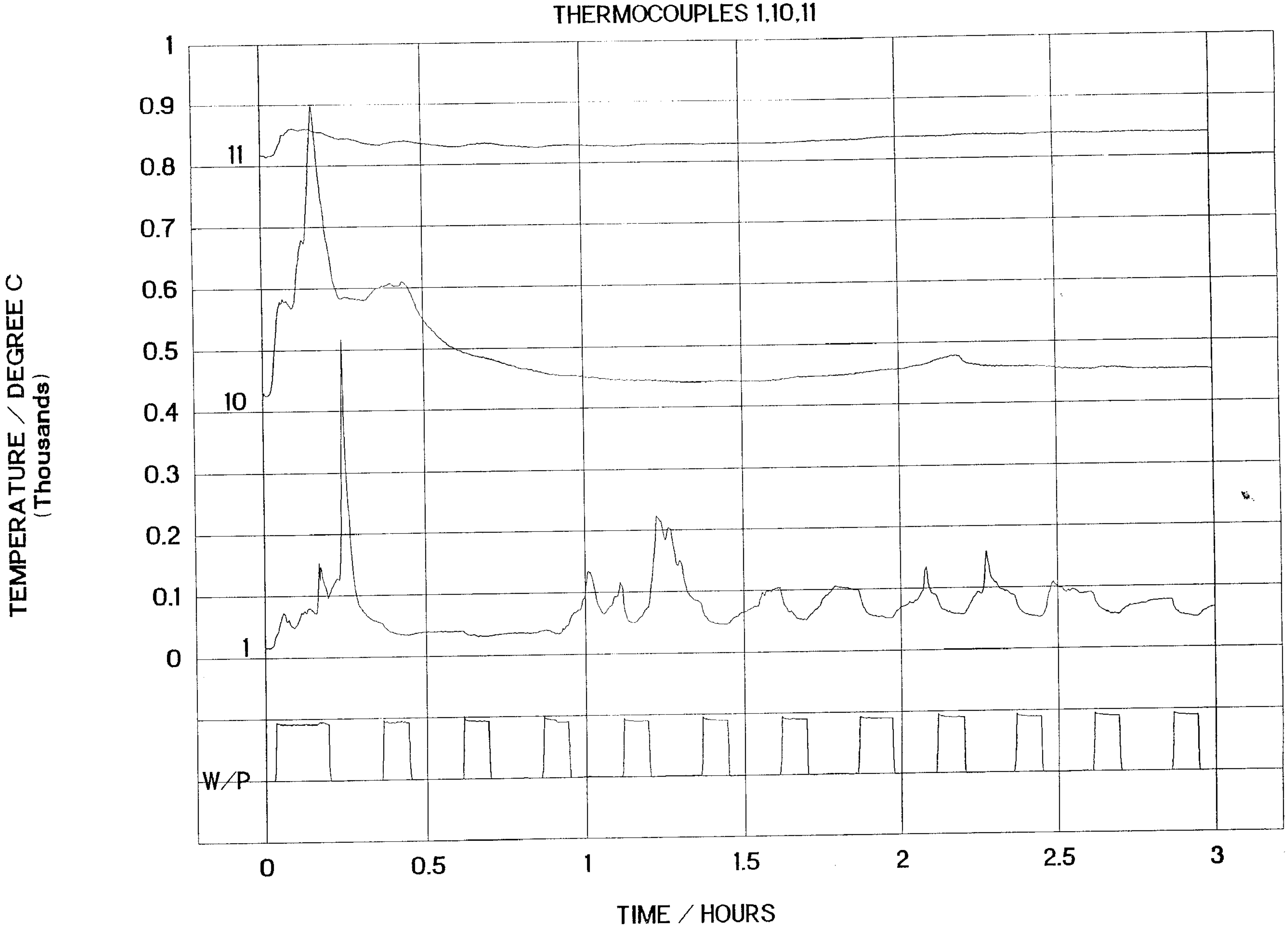


FIGURE 4.54: CAA CARGO BAY TEST NUMBER 14

THERMOCOUPLES 4,5,8,9

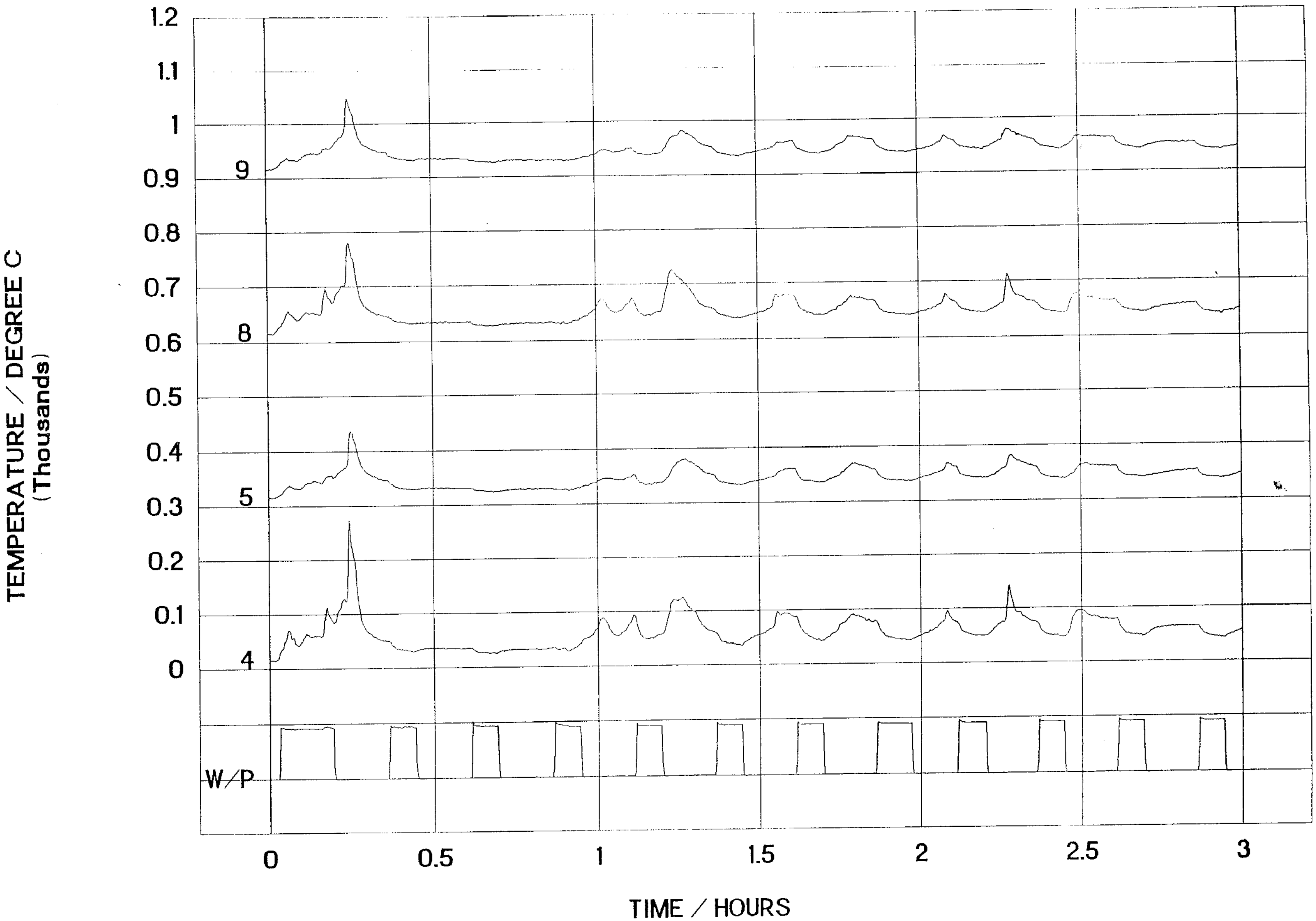


FIGURE 4.55: CAA CARGO BAY TEST NUMBER 14

THERMOCOUPLES 6,7,12,13

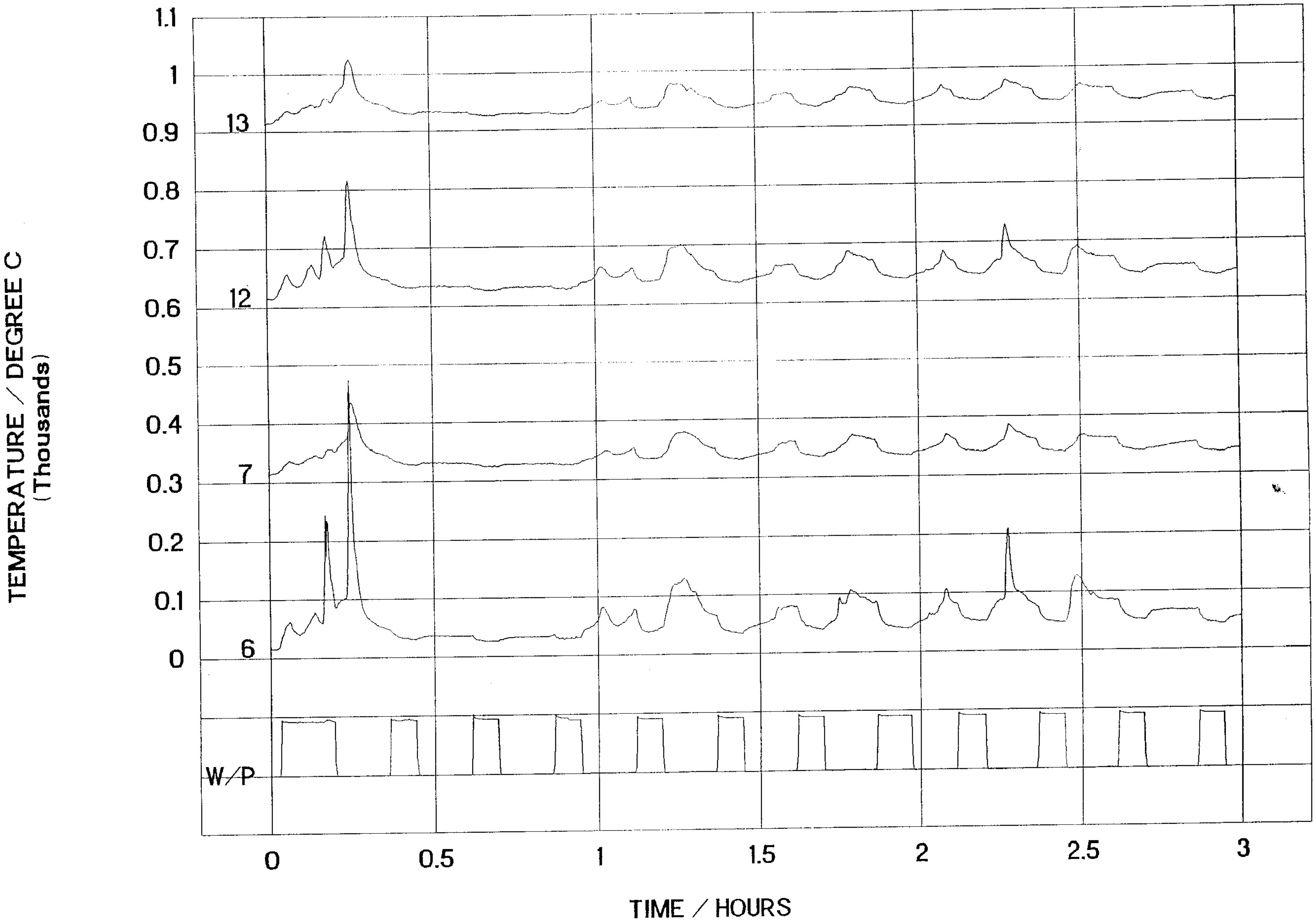


FIGURE 4.56: CAA CARGO BAY TEST NUMBER 14

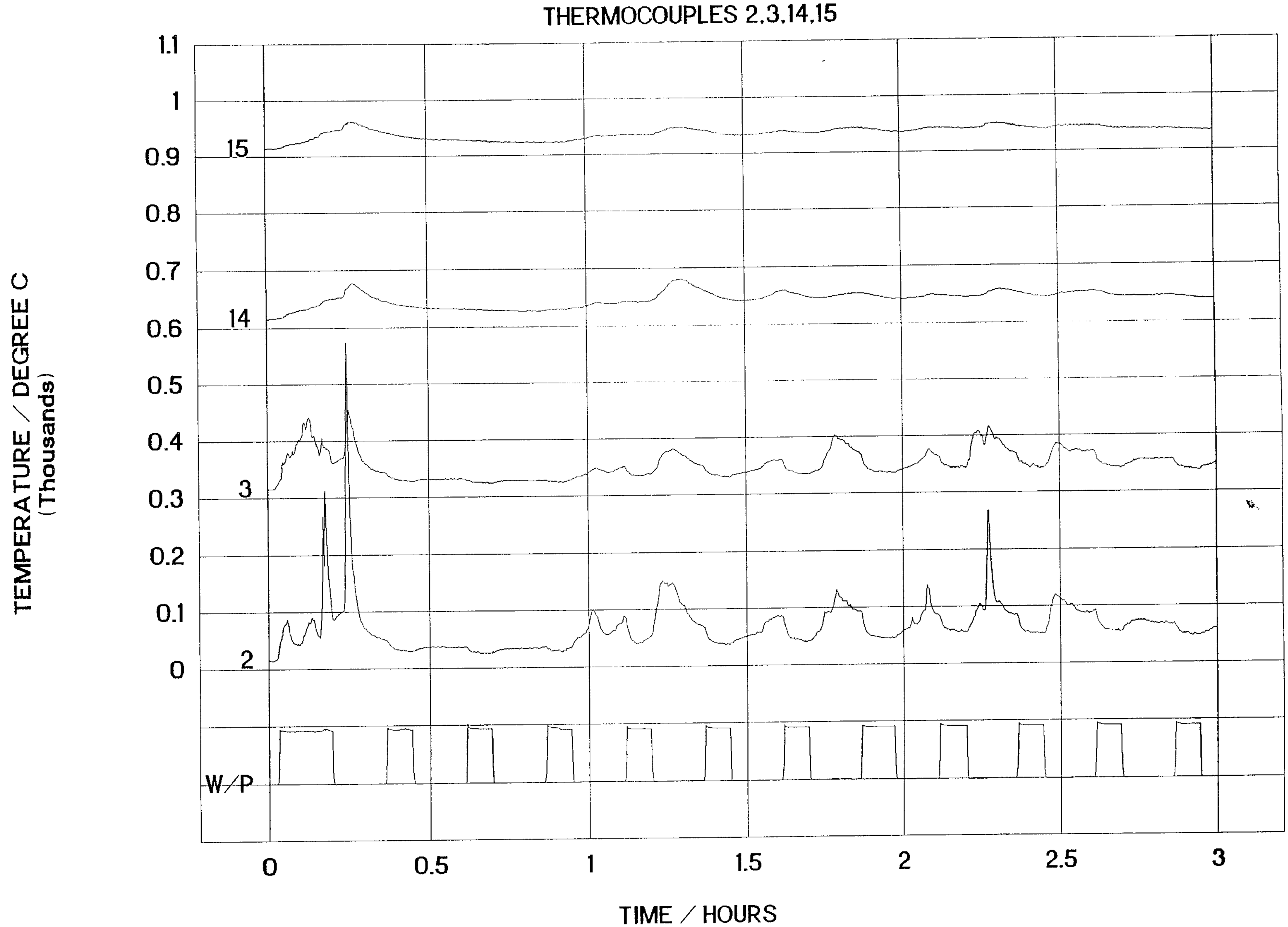


FIGURE 4.57: CAA CARGO BAY TEST NUMBER 15

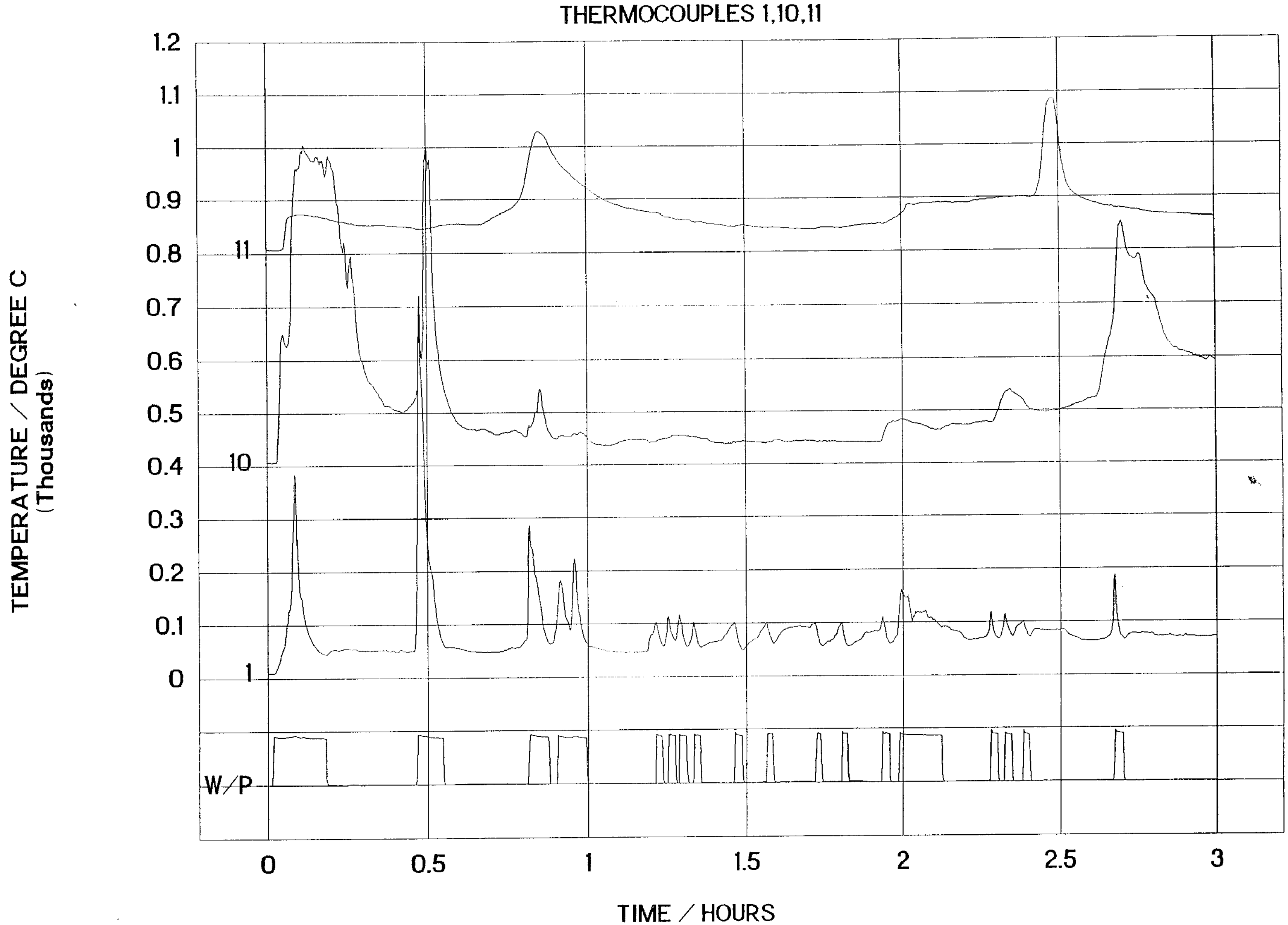


FIGURE 4.58: CAA CARGO BAY TEST NUMBER 15

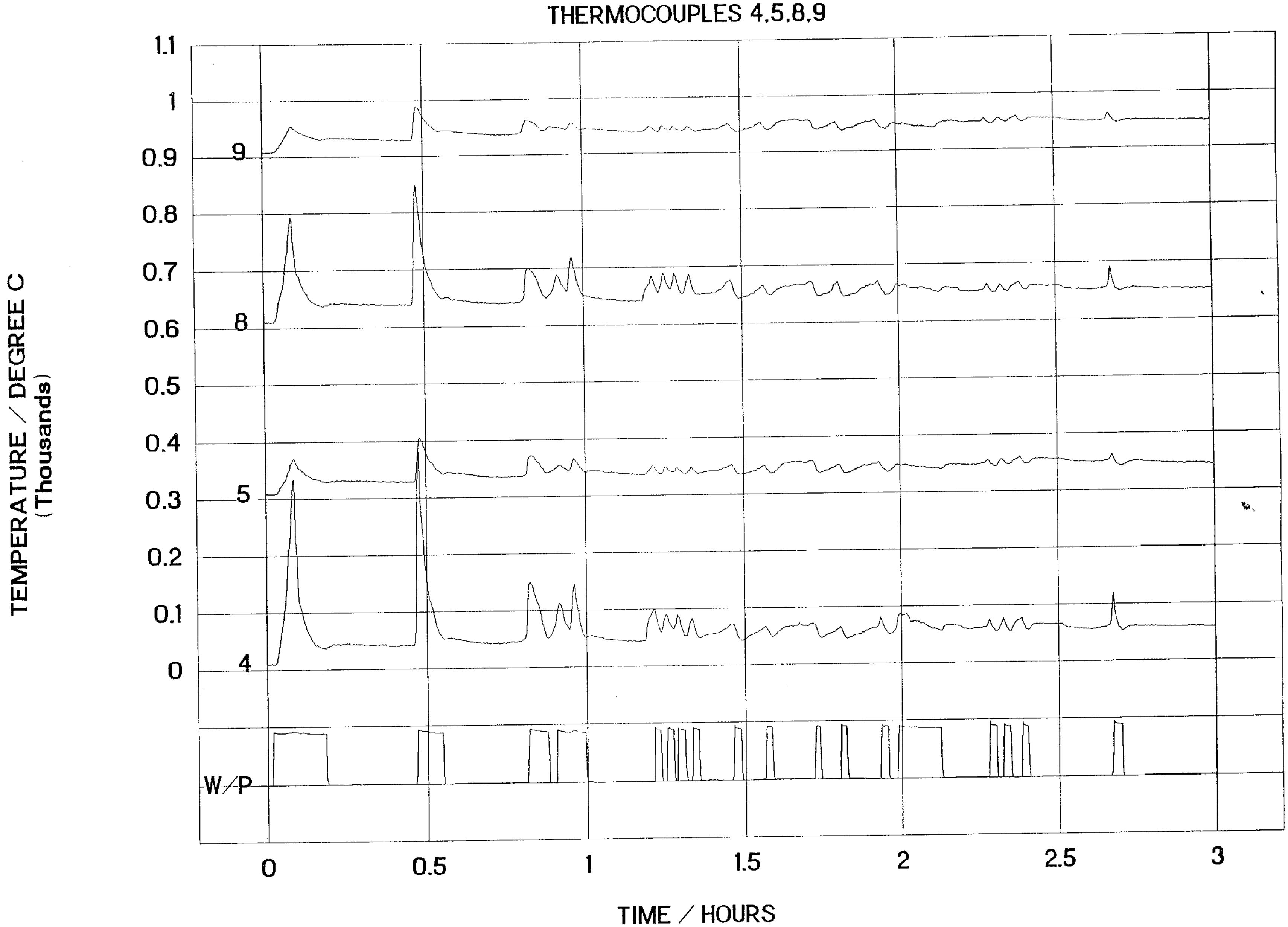


FIGURE 4.59: CAA CARGO BAY TEST NUMBER 15

THERMOCOUPLES 6,7,12,13

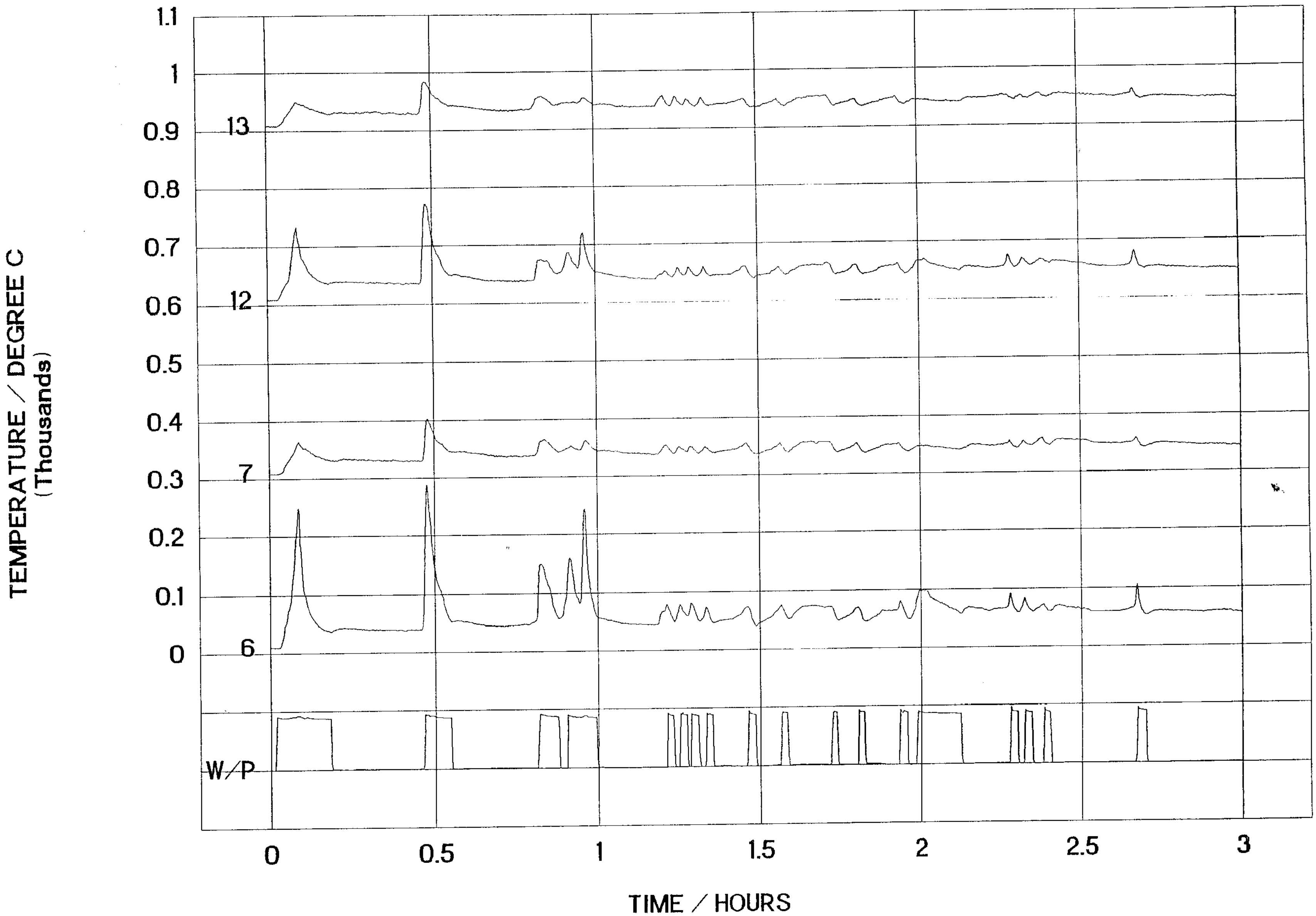


FIGURE 4.60: CAA CARGO BAY TEST NUMBER 15

THERMOCOUPLES 2,3,14,15

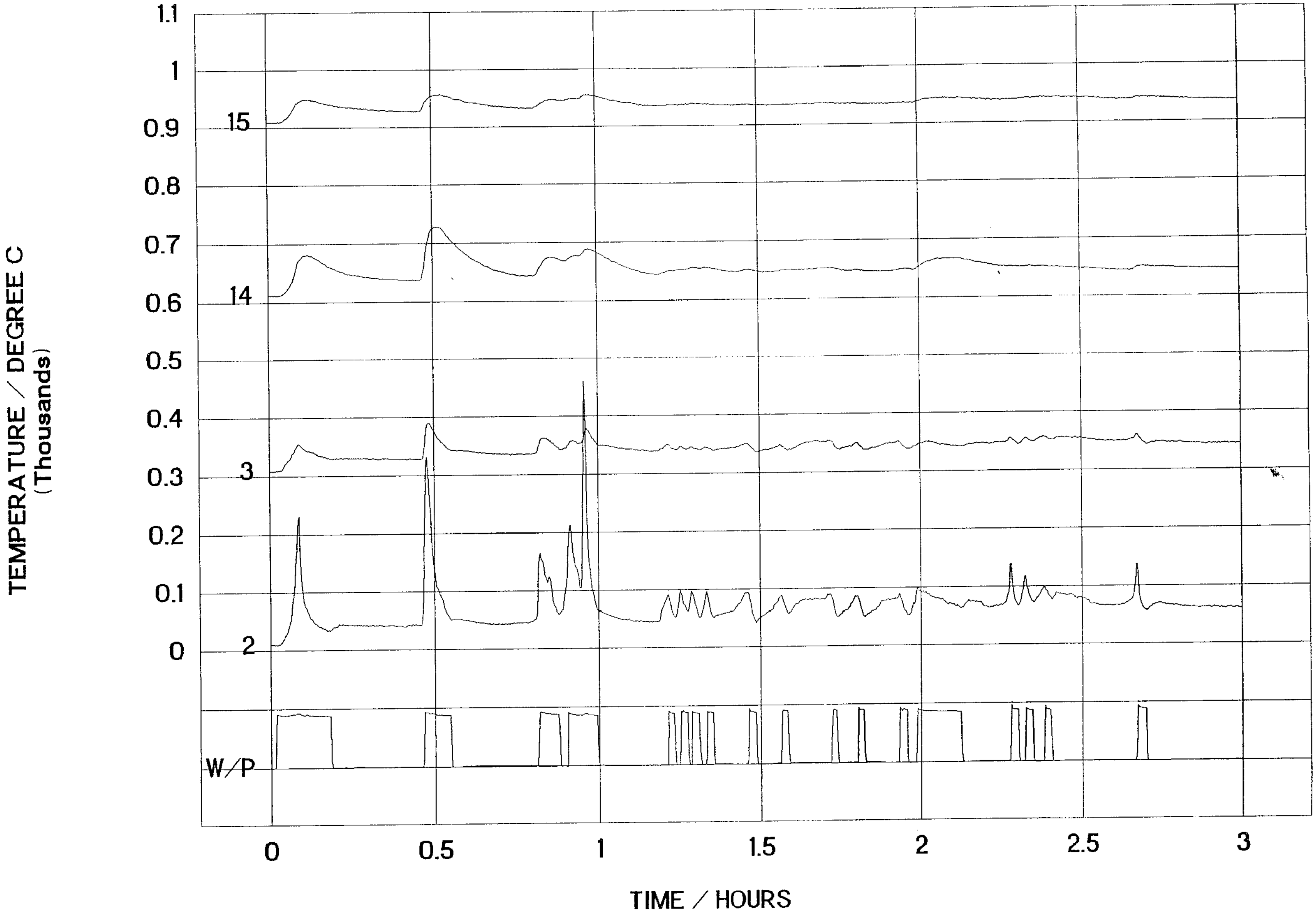


FIGURE 4.61: CAA CARGO BAY TEST NUMBER 16

THERMOCOUPLES 1,10,11

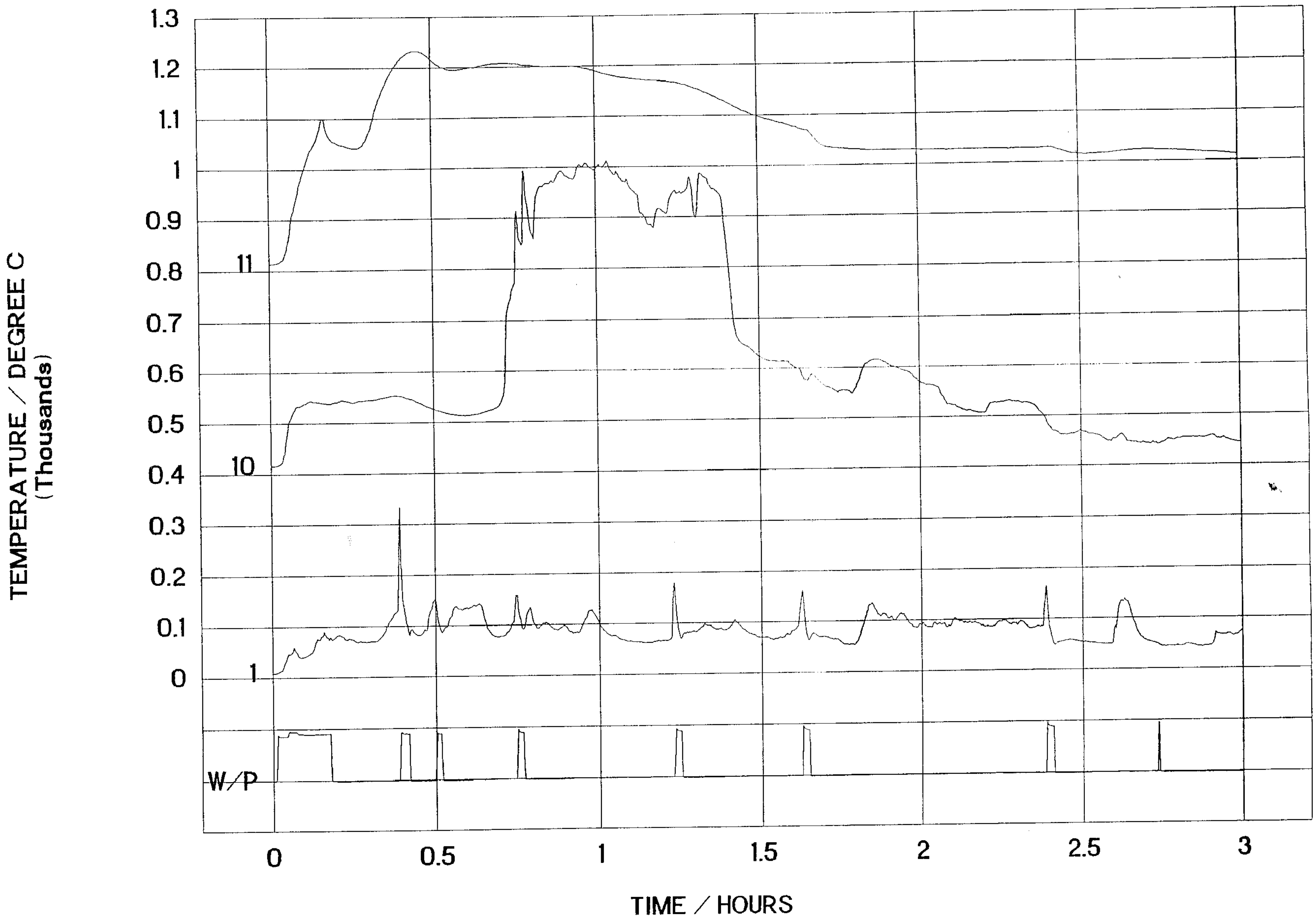


FIGURE 4.62: CAA CARGO BAY TEST NUMBER 16

THERMOCOUPLES 4,5,8,9

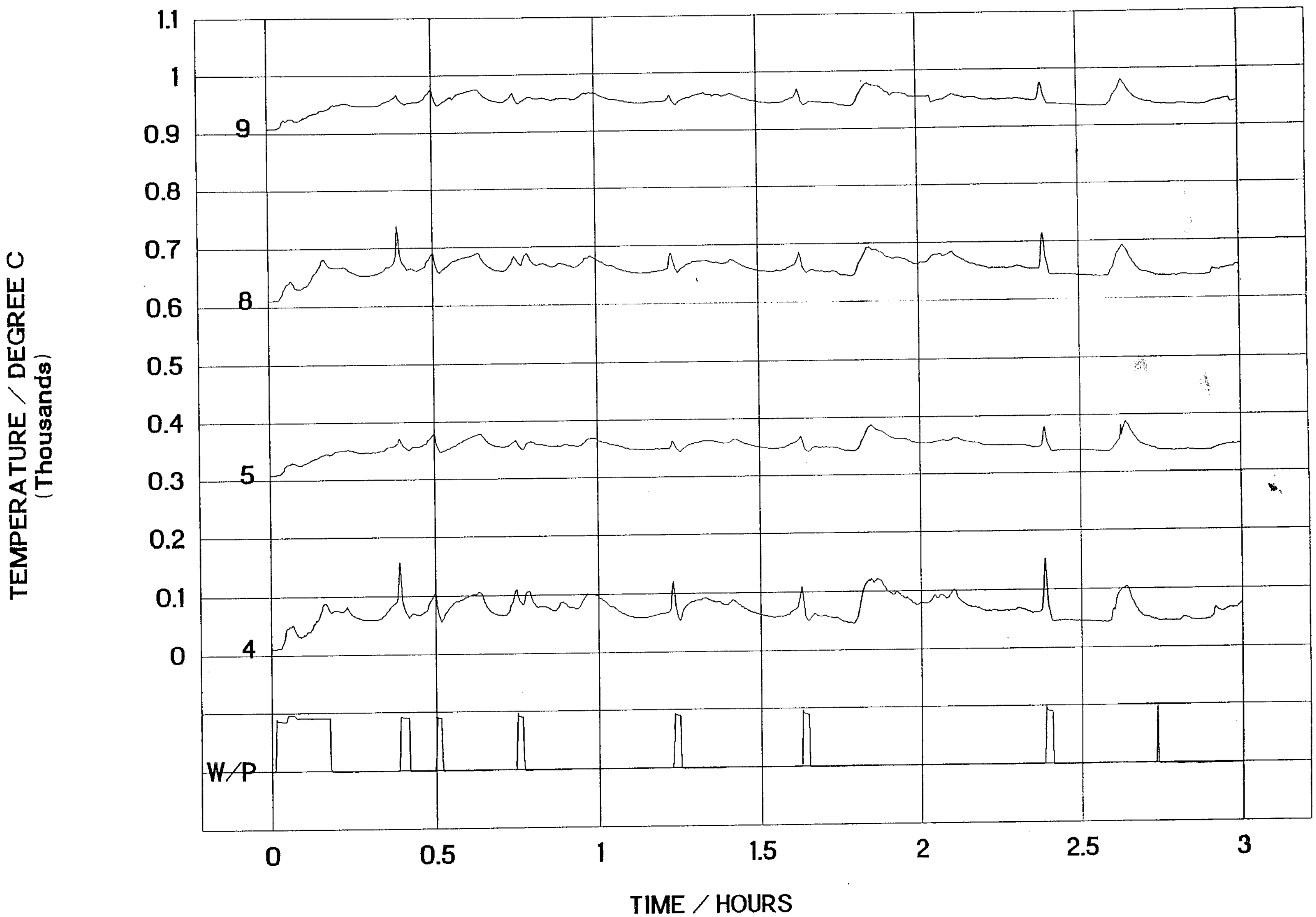


FIGURE 4.63: CAA CARGO BAY TEST NUMBER 16

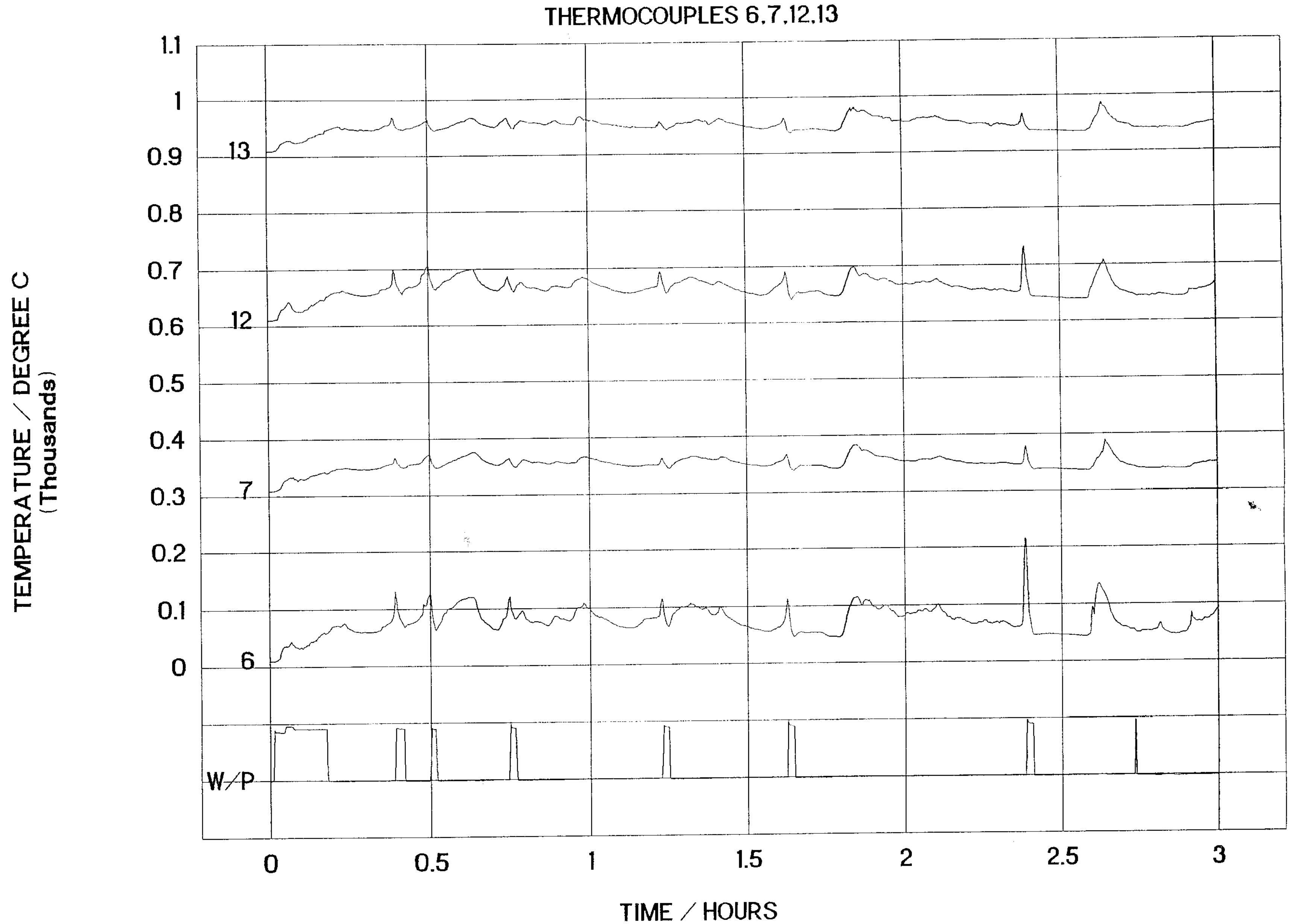


FIGURE 4.64: CAA CARGO BAY TEST NUMBER 16

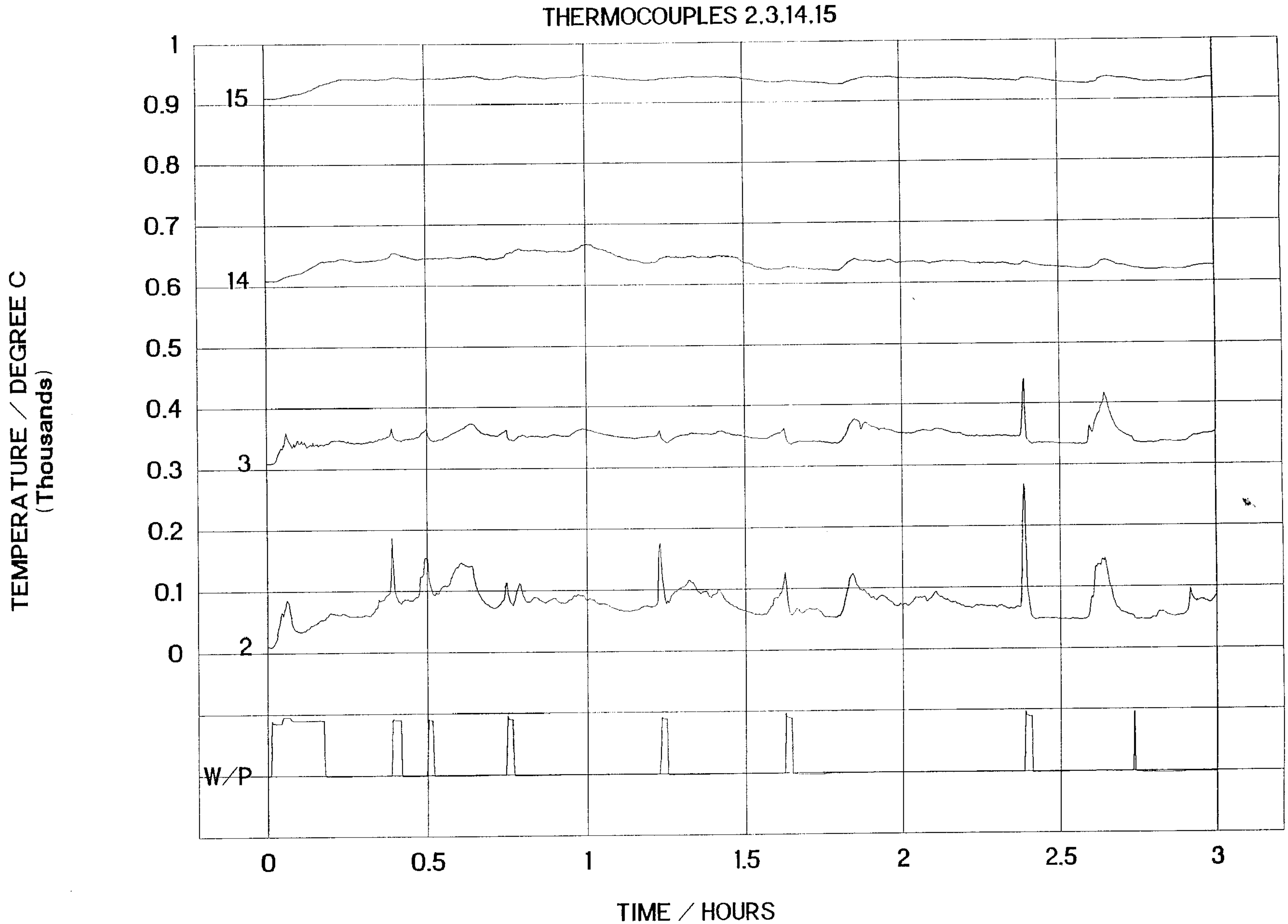


FIGURE 4.65: CAA CARGO BAY TEST NUMBER 17

THERMOCOUPLES 1,10,11

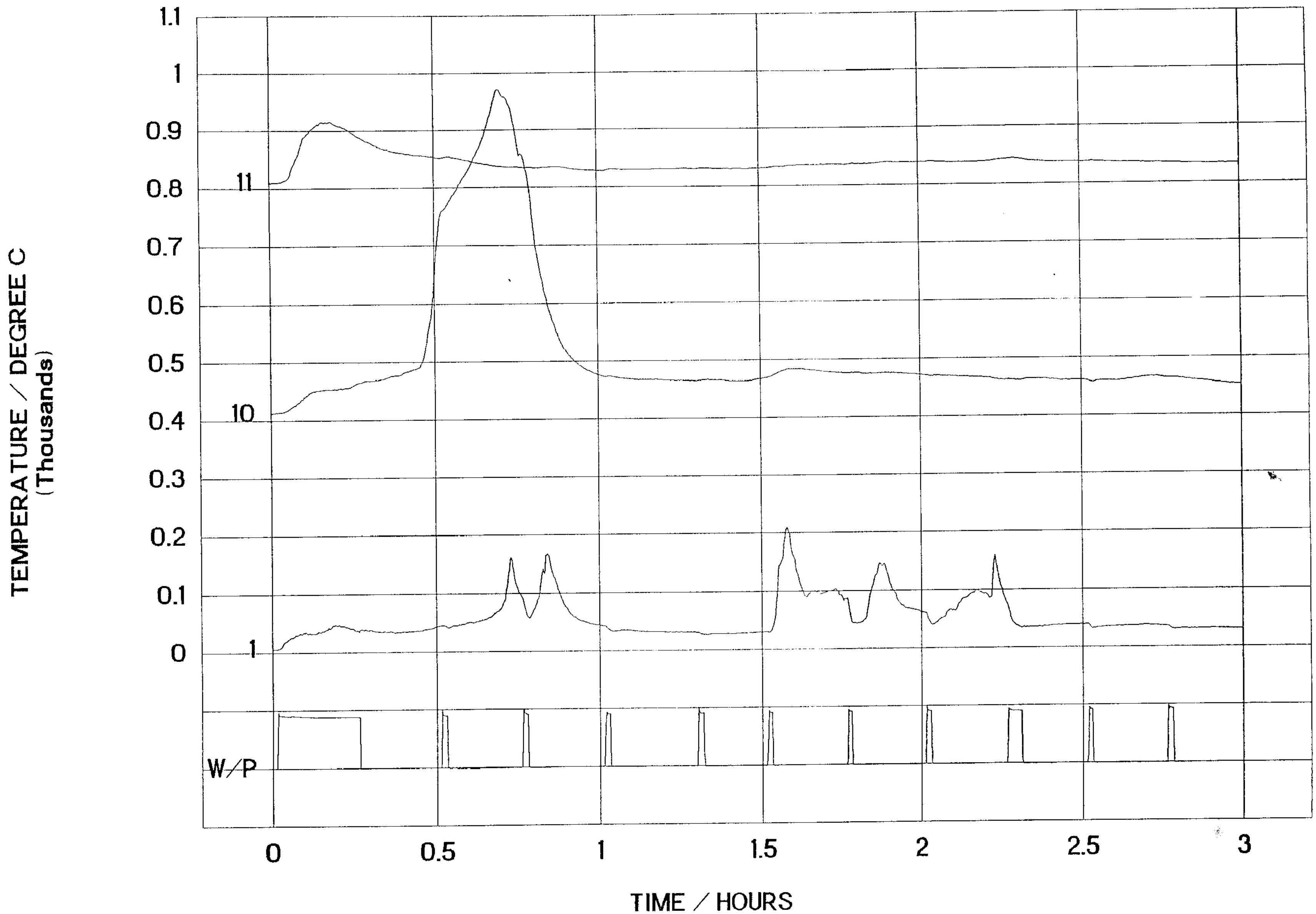


FIGURE 4.66: CAA CARGO BAY TEST NUMBER 17

THERMOCOUPLES 4,5,8,9

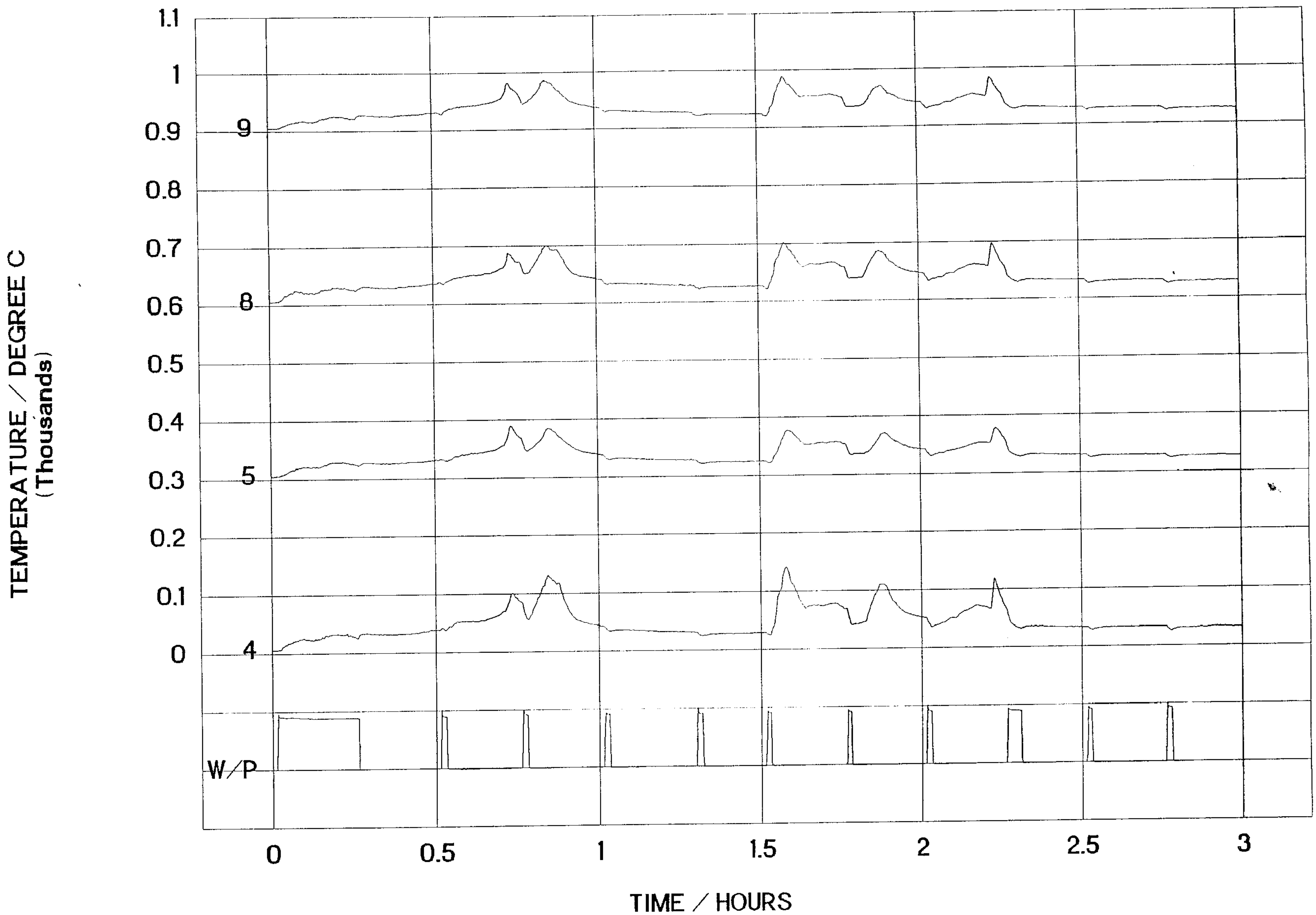


FIGURE 4.67: CAA CARGO BAY TEST NUMBER 17

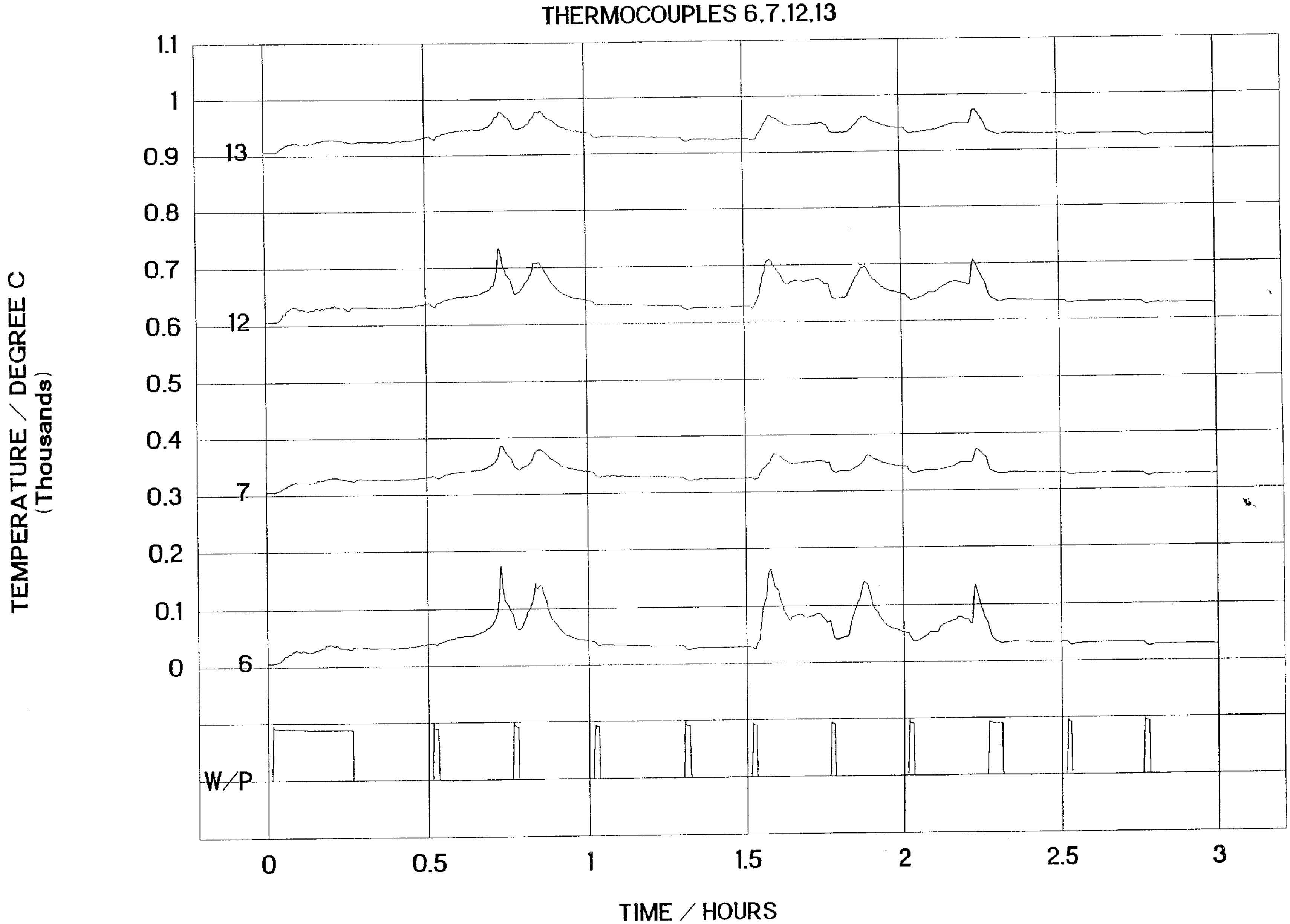


FIGURE 4.68: CAA CARGO BAY TEST NUMBER 17

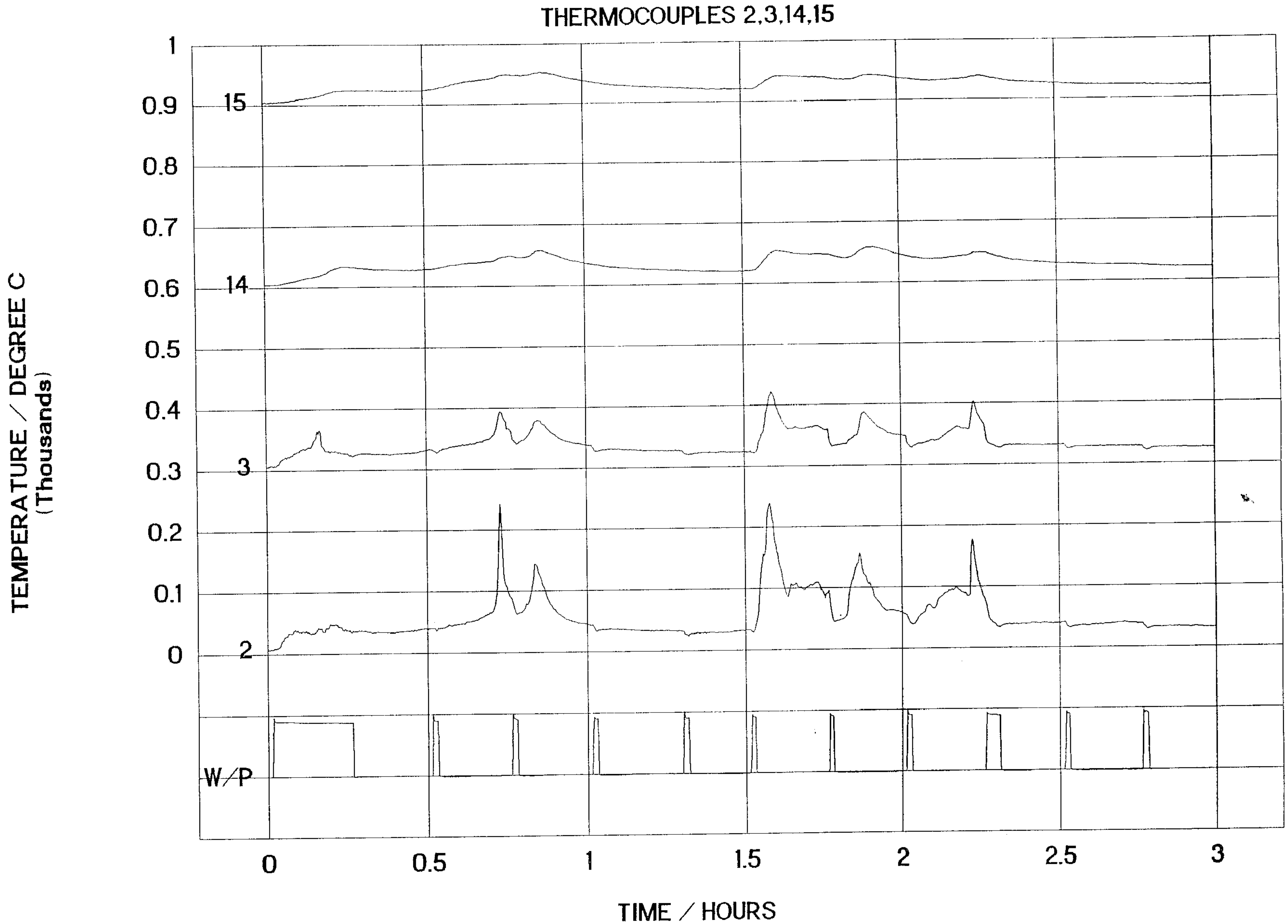


FIGURE 4.69: CAA CARGO BAY TEST NUMBER 18

THERMOCOUPLES 1,10,11

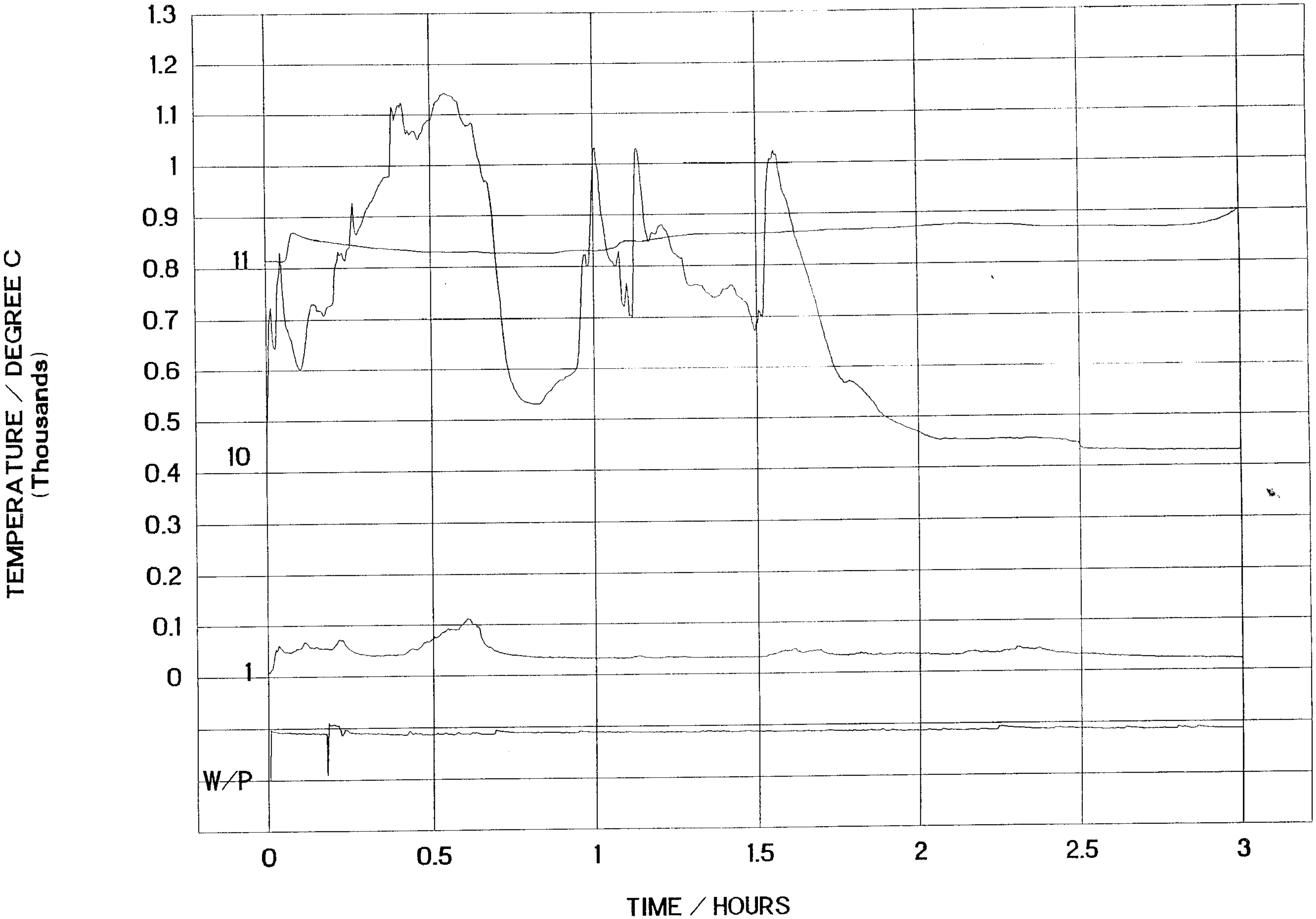


FIGURE 4.70: CAA CARGO BAY TEST NUMBER 18

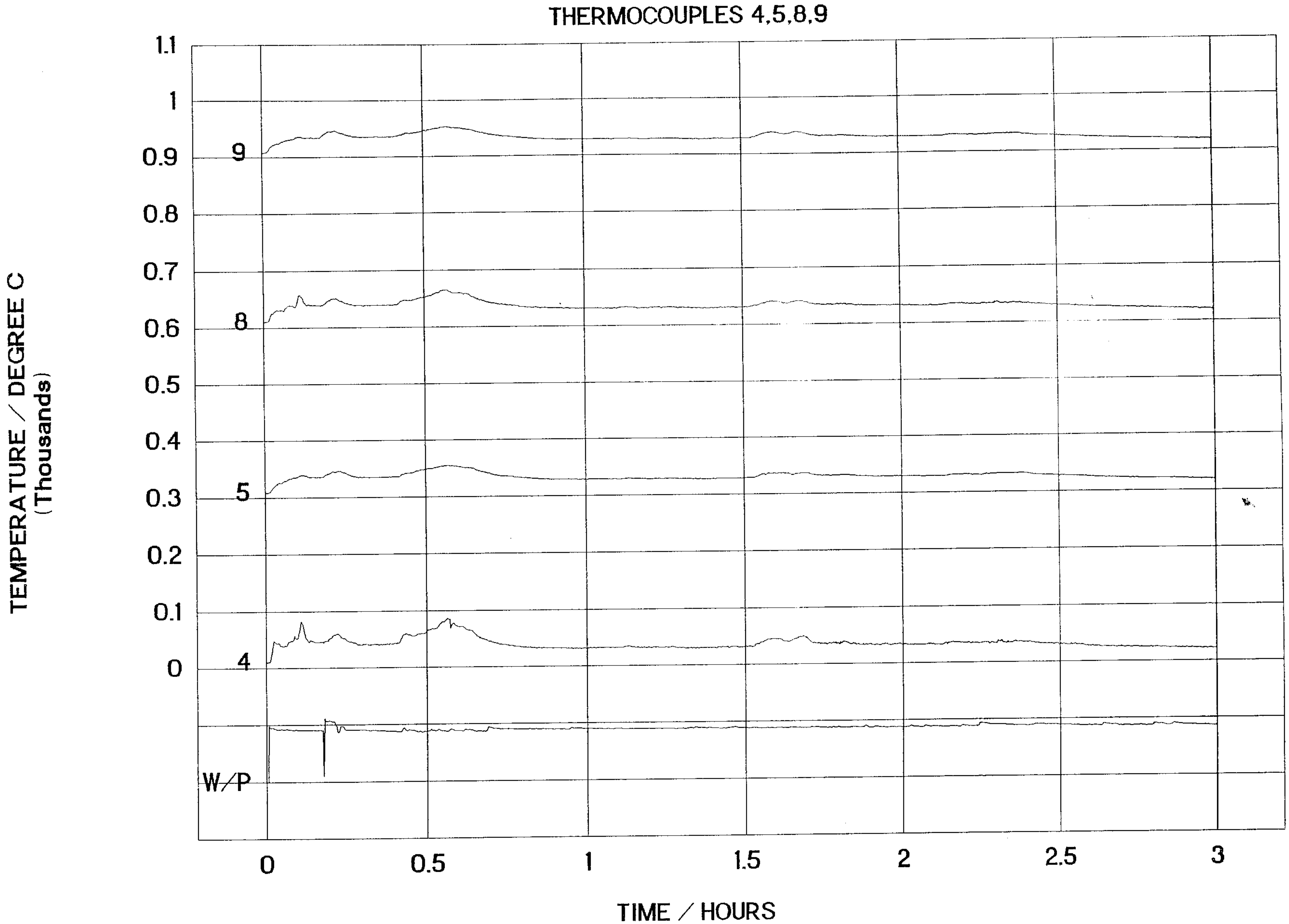


FIGURE 4.71: CAA CARGO BAY TEST NUMBER 18

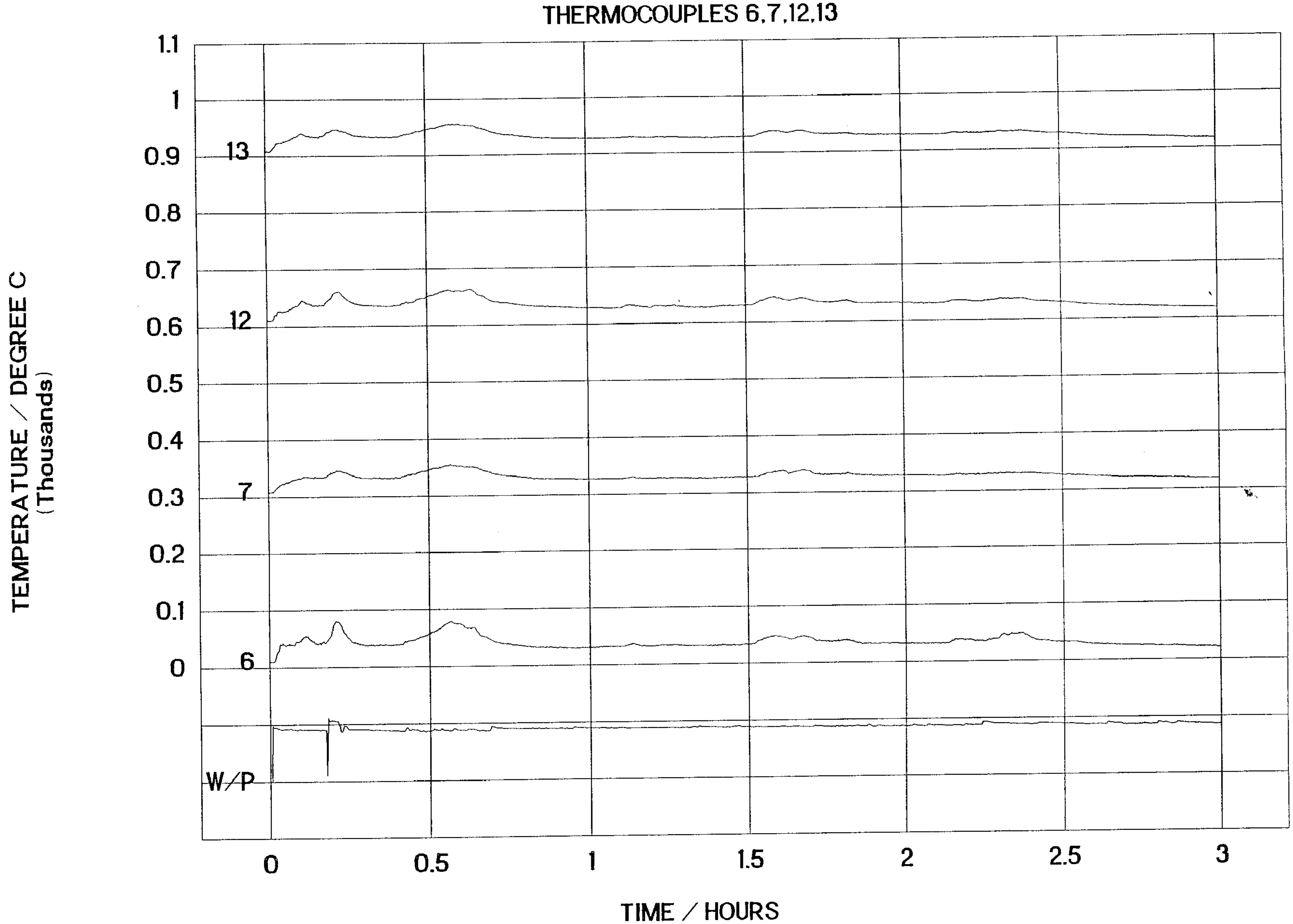


FIGURE 4.72: CAA CARGO BAY TEST NUMBER 18

THERMOCOUPLES 2,3,14,15

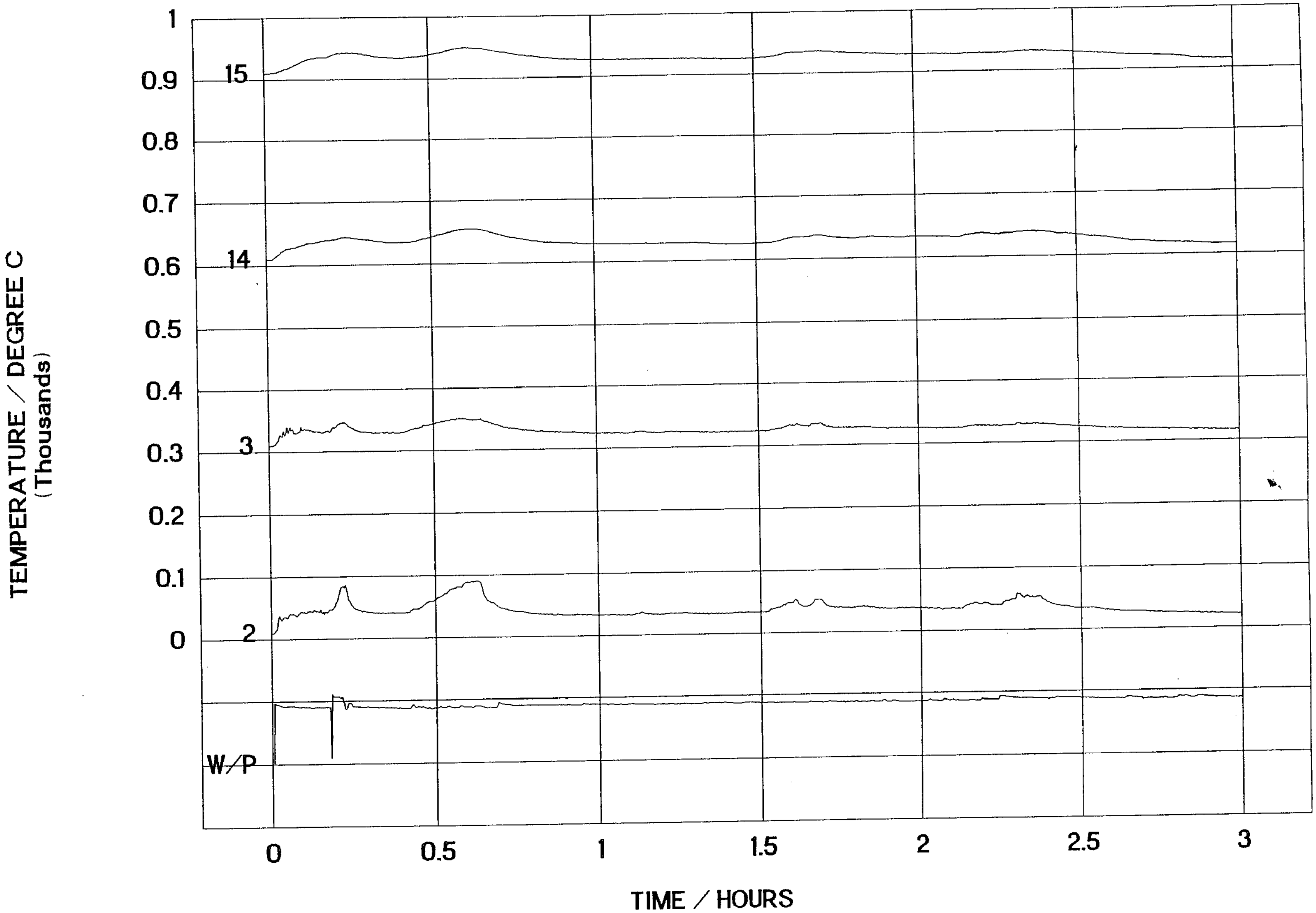


FIGURE 4.73: CAA CARGO BAY TEST NUMBERS 1 & 2

4.4 μm INFRA-RED FLAME DETECTOR

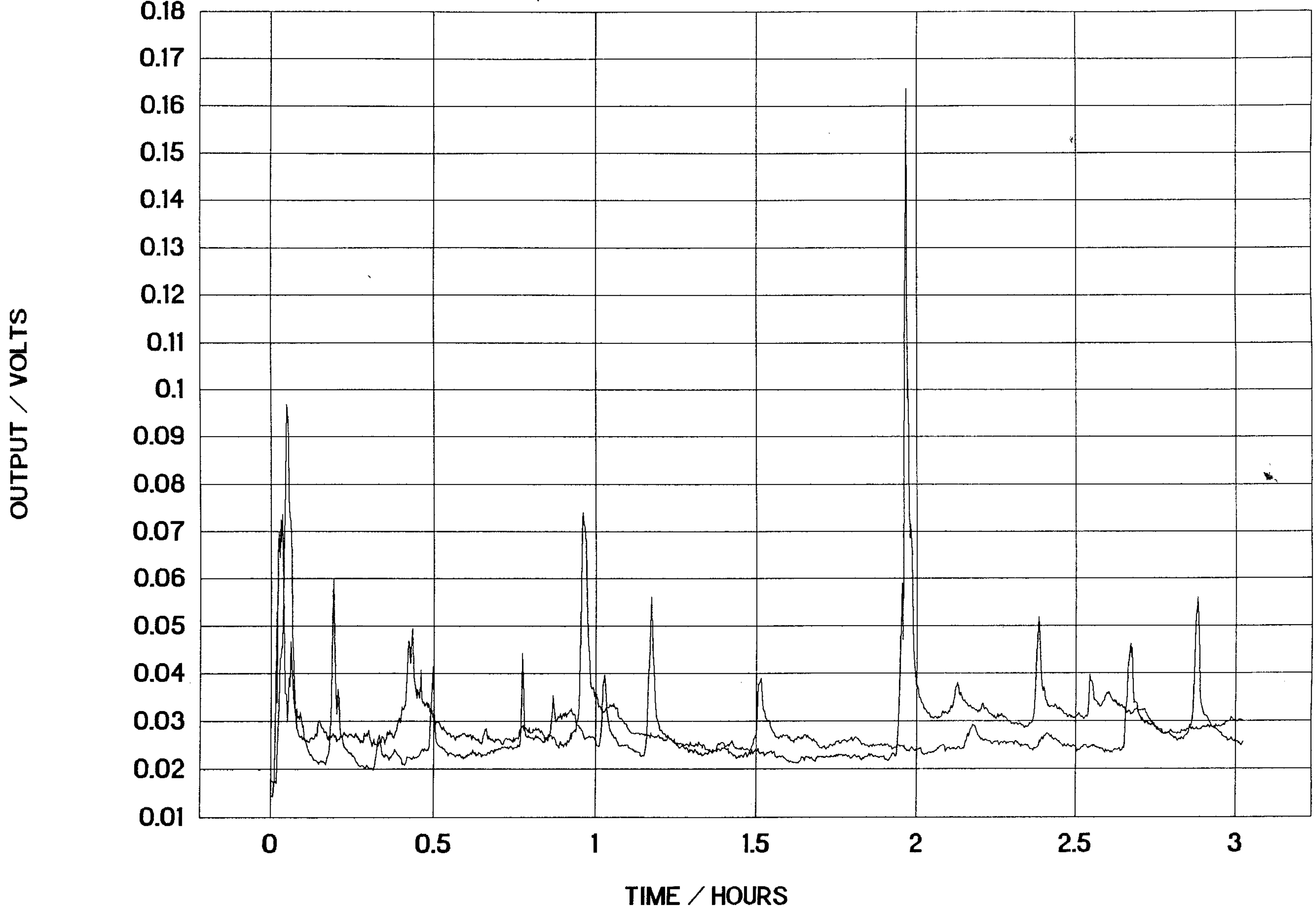


FIGURE 4.74: CAA CARGO BAY TEST NUMBERS 1 & 2

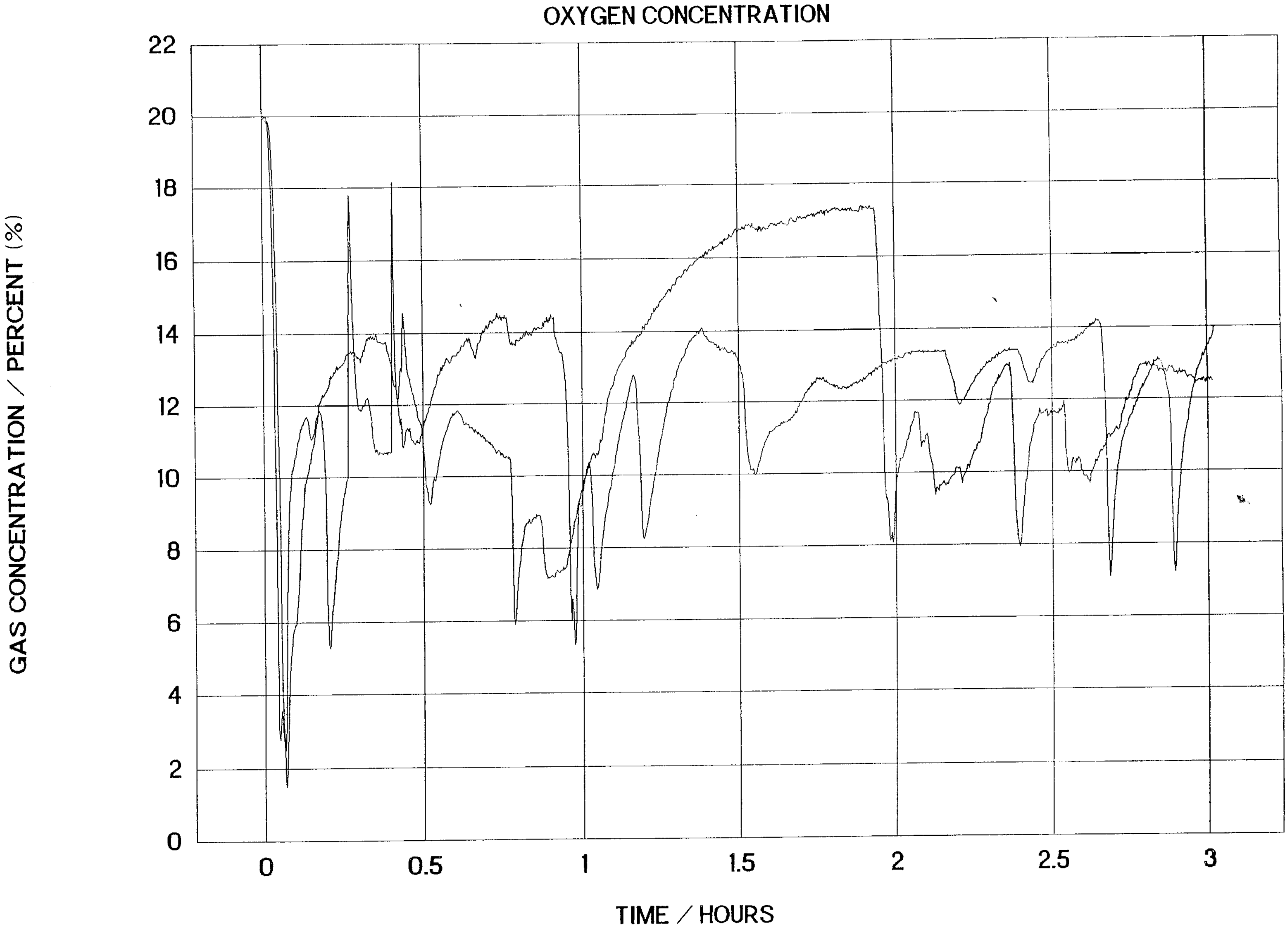


FIGURE 4.75: CAA CARGO BAY TEST NUMBER 1

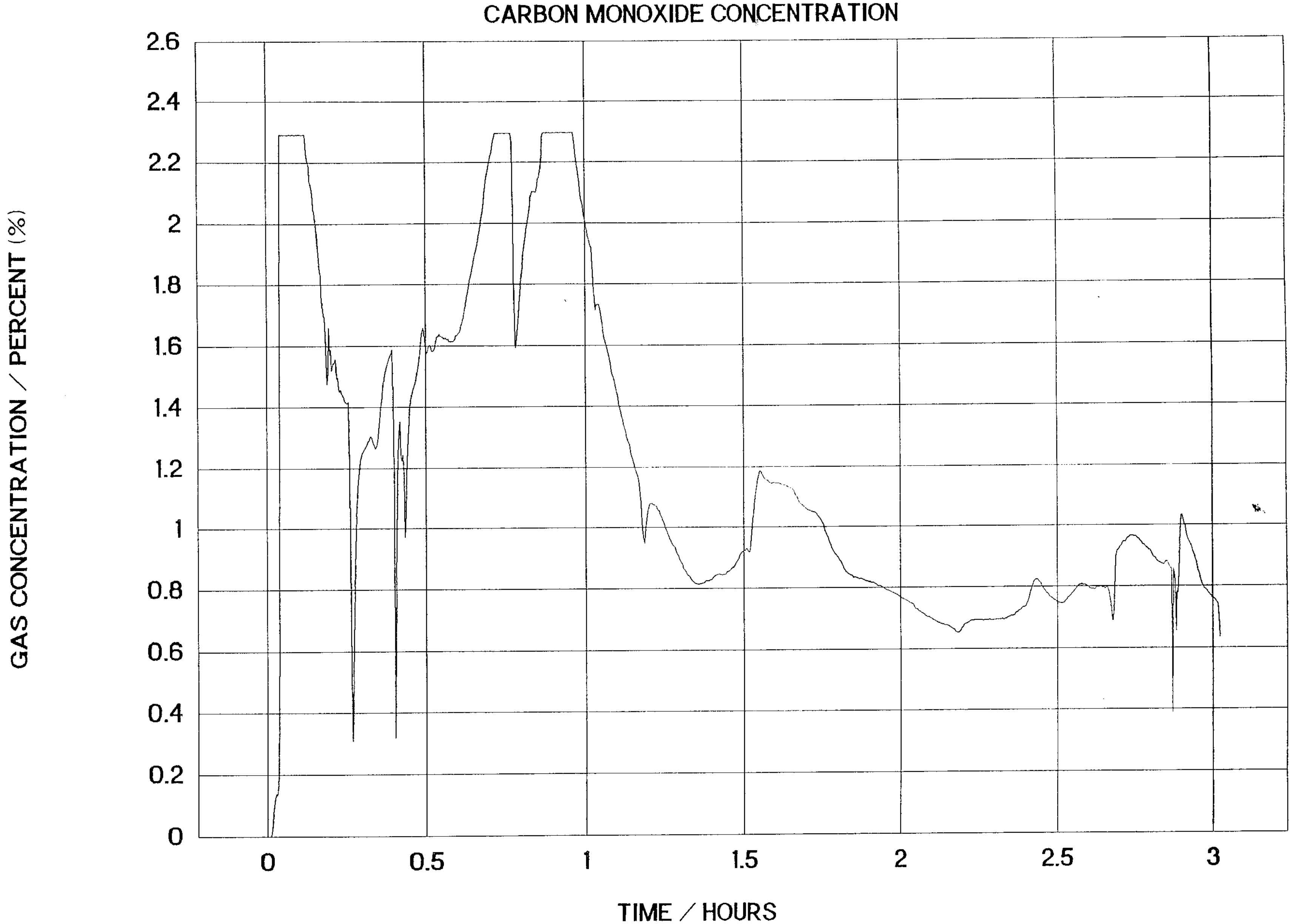


FIGURE 4.76: CAA CARGO BAY TEST NUMBER 2

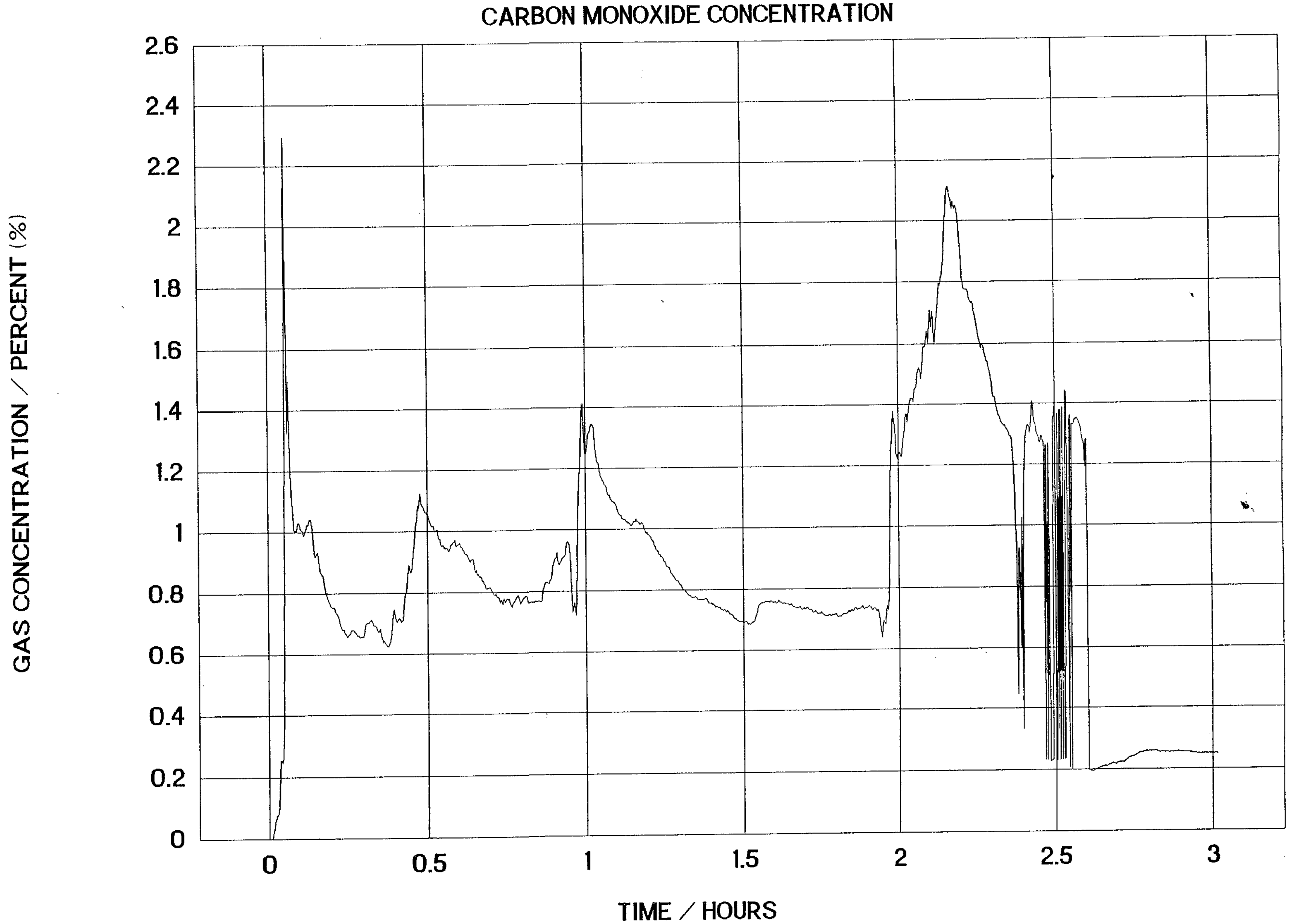


FIGURE 4.77: CAA CARGO BAY TEST NUMBER 4

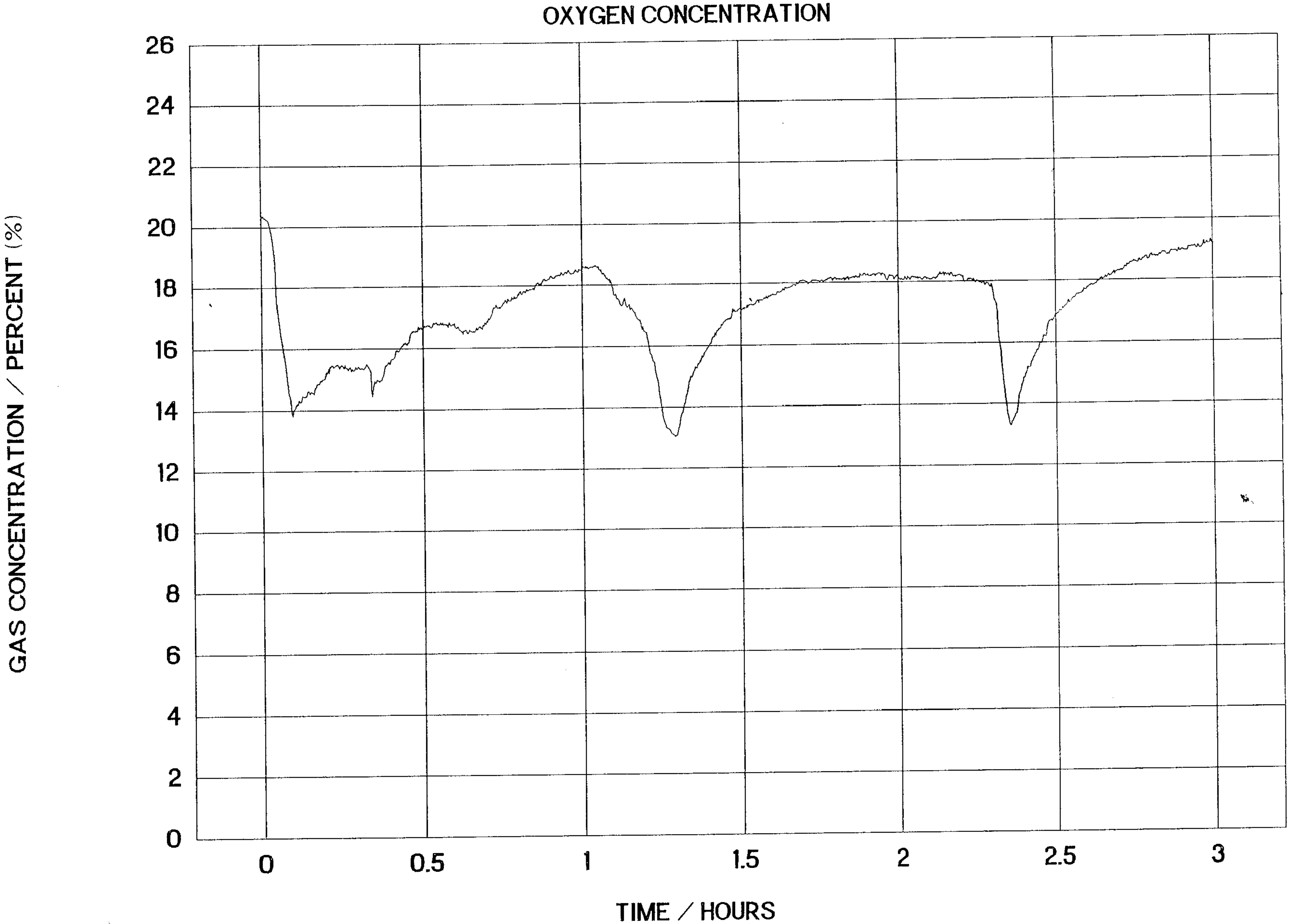


FIGURE 4.78: CAA CARGO BAY TEST NUMBER 11