Mesoscale In Situ Burn Aeration Tests

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Technical Report Series
95-017

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REPORT AVAILABILITY

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CITATION

Suggested Citation:

Nordvik, A. B., J. L. Simmons, J. Burkes, I. Buist, D. M. Blersch, and M. Reed. Mesoscale In Situ Burn Aeration Tests. Marine Spill Response Corporation, Washington, DC. MSRC Technical Report Series 95-017, 116 p.

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Mesoscale In-Situ Burn Aeration Tests

Abstract

In situ burning is currently being investigated as another option and tool for the cleanup of spilled oil at sea. The advantage of in situ burning is significant: it reduces the amount of oil to be collected mechanically, thus reducing costs for cleanup, storage, transportation, and disposal. Since it can be instituted relatively quickly compared to mechanical cleanup, in situ burning can also reduce the potential for spill contact with sensitive marine and coastal environments. However, acceptance of this method has been considerably limited by the concerns and perceptions of the public and regulators about the toxicity of the smoke plume generated by a burn event. Typically, free atmospheric burning of oil results in the generation of large amounts of thick, black smoke, a sign of incomplete combustion due to a limited supply of air to the center of the burn. Although a limitless quantity of air is available surrounding a burn column, not enough is convected to the center of the column for combustion to be complete.

On June 26-30, 1995, MSRC conducted mesoscale burn tests to determine the effects of the introduction of compressed air within the burn column on soot and smoke formation. The approach taken in these experiments was to test two air delivery systems: a steel pipe air jet aeration system, in which a system of nozzles was used to inject air at high velocities within the burn column; and a submerged PVC pipe bubbler system, which injected air from underneath the burning oil slick in the form of air bubbles.

The tests were successful in proving the principle on a large scale that less than the stoichiometric ratio of air, injected strategically into the center of a burn column, can significantly reduce the production of smoke. The most successful air jet burn was test number 13 at zero wind speed. The higher burn temperature (compared to the baseline burn) reduced the burn time. The air jet system, however, was sensitive to wind effects. Smoke reduction was most dramatic when wind had zero velocity; but a slight breeze would cause the flame to move beyond the influence of the air jets, causing more smoke to be produced.

The sub-surface bubbler system reduced smoke considerably over the entire area of the burn section and was very little affected by winds. It created a roiling, bubbling oil surface; this reduced the effective burn area and increased the water being vaporized in the flames, overall slowing the burn rate considerably. In addition, the flame produced was slightly cooler, lower, and less intense.

1.0 Introduction

The Marine Spill Response Corporation (MSRC) is a not-for-profit oil spill remediation organization established by industry to meet the requirements of the Oil Pollution Act of 1990. MSRC has established and supports a vigorous research and development program targeted at improving the equipment and techniques used for oil spill remediation. In the execution of this program, MSRC has worked cooperatively and interactively with a number of U.S. and international organizations to optimize the effectiveness of the limited research resources available.

The Applied Engineering Department of the Research and Development Division of MSRC is conducting research related to improving methods for conducting in situ burning of on-water oil spills. As part of this effort, MSRC has conducted tests on the use of mechanical means to supplement the natural air supply to oil fires to reduce the amount of smoke resulting from a burn. MSRC has continued to support this effort by testing aeration principles based on the introduction of less than stoichiometric quantities of air jetted into the center of the burn column at tangential angles to encourage further air entrainment and by use of a submerged bubbler system.

1.1 Objective

The main objective of this medium-scale aeration test was to prove the principle that introduction of a fraction of the stoichiometric requirement of air via strategically-placed high-velocity jets into the center of the burn column could reduce the production of visible smoke. Further objectives of tests were: 1) to determine if the elimination of smoke during a burn is accompanied by an increase in the free atmospheric burn rate; 2) to determine the effects of variation of operational parameters, such as air discharge velocity, air volumetric flow, and air discharge height, on the combustion process and the production of smoke; 3) to determine the effects of atomized water injection on the combustion process and the production of smoke; 4) to determine the effects of the introduction of sub-surface air bubbles on the combustion process and the production of smoke; 5) to provide practical guidance for the development of a floating system for at-sea testing.

1.2 Background

In situ burning provides an effective and practical alternative for the clean-up of oil at sea provided that burning can take place within the window of opportunity. (Nordvik, 1995) Additionally, in situ burning can result in high rates of oil elimination, reducing the need for collection and disposal.[1] Also, in situ burning is effective in areas of particular logistical difficulty or environmental sensitivity, such as marshlands or arctic ice, where conventional equipment cannot be used.

Despite its advantages, in situ burning has had limited application in the field. This has often been due to public concerns over the possible hazards posed by smoke and soot as well

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[1] Based upon the measured burning rates of oil slicks of varying thickness and diameter, removal rates of approximately 10,000 barrels/hr (1,600 m^3 /hr) can be achieved with a fire area of only about 10,000 m^2 with an efficiency of removal of 90 to 99 per cent. (Buist, *et al.*, 1994, p.4).

as the reluctance of oil industry and maritime interests to intentionally initiate what could become an uncontrolled fire. Ideally, oil oxidizes almost completely to carbon dioxide and water, as long as enough air (oxygen) is provided to the burn. In most large-scale burn situations, however, not enough air is drawn into the fire to supply the oxygen demand of the fire. The burn continues under conditions of 'starved combustion', producing a thick, dense, black plume of smoke composed of partially burned byproducts in particulate (soot) and gaseous forms. Usually equal to 10-15% of the mass of the burned oil, the soot is composed primarily of carbon particulates, although in large-area burns the soot may also contain unburned droplets of oil. Gaseous emissions from a burn include polynuclear aromatic hydrocarbons (PAHs), some of which are carcinogenic, and carbon monoxide and nitrogen dioxide--known toxic gases. Although surface-level concentrations of these emissions usually remain safely below dangerous levels during a burn (Fingas, et al., 1995), the thick black smoke produced in an in situ burn event often appears threatening, eroding the public confidence in the safety of the process. To address public concerns over emissions, research in aeration techniques focuses on supplying sufficient air to completely oxidize burning oil to reduce or eliminate visible smoke and its potentially hazardous components.

1.2.1 Air Jet Aeration

Based on earlier testing by MSRC and on the information and recommendations provided by Mr. Ian Buist of S.L. Ross Environmental Research, Ltd., the approach taken in these experiments was to inject air within the burn column at high velocity, but at less than stoichiometric quantities. Testing by MSRC in December of 1994 introduced the stoichiometric amount of air (approximately 15 lb of air for each lb of oil) at low pressure into the flame's perimeter. Despite doubling the burn rate from 3.0 to roughly 7 millimeters per minute, it was obvious that supplemental air would not mitigate the problem of soot formation. Recent small-scale experiments, conducted by Dr. Franken of the University of Arizona (Franken, et al., 1992), have indicated that less than stoichiometric ratios of air, injected at high velocities at strategic locations within the burn column, can significantly reduce soot formation.

Proper placement of the injected air within the burn column is important to encourage the necessary "leveraging" of the supplied air with additional drafting effects. The physical mechanism to create this leveraging effect is the natural swirling motion attained in combustion columns. A rising column of hot buoyant air tends to develop a swirl component, creating a "fire whirl". The fire whirl encourages the entrainment of additional air from the surrounding atmosphere into the fire column, promoting the mixing of fuel and air within the fire column and increasing the efficiency of the combustion process. This natural tendency for swirling within the fire column can be enhanced by external means. Based on the results of the University of Arizona team, the jets of air in these experiments were oriented to enhance the tangential velocities, and thus the fire whirl, within the burn column.

The extent of the leveraging effect may be quantified by means of a "leverage ratio", a measure of the additional volume of air consumed in the burn for each unit of volume of high velocity air supplied by mechanical means. In SI units, this ratio is given quantitatively by the following formula:

$$\text{Leverage Ratio (LR)} = r \times 10.85 \times (1/p)$$

where r is the burn rate in liters of oil per second, p is the volume of compressed air supplied by an external compressor in cubic meters of free air per second, and 10.85 is the number of cubic meters of air at STP required to completely burn one liter of oil. In English units, this ratio is given by:

$$\text{Leverage Ratio (LR)} = r \times 1450 \times (1/p)$$

where r is the burn rate in gallons of oil per minute, p is the volume of compressed air supplied by an external compressor in cubic feet of free air per minute, and 1450 is the number of cubic feet of air at STP required to completely burn one gallon of oil. Past experiments have achieved leverage ratios of over 100 (Franken, et al., 1992). In this set of tests, up to seven percent of the stoichiometric quantity of air was introduced into the flame column. This small percentage, however, was jetted in at high velocity (approximately 122 m/s) in an effort to produce the desired leverage ratios.

1.2.2 Sub-Surface Bubble Aeration

The use of an underwater plume of air bubbles as a barrier for containment of an oil slick has been documented by previous investigators (Williams and Cooke, 1985). Little, however, has been reported on the effects of sub-surface air bubbles on the combustion process of a burning slick of oil.

When air is supplied from an underwater source, it rises to the surface as a sheet of bubbles, imparting an upward velocity to the surrounding water. As it reaches the water-air interface, the rising plume of water changes direction and flows horizontally along the surface, perpendicular to the centerline of the bubble plume (Williams and Cooke, 1985). The horizontal velocity counters the spreading velocity of the oil. In a quiescent pool, the oil slick may be contained by the bubbles in localized regions of the pool, effectively reducing the burn area. However, the actual effects of subsurface air bubbles on the combustion process (flame temperature, smoke reduction, and burn time) has not been documented.

In this set of experiments, investigation was conducted into the effects of the introduction of sub-surface air into the burn perimeter. A submerged network of perforated PVC pipe injected air in the form of small air bubbles. Observations and measurements were taken to determine if sub-surface air injection reduced smoke or caused any noticeable effects on the combustion process.

1.2.3 Atomized Water Injection

Atomized water (i.e., a fine mist) was injected into the jetted air stream to test its success as an agent in soot reduction. In the high-temperature combustion environment, water molecules disassociate into a positively-charged hydrogen atom (H^+) and a negatively-charged hydroxyl molecule (OH^-). The hydroxyl molecule binds electrostatically to positively-charged carbon molecules, preventing the carbon molecules from adhering to each other to form soot. The maximum amount of water that can be added without having adverse effects on the combustion process is equivalent to 25% of the burn rate of the fuel, a standard amount accepted in the combustion engineering field (Buist, 1995). Thus for a fuel burn rate of 3 mm/min, the approximate burn rate for this series of tests, the corresponding volume of water injected is 9.5 l/min.

2.0 Test Sponsors And Participants

The organizations involved in the test were:

- Marine Spill Response Corporation (MSRC)
- PCCI Marine and Environmental Engineering
- S.L. Ross Environmental Research
- U.S. Navy Supervisor of Diving and Salvage (SUPSALV)
- Southwest Research Institute (SwRI)
- Oceaneering Technologies

The tasks and responsibilities of all participants of the test are described in the following sections.

2.1 Marine Spill Response Corporation (MSRC)

The Marine Spill Response Corporation Applied Engineering Department of the R&D Division sponsored and funded these tests. They provided a Project Manager and funding for:

- preparation of the test plan
- detail design and preparation of the air jet aeration system
- detail design and preparation of the sub-surface bubbler system
- procurement of all necessary materials and equipment
- on site test direction, and
- use of the SwRI test facility.

The MSRC R&D Division also provided use of some instrumentation and video equipment, including a video camera, pitot tubes for calibration of the system, and an infrared camera to measure temperatures.

2.2 PCCI Marine And Environmental Engineering

PCCI was contracted by MSRC to accomplish the following tasks for this series of burn tests:

- develop test plan and test matrix;
- design and develop air injection test apparatus and make modifications as necessary;
- perform flow and thermodynamic analysis on injection apparatus;
- procure all materials to fabricate equipment in accordance with the design specifications for delivery to Cheatham Annex in Williamsburg, VA;
- contract out necessary parts of design for fabrication;
- determine equipment needed for calibration of design and for measuring test parameters;
- provide on-site engineering support during testing;
- coordinate the collection of all data during testing;

- coordinate efforts of all participants throughout planning and testing phases; and,
- prepare summary report on test results and conclusions of aeration burn tests.

2.3 S.L. Ross Environmental Research, Ltd.

S.L Ross Environmental Research, Ltd., was subcontracted by PCCI to accomplish the following:

- provide technical expertise and assistance in development of the test plan and matrix;
- assist in the design and development of the air injection test apparatus;
- perform flow and thermodynamic analysis on the air injection test apparatus; and,
- provide on-site engineering support for test procedures and data collection.

2.4 U.S. Navy SUPSALV

Once the design was completed and all materials were obtained and fabricated, U.S. Navy SUPSALV provided the following support:

- validated all air flows specified in design schematic;
- performed calibration test on system at Cheatham Annex;
- provided air compressor specified in design (for calibration testing only);
- monitored tests at SwRI test facility using specified instrumentation and provided on-site support during testing.

2.5 Southwest Research Institute (SwRI)

Southwest Research Institute was responsible for the following tasks:

- provide access to the test site and test tank used in previous MSRC burn tests
- set up the test apparatus and equipment at the test site
- prepare additional sections of the site safety plan for communications, fire protection, emergency evacuation, etc. in preparation for the testing event
- provide support to change test equipment configuration (i.e., nozzles) when specified
- secure the burn permit
- prepare and provide waste disposal and site rehabilitation plans to MSRC
- provide water and diesel fuel for burn tests
- provide access to electrical power as needed to support data acquisition efforts
- provide compressors, manifold and interface connections to air jet aeration system design
- provide limited on-site storage capacity for equipment between test days
- make arrangements for proper disposal of any waste products created during testing, including site remediation and rehabilitation as needed or required by regulatory authorities
- provide an on-site safety/test engineer to assist in burn tests and ensure the safety of all personnel involved in testing, and
- provide engineering support to interpret the results and recommend modifications in test parameters after review of preliminary test results.

3.0 Test Equipment And Setup

The test site was located in D'Hanis, Texas, at the Southwest Research Institute's Department of Fire Technology Remote Test Site. This site was the same one used for testing in December, 1994 by MSRC for mesoscale diesel fuel burn experiments. The facility is approximately 10 miles from D'Hanis on the property of the Parker Creek Ranch. A complete schematic of the test area is shown in figure 3.1 and described in the sections below.

3.1 Burn Tank

All tests performed at the SwRI D'Hanis test facility were conducted within an existing steel burn tank: a 7.6m x 7.6m tank, 61 cm deep, with a 76 cm cofferdam to protect against a spill. During the test, the tank was filled with water such that the surface of oil was approximately 10 cm below the rim of the tank. A 4.2 m square section in the center of the tank was used for testing purposes. This section was separated from the rest of tank using a frame of wood and galvanized steel flashing for fuel containment and fire protection. This frame was anchored to remain at the surface of the water, providing a barrier to contain the oil within the test section. The cofferdam surrounding the test tank provided a supplemental spill barrier in case of tank rupture or overflow.

3.2 Prototype Air Jet Aeration System

The air jet aeration system was centered inside the test section described above, as shown in Figure 3.2. The function of this system was to provide a high velocity air stream into the burn at a velocity of up to 113 m/s. ft The system consisted of a below-water network of standard 1 1/2 in. diameter steel piping, which was leveled and tack-welded to the bottom of the tank using flat bar iron stock. The piping network delivered air into the burn test section at five riser locations: one placed in the center of the test section, and four others placed roughly equidistant from the center and each of the corners of the test section.

Two Ingersoll-Rand Model P-1600-W-CV air compressors supplied the air to the system through 100 ft of 3 in diameter industrial rubber air hose. Each compressor had a delivery rating of 45.3 cubic meters per minute at 7 bar at 1800 RPM; the pressure and capacity of the delivered air could be varied by varying the RPM of the compressors.

Above water, each riser terminated in a nozzle assembly, which could be interchanged with various sized nozzles to control the air flow velocity. The system was designed such that the riser components above the water line could be interchanged and varied between test runs, allowing for variability of control parameters such as nozzle height above water, nozzle diameter, and angle of nozzle direction about a vertical axis. In the original baseline riser configuration, the nozzle on the center riser of the network was mounted perpendicular to the water surface, while the four peripheral nozzles were angled 30 degrees from the vertical. Originally, these four were angled along tangents to an imaginary circle centered at the center of the test section to encourage cyclonic velocities and to enhance the fire whirl. The height of the nozzles above the waterline was set at 0.9 m for the baseline configuration, and could be varied at discrete heights between 10 and 180 cm to determine the effects of height on the burn efficiency and smoke reduction.[2]

Nozzles with diameters of 12.7 mm, 9.5 mm, and 6.4 mm were provided for each riser. The nozzles were fabricated to provide specified air velocities at predesignated compressor air flow rates and pressures. At the maximum air volume delivery of 1400 l/s, the velocity of the stream of air from each of the nozzles would be 113 m/s.

The nozzles were constructed of stainless steel to protect them from damage from the high temperature environment. All riser joints and connections above the waterline were insulated with heat and flame-resistant fabric to prevent warping and other damage from the high temperature environment.

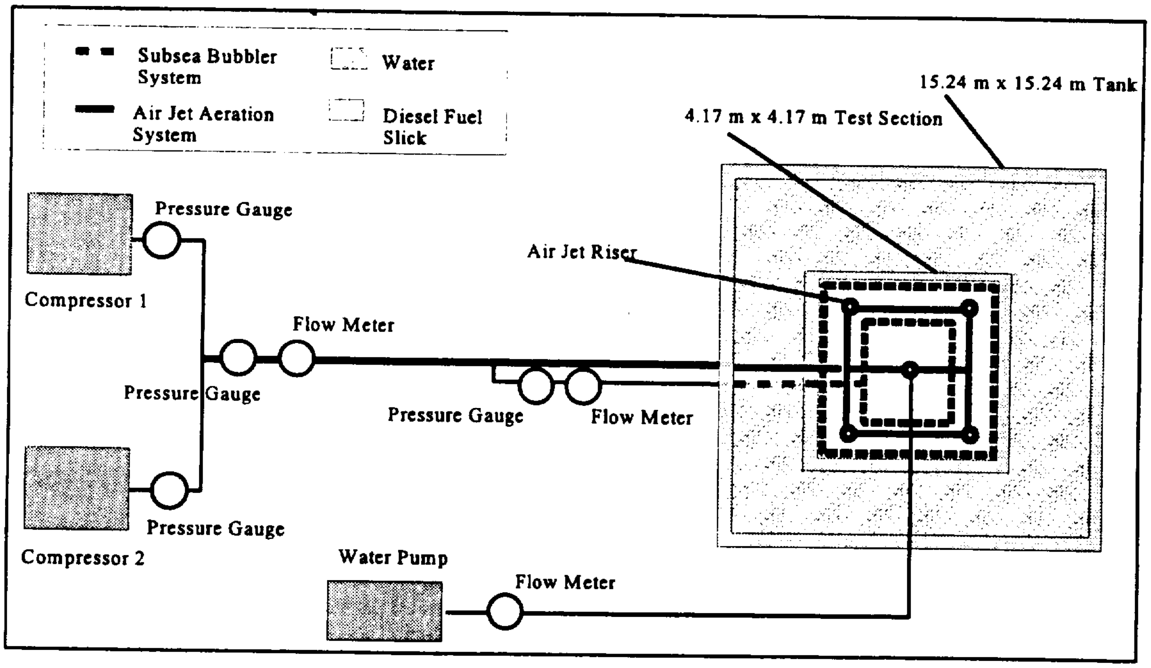

Figure 3.1: Schematic of test assembly and area

3.3 Water Injection System Description

Water was injected into the air stream in each riser just below the water line. The water was supplied by a positive displacement diaphragm pump, controllable from a safe distance from the test pan. The pump took suction from an external holding tank. The water flow rate could be varied by a ball valve and pressure relief valve at the pump discharge, with a maximum possible flow rate of 9.5 l/min for the pump, or 1.9 l/min per riser. The pump supplied water through a 13 mm diameter high-pressure rubber hose which connected to a 13 mm diameter pipe through the wall of the test pan. Inside the test pan, the high pressure rubber hose split at a manifold into five 13 mm diameter rubber hoses, one running to each riser. At each riser, the hose connected to a 9.5 mm diameter steel pipe connected to a tee on the riser just below the water line. Each pipe was equipped with a high pressure ball valve to

[2]Experiments conducted by Dr. Franken at the University of Arizona utilized injection nozzles approximately 1 meter (3 feet) above the oil surface (Buist, et al. 1994, p.145). Thus the height variation for this test series was planned for 0.45m to 1.82 m, using Dr. Franken's height parameter as general guidance.

individually vary the water flow rate to each riser, and with a high pressure check valve to prevent the high pressure air in the riser from entering the water supply line. Because of the high velocity of the air flow in the riser, the water was atomized upon entering it and was ejected with the air stream from the nozzle ends as a fine mist. A volumetric flowmeter was attached in the water delivery line near the pump discharge to measure the flow rate of water supplied during each test.

3.4 Sub-Surface Bubbler Aeration System

To supply sub-surface air bubbles, a secondary network of 3.81 cm diameter PVC pipe was constructed. The PVC network had 5 mm holes drilled with a 30 cm spacing along its length. In the original design, the PVC network was the same dimensions as the air jet aeration piping network, forming a rectangle centered in the test section with its sides midway from the center and the perimeter of the test section. The PVC network rested on top of the air jet piping, and was anchored to it with plastic strappings, as shown in figure 3.3.

After testing began, it was decided that more than one bubbler configuration should be tested. A second PVC network was constructed and installed in the test section. This second network had similar hole size and spacing as the first, but it was installed around the perimeter of the test section. The air supply hose for the bubbler system was a 3.81 diameter high pressure rubber air hose, 15 m long: it was spliced into the main 7.6 mm air hose with a tee. A ball valve at the connection point allowed for control of the air flow to the bubbler system; air could be directed to the bubbler system only, to the air jet aeration system only, or to both simultaneously.

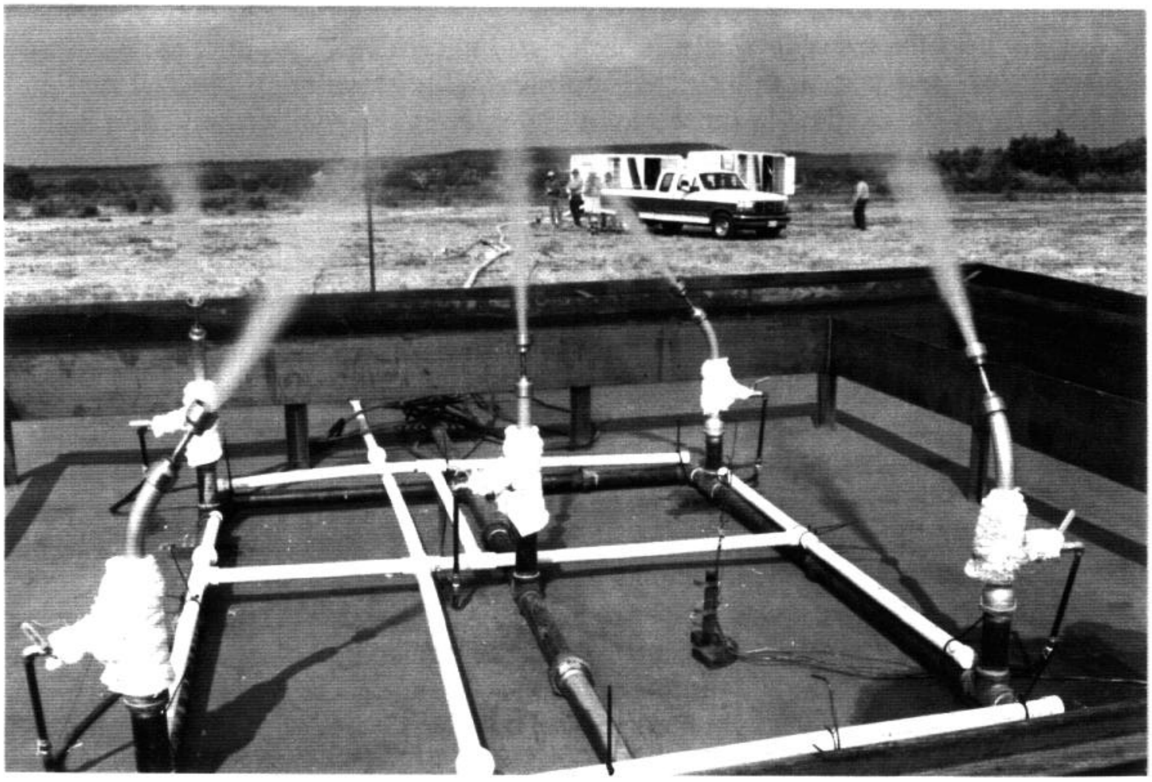

Figure 3.2: *Air jet aeration system*

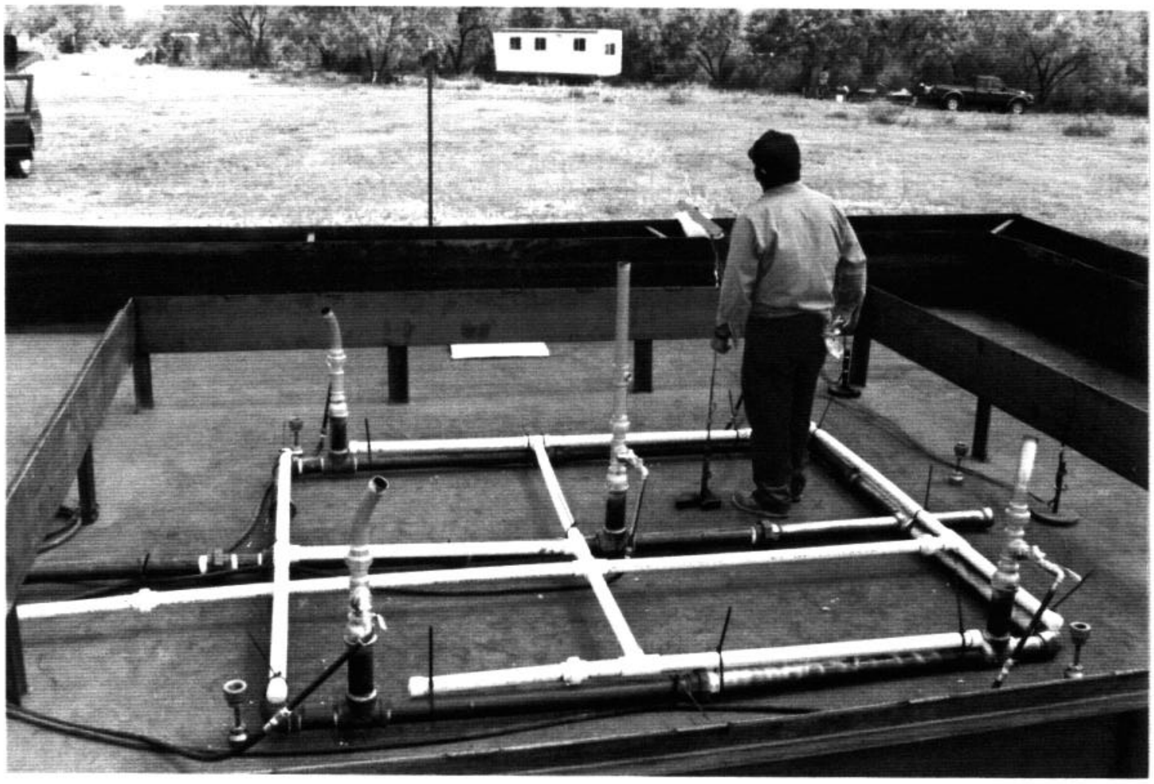

Figure 3.3*: Sub-surface bubbler system*

4.0 Instrumentation And Data Collection

4.1 Flow And Pressure Meters

The air flow rate provided by the compressors was one of the primary control variables for the tests, affecting the rate of air supply to the burn and the exit velocity of the air at the nozzles. Thus air flow meters were inserted in the air supply lines: one was placed at the discharge side of the compressor manifold (at the inlet side of the large air hose), and another was placed at the inlet side of the air supply hose for the subsurface bubbler system. Both meters measured volumetric air flow in standard cubic feet per minute (scfm), which could be converted to actual cubic feet per minute (acfm) using a correction factor determined in earlier calibration of the air delivery system. Both meters were regularly monitored during all tests to verify maintenance of the specified control parameters.

Pressure gauges were installed at the discharge side of each of the compressors, at the discharge side of the compressor manifold, and at the inlet side of the air supply line for the bubble aerator.The air pressure was monitored regularly during all testing to ensure maintenance of control parameters, and to ensure that the pressure did not exceed the limits posed by the hoses and fittings.

A flow meter was attached to the discharge side of the water pump to readily gauge the water flow rate. Flow rate measurements were taken from this meter at the beginning of each test run utilizing the water delivery system. Locations of all flow and pressure meters are shown on figure 3.1.

4.2 Smoke Production Measurement

The primary objective of this series of tests was to validate the principle that aeration of a burn could produce a noticeable reduction in smoke. Hence, no quantitative data collection was planned to measure smoke reduction. Rather, smoke reduction was assessed qualitatively by designated data collectors and observers. It was assumed that the reduction of smoke would be dramatic enough to be visibly detectible to the naked eye. The method of observation is based on the method described in 40 CFR Part 60, Appendix A, Method 9, "Visual Determination of the Opacity of Emissions from Stationary Sources". An initial burn without adding air was performed to establish a benchmark against which smoke production of subsequent burns could be compared.

4.3 Temperature and Pressure Gages

An infrared temperature monitoring device was provided to take readings at various elevations in the burn column. Past experiments indicate that the temperature increases with increasing elevation above the waterline, with temperatures ranging from 950-1200°C within the burn column.

Twelve thermocouples were installed to measure the temperature in the flame perimeter during each of the tests. The thermocouples were placed within the test section at four elevations at three separate locations, the same as those used in the prior MSRC burn test in December, 1994. The placement locations were the midpoint of one edge of the test section, the middle of the test section, and near one corner of the test section (refer to figure 4.1). The elevations at each of these locations were 15 cm above the oil surface, 5 cm above the oil surface, at the oil surface, and at the oil-water interface.

4.4 Burn Rate and Oil Measurements

The burn rate for diesel fuel oil is well established from many recent tests.[3] The nominal free air burn rate for the diesel fuel in this test tank was approximated at 3.0 mm/min, which equates to 52.9 l/min for the dimensions of the test tank section. A complete 10 minute test run thus required at least 529 l of oil. The depth of this oil was 3 cm on the surface of the water for the test tank section dimensions. Stopwatches were used to time the length of the burn, from which an average burn rate could be calculated.

4.5 Atmospheric Conditions Measurement

Weather instruments were provided to measure the temperature, barometric pressure, and relative humidity of the ambient air. Wind direction and speed were also measured.

4.6 Air Entrainment Flow Measurement

Qualitative measurement of air entrainment flow (i.e., the flow of the air surrounding the burn column) was attempted during the series of tests. For this measurement, fire-resistant ribbons attached to rods were positioned at the midpoint of each side of the test section, at a distance of one fire diameter from the test tank (4.7 m.)[4] Data collectors noted the direction of the air flow (if any) in the vicinity of the burn column by observing the activity of the ribbons.

4.7 Video And Photography Equipment

A video camera was used to document the tests and smoke plumes during burning. A Thermal Imaging Camera was used to produce real time images of thermal gradients within the burn column.

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[3]The burn rate for diesel fuel in a pool of infinite diameter is 3.5 mm/min. In a pool with finite diameter, the burn rate is approximated by the equation:

$$m'' = 3.5\ (1-e^{-D})$$

where m" is the burn rate in mm/min and D is the pool diameter in meters. (Buist, et al. 1994.50.)

[4]The equivalent fire diameter is found by equating the fire area to the area of a circle, and solving for the circle diameter ($A=\pi d^2/4$). The area of the test tank is 17.35 m^2 (186.8 ft^2); thus the equivalent diameter is 4.7 m (15.4 ft).

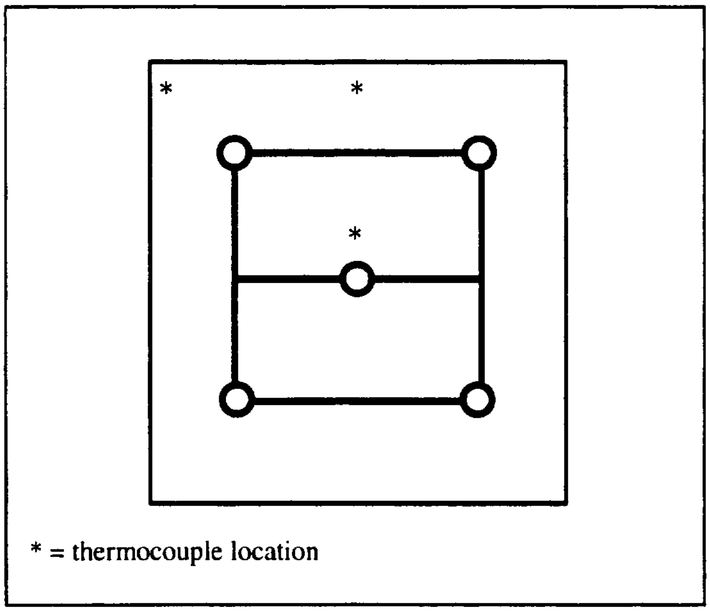

***Figure 4.1**: Location of thermocouples in test section of tank*

5.0 Test Procedures

The tests were conducted over a three day period from June 27 to 29, 1995. A series of 15 burns were performed, with control parameters varied on each burn. Prior to shipment to the test site, the piping equipment and the water delivery system for the air jet aeration system were preassembled, calibrated, and tested. After shipment to Texas, the system was assembled in the test tank and tested again just prior to burn testing.

The PVC network was assembled and installed on top of the air jet piping in place in the test section. The second bubbler network around the perimeter of the test section was decided upon after testing had already begun. This network was assembled outside the test tank and installed in the test section on the second day of testing. After all equipment was in place in the test section, the entire test tank was filled with fresh water such that the water surface was approximately 10 cm below the top of the walls. This water remained in the test tank throughout the entire test sequence.

For all burns, diesel fuel oil #2 was used because of its relative availability and ignitability. It was decided by the testing team that a burn length on the order of 10 minutes would be ideal for data collection. Based on the estimated burn rate for diesel fuel for the dimensions of the test tank (see Section 4.4), at least 529 liters of fuel would be necessary for a 10 minute burn. For most of the tests, 600 liters of diesel were used, producing a 35 mm thick slick on top of the water in the quare test section. The last two burns (burns 14 and 15) used only half as much fuel because of the slower burn rate due to the bubblers being tested.

5.1 Procedure for Each Burn

Each burn was performed using the same general procedure. After the control parameters to be tested were decided upon by the test coordinators, a worker installed the above-water riser and nozzle components specified. All ball and gate valves were checked to ensure air was supplied to the specified delivery system (either the air jet or the bubbler system). Once set-up operations were complete, the diesel fuel was measured into the test section, and formed a slick on top of the water.

After verification that all personnel were at a safe distance, the slick was ignited. Since the ignition technique would have no effect on the outcome of the burn, various ignition techniques were used throughout the series of burns. Three burns were ignited using a flare-type igniter being tested by U.S. Navy SUPSALV. Another burn was ignited using a floating electronic torch mechanism designed by Oceaneering Technologies (See Appendix C) and sponsored by MSRC. All other burns were ignited using a gasoline-soaked sorbent pad. Once the flame spread from the point of ignition to the entire area of the slick (up to two minutes time from the moment of ignition), the compressors were started and set at the RPM corresponding to the desired air flow rate. If water was to be injected, the water pump was started. The burn was allowed to proceed uninterrupted until all the fuel was used up in the combustion. Extinction of the flames occurred readily and without outside interference or fire control.

5.2 Monitoring and Data Collection for Each Burn

5.2.1 Environmental Conditions

Prior to each burn, the environmental conditions were noted: in particular, the temperature, barometric pressure, relative humidity, and wind direction and approximate velocity were measured and recorded. Table 5.1 summarizes the environmental conditions during each burn.

Table 5.1 Ambient air conditions during burns

Test Day	Time	Burn No.	Air Temp. °C	Bar. Pressure bar	Rel. Humid.	Max.Wind Velocity m/s	Wind Direction
1 27 Jun 95	1100	1	27	1.016	75%	1.3	S
	1430	2	31	1.015	61%	2.5	E
	1600	3	33	1.015	50%	3.5	SE
2 28 Jun 95	0930	4	27	1.014	81%	1.5	S
	1000	5	29	1.014	72%	1.8	S
	1045	6	30	1.014	66%	1.8	S
	1228	7	32	1.014	53%	1.8	S
	1600	8	37	1.013	36%	2.8	SSE
	1658	9	38	1.011	35%	3.8	SE
3 29 Jun 95	0820	10	23	1.010	82%	1.3	NW
	1002	11	27	1.012	67%	2.3	NW
	1116	12	28	1.012	72%	2.8	NW
	1330	13	31	1.014	55%	2.0	WNW
	1625	14	35	1.013	50%	1.5	SE
	1720	15	31	1.012	64%	3.8	E

The most important environmental condition for this series of tests was the wind speed and direction. For most tests, the wind speed remained light, and probably had some but not substantial effect on the outcome of the burns.

5.2.2 Air And Water Flow Control

When the compressors were started, the flow rate and pressure in the air delivery hoses were noted and recorded. If water was being injected, the water flow rate was also noted and recorded.These meters were monitored periodically throughout each burn to ensure the prescribed test conditions were maintained.

5.2.3 Flame And Smoke Characteristics

The dependent variables measured for all burns were:

- burn rate
- flame temperature.

Stopwatches were used to time the length of each burn. These times were used as an indication of the fuel burn rate. Times were noted for each burn for the time from ignition to steady full-area burn; for the inception of the vigorous burn phase; for the inception of the extinction phase; and for complete flame extinction.[5]

Observers were designated to watch the flames and smoke during each burn and record their observations in comparison with a benchmark burn without air introduction. Video equipment was also used to record each burn for later analysis and comparisons. A thermal imaging camera was used on each burn to record the approximate flame temperatures. Temperatures within the fire perimeter were taken at each of the thermocouples every 10 seconds; this data was recorded electronically using a data logger.

5.3 Independent Variables And Control Parameters

The independent variables for the series of burns were:

- **Air Delivery System**: Air could be delivered into the test section perimeter either by the air jet aeration system, the sub-surface bubbler system, both systems, or neither.
- **Air Volumetric Flow Rate**: The volumetric flow rate of the air could be manipulated by changing the compressor RPM and measured with the flowmeters installed on the discharge end of the compressor manifold.
- **Nozzle Exit Velocity (Air Jet Aeration System only)**: For any given flow rate, the air stream velocity at the nozzle exits could be changed by installing nozzles of different diameters; a smaller diameter nozzle would cause an increase in the exit velocity.

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[5]From the time of ignition until complete extinction, a burning oil slick will go through various phases, each of which is visibly detectable. Ignition occurs in a small, localized area, and a certain time is required for the flame to spread to the entire surface area of the slick. Once this occurs, the burn enters a steady combustion phase for a time. The vigorous burn phase is reached when the burning slick has thinned, allowing enough heat to transfer to the water below to start it boiling; the generated steam vigorously stirs up the remaining oil, increasing the burn rate, flame height, and radiative output. Rapid extinguishing then follows (Buist, et al., 1994).

- **Nozzle Exit Height (Air Jet Aeration System only)**: The height of the nozzle exits above the oil slick surface could be changed by installing riser components of different heights.
- **Nozzle Exit Orientation (Air Jet Aeration System only)**: The orientation of the nozzles about a vertical axis could be changed by turning the nozzle in the desired direction.[6]
- **Water Introduction (Air Jet Aeration System only)**: The introduction of water into the air supply was controlled by varying the speed of the water pump during the burn.

The original test plan included testing at three nozzle heights, three exit velocities (nozzle diameters), and three air flow rates. However, the first day of testing showed that some independent variable settings were considerably better than others (for example, all three nozzle heights planned for testing were shown within the first few tests to be too high to be effective). Hence, most independent variable settings were selected by project management according to trial and error in an attempt to focus in on the optimum parameters for operation. Table 5.2 gives the testing schedule over the three days and the independent variable settings for each burn run.

[6]The four peripheral nozzles were canted 30° from vertical; rotation of these nozzles about an axis perpendicular to the oil surface could produce various effects on the fire whirl and air entrainment. The baseline design for the system aligned these nozzles at a 30° angle to a radius drawn from the center nozzle, all facing counterclockwise to encourage cyclonic velocities.

Table 5.2 Schedule of burns and independent variables

Test No.	Oil Vol. l	Air Delivery System*	Calc. Air Flow** m3/min	Water Flow l/min	Nozzle Height cm	Nozzle Diam. cm	Nozzle Orien-tation†	Comments
1	606.2	none	0	0	n/a	n/a	n/a	Benchmark burn
2	610.9	air jet	41.4	0	91	0.95	30° ccw	
3	600.0	air jet	41.1	0	46	0.95	30° ccw	
4	608.6	air jet	68.8	0	30	1.27	45° cw	
5	606.2	air jet	67.8	10.6	30	1.27	45° cw	
6	604.5	air jet and bubbler 1	68.5 tot. 5.1 bubbler	10.6	30	1.27	45° cw	Both systems used throughout burn
7	603.2	air jet	67.5	0	15	3.81	45° cw	
8	605.6	air jet	67.8 tot. 12.3 bubbler	0	15	3.81	45° cw 30°down -wind	Bubbler active for only 2:05 of steady burn
9	605.8	bubbler 1	7.8	0	n/a	n/a	n/a	
10	605.8	air jet	66.9	0	10	3.81	45° cw	
11	605.8	air jet	66.7	11.4	10	3.81	45° cw	
12	605.8	air jet	66.4	11.4	10	3.81	45° cw	Center pipe capped & drilled w/8 1/4" holes
13	605.6)	air jet	66.3	11.4	10	3.81	45° cw ctr. down-wind	One compressor offline 4:31 into steady burn
14	300.0	bubbler 1 & 2	5.4 to 0.6	0	n/a	n/a	n/a	
15	304.9	bubbler 1	3.8	0	n/a	n/a	n/a	Airflow varied to maintain constant fire area

*Indicates type of air delivery used: "air jet" = air jet aeration system; "bubbler 1" = center bubbler system; "bubbler 2" = perimeter bubbler system.

**The calculated air flow is the actual flow rate, found by correcting the indicated flow rate for ambient air temperature and pressure.

† Nozzle Orientation refers to the angle of rotation of the peripheral nozzles about a vertical axis. The given angle indicates the angle from a radius drawn from the nozzle to the center nozzle. Also, "ccw" indicates counterclockwise; "cw" indicates clockwise.

6.0 Test Results And Discussion

6.1 Smoke Production and Flame Characteristics

The smoke production of each burn was compared to that of burn 1, the benchmark burn, shown in figure 6.1. Table 6.1 summarizes the observations collected for all test burns on smoke production. A complete discussion of results follows.

Table 6.1 Observations of smoke production for all burns

Burn No.	Air Delivery System	Smoke Production--Comments
1	none	Baseline burn--thick, black, opaque, billowing smoke plume rising high. Flame column orange and billowing.
2	air jet	Dense, dark gray smoke (lighter color than baseline) with slight swirling. Jets of yellow flame produced at nozzle exits, dancing in and out of the orange flame column; however, wind pushed flames on surface beyond influence of air jets.
3	air jet	Dark to medium gray smoke with little swirling. Intense yellow flame from nozzle exits.
4	air jet	Dark to light gray smoke plume; compacted, smaller diameter smoke plume compared to previous burns. Significant reduction seen only when wind velocity near zero.
5	air jet	More transparent, smaller diameter smoke plume than previous test.
6	air jet and bubbler 1	More smoke created than previous tests, although color was consistently medium gray. Smoke plume hung close to ground and did not travel as far as in previous burns.
7	air jet	Gray smoke; little or no significant reduction.
8	air jet	Gray smoke; little or no significant reduction.
9	bubbler 1	Clear, translucent, diffuse smoke plume of medium gray color. Immediate increase in smoke when air turned off.
10	air jet	Considerable reduction in smoke; clear, translucent, and compact smoke plume.
11	air jet	Considerable reduction in smoke when little or no wind present; similar to Burn 10.
12	air jet	Reduction in smoke similar to Burns 10 and 11.
13	air jet	Most pronounced reduction in smoke of all burns: smoke production reduced to almost zero. Smoke plume a very thin, very transparent, swirling trail of smoke rising high and diffusing quickly. Almost no wind present during test.
14	bubblers 1 & 2	Relatively translucent smoke plume of medium gray color; not as successful as Burn 9.
15	bubbler 1	Relatively translucent smoke plume of medium gray color; not as successful as Burn 9.

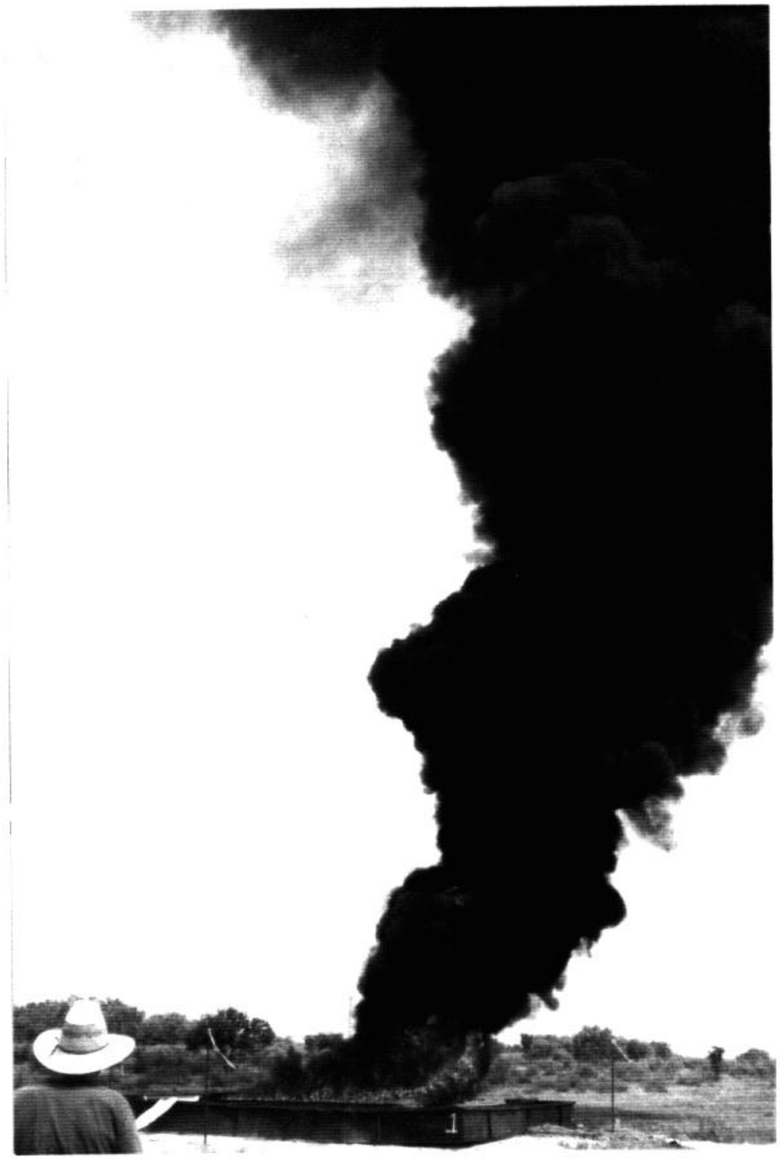


Figure 6.1*: Smoke production of baseline burn on day 1 of testing*

6.1.1 Air Jet Aeration System

In general, the use of the air jet aeration system resulted in noticeable reduction in smoke opacity and production. The smoke reduction was directly related to the characteristics of the flames. In the benchmark burn, the flames were orange and billowing, and the smoke produced was thick and black. When blowing through the flames burning on the fuel surface, the high velocity air jets produced jets of intense, bright yellow flames, as shown in figure 6.2. This increased the burn rate and decreased the smoke production in the immediate vicinity of the air jets. In conditions of little or no wind, the jets produced noticeable swirling or fire whirl effect.

Although most burn tests using the air jet aeration system had noticeable reduction in smoke, only a few test runs could be considered almost smoke-free. In general, smoke reduction depended most upon the wind conditions during the burn. The air jet system proved to be very sensitive to wind effects: when wind was present, the flames on the pool surface would be pushed over to the side, often displacing the flame beyond the range and influence of the upwind nozzles (see figure 6.2). When this occurred, the plume of smoke reverted back to a thick, black, billowing cloud. However, when wind velocity was near zero, a considerable reduction in smoke was consistently observed when using the air jet system.

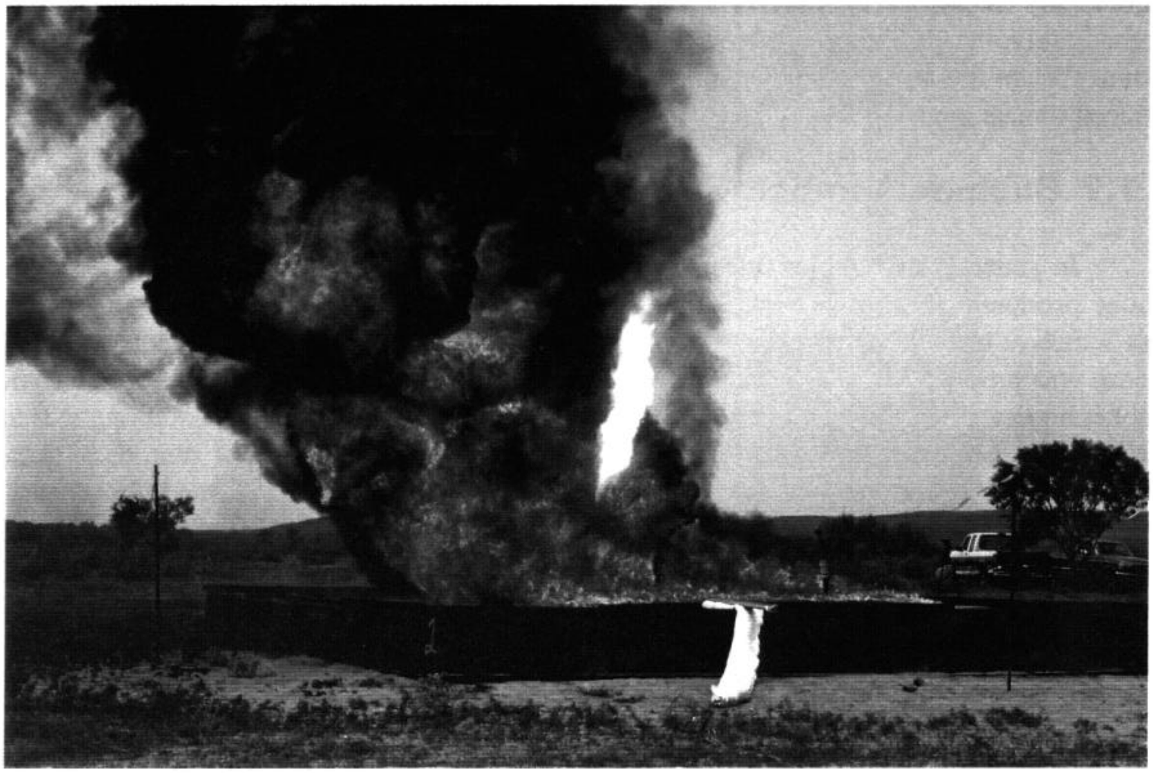


***Figure 6.2**: Effect of injected air and wind on flame of burn*

Other factors also affected the removal capacity of the air jet aeration system. The nozzle height was a significant factor and was related to the effects of wind. Less wind was necessary to push the flames beyond the influence of the air jets when the nozzle exit placement was higher. For example, burns 2-5, with nozzle heights between 91 and 30 cm showed little decrease in smoke production. When the nozzle height was reduced to 10 cm for later burns, the smoke reduction was more dramatic.

Another significant factor affecting smoke reduction capabilities was the exit velocity of the air jets, a function of the air flow rate and nozzle exit diameter. In burns 2-5, the high velocity air jets produced by the small diameter nozzles often seemed to penetrate the orange flames without producing the characteristic yellow flame jet. Performance was improved in later burns when the nozzle diameter was increased to 3.81 cm, decreasing the velocity of the air jets.

Introduction of water had no visible effect on the reduction of smoke. The water would produce a smoke plume of a lighter gray color, although not necessarily more transparent. This is most likely due to the formation of steam, which, when mixed with the smoke, appeared lighter in color.

Smoke reduction was overwhelmingly successful in only one test. burn 13 at times showed almost complete and dramatic removal of the smoke plume (see figure 6.3). This was due in part because wind velocity was near zero for the entire length of the burn. For the first minute of the burn, before the air compressors were activated, the smoke plume was thick and black. As soon as the air was turned on, bright yellow jets of flame were visible, and the smoke plume was immediately reduced to a thin, transparent, swirling plume that dispersed quickly. By chance, one compressor shut down 4:31 into the burn, cutting the airflow in half. Immediately, the production of smoke increased, returning to a thicker, more opaque, black plume. When the compressor was brought on line again, the smoke production was again reduced to near zero.

6.1.2 Bubbler Aeration Systems

In general, the bubbler systems were less effective than the air jet system in reducing smoke production in no-wind conditions. However, the bubbler systems were considerably less sensitive to wind effects, and overall were more successful in smoke reduction when a breeze was present. Most burns using the bubblers (6, 14, and 15) appeared to produce more smoke; however, the color of the smoke produced was considerably lighter and hung closer to the ground, not traveling as far as in other burns. This is possibly due to a greater concentration in water vapor as steam, as the surface turbulence created by the bubbles cast up water into the flames. The air flow rate required to produce effective smoke reduction was considerable lower than that necessary for the air jet system.

Burn 9 exhibited significant reduction of smoke, and was the most dramatic for the bubbler burns despite the presence of a breeze (see figure 6.4). The plume of smoke was relatively clear, translucent, and diffuse with a medium gray color. The slower burn rate for burn 9 may have contributed to the apparent smoke reduction. With a slower burn rate, the rate of release of combustion products was less, allowing the smoke to diffuse more readily into the surrounding atmosphere.

***Figure 6.3**: Noticeable smoke reduction in test 13*

6.2 Burn Rate

Table 6.2 summarizes the burn time data collected for each burn, and the calculated average burn rate based on these times. An explanation of each of the table headings and the pertinent calculations follows.

Table 6.2 Burn times and calculated burn rates for each burn test.

Burn No.	Ignition Time min:sec	Steady Burn Time min:sec	Vigorous Burn Time min: sec	Extinction Time min:sec	Avg Burn Rate mm/min (in./min)	Avg Burn Rate $l/m^2 \cdot min$ ($gal/ft^2 \cdot min$)
1	1:16	7:26	0:45	7:23	3.9 (0.15)	3.9 (0.096)
2	0:52	10:05	n/a	4:15	3.4 (0.13)	3.4 (0.083)
3	0:28	8:31	0:12	0:31	3.9 (0.15)	3.9 (0.096)
4	1:28	9:24	n/a	0:46	3.6 (0.14)	3.6 (0.088)
5	0:55	8:51	n/a	1:09	3.8 (0.15)	3.8 (0.093)
6*	1:04	16:29	3:27	2:13	2.2 (0.086)	2.2 (0.053)
7	0:22	6:46	n/a	1:47	5.0 (0.20)	5.0 (0.021)
8	0:59	9:10	n/a	1:07	3.7 (0.15)	3.7 (0.091)
9*	0:26	77:24	n/a	1:26	0.57 (0.022)	0.57 (0.014)
10	1:20	6:27	n/a	1:18	5.3 (0.21)	5.3 (0.013)
11	1:42	6:02	0:24	1:12	5.3 (0.21)	5.3 (0.013)
12	1:49	7:34	n/a	2:34	4.5 (0.18)	4.5 (0.011)
13	1:03	7:23	n/a	2:00	4.6 (0.18)	4.6 (0.011)
14**	0:55	22:12	n/a	n/r***	1.3 (0.053)	1.3 (0.033)
15*	0:42	25:02	1:29	2.13	0.81 (0.032)	0.81 (0.020)

* Bubbler 1 used only--effective burn area reduced (see below).

**Bubbler 1 and 2 used together--effective burn area reduced (see below).

***Not Recorded

Figure 6.4: *Smoke plume produced during test 9 with sub-surface bubbler*

6.2.1 Discussion Of Data

The times summarized in table 6.2 are based on observations by data collection personnel. They are split up in this table into the times for the different phases of the burn. Since no fine boundaries exist between the phases of a burn, all times are approximate.

The following is a clarification of the table headings in table 6.2:

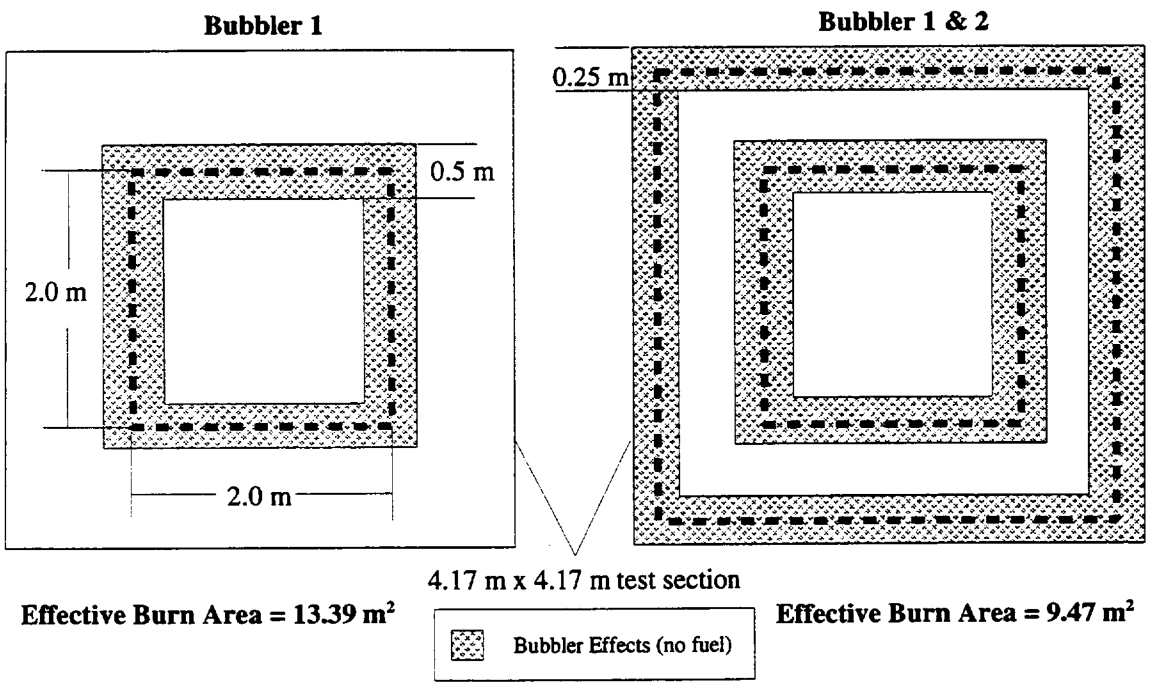
- **Ignition Time** is the time required for the igniter flame to spread from the point of contact on the fuel surface to the entire area of the test section.
- **Steady Burn Time** is the time that the burn remained at steady state conditions; this phase begins immediately following the ignition phase, and lasts to the vigorous burn phase.
- **Vigorous Burn Time** is the time from the inception of vigorous burning to the inception of the extinction phase. The transition from steady state burning to vigorous burning was often visually and audibly detectable: the vigorous phase is characterized by increased flame height and radiative output. Some burns had no noticeable transitions to vigorous burning; either the transitions were too gradual to be notices or did not occur at all.
- **Extinction Time** is the time from the beginning of the extinction phase, characterized by the beginning breakup of flames into localized areas, until all flame is completely out.
- **Average Burn Rate** is the approximate rate of combustion of fuel averaged over the effective length of the burn. The effective length of the burn is taken as the steady and vigorous burn phases only; the ignition and extinction phases are omitted because of the non-steady state conditions which exist. The average burn rate is expressed a the volume of fuel burned per unit of area per unit of time: units in SI are liters of fuel per square meter of burn area per minute, which can be reduced to millimeters per minute; units in English are gallons of fuel per square foot of burn area per minute, which (with difficult conversion) can be reduced to inches per minute. The average burn rate for this series of tests was found using the following formula (Buist, 1995):

$$\text{burn rate} = (V_0 - 17.35) / (A_e)(T_s + T_v)$$

where:

V_0	=	the initial volume of diesel fuel used in the burn test, in liters,
17.35	=	the amount of fuel, in liters, assumed to have been burned in the ignition and extinction phases (equivalent to a layer of fuel 1 mm thick),
A_e	=	the effective area of the burn, in square meters (see below),
T_s, T_v	=	the time, in minutes, for the steady state and vigorous burn phases, respectively.

The **effective area** of the burn is the area of burning fuel in the test section. In burns not using the bubbler systems, the area of the burn was the area of the test section: 17.35 square meters. However, when the bubbler system was activated, the air bubbles pushed the fuel on the water's surface away from the bubble region (see section 1.2.2), effectively reducing the burn area by an amount equal to the area of the rising plume of bubbles at the water's surface. The area of the bubble plume could only be visually approximated: bubbler 1 (center bubbler) produced a band on the surface approximately 0.5 m in width; bubbler 2 (perimeter bubbler) produced a band approximately 0.25 m in width. The bands were centered over their respective delivery systems. Referring to figures 6.5 and 6.6, the effective burn areas for any tests using bubblers can be readily visualized and calculated: 13.39 m^2 for bubbler 1 alone, and 9.47 m^2 for bubblers 1 and 2 combined.



*.**Figure 6-5**: Diagram showing effective burn areas for bubbler system operation.*

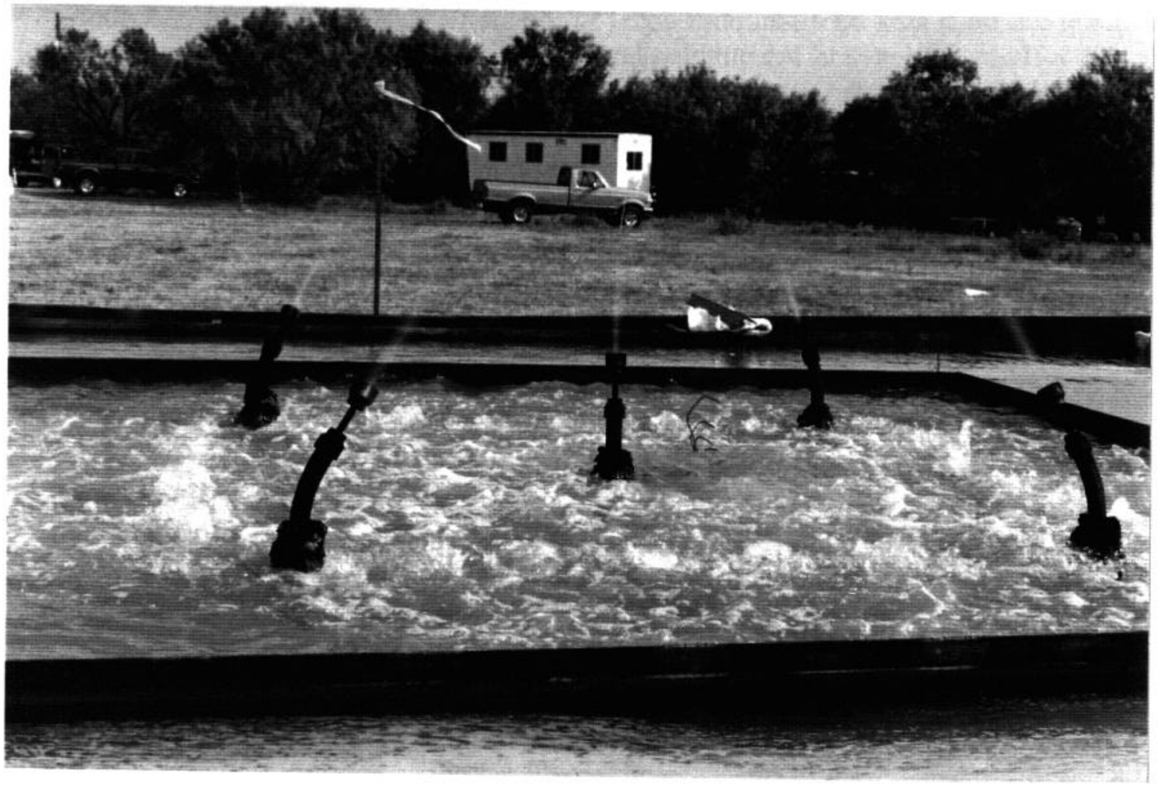


Figure 6.6: *Sub-surface bubbler effect on the water surface at test site*

6.2.2 Results

The benchmark burn rate to which all others may be compared is the burn rate calculated for burn 1, the baseline burn with no supplemental air introduction. The calculated burn rate is 3.9 mm/min; the actual burn rate was probably slightly lower than this, since some fuel was observed to be burning outside the test section.

In general, air introduction using the air jet aeration system increased the burn rate. The highest burn rates out of all burns were measured in burns 7, 10, 11, and 13, all of which used the air jet aeration system only. Burns 2-5 showed little increase in the burn rate, despite using only the air jet system as well; this was probably because the nozzle exits were placed too high (between 30 and 91 cm, or 12 to 36 in.) to have substantial effect on the combustion process at the oil surface. An increase in the burn rate was consistent with the reduction of the nozzle height to just above the oil surface: burns 7 and 10-13 all showed a dramatic increase in the burn rate, with a nozzle height of 10 cm. Little correlation was seen between the introduction of atomized water into the air stream and the burn rate: for example, burns 10 and 11 both had the highest burn rate of 5.3 mm/min (0.21 in/min), despite water injection during one but not during the other.

Use of the submerged bubbler systems dramatically decreased the burn rate in all cases (burns 6, 9, 14, and 15). Two mechanisms of bubble introduction were probably instrumental in burn rate reduction: the reduction in effective burn area reduced the amount of fuel available for combustion at any one time, and the surface turbulence induced by the rising bubbles caused a mixing and cooling effect. The lowest burn rate was seen in burn 9, which had a burn rate of 0.57 mm/min; total burn time for 606 l of fuel was nearly 80 minutes, roughly 10 times the benchmark burn rate.[7] Burn 6 also showed a substantial decrease in the burn rate, despite using the bubbler system in combination with the air jet system. Although it had the smallest effective burn area (because of the use of both bubbler systems), burn 14 showed a slightly higher rate than other bubbler tests. This is possibly due to a lower air supply flow diffused more evenly throughout the test section.

6.3 Flame Temperatures

Data on the flame temperatures were collected with the thermocouples placed in the test section and with the thermal imaging camera. In general, the average flame temperatures were not dramatically changed in most burns. Because of their success in reduction of smoke compared to other burns, only burns 9 and 13 are discussed here.

The thermocouple data showed that, in general, temperatures in burn 9 were decreased compared to the baseline burn, probably because of both the burn rate reduction and the water introduction from the surface turbulence of the bubbles. In general, temperatures were increased in burn 13 because of the increased flame intensity and increased burn rate. All thermocouple data are included in Appendix B. In burn 1 (baseline burn), temperatures both in the center and at the edge remained approximately constant at 1500°C 6 inches above the surface, and 1300°C 2 inches above the surface; temperatures were slightly cooler in the corners.

Temperatures were considerably cooler in the center of burn 9 (bubbler system), at 800°C 6 inches above the surface, and at 1050°C 2 inches above the surface; these gradually decreased, steadying at 250°C 40 minutes before the vigorous phase began. Temperatures in the corners and edges of the test section, outside the influence of the bubbles, were higher and more constant: approximately 1300°C 2 inches above the surface, and 800°C 6 inches above the surface.

Temperatures were considerably higher in burn 13 (air jet system). In the center, temperatures remained relatively constant at 1600°C 6 inches above the surface, and 1400°C 2 inches above the surface. At the edge, temperatures were lower at 1000°C 6 inches above the surface, and 1400°C 2 inches above the surface. At the corner, temperatures were still lower at 800°C 6 inches above, and 1300°C 2 inches above the surface.

Results of the thermal imaging camera are contained in Appendix B. These results show no significant differences in temperature between any of the burns and the baseline burn. The average steady state flame temperature for burn 1 was 1150 to 1200°C; for burn 9, 1200 to 1400°C; and for burn 13, 1175 to 1250°C. These data seem to correlate to the thermocouple data collected for the edge of the test section only, and thus may not be a truly accurate reflection of burn temperatures.

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[7] Because of this lengthy burn time, the amount of fuel was cut in half for burns 14 and 15.

7.0 Conclusions And Recommendations

7.1 Conclusions

This series of mesoscale in situ burn tests was successful in validating the principle that the introduction of air into the center of a burn column can significantly reduce the overall production of smoke. These tests also show that it is operationally and technically feasible to reduce the smoke in applications larger than laboratory scale. However, since only a few burns out of 15 showed any appreciable reduction in smoke; more work is needed to narrow down and pinpoint operational parameters and constraints.

Smoke reduction was most successful with the introduction of air in jets but only during completely calm conditions. The most effective arrangements was used in burn 13: lower velocity air jets (nozzle of greater diameters); nozzle placement just above the oil surface; nozzle orientation for cyclonic velocities, compensating for wind effects; air flow less than 10% of the stoichiometric requirement; and a small amount of water introduced. Accompanying the smoke reduction were increased burn rate and flame temperatures. However, most burns in this series of tests showed that the air jet aeration method was sensitive to wind effects. If wind was present, the flames were pushed beyond the influence of the upwind nozzles, reducing the overall smoke reduction effectiveness. This could make development of an at-sea response technology difficult.

Relatively successful smoke reduction was achieved with the bubbler systems. Using a small fraction of the air used in the air jet system, the bubbler system effectively reduced smoke production, although not as dramatically as the air jet system. The mechanism for smoke reduction was the surface turbulence induced by the air bubbles, which increased the water exposed to the flames and reduced the burn area, in turn reducing the burn rate. With the burn rate reduced, the rate of production of combustion products was also reduced, allowing them to diffuse more readily into the surrounding atmosphere. The reduced burn rate reduced the intensity of the flames, allowing for easier control over the burn, an important consideration for the development of an at-sea response technology. More importantly, the smoke reduction capabilities were not affected by the presence of wind: burn 9 produced little smoke throughout the entire burn, despite the presence of a slight breeze. This method of aeration thus might be more easily incorporated into an at-sea response option.

7.2 Recommendations

Future development should focus on transforming aeration methods into an operationally feasible at-sea response technology. The air jet system was shown to have a considerable effect in calm conditions; but attention needs to be directed at reducing the negative effects of wind on smoke reduction. The problems with wind observed in this series of tests indicate that future jet designs should possibly incorporate a large number (10 or more) of low velocity nozzles very close to the surface. These nozzles should be strategically distributed throughout the burn perimeter to enhance the fire whirl and to counter wind direction. The bubbler systems evidenced considerable resistance to wind effects. However, the slower burn rate might make application to large-scale burns more time consuming. Also, the effects of water currents on the effectiveness of a bubbler aeration system needs further investigation. A combination of the air jet system with the bubbler system might be the most effective in many conditions. More testing and development is necessary, however, to determine the feasibility of these prospects.

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Appendix A

Summary of Burn Tests

Table A.1 Summary of Burn Tests (from Buist, June 1995)

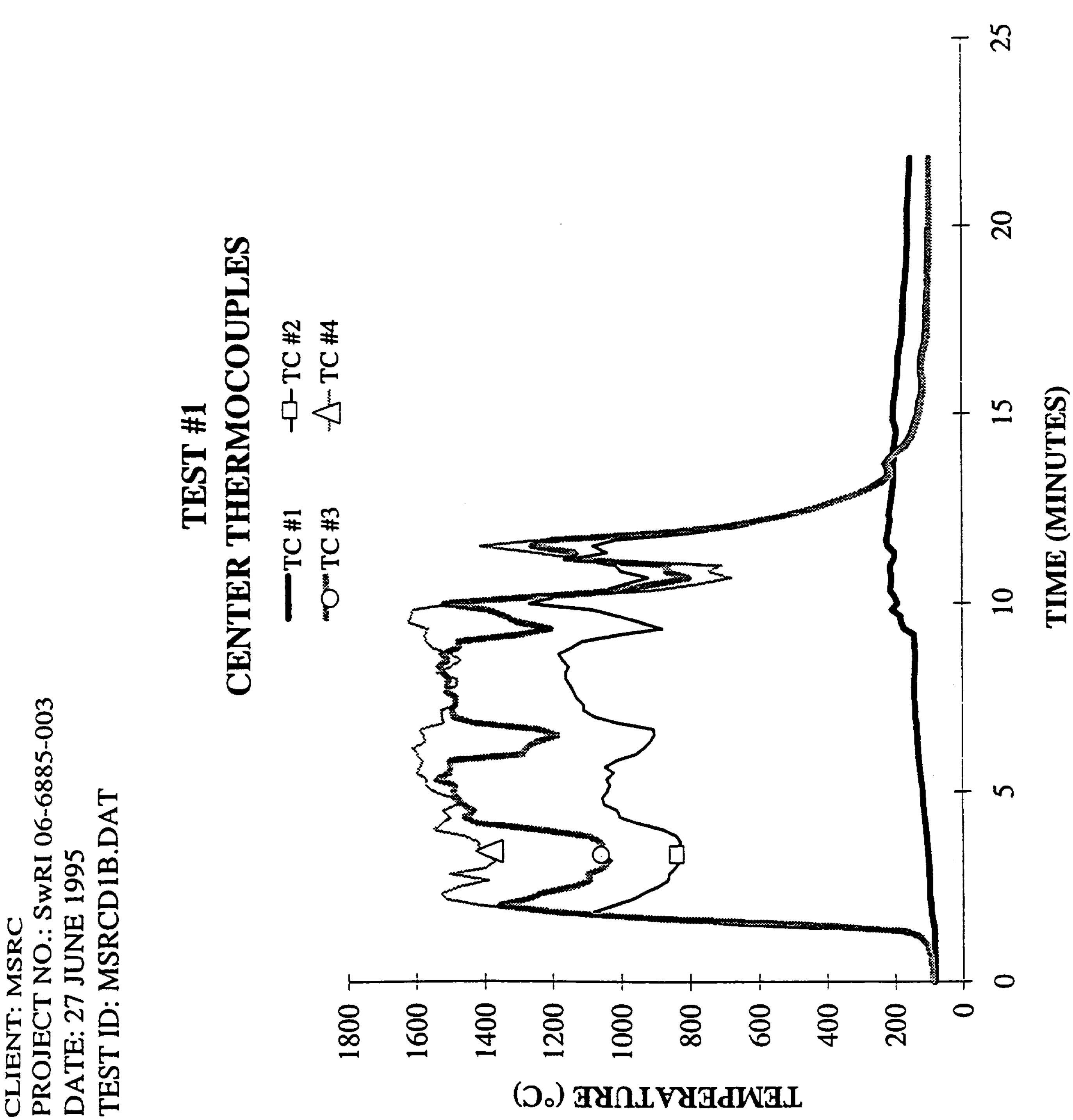
Run	Air Deliv. Sys.	Oil Vol. l	Calc. Air Flow m^3/min	Water Flow l/min	Ignition Time M:s	Steady Burn Time m:s	Vigorous Burn Time m:s	Extinction Time m:s	Avg Burn Rate mm/min	Comments
1	none	606.2	0	0	1:16	7:26	0:45	7:23	3.9	flared and died at end
2	air jet	610.9	41.4	0	0:52	10:05	n/a	4:15	3.4	3/8" nozzles @ 3' & 30° ccw
3	air jet	600.0	41.1	0	0:28	8:31	0:12	0:31	3.9	3/8" nozzles @ 18" & 30° ccw
4	air jet	608.6	68.8	0	1:28	9:24	n/a	0:46	3.6	1/2" nozzles @ 1' & 45° cw
5	air jet	606.2	67.8	10.6	0:55	8:51	n/a	1:09	3.8	1/2" nozzles @ 1' & 45° cw
6	air jet & bub. 1	604.5	68.5 tot. 5.1 bub.	10.6	1:04	16:29	3:27	2:13	2.2	1/2" nozzles @ 1' & 45° cw; 180 cfm bubbler
7	air jet	603.2	67.5	0	0:22	6:46	n/a	1:47	5.0	1.5" pipe @ 6" & 45° cw
8	air jet	605.6	67.8 tot. 12.3 bub.	0	0:59	9:10	n/a	1:07	3.7	1.5" pipe @ 6" & 45° cw + 30° downwind; 600 cfm (indicated) to bubbler for 2:05 of steady burn time
9	bub. 1	605.8	7.8	0	0:26	77:24	n/a	1:26	0.57	bubbler at 275 cfm (calculated) for 73:29
10	air jet	605.8	66.9	0	1:20	6:27	n/a	1:18	5.3	1.5" pipe @ 4" & 45° cw
11	air jet	605.8	66.7	11.4	1:42	6:02	0:24	1:12	5.3	1.5" pipe @ 4" & 45° cw
12	air jet	605.8	66.4		1:49	7:34	n/a	2:34	4.5	1.5" pipe @ 4" & 45° cw + center pipe capped and drilled with 8 x 1/4"

Table A.1 Summary of Burn Tests (from Buist, June 1995) (cont.)

Run	Air Deliv. Sys.	Oil Vol. l	Calc. Air Flow m^3/min	Water Flow l/min	Igni-tion Time M:s	Steady Burn Time m:s	Vig-orous Burn Time m:s	Extinc-tion Time m:s	Avg Burn Rate mm/min	Comments
13	air jet	605.6	66.3		1:03	7:23	n/a	2:00	4.6	1.5" pipe @ 4" & 45° cw + center downwind; one compressor offline 4:31into steady burn
14	bub. 1 & 2	300.0	5.4 - 0.6		0:55	22:12	n/a	n/r	1.3	Added low-submergence bubbler around inside edge; bubbler air flow not recorded
15	bub.1	304.9	3.8		0:42	25:02	1:29	2.13	0.81	Original bubbler only; varied airflow from 350 to 100 cfm (indicated) to maintain constant fire area

Appendix B

Flame and Fire Temperature Results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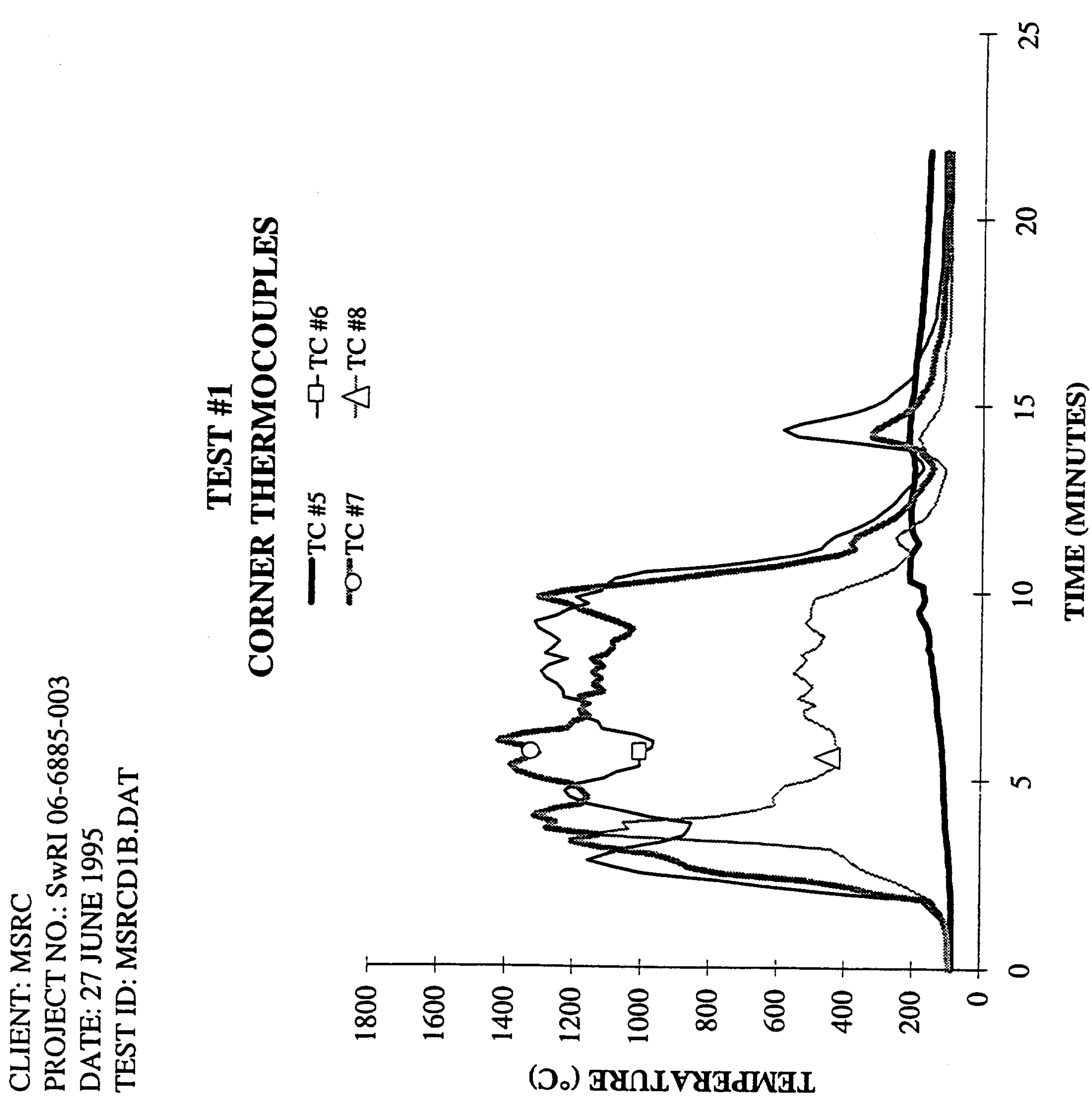
DATE: 27 JUNE 1995
TEST ID: MSRCD1B.DAT
TEST #1
CENTER THERMOCOUPLES
TC #1
TC #2
TC #3
TC #4
TEMPERATURE (°C)
TIME (MINUTES)
0
200
400
600
800
1000
1200
1400
1600
1800
0
5
10
15
20
25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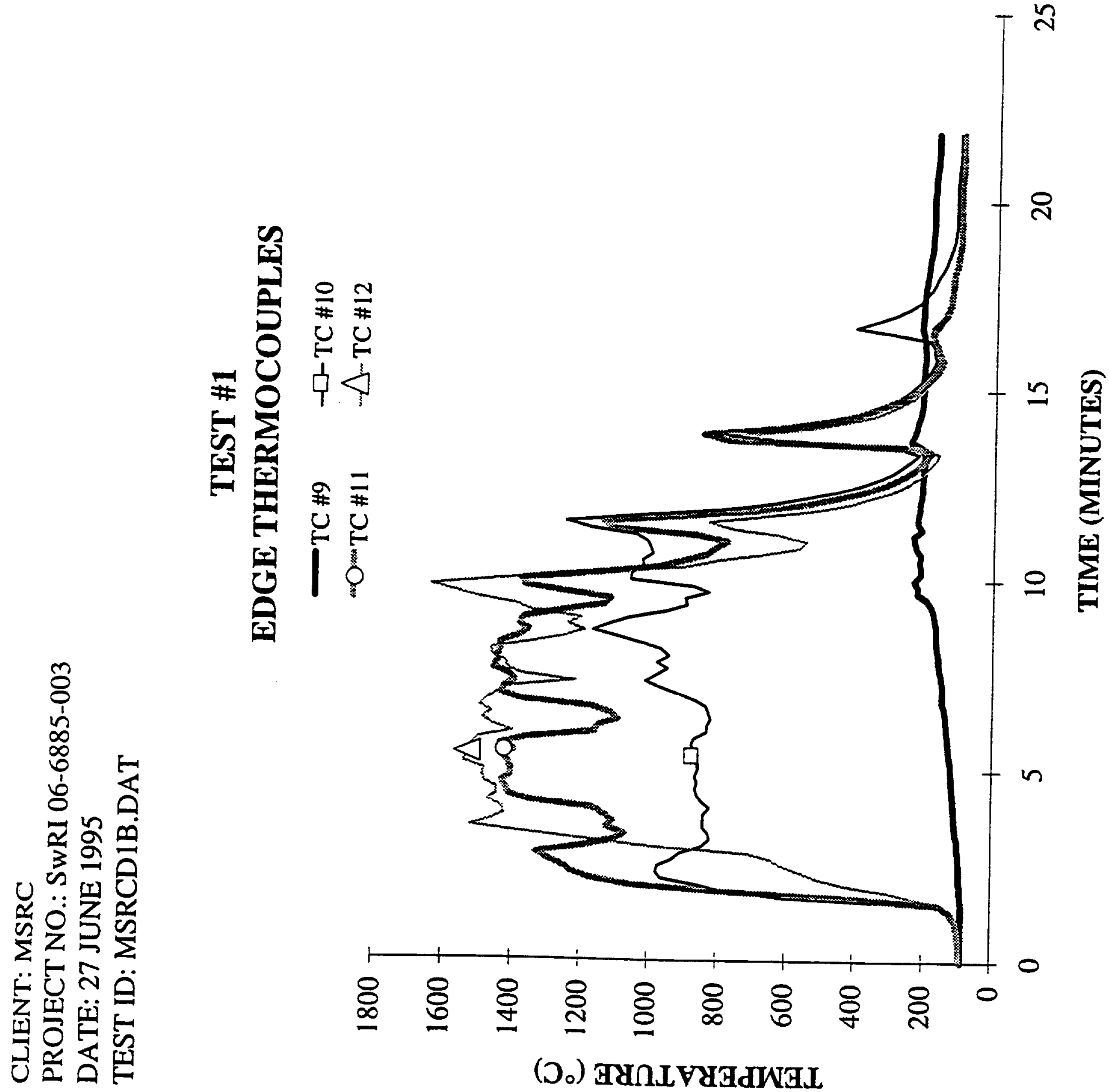
PROJECT NO.: SwRI 06-6885-003
DATE: 27 JUNE 1995
TEST ID: MSRCD1B.DAT
TEST #1
CORNER THERMOCOUPLES
TC #5
TC #6
TC #7
TC #8
TEMPERATURE (°C)
1800
1600
1400
1200
1000
800
600
400
200
0
TIME (MINUTES)
0
5
10
15
20
25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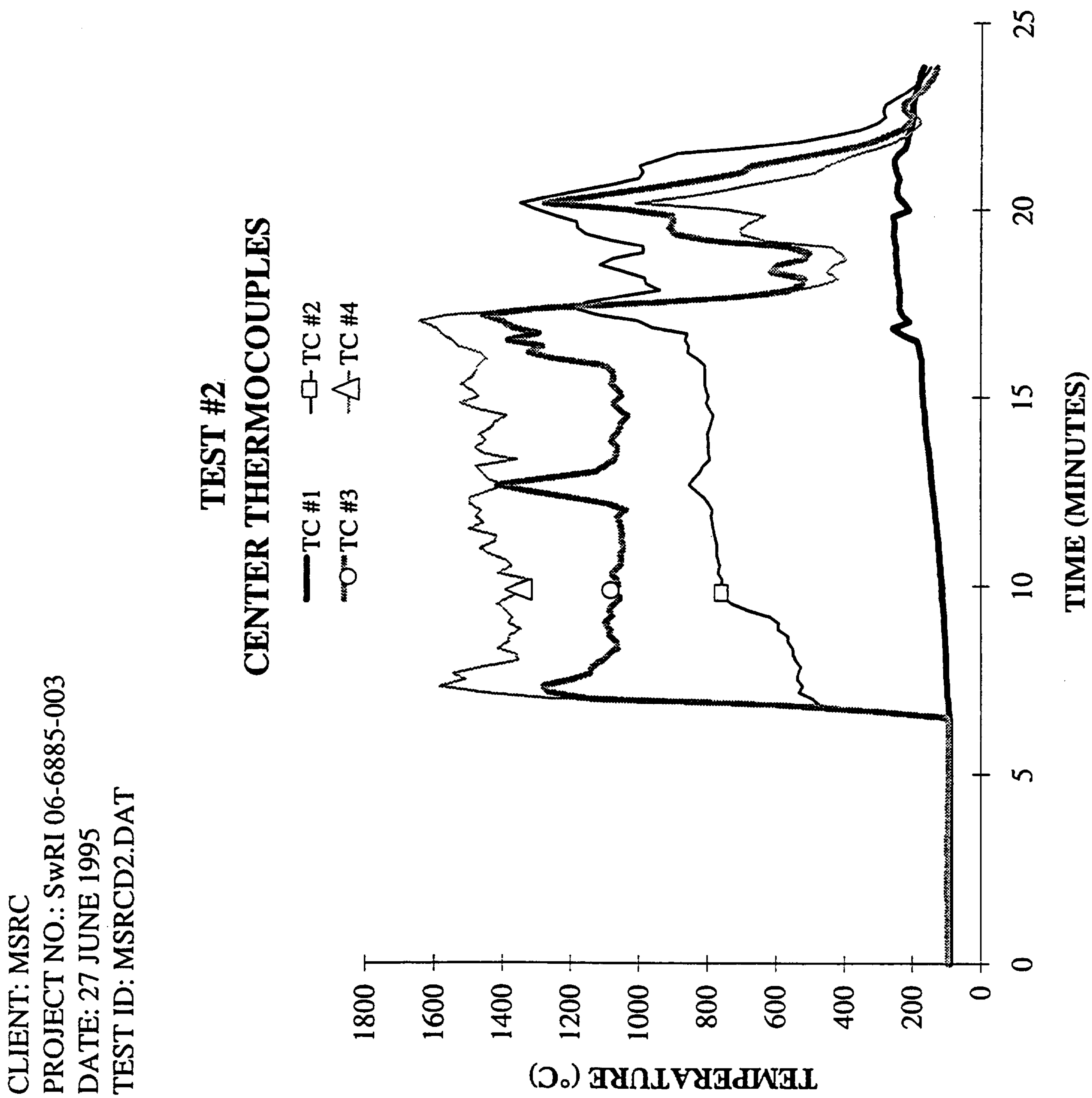
DATE: 27 JUNE 1995
TEST ID: MSRCD1B.DAT
TEST #1
EDGE THERMOCOUPLES
TC #9
TC #10
TC #11
TC #12
TEMPERATURE (°C)
0
200
400
600
800
1000
1200
1400
1600
1800
TIME (MINUTES)
0
5
10
15
20
25



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DATE: 27 JUNE 1995
TEST ID: MSRCD2.DAT
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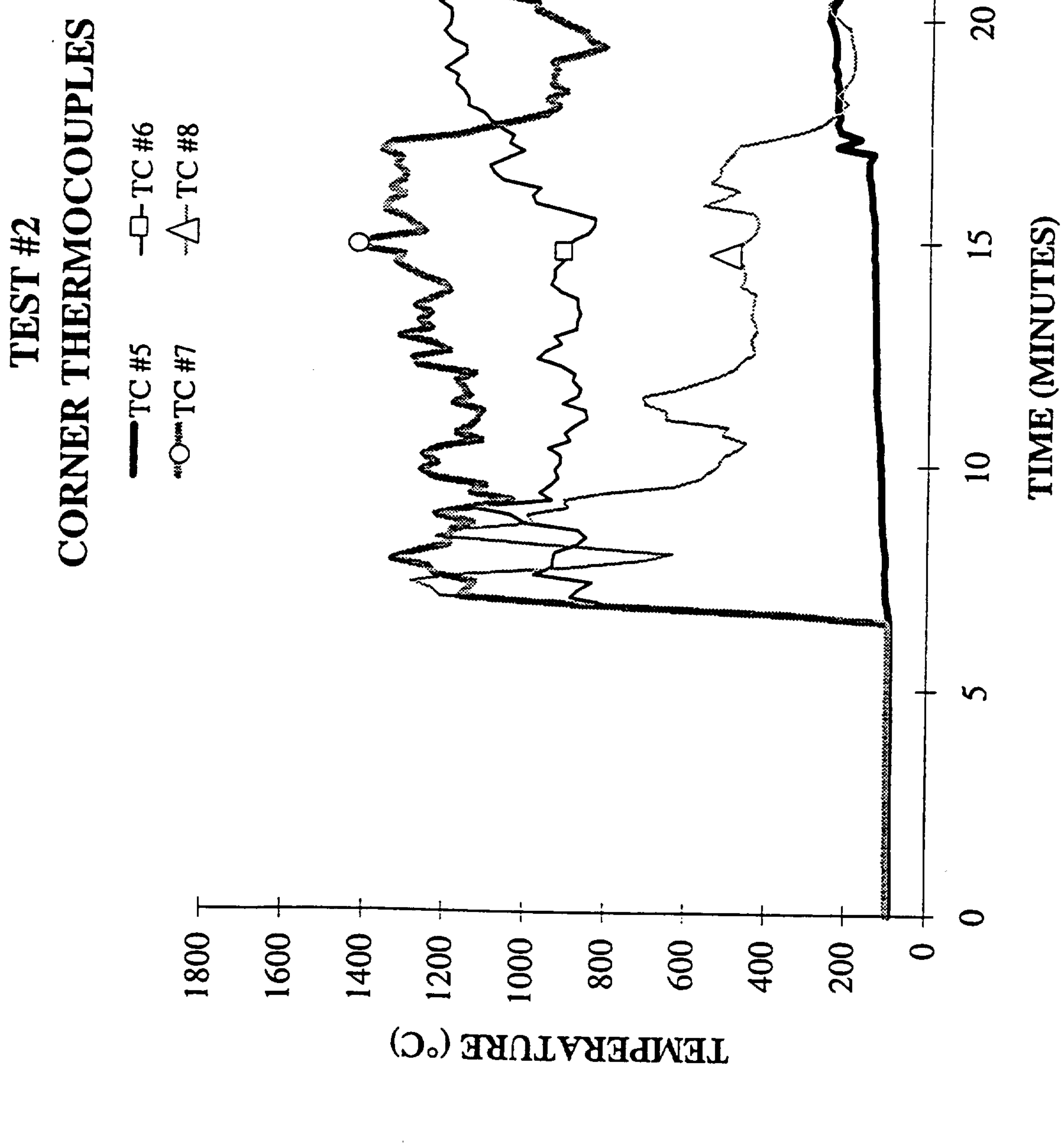
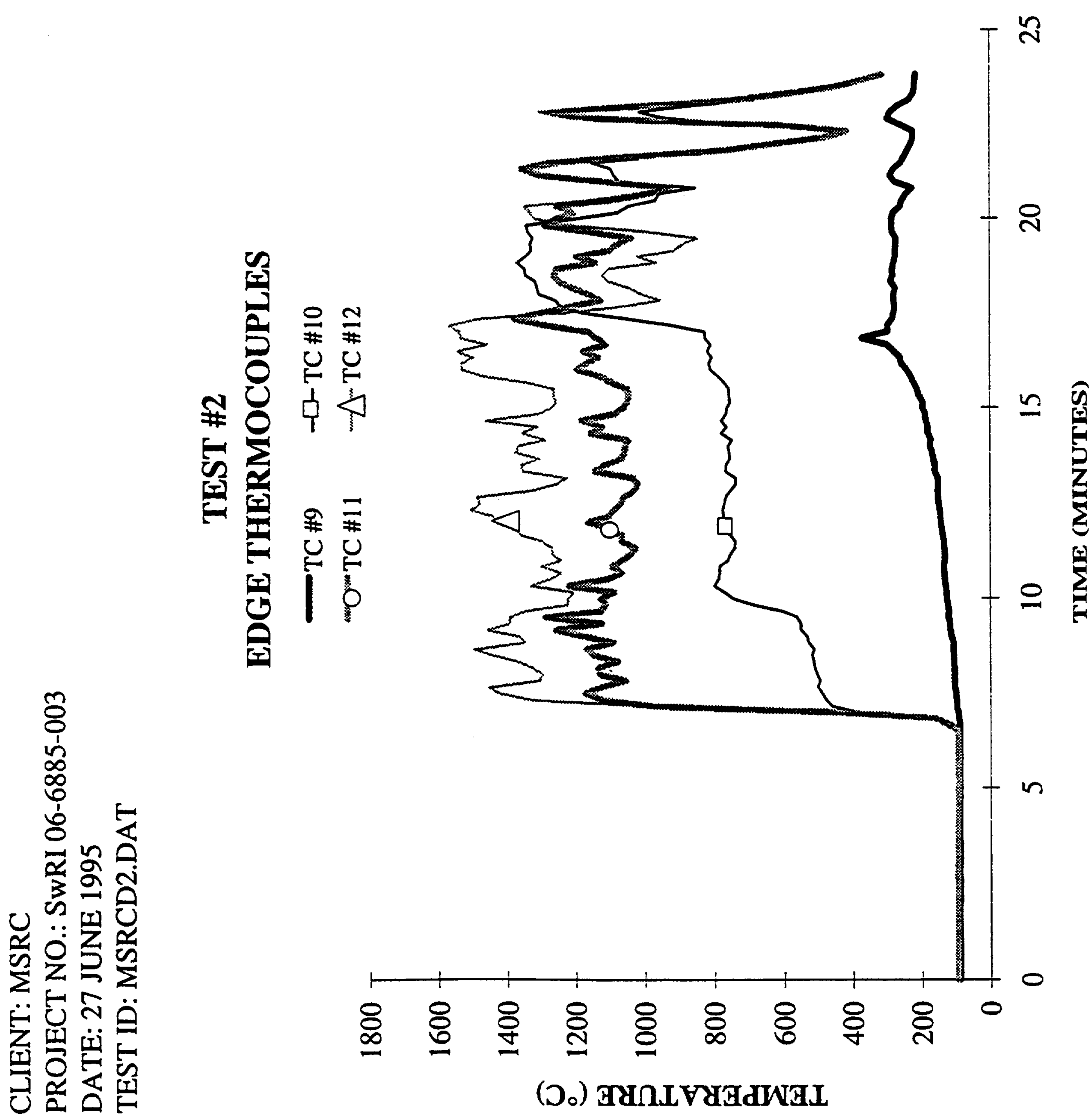
CENTER THERMOCOUPLES
TC #1
TC #2
TC #3
TC #4
TEMPERATURE (°C)
0
200
400
600
800
1000
1200
1400
1600
1800
TIME (MINUTES)
0
5
10
15
20
25

CLIENT: MSRC
PROJECT NO.: SwRI 06-6885-003
DATE: 27 JUNE 1995
TEST ID: MSRCD2.DAT

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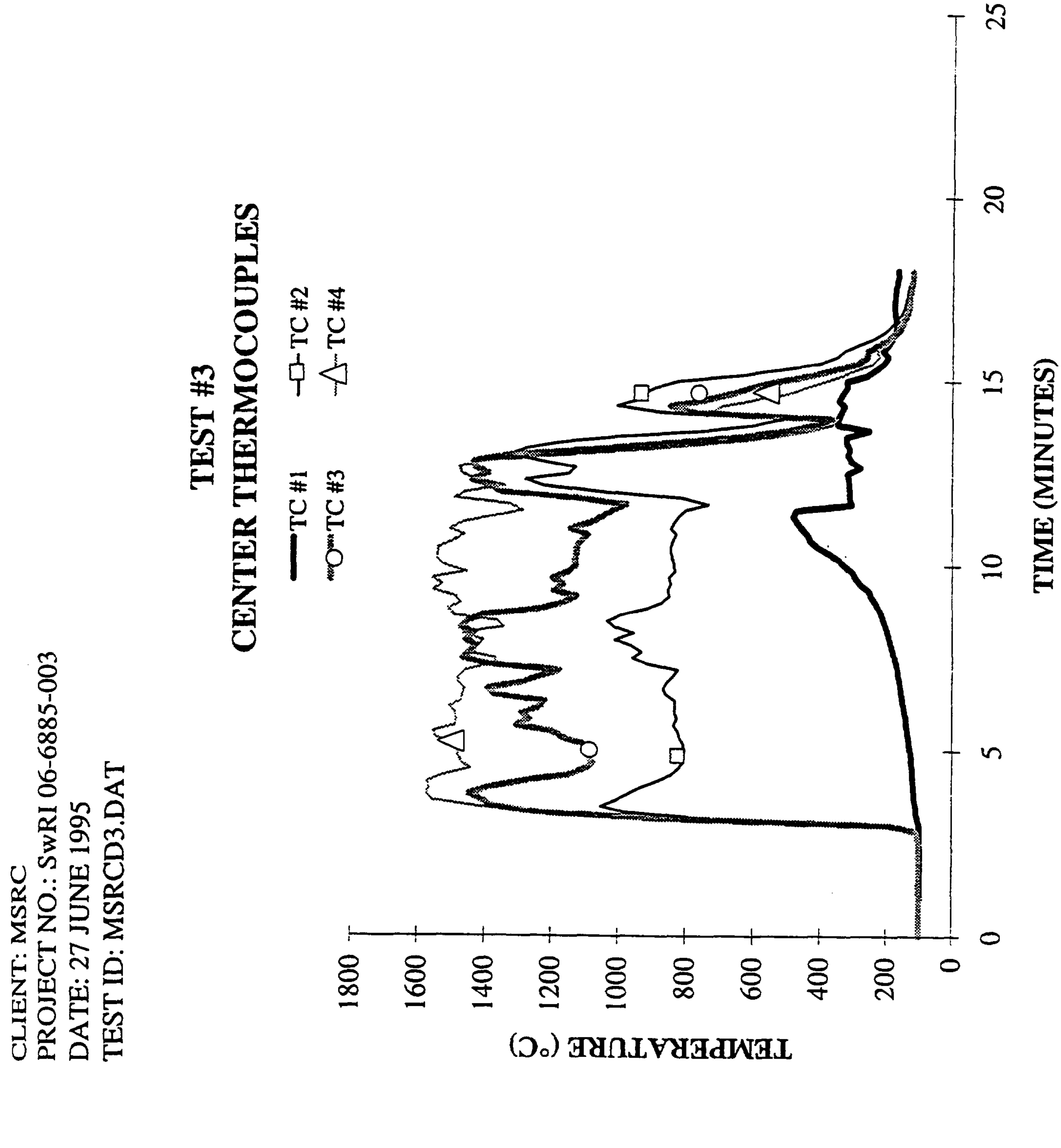
TEST #2
EDGE THERMOCOUPLES
TC #9
TC #10
TC #11
TC #12
TEMPERATURE (°C)
0
200
400
600
800
1000
1200
1400
1600
1800
TIME (MINUTES)
0
5
10
15
20
25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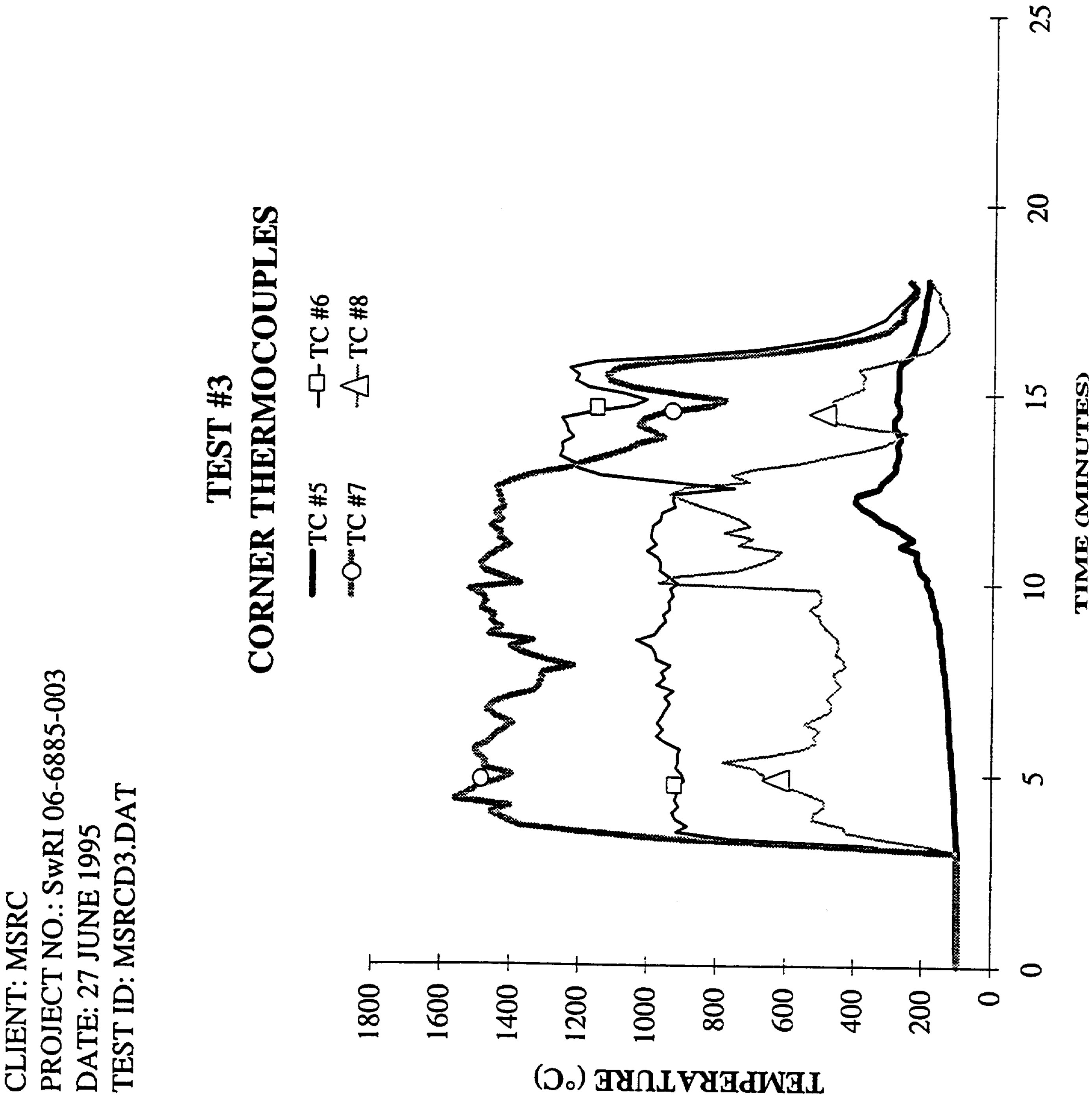
DATE: 27 JUNE 1995
TEST ID: MSRCD3.DAT
TEST #3
CENTER THERMOCOUPLES
TC #1
TC #2
TC #3
TC #4
TEMPERATURE (°C)
1800
1600
1400
1200
1000
800
600
400
200
0
0
5
10
15
20
25
TIME (MINUTES)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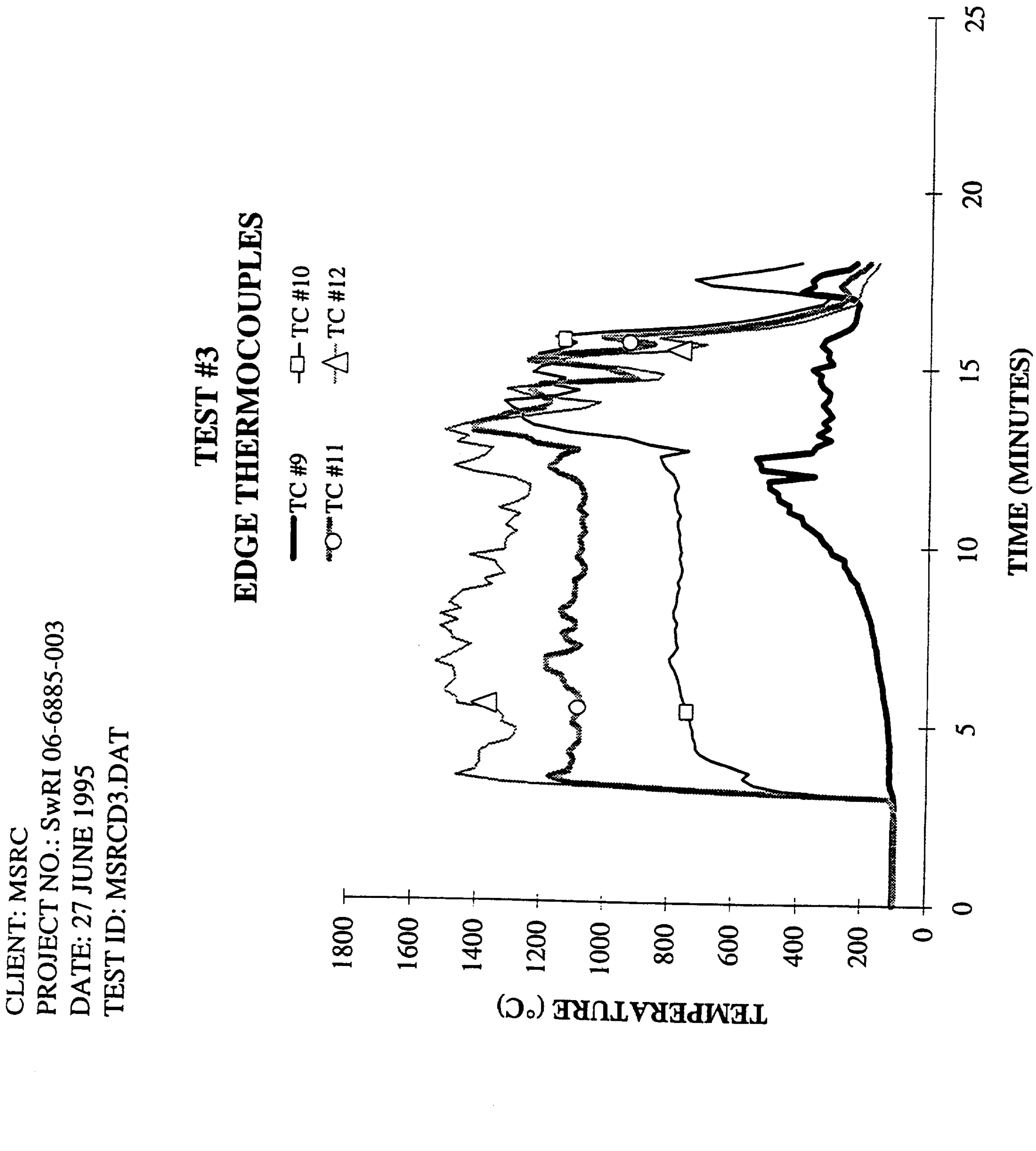
DATE: 27 JUNE 1995
TEST ID: MSRCD3.DAT
TEST #3
CORNER THERMOCOUPLES
TC #5
TC #6
TC #7
TC #8
TEMPERATURE (°C)
0
200
400
600
800
1000
1200
1400
1600
1800
TIME (MINUTES)
0
5
10
15
20
25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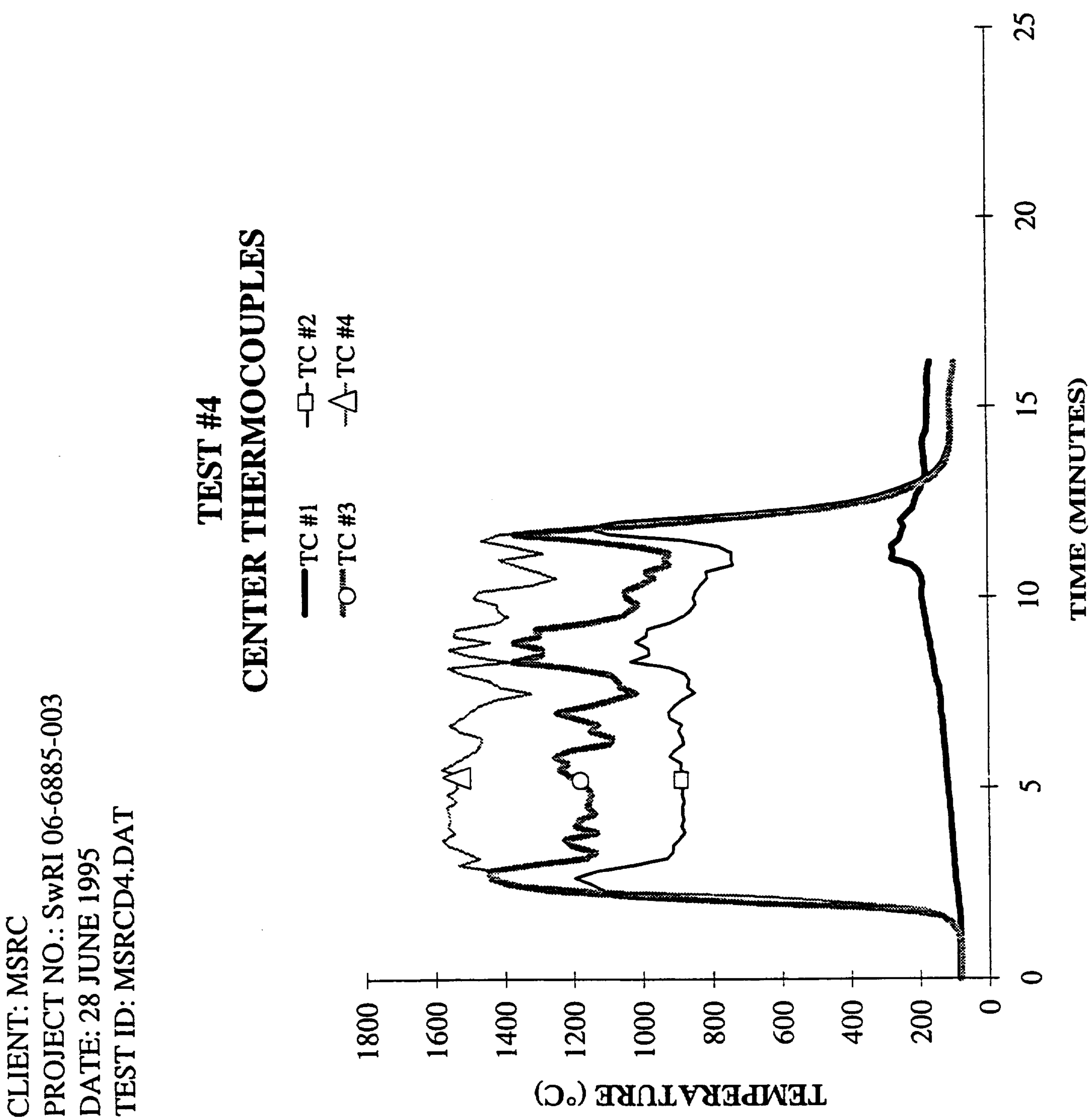
DATE: 27 JUNE 1995
TEST ID: MSRCD3.DAT
TEST #3
EDGE THERMOCOUPLES
TC #9
TC #10
TC #11
TC #12
TEMPERATURE (°C)
1800
1600
1400
1200
1000
800
600
400
200
0
TIME (MINUTES)
0
5
10
15
20
25



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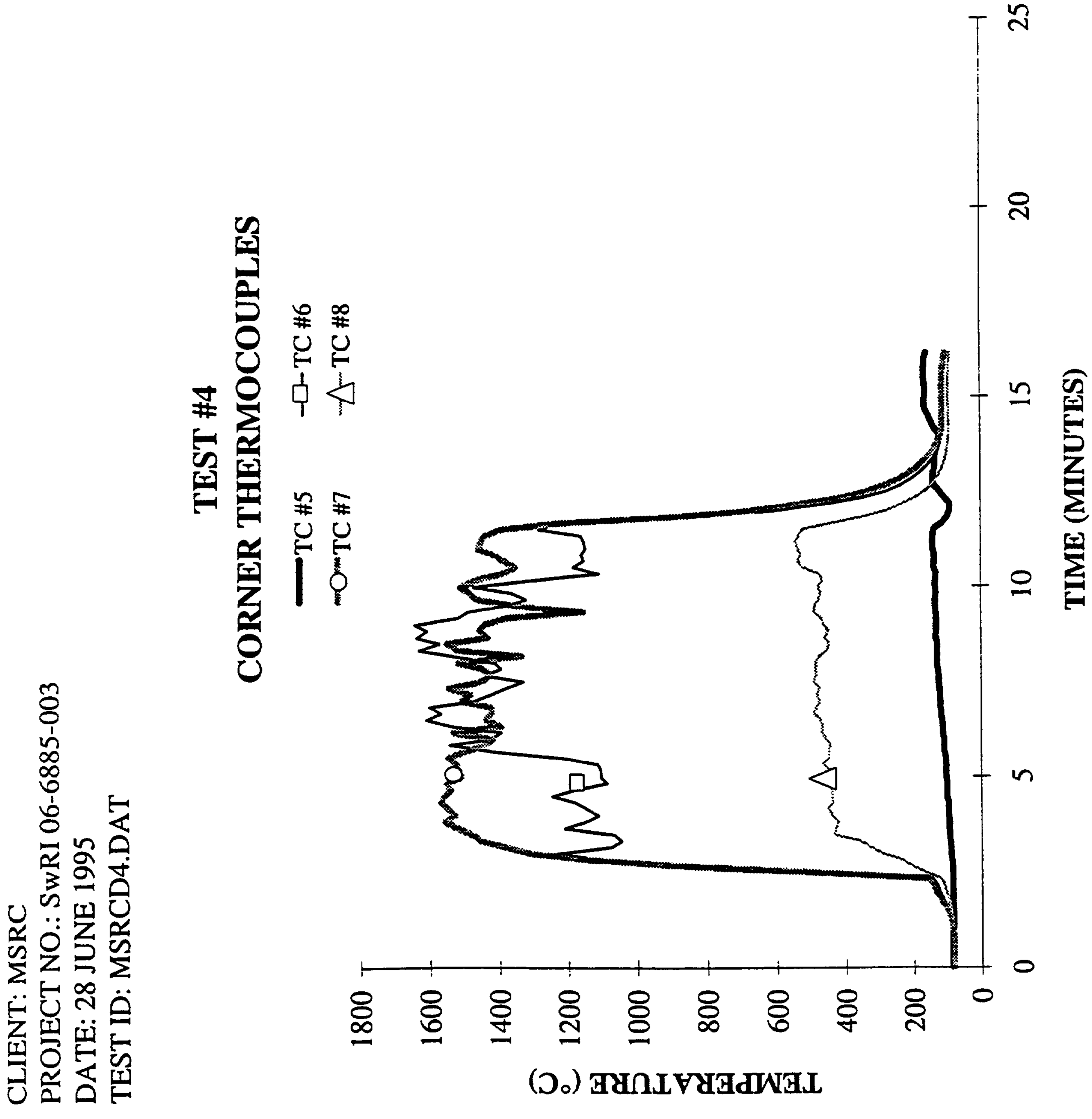
PROJECT NO.: SwRI 06-6885-003
DATE: 28 JUNE 1995
TEST ID: MSRCD4.DAT
TEST #4
CENTER THERMOCOUPLES
TC #1
TC #2
TC #3
TC #4
TEMPERATURE (°C)
TIME (MINUTES)
0
200
400
600
800
1000
1200
1400
1600
1800
0
5
10
15
20
25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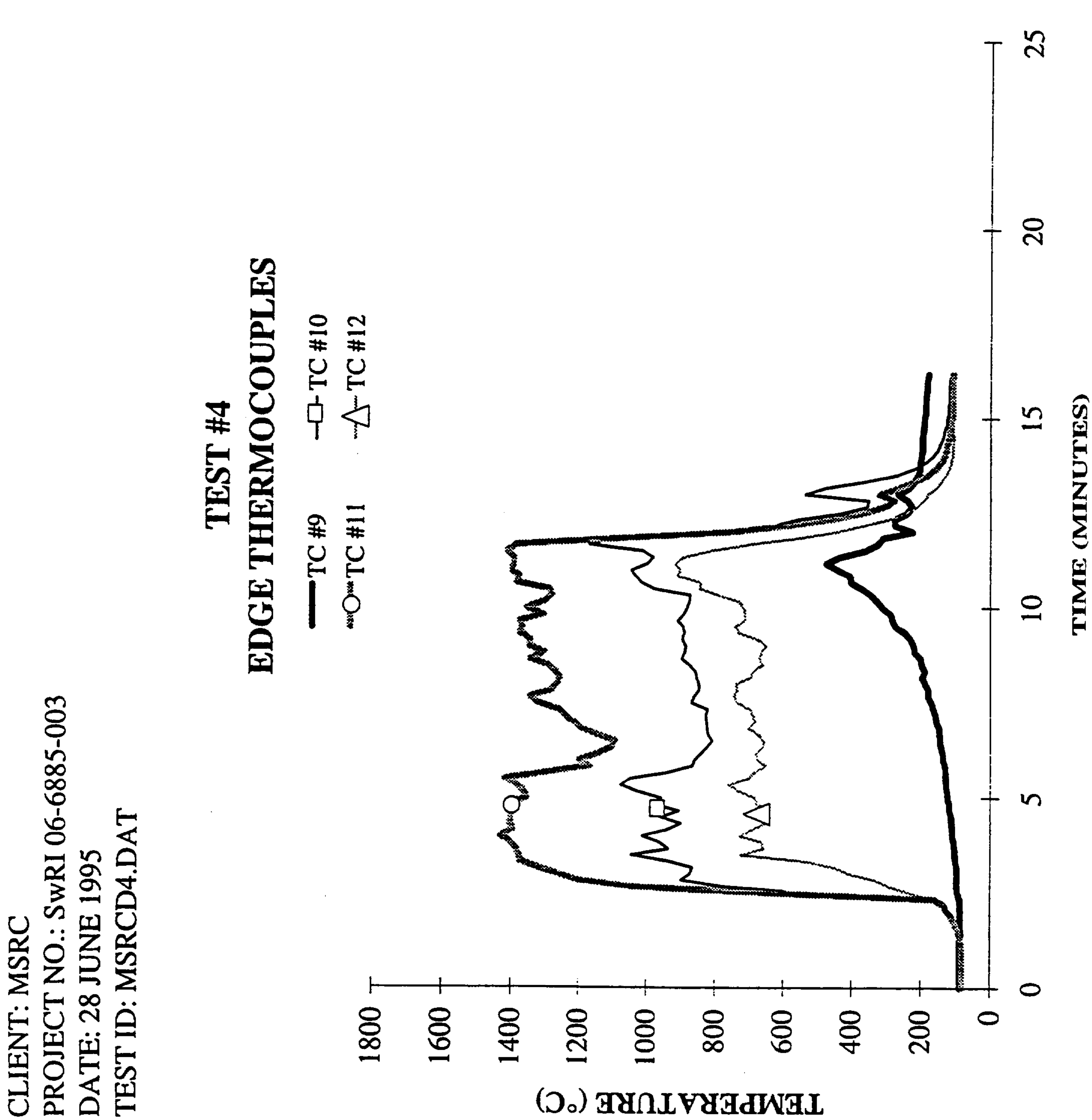
DATE: 28 JUNE 1995
TEST ID: MSRCD4.DAT
TEST #4
CORNER THERMOCOUPLES
TC #5
TC #6
TC #7
TC #8
TEMPERATURE (°C)
0
200
400
600
800
1000
1200
1400
1600
1800
TIME (MINUTES)
0
5
10
15
20
25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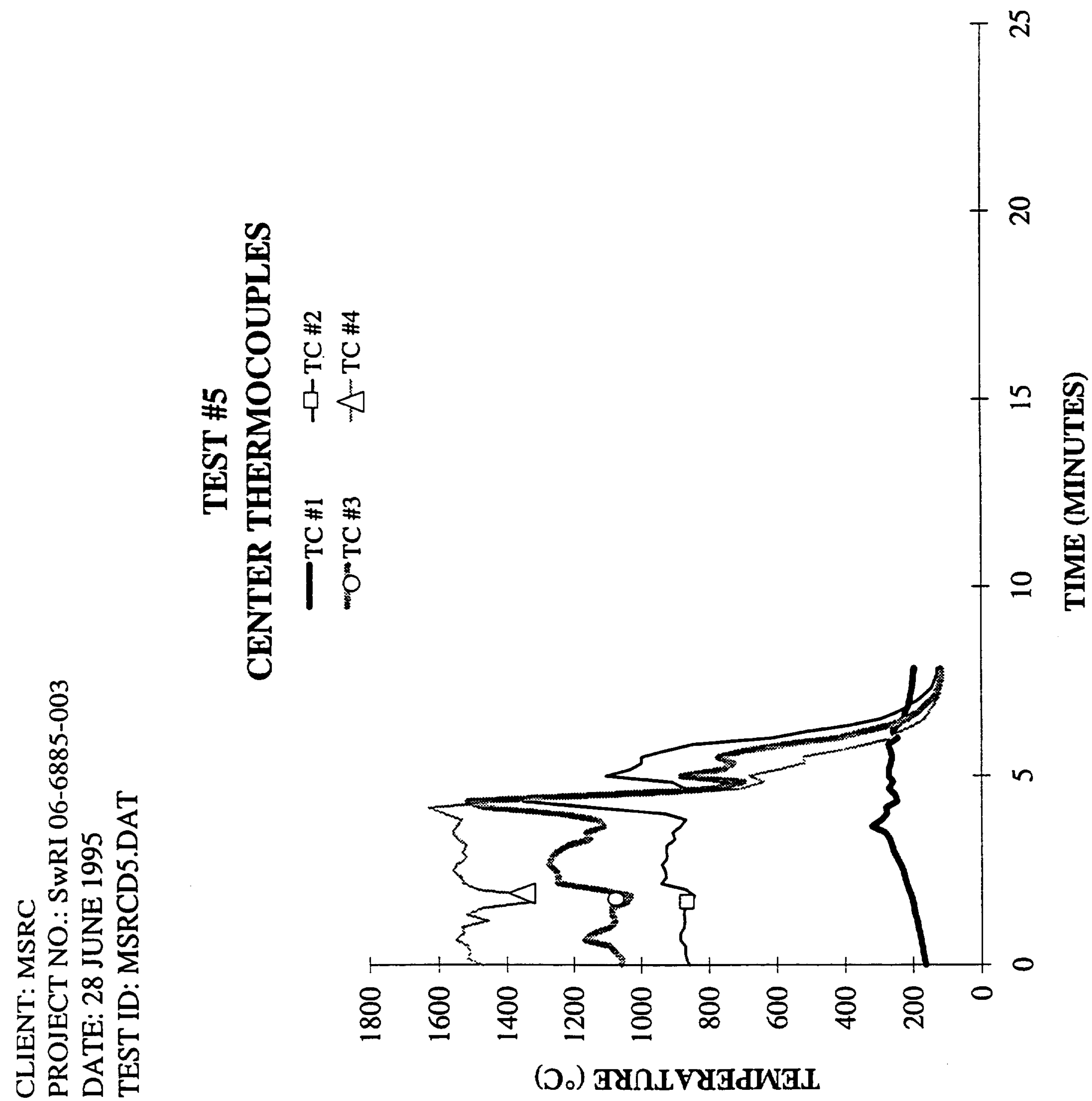
DATE: 28 JUNE 1995
TEST ID: MSRCD4.DAT
TEST #4
EDGE THERMOCOUPLES
TC #9
TC #10
TC #11
TC #12
TEMPERATURE (°C)
TIME (MINUTES)
0
200
400
600
800
1000
1200
1400
1600
1800
0
5
10
15
20
25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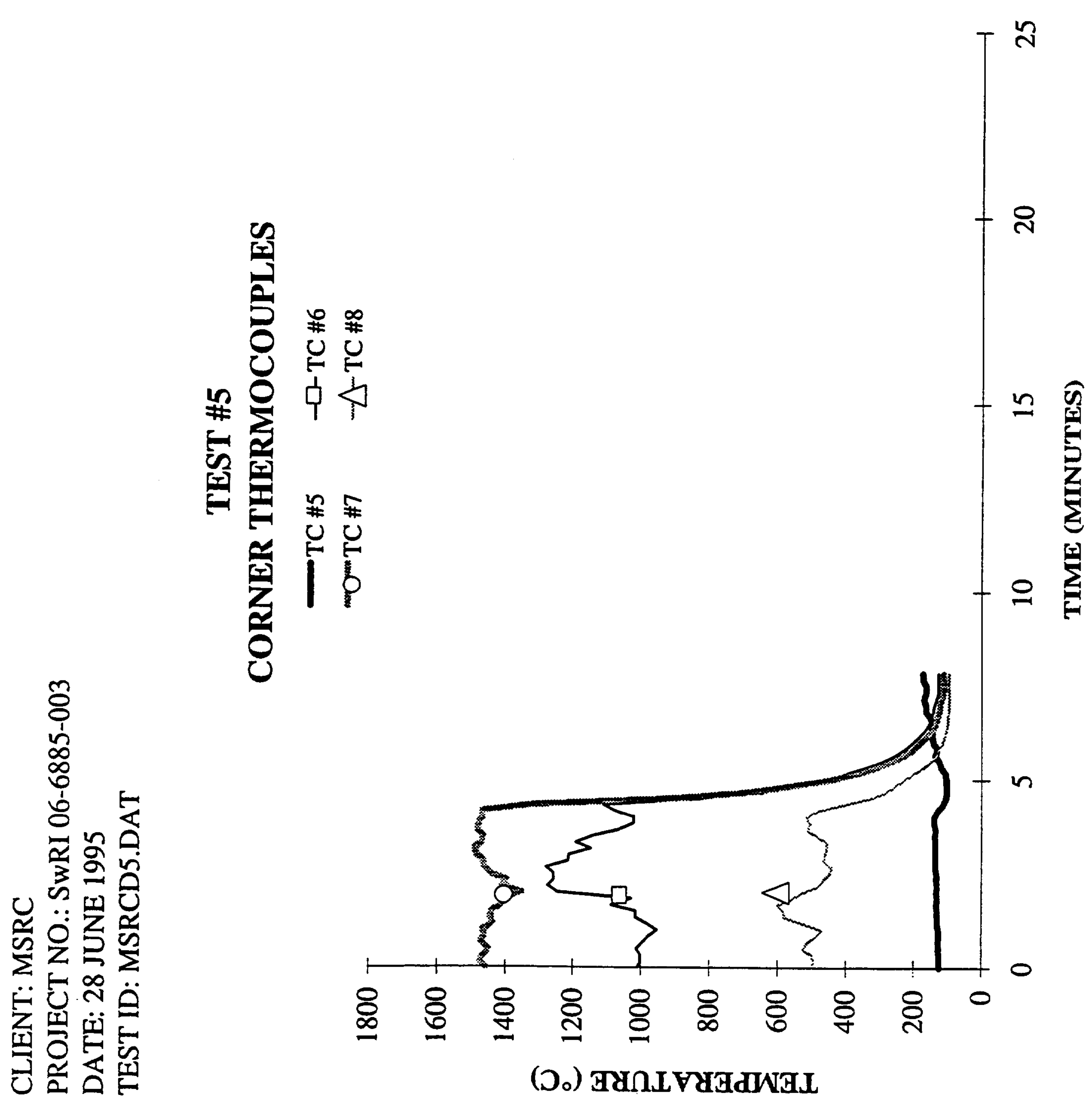
DATE: 28 JUNE 1995
TEST ID: MSRCD5.DAT
TEST #5
CENTER THERMOCOUPLES
TC #1
TC #2
TC #3
TC #4
TEMPERATURE (°C)
TIME (MINUTES)
0
200
400
600
800
1000
1200
1400
1600
1800
0
5
10
15
20
25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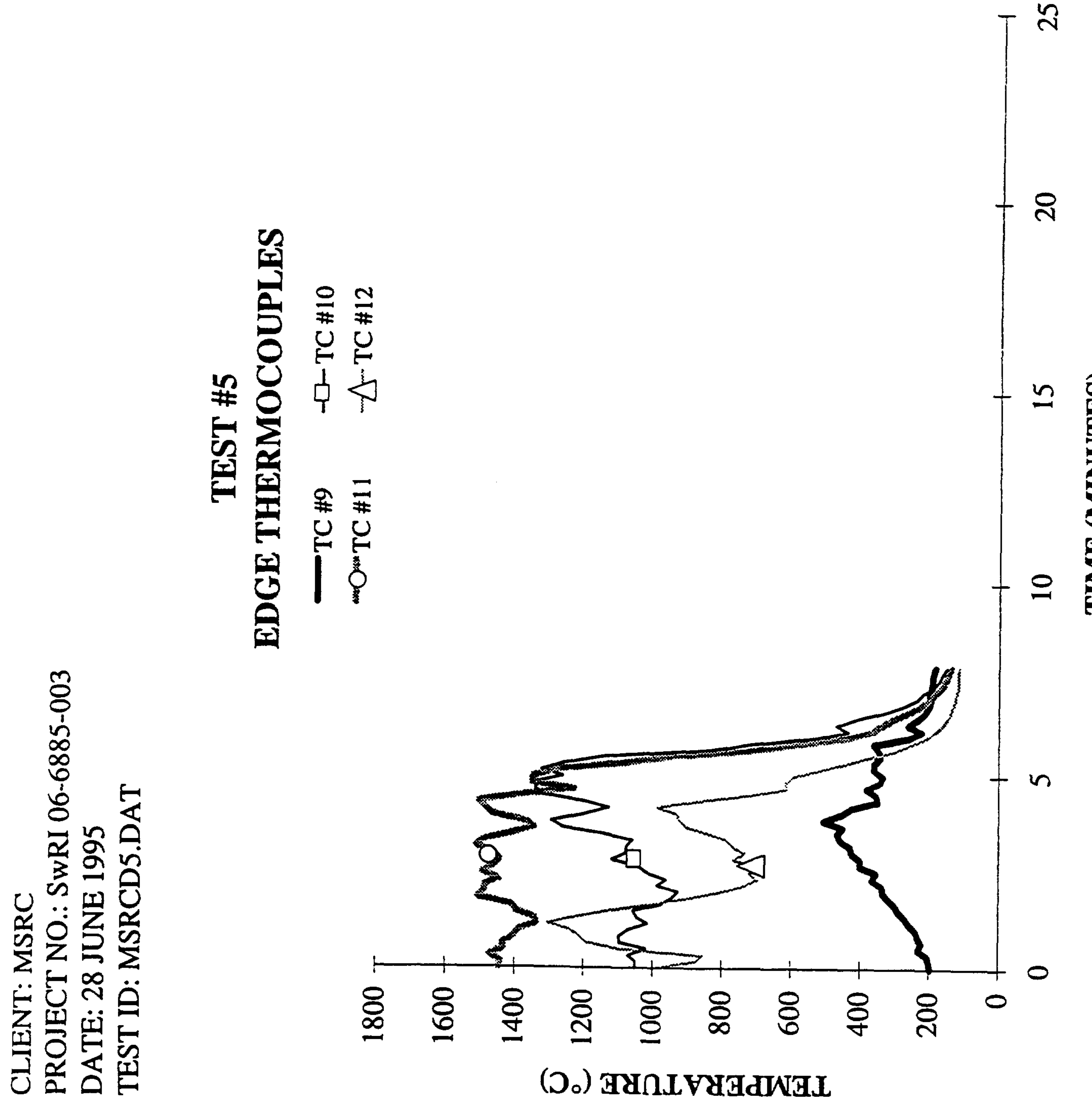
PROJECT NO.: SwRI 06-6885-003
DATE: 28 JUNE 1995
TEST ID: MSRCD5.DAT
TEST #5
CORNER THERMOCOUPLES
TC #5
TC #6
TC #7
TC #8
TEMPERATURE (°C)
TIME (MINUTES)
0
200
400
600
800
1000
1200
1400
1600
1800
0
5
10
15
20
25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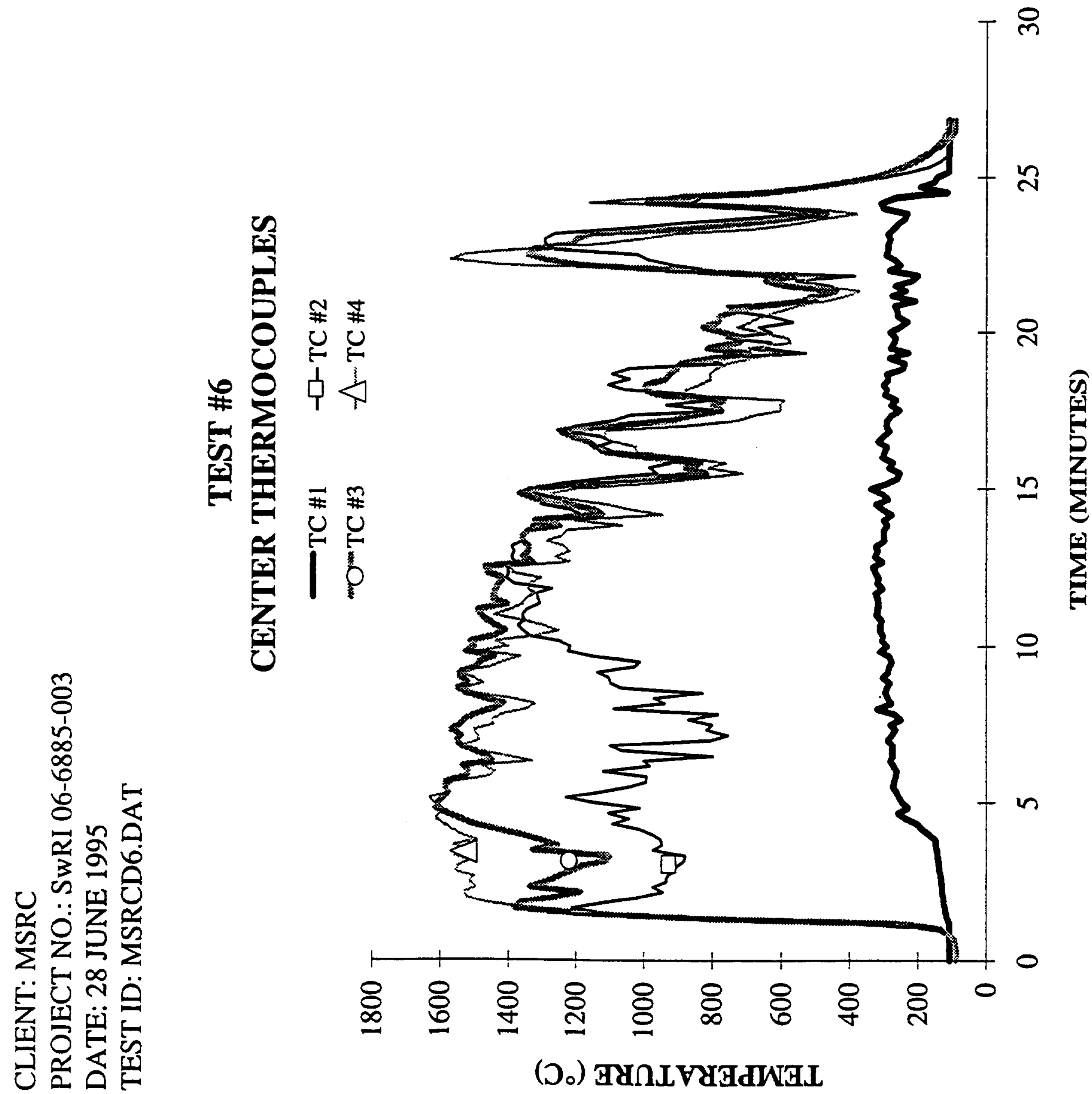
DATE: 28 JUNE 1995
TEST ID: MSRCD5.DAT
TEST #5
EDGE THERMOCOUPLES
TC #9
TC #10
TC #11
TC #12
TEMPERATURE (°C)
0
200
400
600
800
1000
1200
1400
1600
1800
TIME (MINUTES)
0
5
10
15
20
25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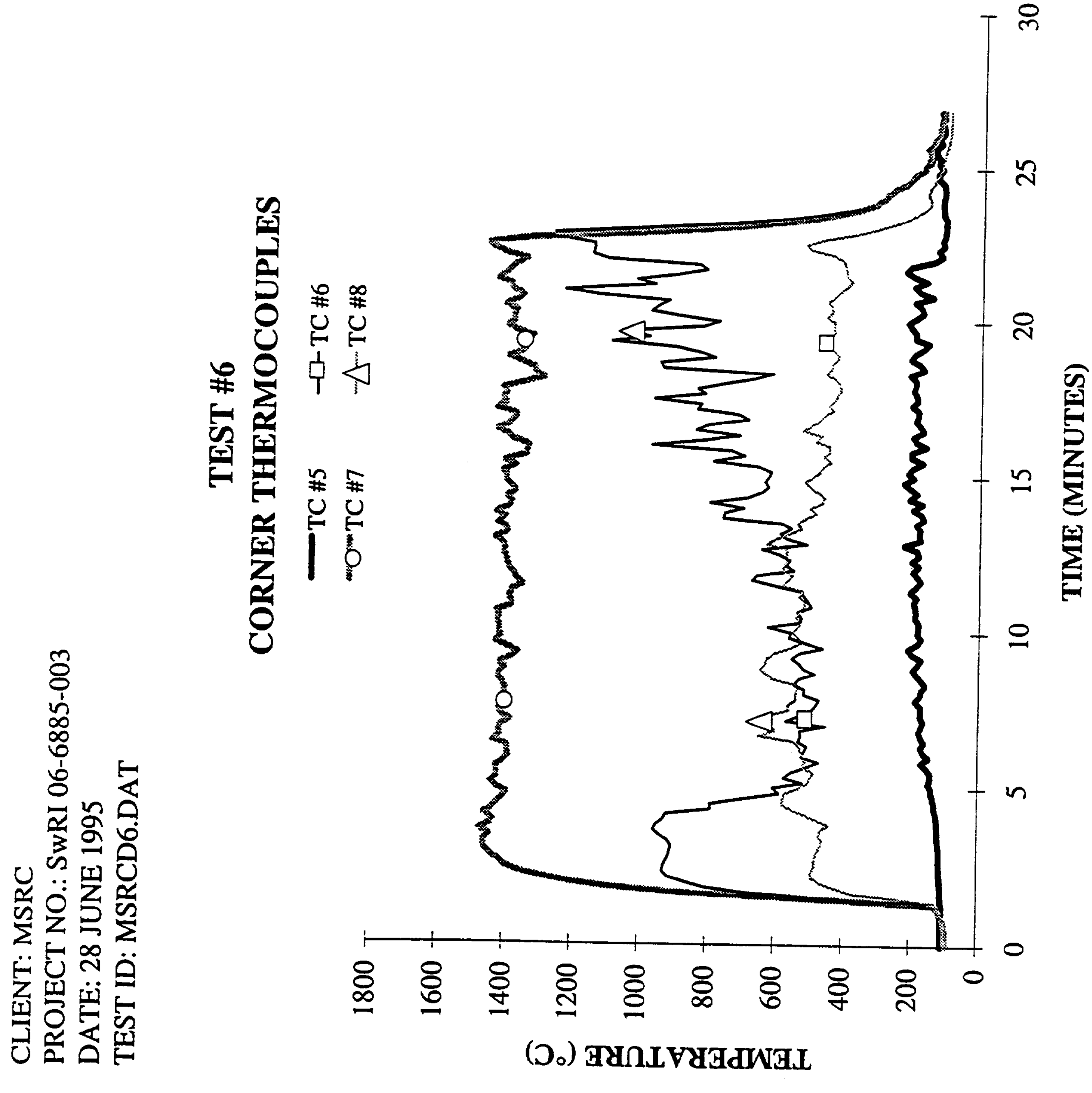
PROJECT NO.: SwRI 06-6885-003
DATE: 28 JUNE 1995
TEST ID: MSRCD6.DAT
TEST #6
CENTER THERMOCOUPLES
TC #1
TC #2
TC #3
TC #4
TEMPERATURE (°C)
0
200
400
600
800
1000
1200
1400
1600
1800
TIME (MINUTES)
0
5
10
15
20
25
30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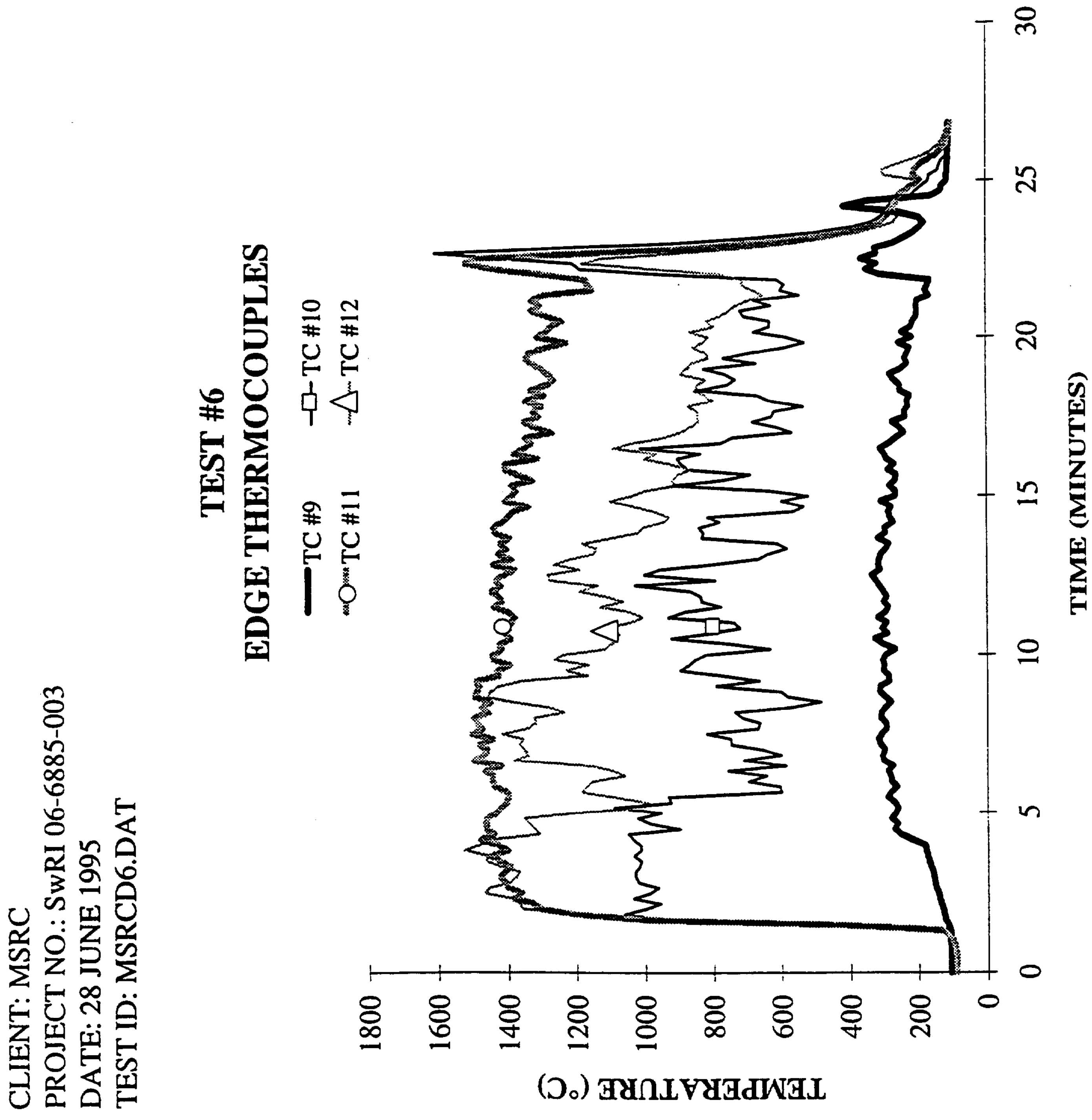
PROJECT NO.: SwRI 06-6885-003
DATE: 28 JUNE 1995
TEST ID: MSRCD6.DAT
TEST #6
CORNER THERMOCOUPLES
TC #5
TC #6
TC #7
TC #8
TEMPERATURE (°C)
1800
1600
1400
1200
1000
800
600
400
200
0
0
5
10
15
20
25
30
TIME (MINUTES)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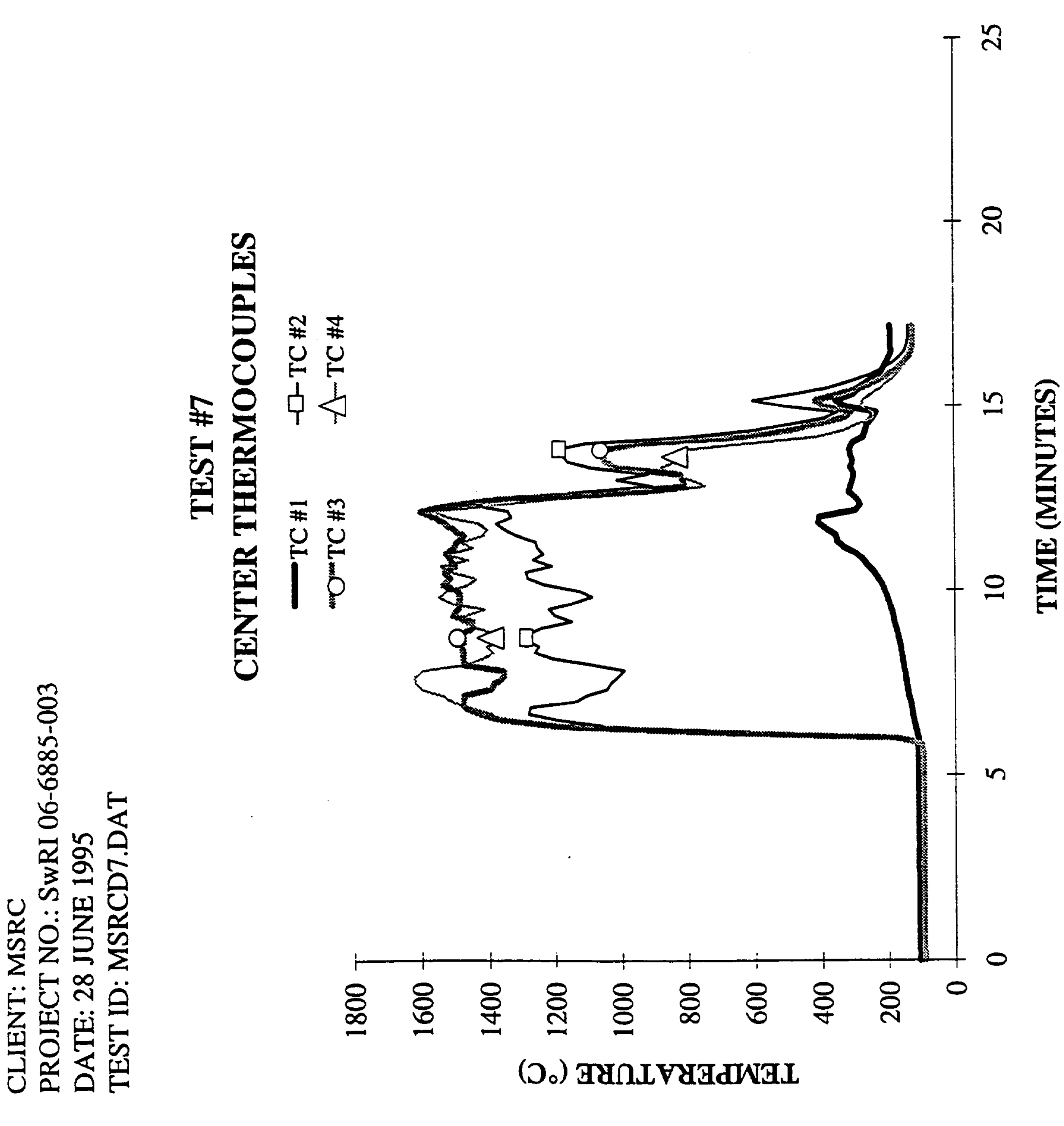
PROJECT NO.: SwRI 06-6885-003
DATE: 28 JUNE 1995
TEST ID: MSRCD6.DAT
TEST #6
EDGE THERMOCOUPLES
TC #9
TC #10
TC #11
TC #12
TEMPERATURE (°C)
TIME (MINUTES)
0
200
400
600
800
1000
1200
1400
1600
1800
0
5
10
15
20
25
30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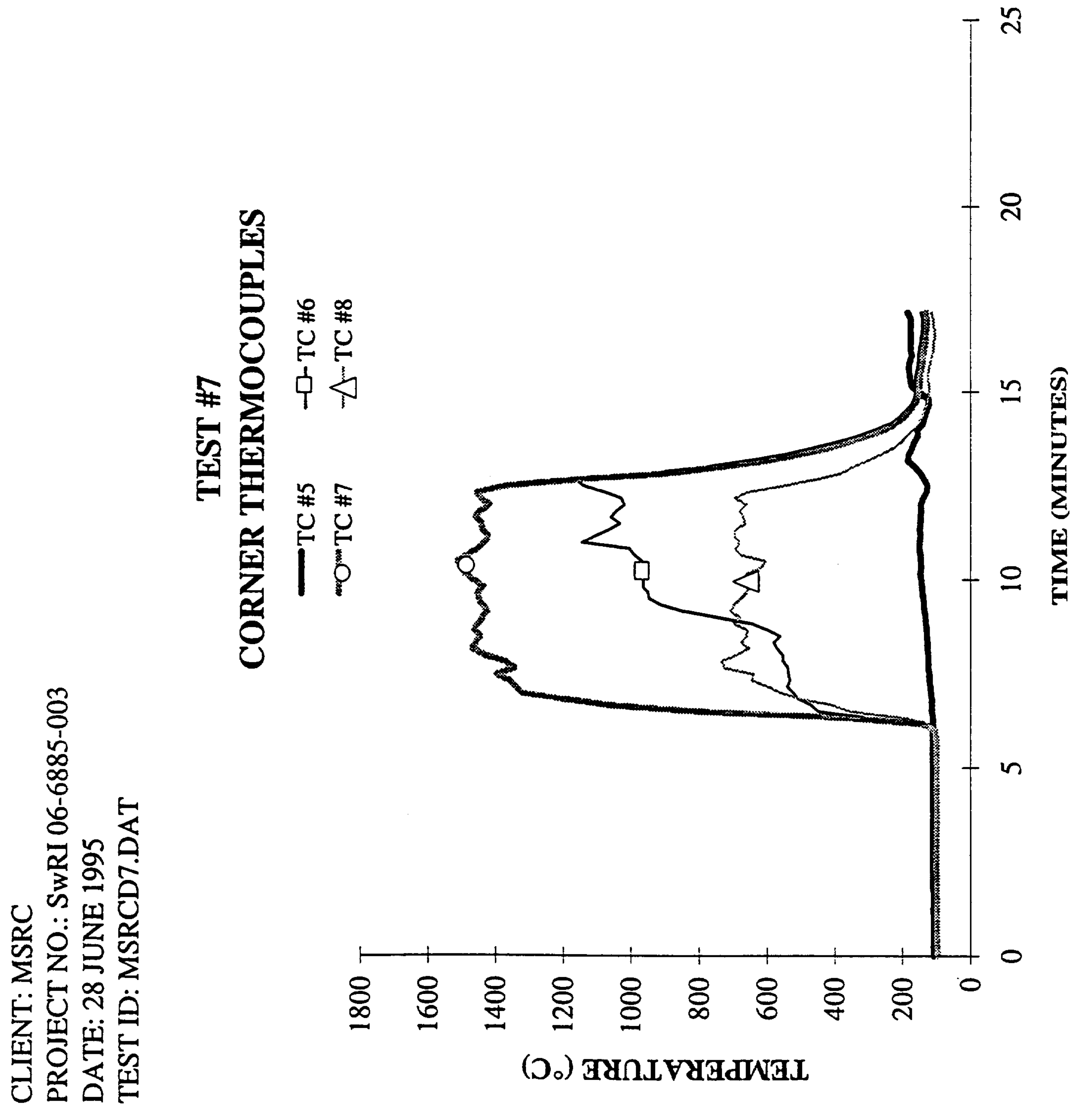
PROJECT NO.: SwRI 06-6885-003
DATE: 28 JUNE 1995
TEST ID: MSRCD7.DAT
TEST #7
CENTER THERMOCOUPLES
TC #1
TC #2
TC #3
TC #4
TEMPERATURE (°C)
0
200
400
600
800
1000
1200
1400
1600
1800
TIME (MINUTES)
0
5
10
15
20
25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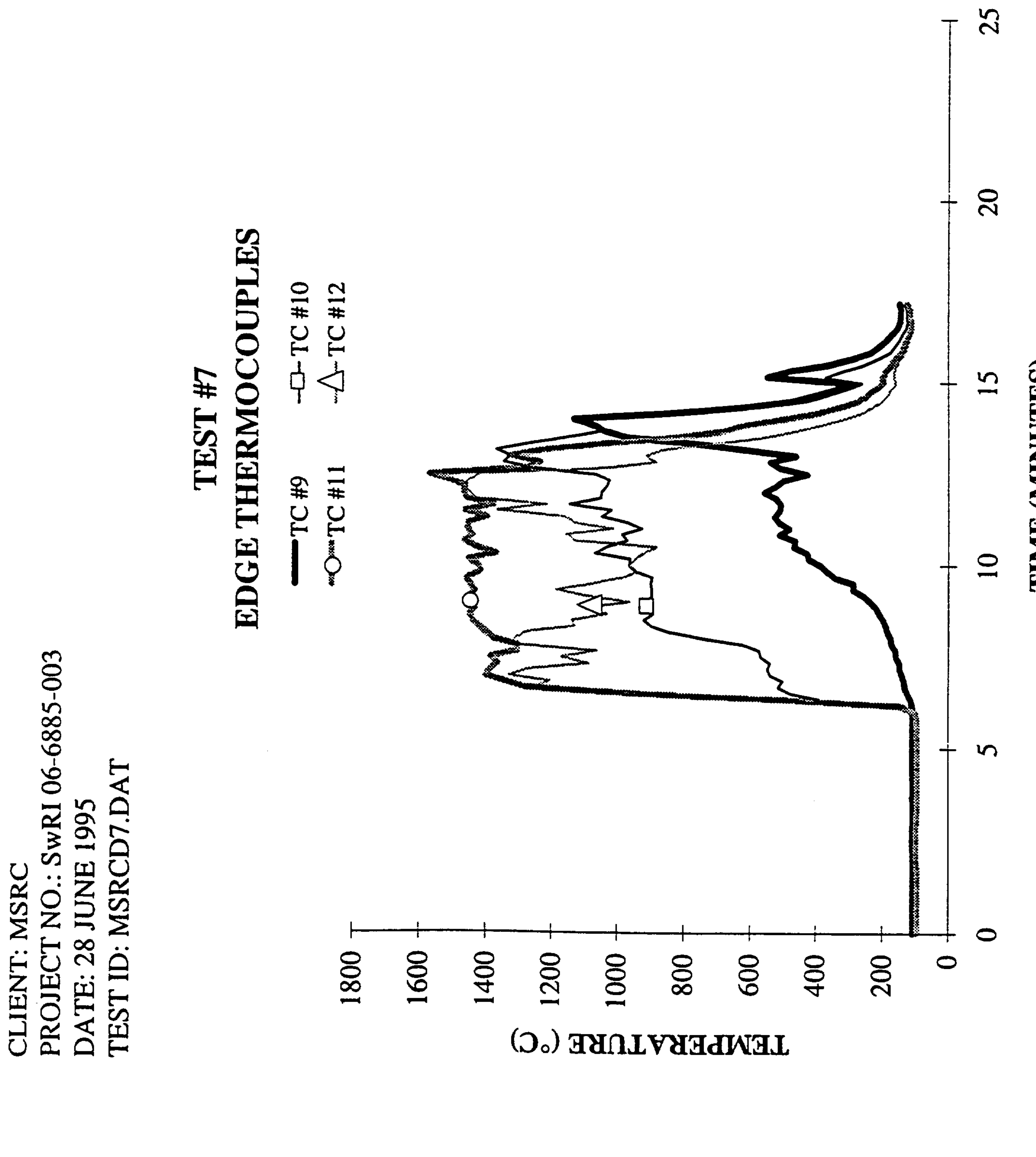
PROJECT NO.: SwRI 06-6885-003
DATE: 28 JUNE 1995
TEST ID: MSRCD7.DAT
TEST #7
CORNER THERMOCOUPLES
TC #5
TC #6
TC #7
TC #8
TEMPERATURE (°C)
1800
1600
1400
1200
1000
800
600
400
200
0
0
5
10
15
20
25
TIME (MINUTES)



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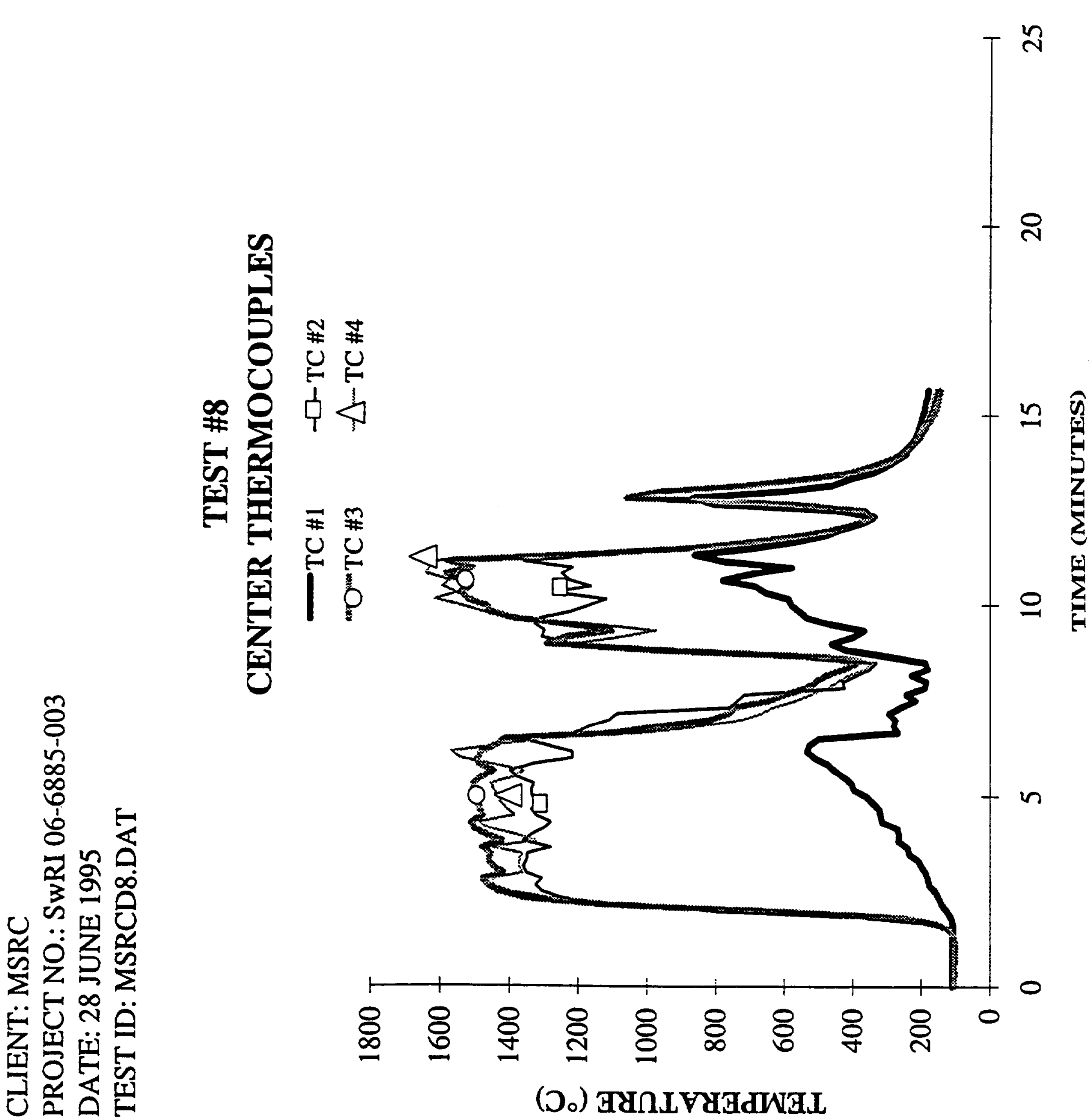
PROJECT NO.: SwRI 06-6885-003
DATE: 28 JUNE 1995
TEST ID: MSRCD7.DAT
TEST #7
EDGE THERMOCOUPLES
TC #9
TC #10
TC #11
TC #12
TEMPERATURE (°C)
0
200
400
600
800
1000
1200
1400
1600
1800
TIME (MINUTES)
0
5
10
15
20
25



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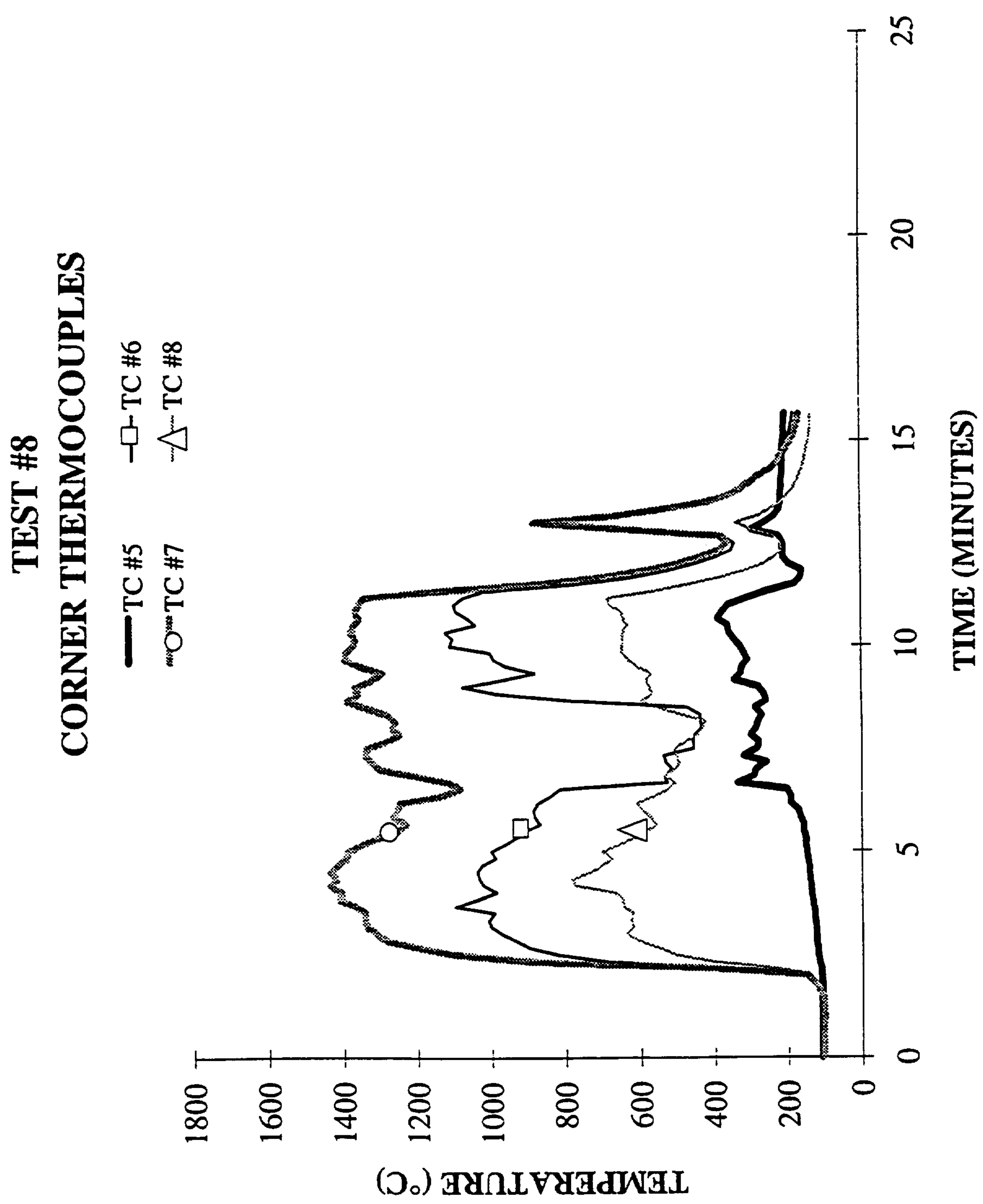
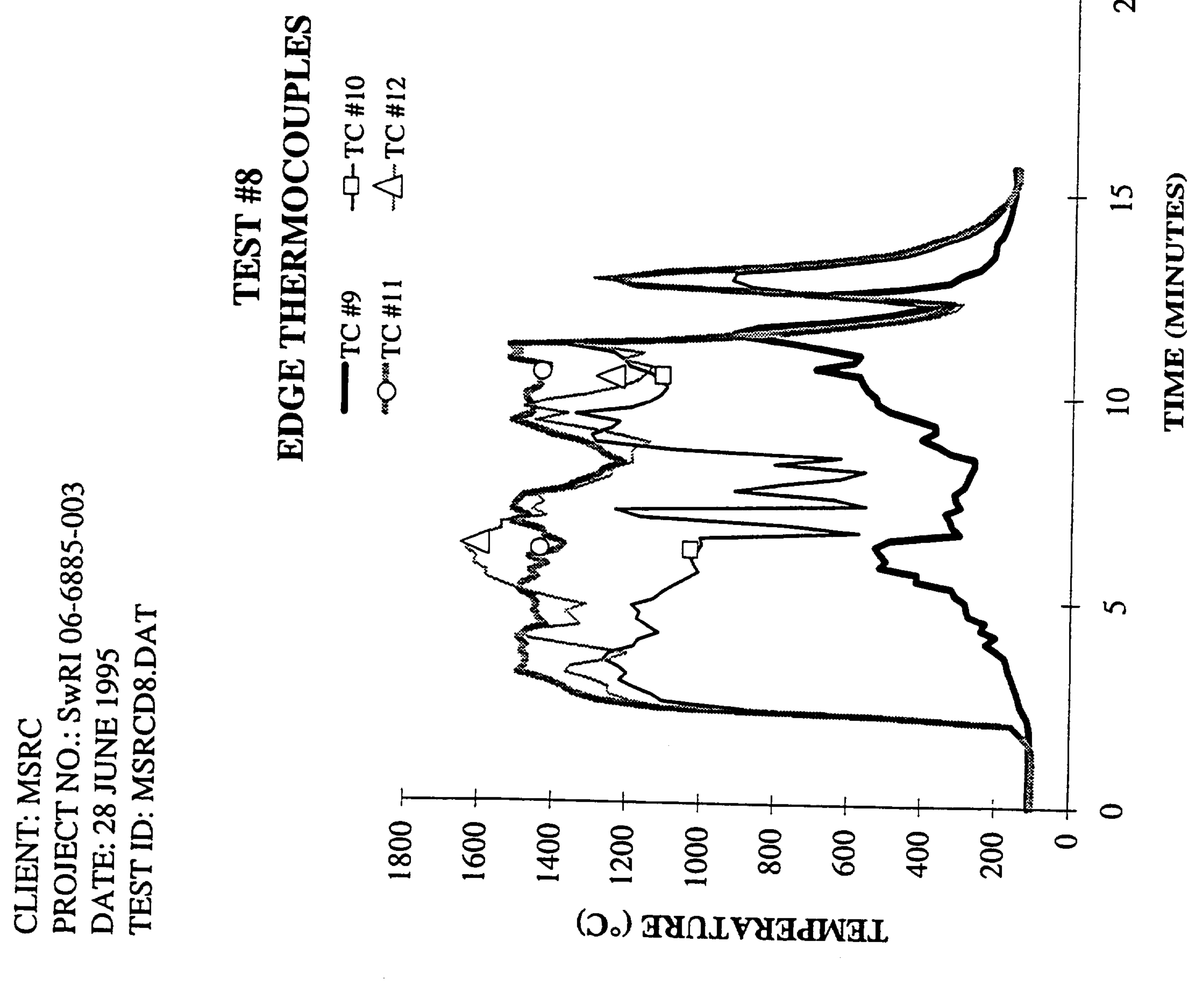
PROJECT NO.: SwRI 06-6885-003
DATE: 28 JUNE 1995
TEST ID: MSRCD8.DAT
TEST #8
CENTER THERMOCOUPLES
TC #1
TC #2
TC #3
TC #4
TEMPERATURE (°C)
TIME (MINUTES)
0
200
400
600
800
1000
1200
1400
1600
1800
5
10
15
20
25

CLIENT: MSRC
PROJECT NO.: SwRI 06-6885-003
DATE: 28 JUNE 1995
TEST ID: MSRCD8.DAT





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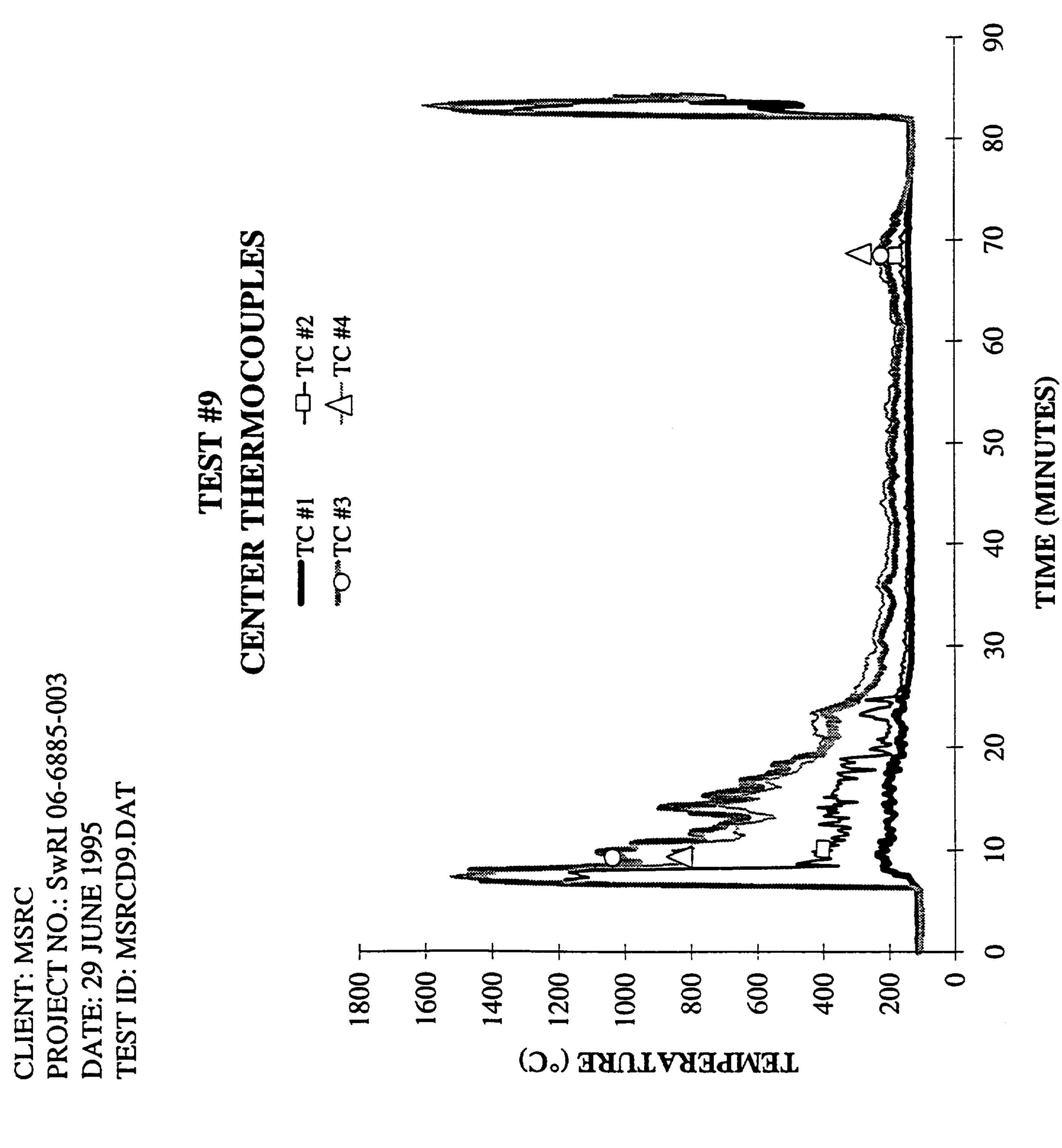
PROJECT NO.: SwRI 06-6885-003
DATE: 28 JUNE 1995
TEST ID: MSRCD8.DAT
TEST #8
EDGE THERMOCOUPLES
TC #9
TC #10
TC #11
TC #12
TEMPERATURE (°C)
TIME (MINUTES)
0
200
400
600
800
1000
1200
1400
1600
1800
0
5
10
15
20
25



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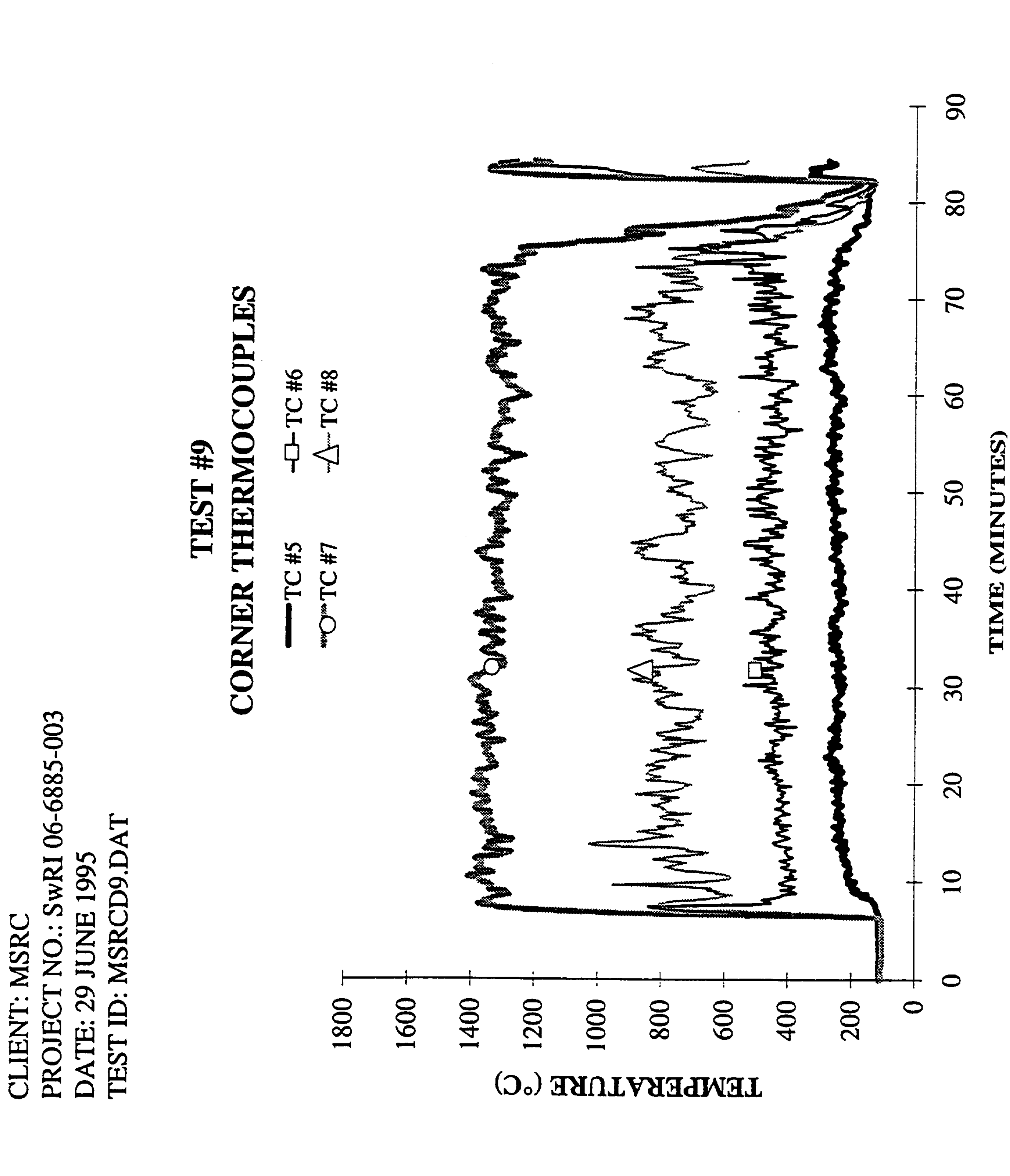
PROJECT NO.: SwRI 06-6885-003
DATE: 29 JUNE 1995
TEST ID: MSRCD9.DAT
TEST #9
CENTER THERMOCOUPLES
TC #1
TC #2
TC #3
TC #4
TEMPERATURE (°C)
TIME (MINUTES)
0
200
400
600
800
1000
1200
1400
1600
1800
10
20
30
40
50
60
70
80
90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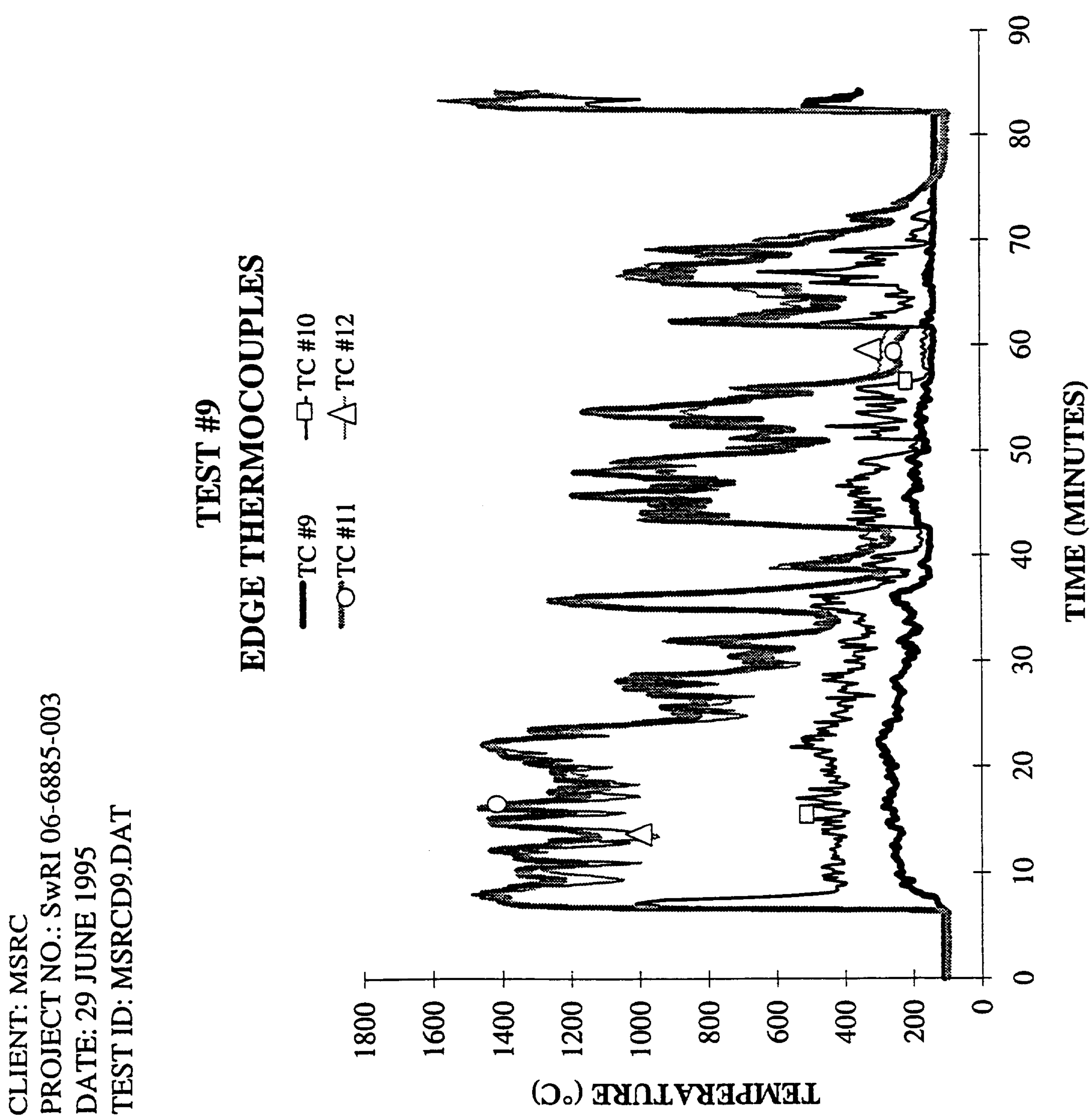
DATE: 29 JUNE 1995
TEST ID: MSRCD9.DAT
TEST #9
CORNER THERMOCOUPLES
TC #5
TC #6
TC #7
TC #8
TEMPERATURE (°C)
TIME (MINUTES)
0
200
400
600
800
1000
1200
1400
1600
1800
0
10
20
30
40
50
60
70
80
90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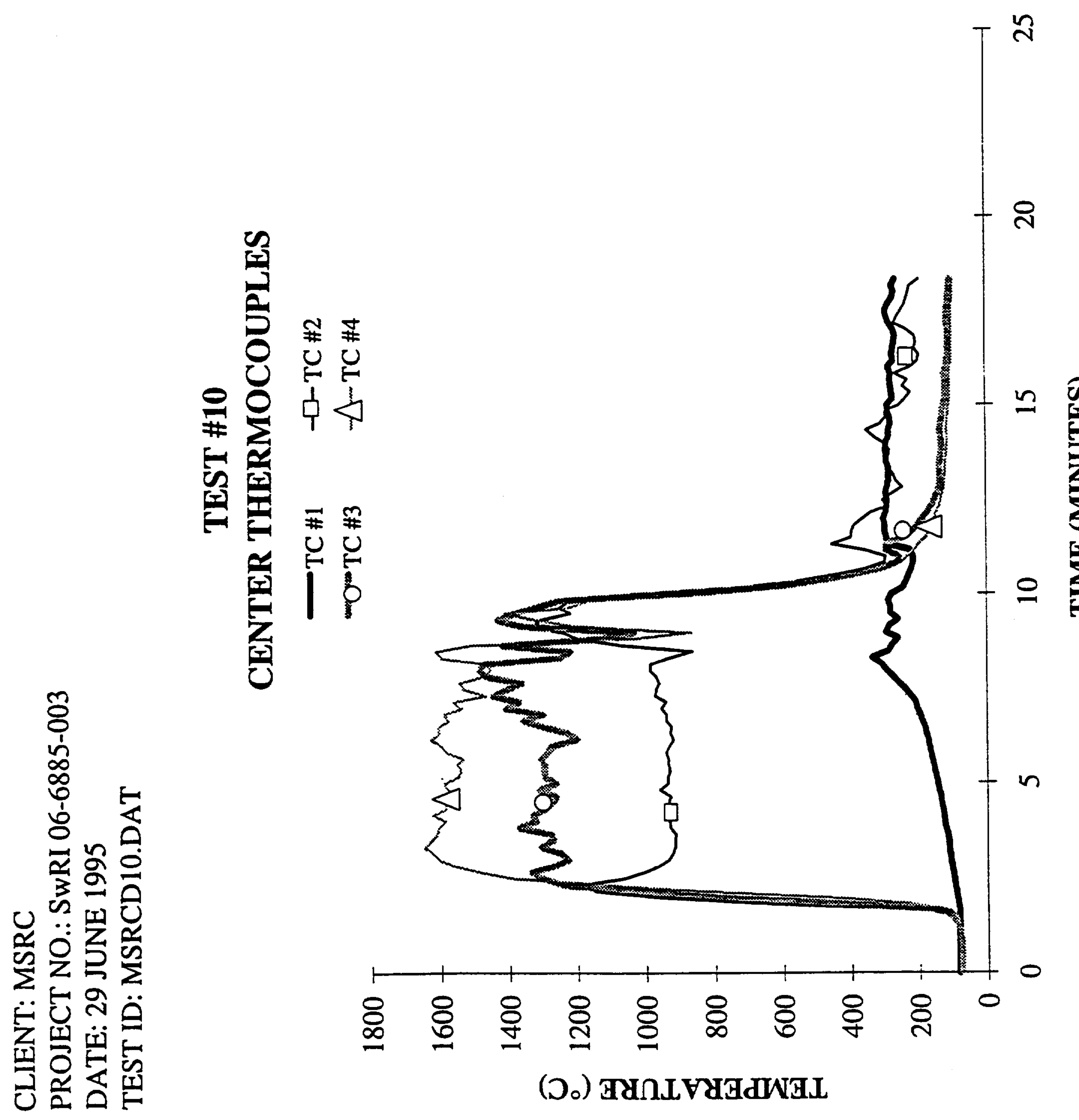
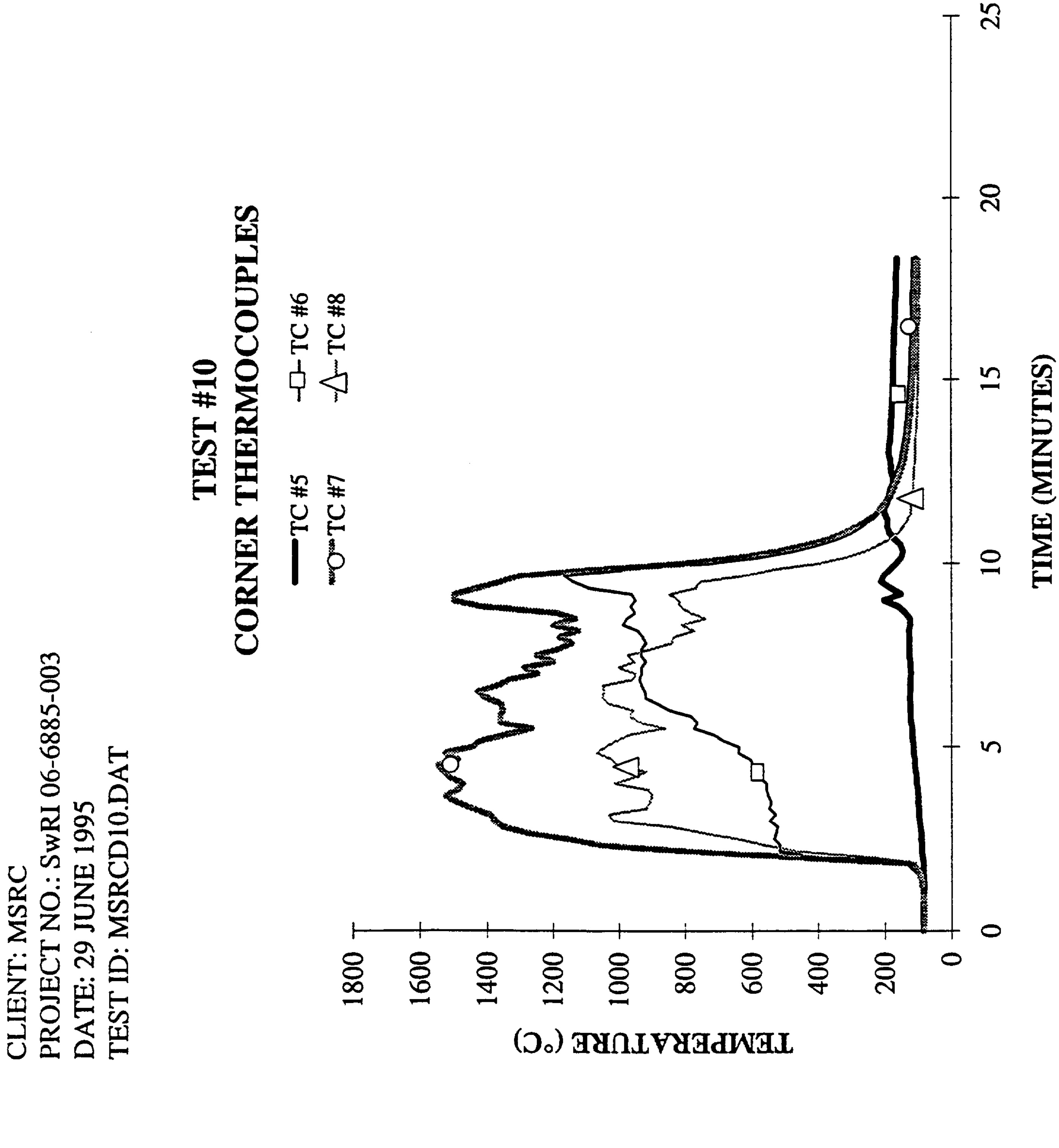
DATE: 29 JUNE 1995
TEST ID: MSRCD9.DAT
TEST #9
EDGE THERMOCOUPLES
TC #9
TC #10
TC #11
TC #12
TEMPERATURE (°C)
0
200
400
600
800
1000
1200
1400
1600
1800
TIME (MINUTES)
0
10
20
30
40
50
60
70
80
90



CLIENT: MSRC
PROJECT NO.: SwRI 06-6885-003
DATE: 29 JUNE 1995
TEST ID: MSRCD10.DAT
TEST #10
CENTER THERMOCOUPLES
TC #1
TC #2
TC #3
TC #4
TEMPERATURE (°C)
0
200
400
600
800
1000
1200
1400
1600
1800
TIME (MINUTES)
0
5
10
15
20
25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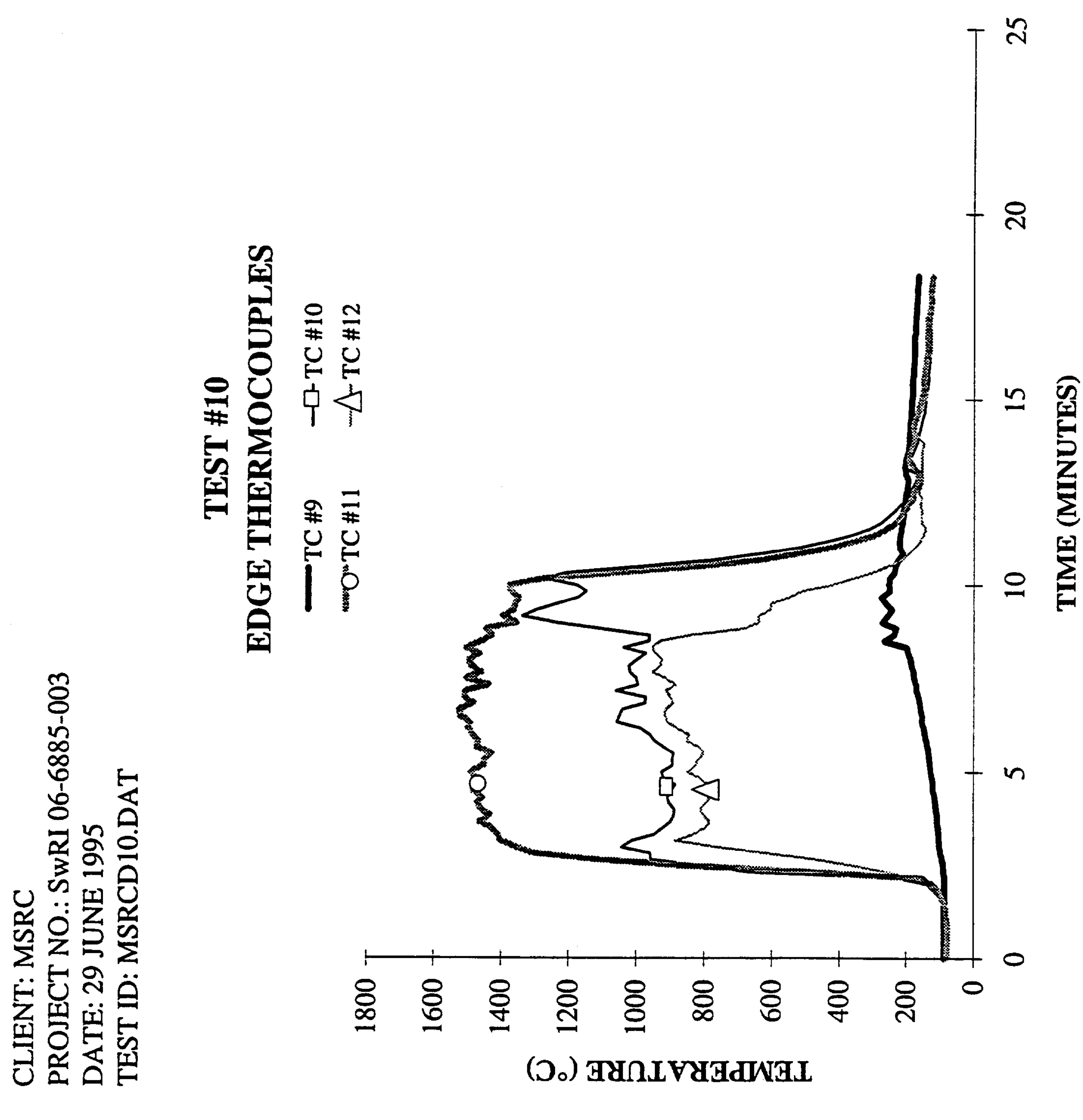
DATE: 29 JUNE 1995
TEST ID: MSRCD10.DAT
TEST #10
CORNER THERMOCOUPLES
TC #5
TC #6
TC #7
TC #8
TEMPERATURE (°C)
0
200
400
600
800
1000
1200
1400
1600
1800
TIME (MINUTES)
0
5
10
15
20
25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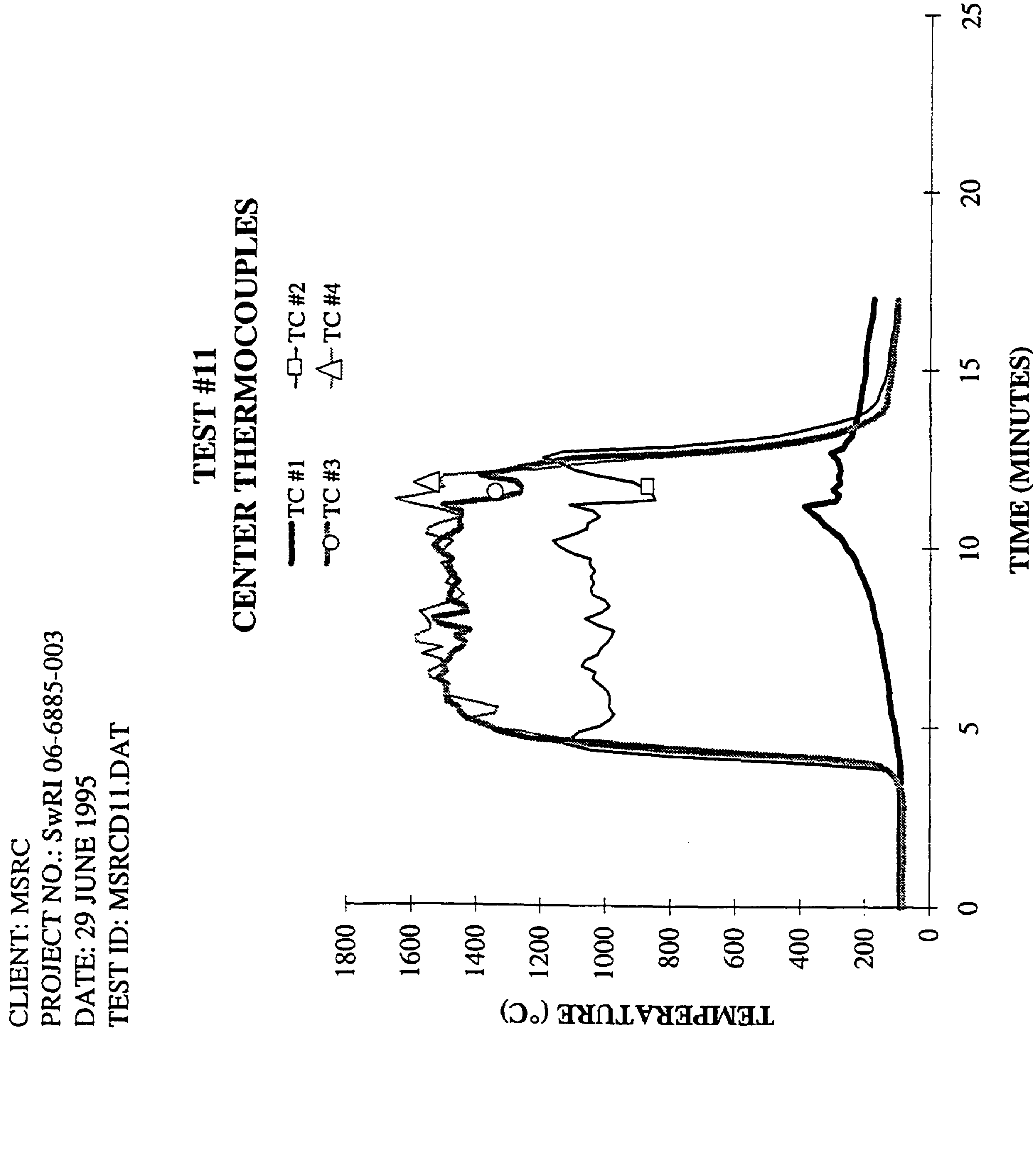
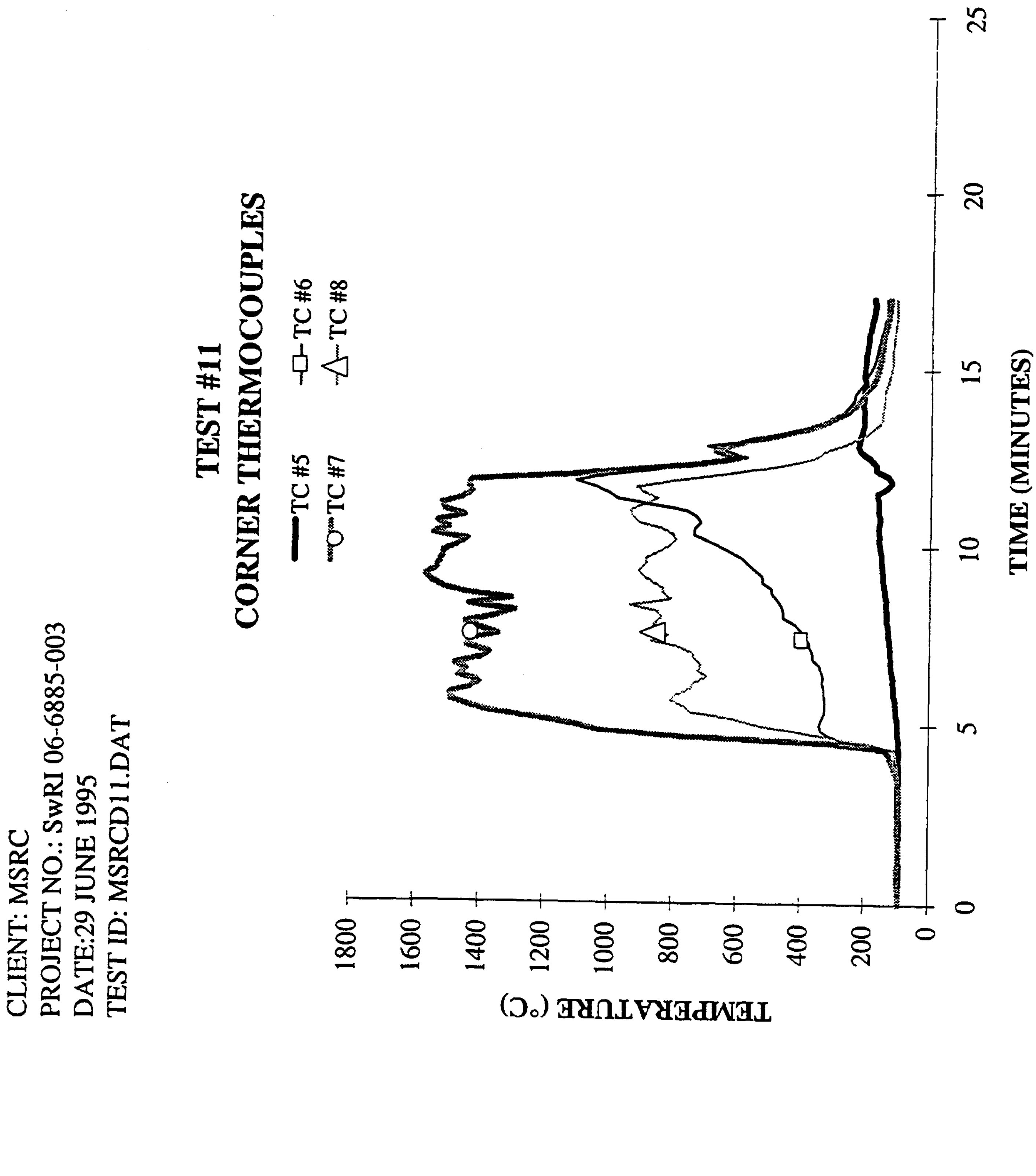
PROJECT NO.: SwRI 06-6885-003
DATE: 29 JUNE 1995
TEST ID: MSRCD10.DAT
TEST #10
EDGE THERMOCOUPLES
TC #9
TC #10
TC #11
TC #12
TEMPERATURE (°C)
TIME (MINUTES)
0
200
400
600
800
1000
1200
1400
1600
1800
0
5
10
15
20
25



CLIENT: MSRC
PROJECT NO.: SwRI 06-6885-003
DATE: 29 JUNE 1995
TEST ID: MSRCD11.DAT
TEST #11
CENTER THERMOCOUPLES
TC #1
TC #2
TC #3
TC #4
TEMPERATURE (°C)
0
200
400
600
800
1000
1200
1400
1600
1800
TIME (MINUTES)
0
5
10
15
20
25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TC #5
TC #6
TC #7
TC #8
TEMPERATURE (°C)
0
200
400
600
800
1000
1200
1400
1600
1800
TIME (MINUTES)
0
5
10
15
20
25

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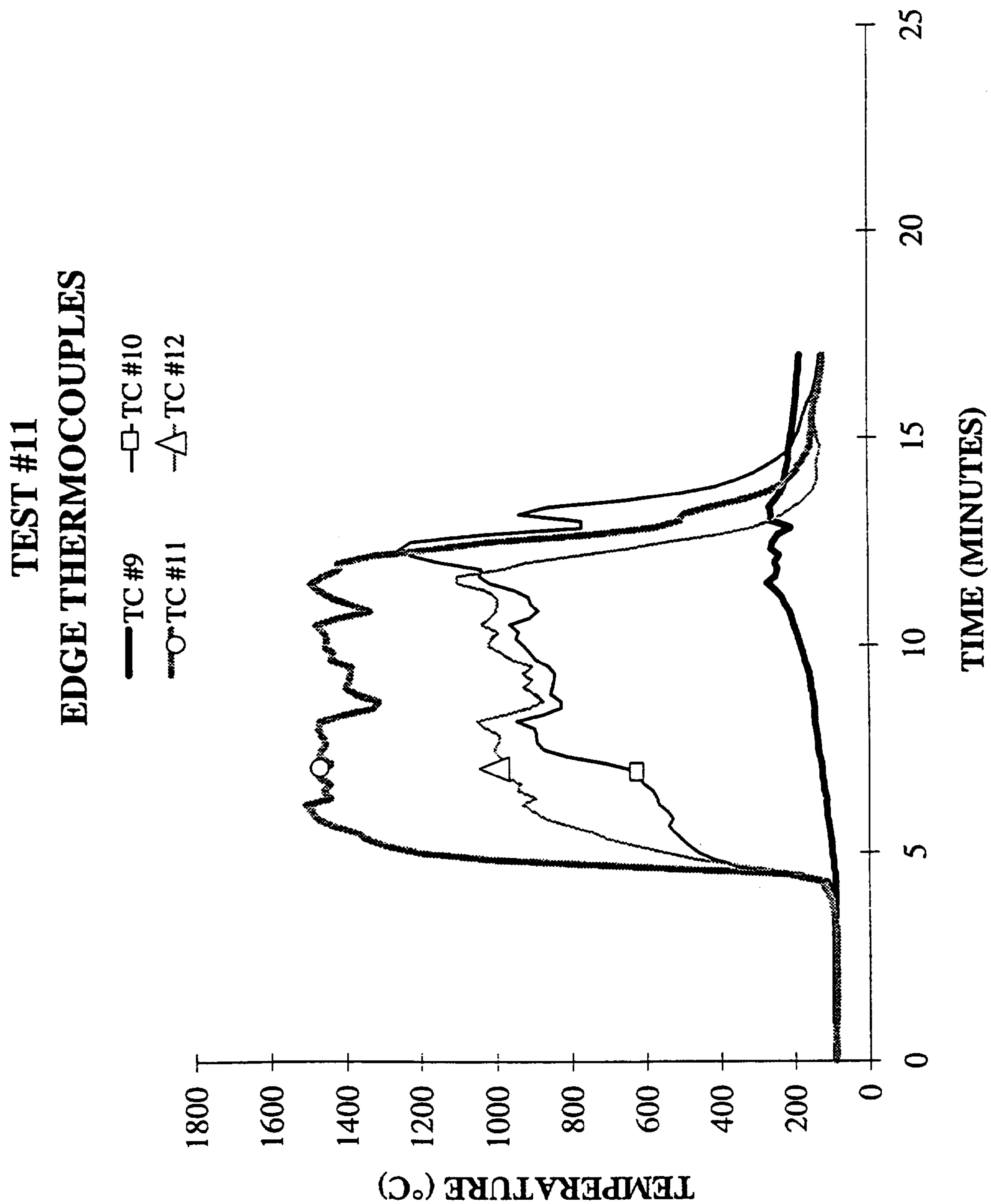

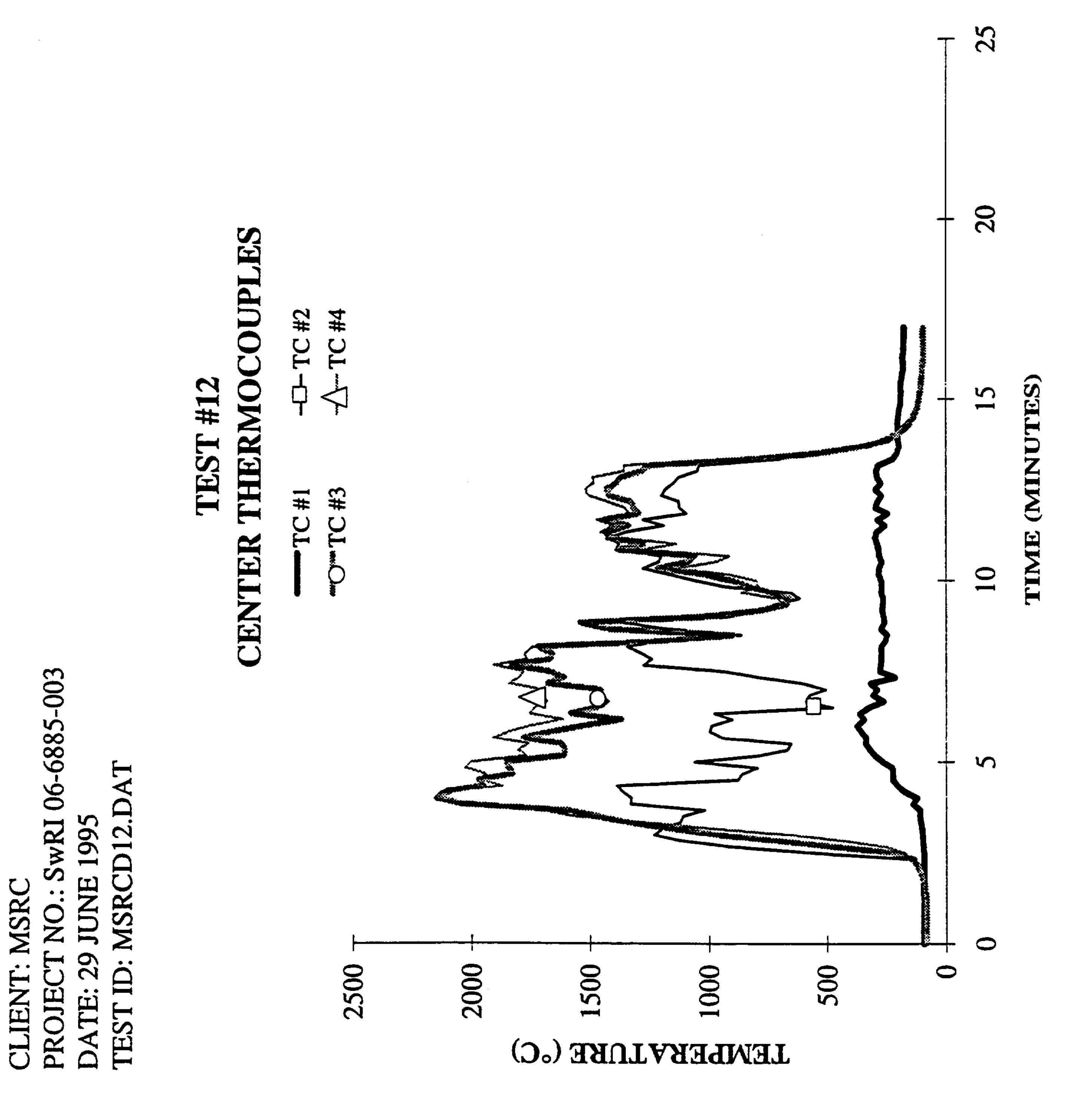

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CENTER THERMOCOUPLES
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TC #2
TC #3
TC #4
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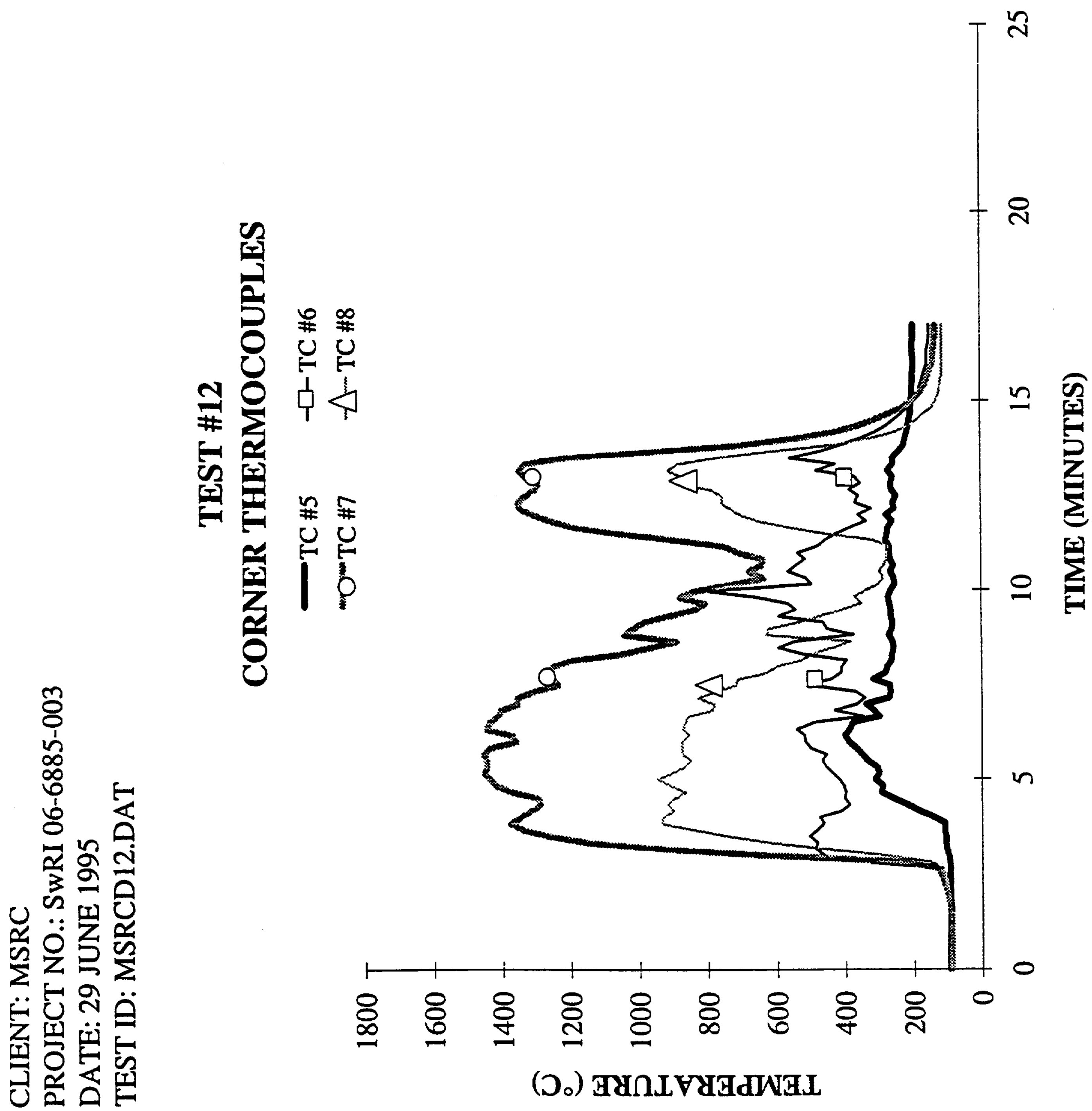
500
1000
1500
2000
2500
TIME (MINUTES)
0
5
10
15
20
25



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TC #5
TC #6
TC #7
TC #8
TEMPERATURE (°C)
TIME (MINUTES)
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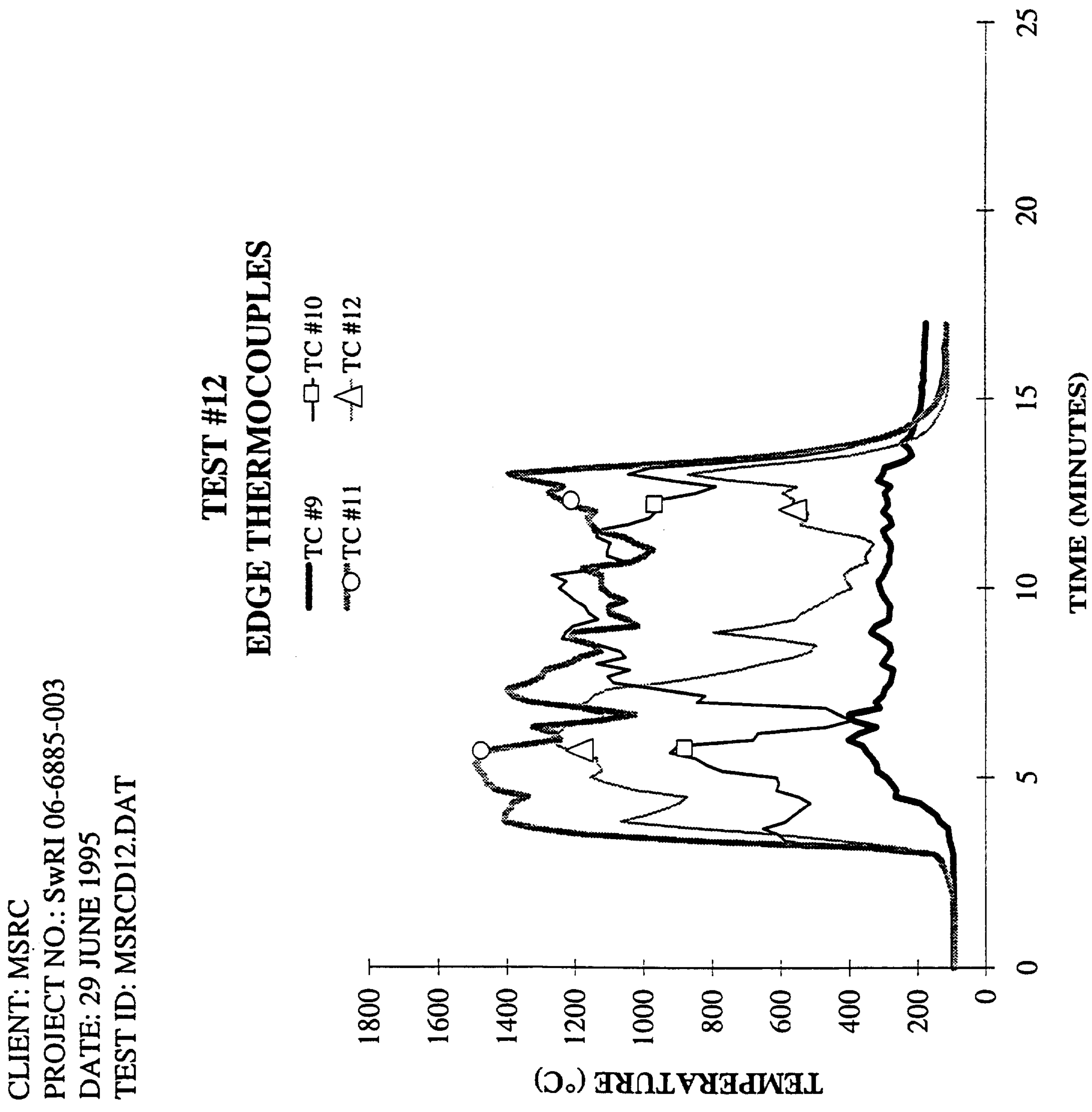
400
600
800
1000
1200
1400
1600
1800
0
5
10
15
20
25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TC #9
TC #10
TC #11
TC #12
TEMPERATURE (°C)
TIME (MINUTES)
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200
400
600
800
1000
1200
1400
1600
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10
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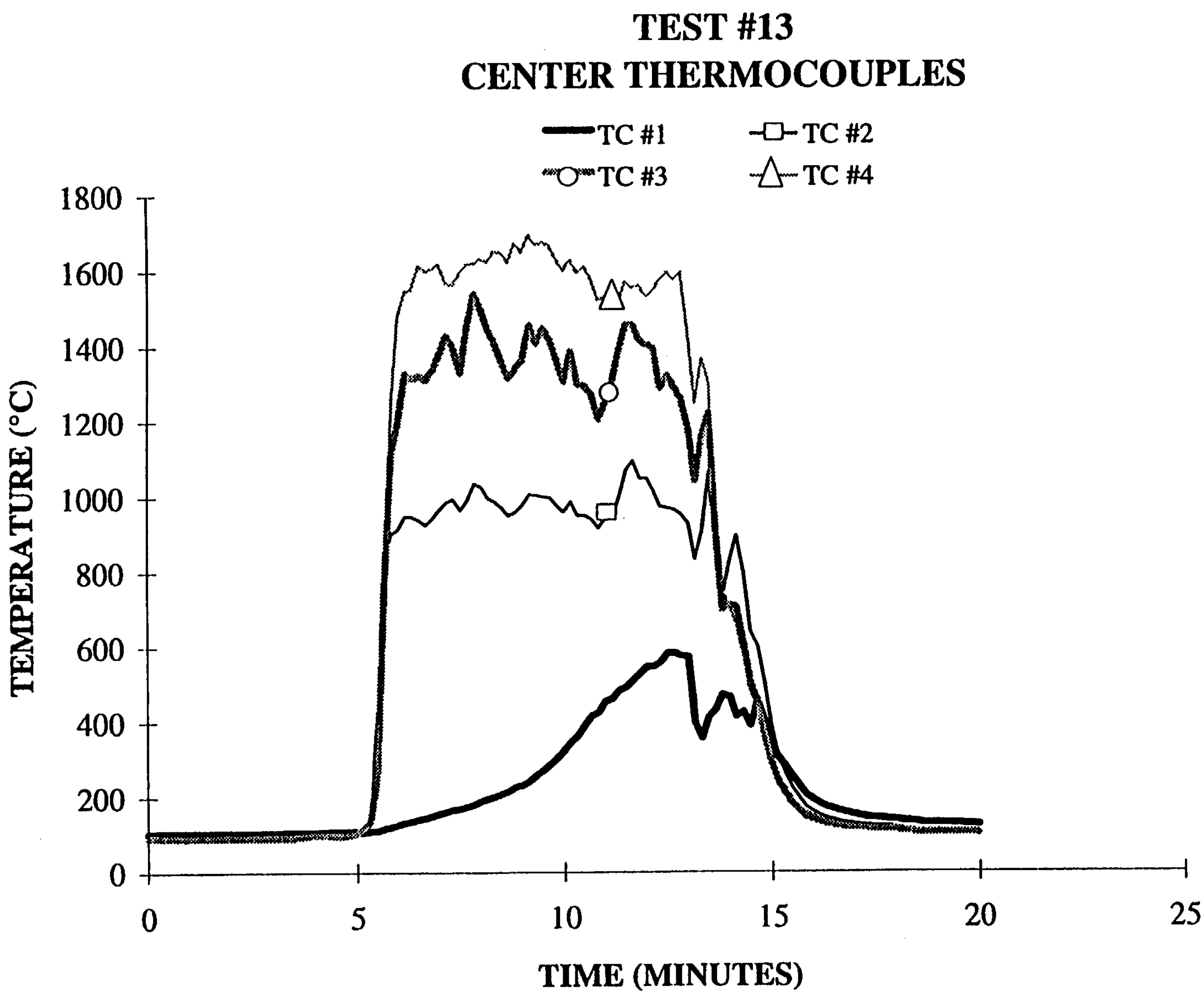

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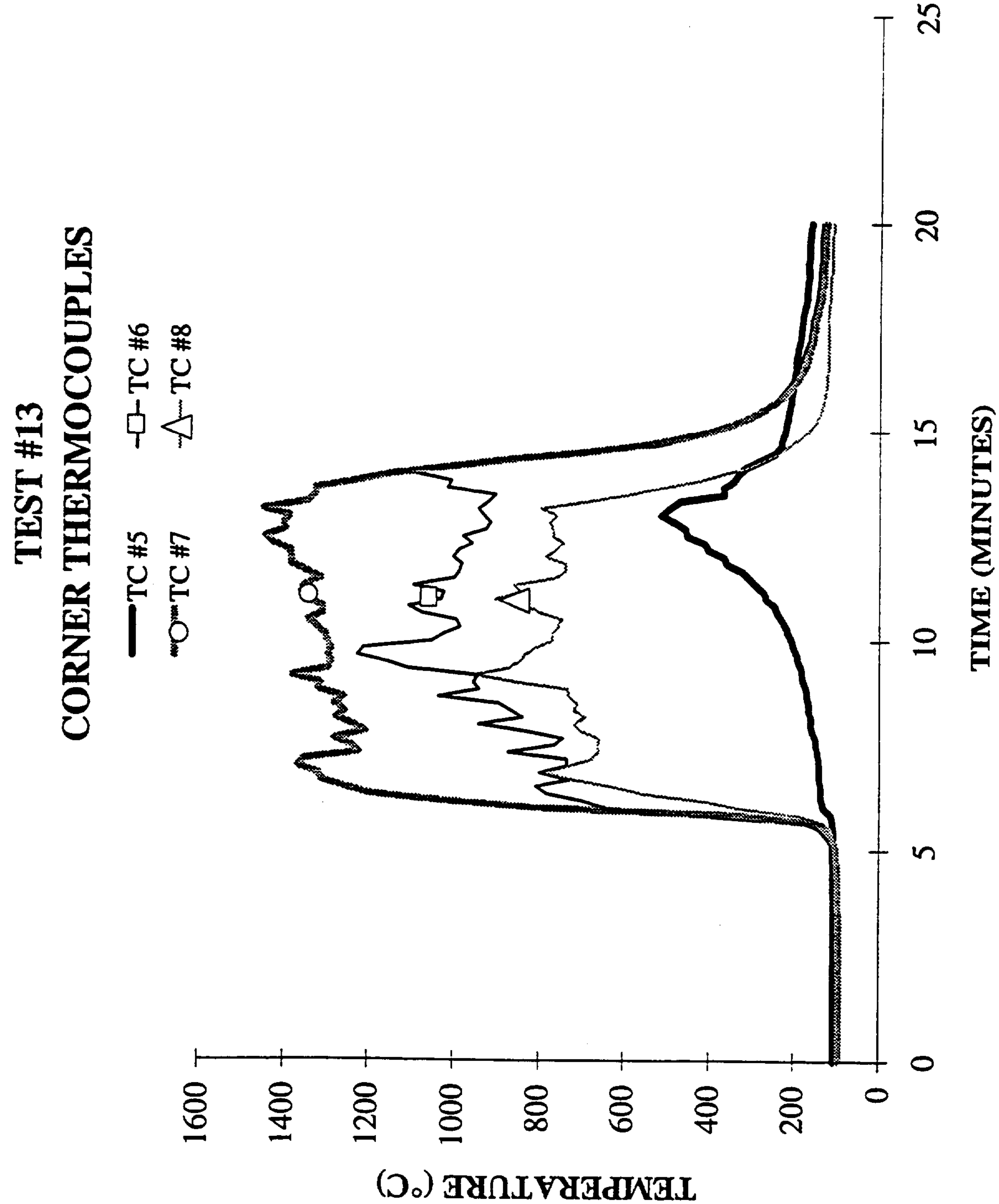

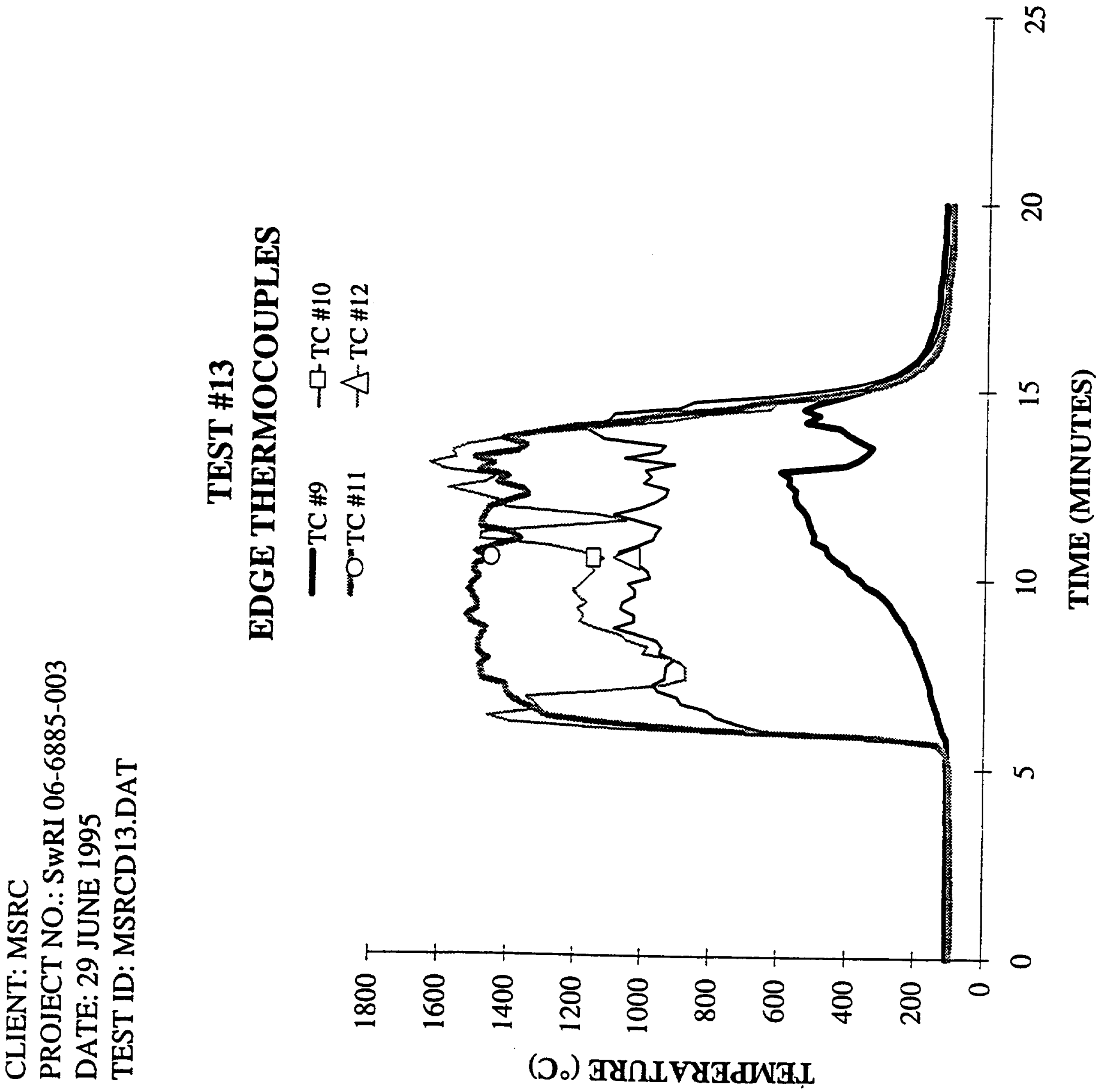

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TC #9
TC #10
TC #11
TC #12
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TIME (MINUTES)
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200
400
600
800
1000
1200
1400
1600
1800
5
10
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20
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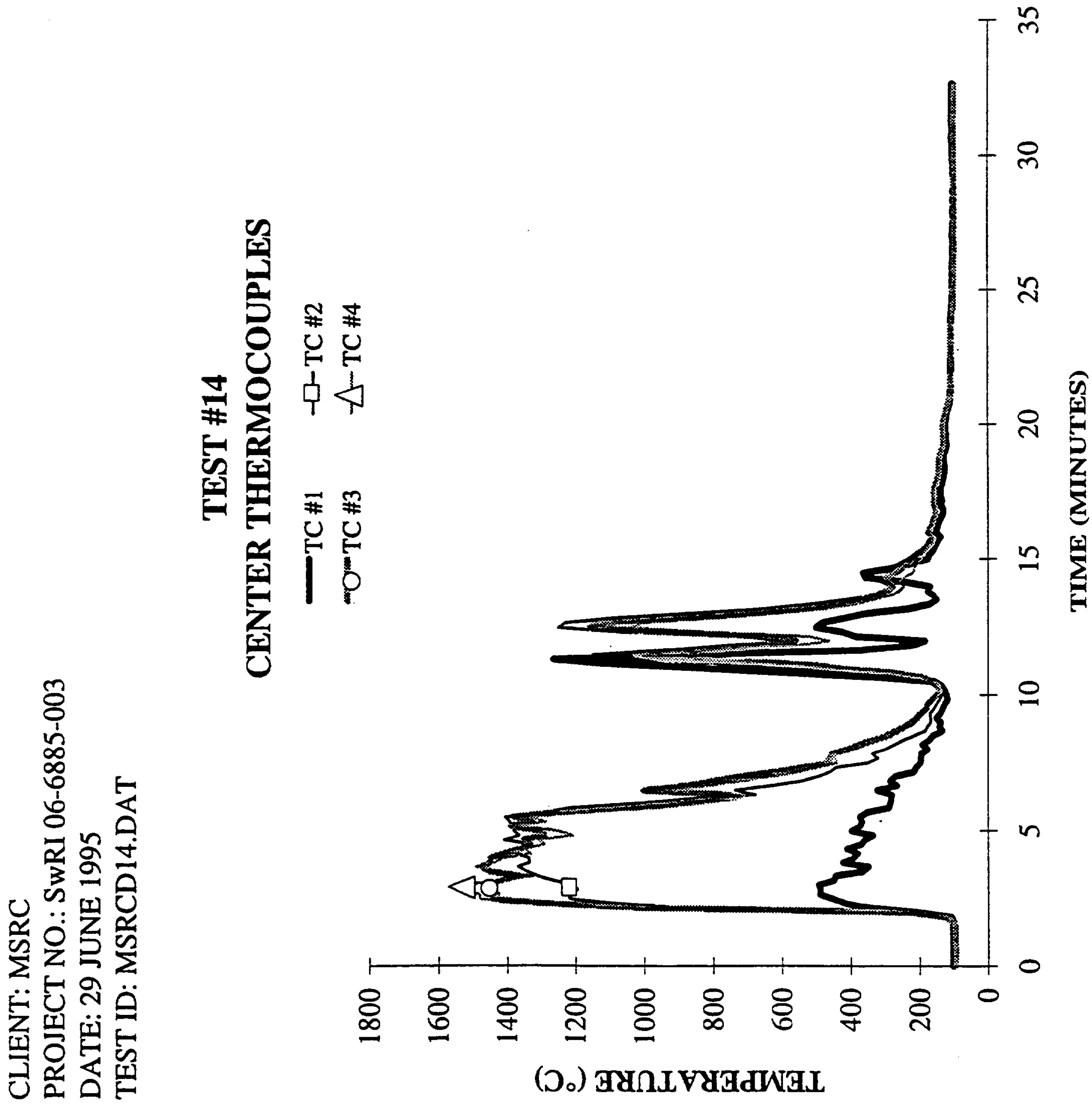
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TC #1
TC #2
TC #3
TC #4
TEMPERATURE (°C)
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1000
1200
1400
1600
1800
TIME (MINUTES)
0
5
10
15
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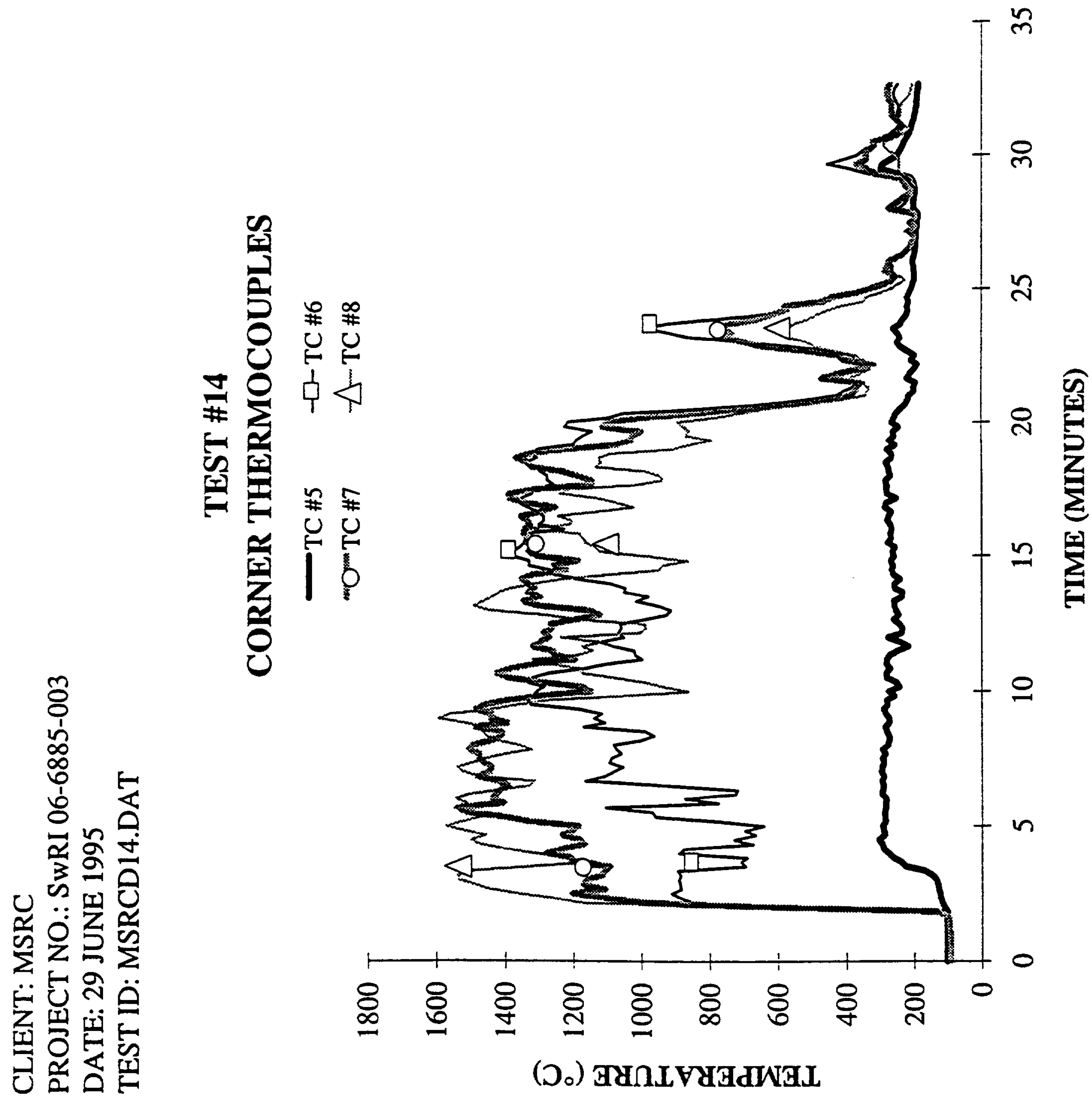
25
30
35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CORNER THERMOCOUPLES
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TC #6
TC #7
TC #8
TEMPERATURE (°C)
TIME (MINUTES)
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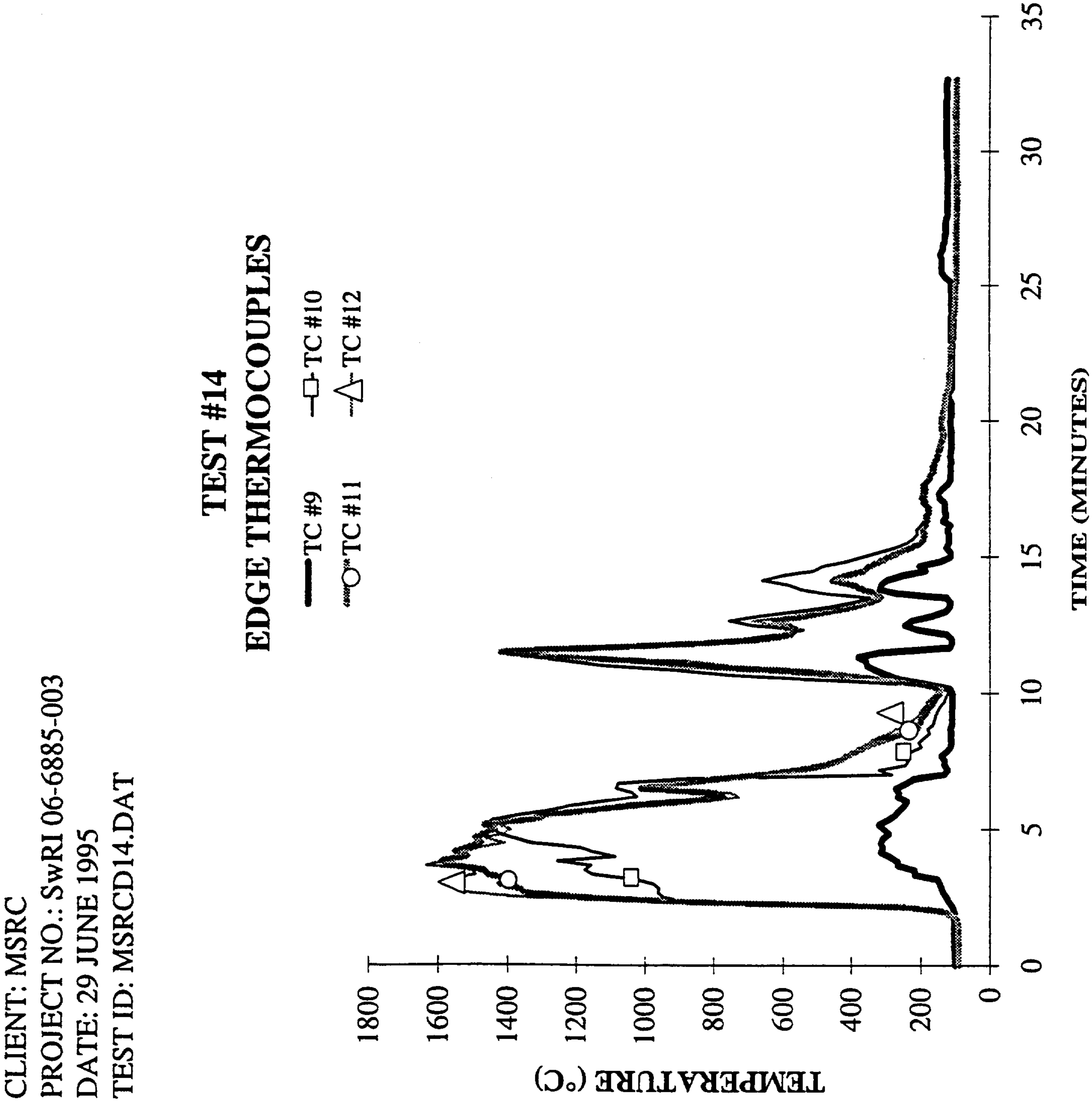
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TC #10
TC #11
TC #12
TEMPERATURE (°C)
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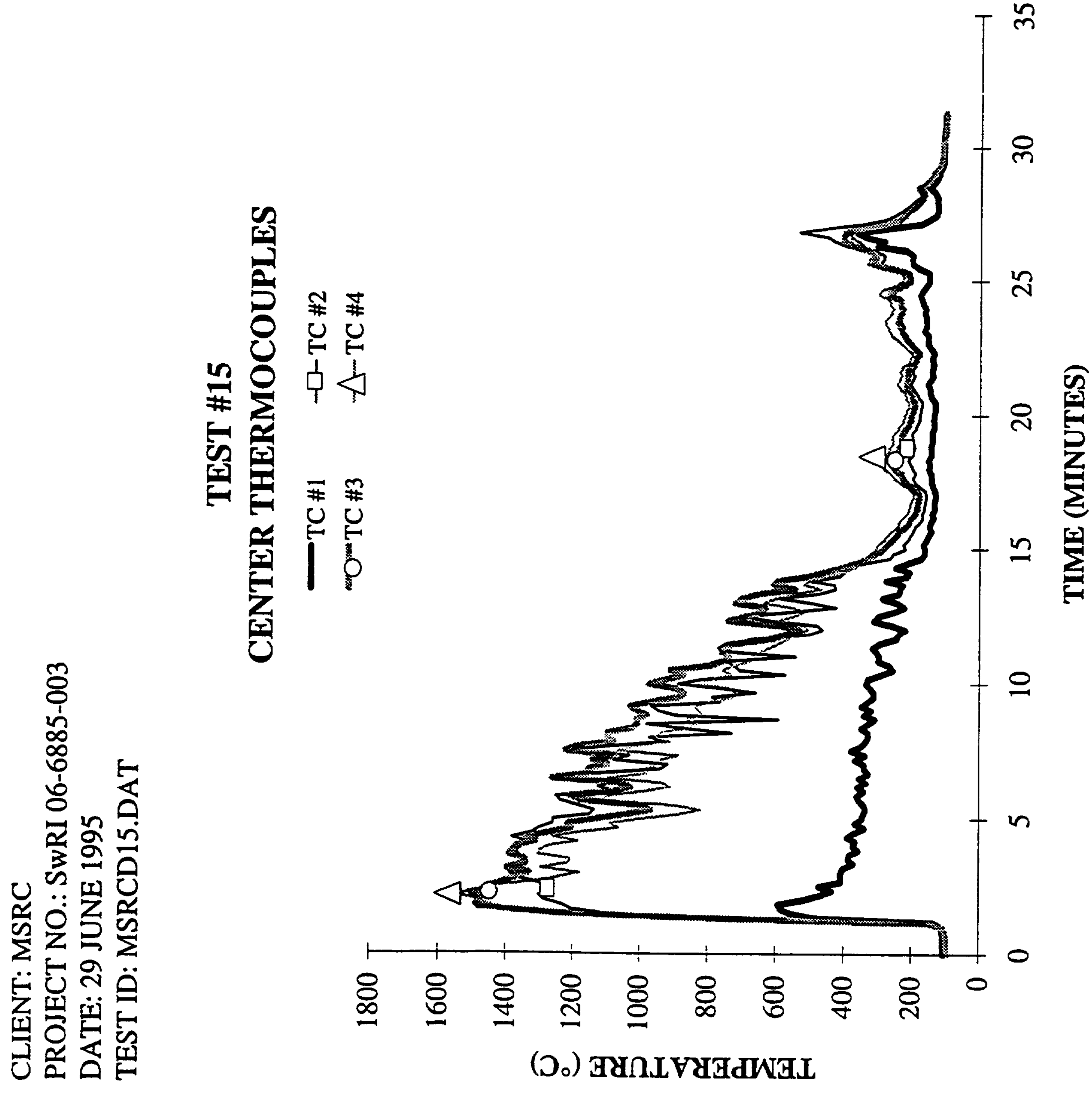
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TC #1
TC #2
TC #3
TC #4
TEMPERATURE (°C)
TIME (MINUTES)
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1200
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0
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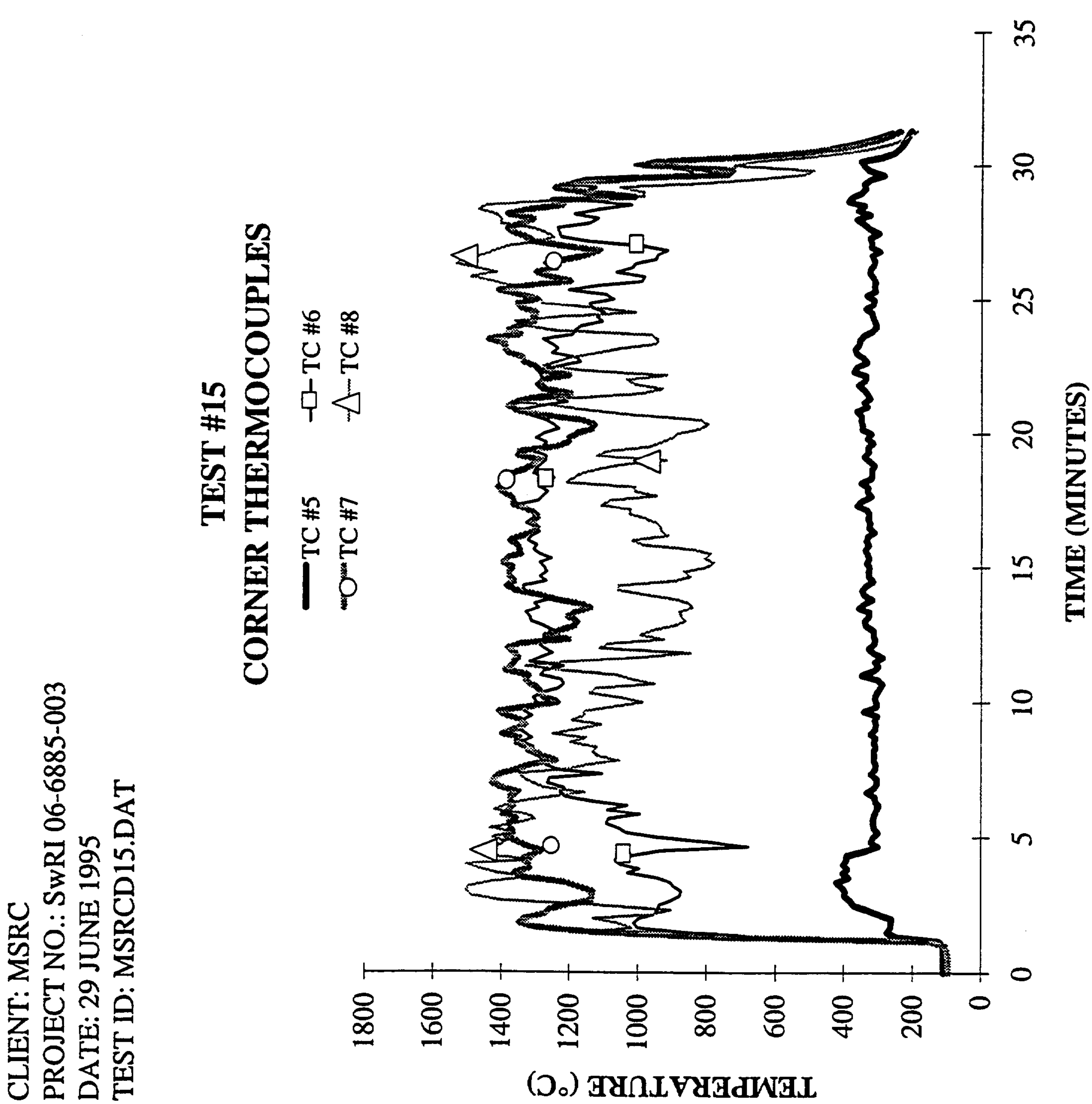
20
25
30
35



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TC #5
TC #6
TC #7
TC #8
TEMPERATURE (°C)
TIME (MINUTES)
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1800
5
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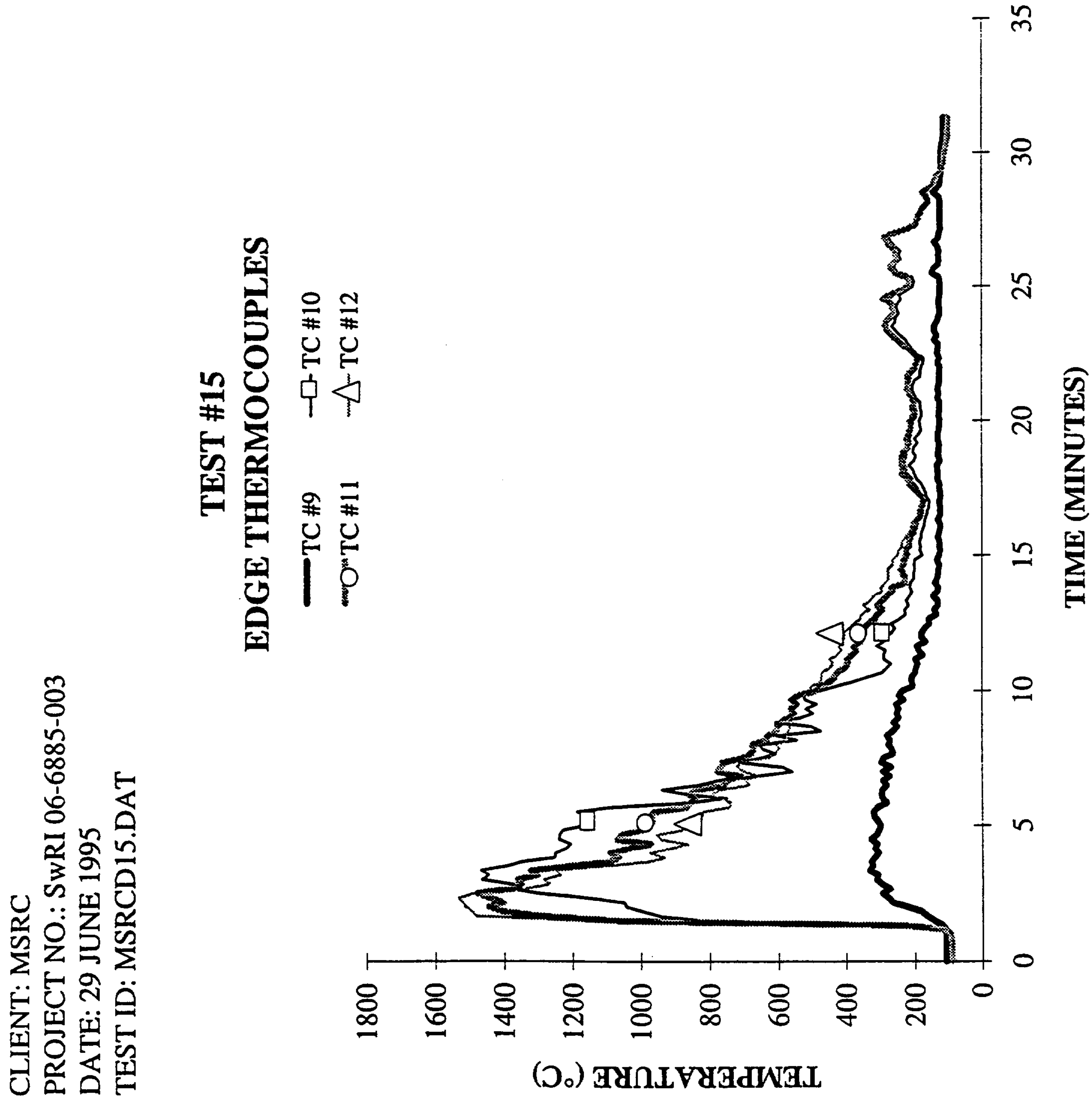
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TC #9
TC #10
TC #11
TC #12
TEMPERATURE (°C)
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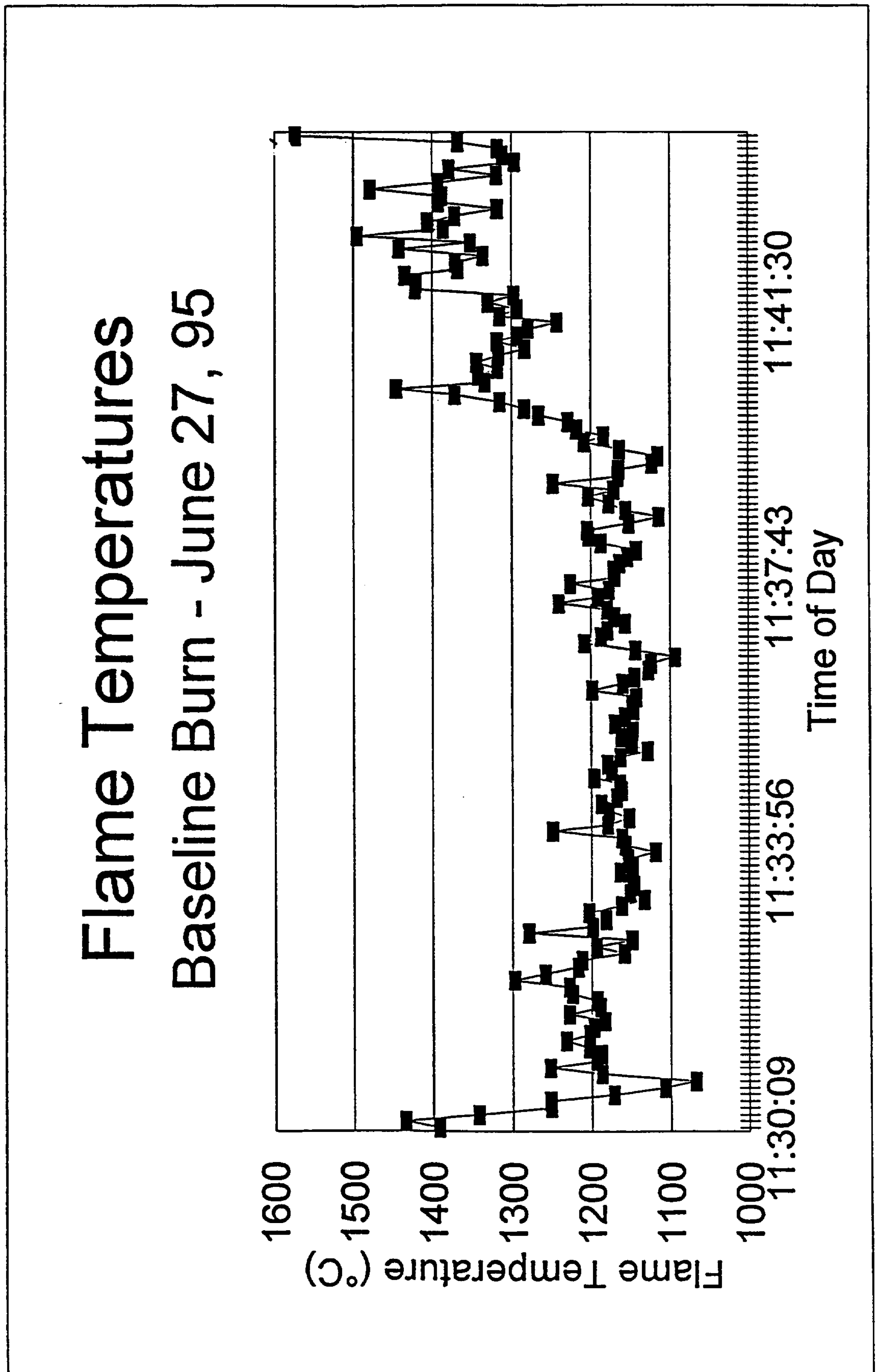
200
400
600
800
1000
1200
1400
1600
1800
TIME (MINUTES)
0
5
10
15
20
25
30
35


Flame Temperatures
Baseline Burn - June 27, 95
Flame Temperature (°C)
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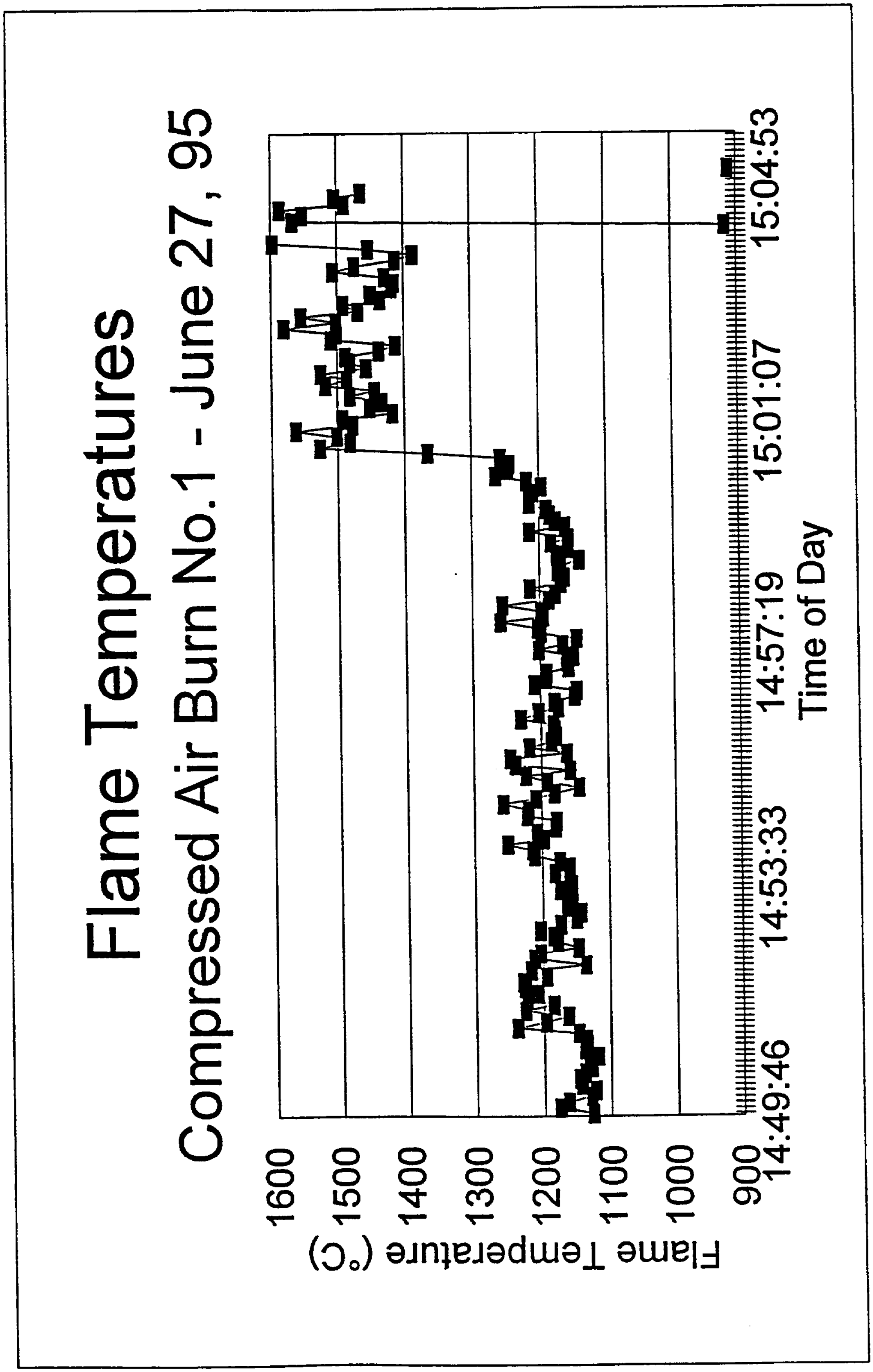
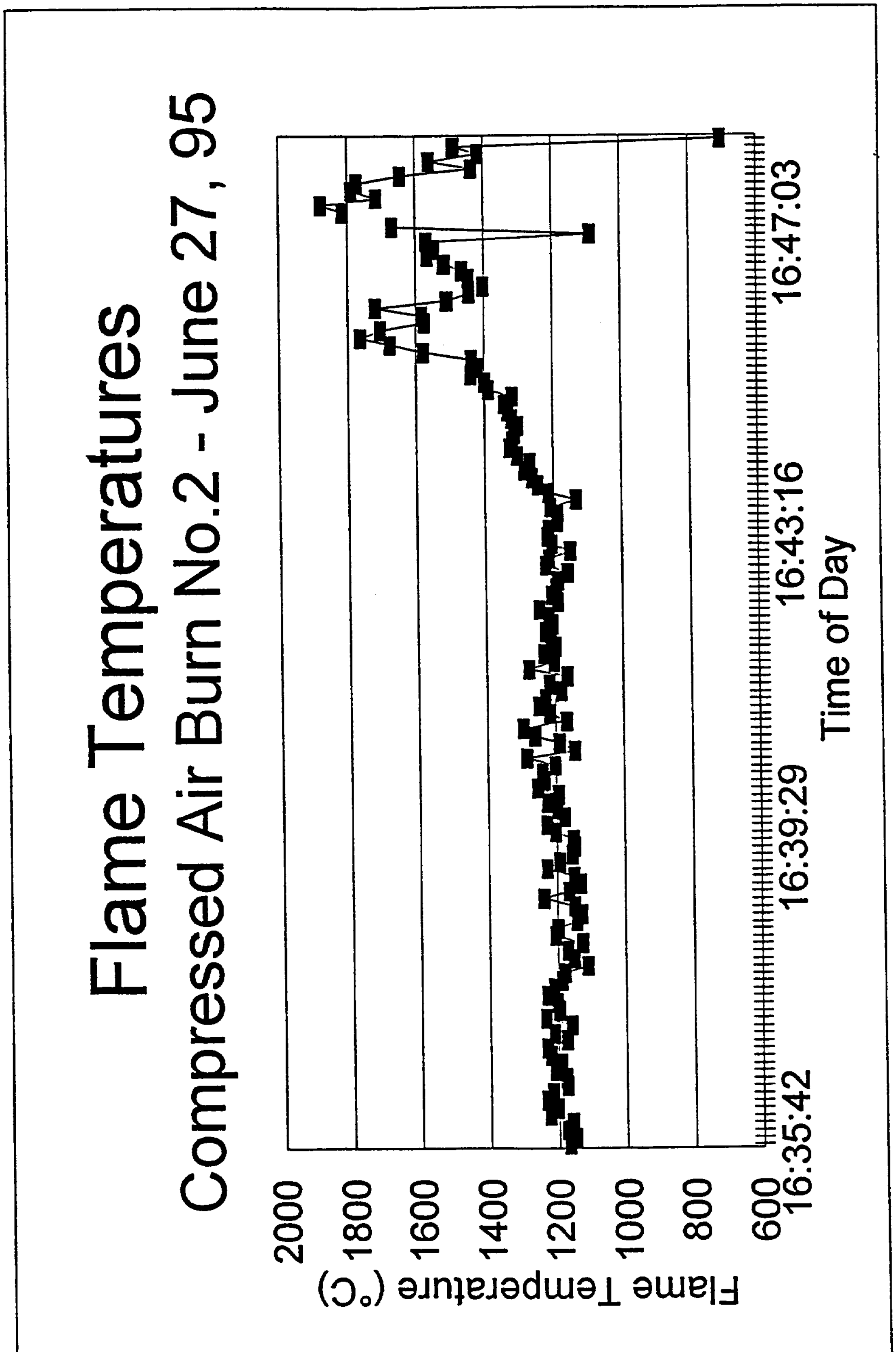
1500
1400
1300
1200
1100
1000
11:30:09
11:33:56
11:37:43
11:41:30
Time of Day


Flame Temperatures
Compressed Air Burn No.1 - June 27, 95
Flame Temperature (°C)
1600
1500
1400
1300
1200
1100
1000
900
14:49:46
14:53:33
14:57:19
15:01:07
15:04:53
Time of Day


Flame Temperatures
Compressed Air Burn No.2 - June 27, 95
Flame Temperature (°C)
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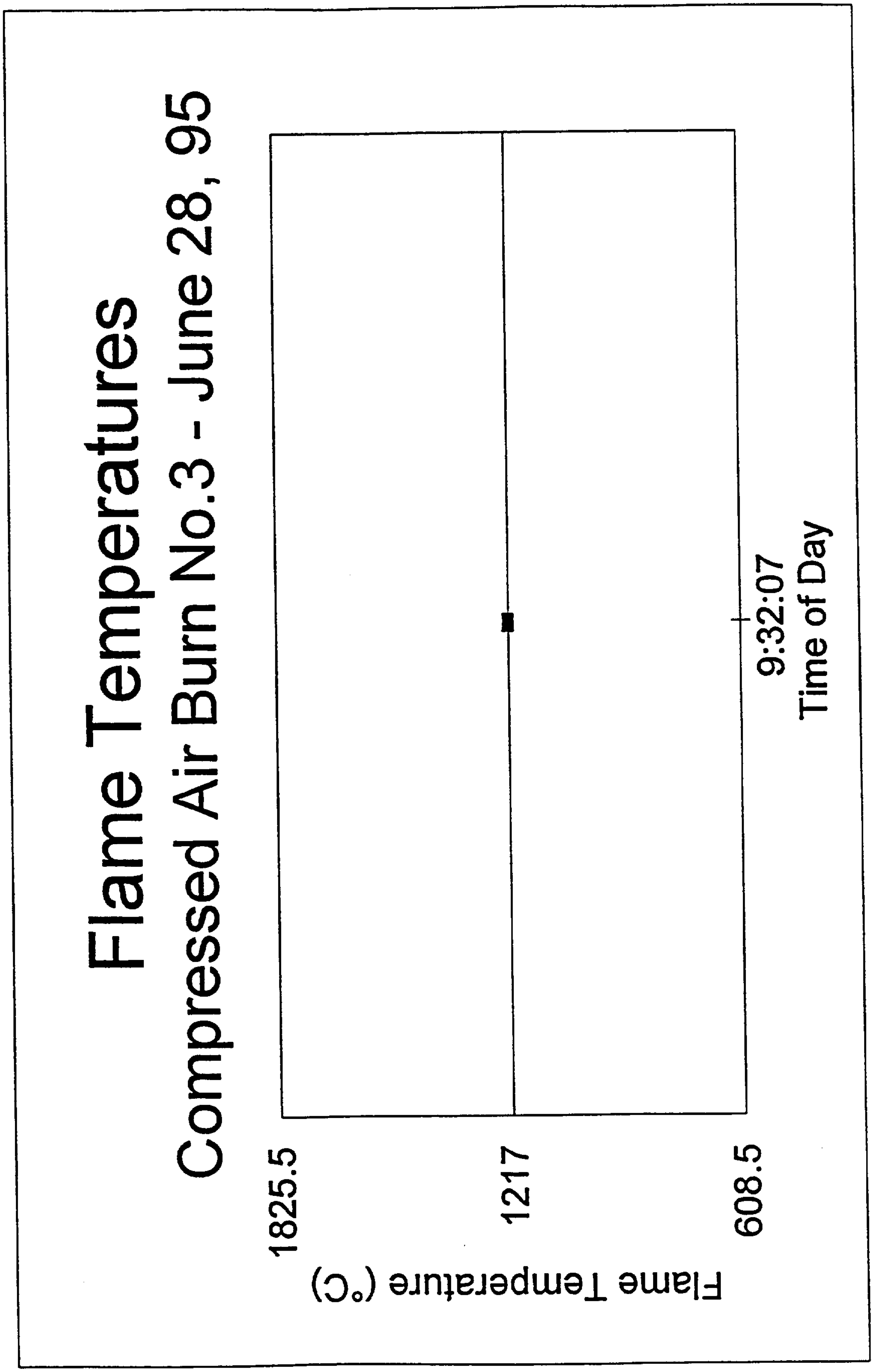
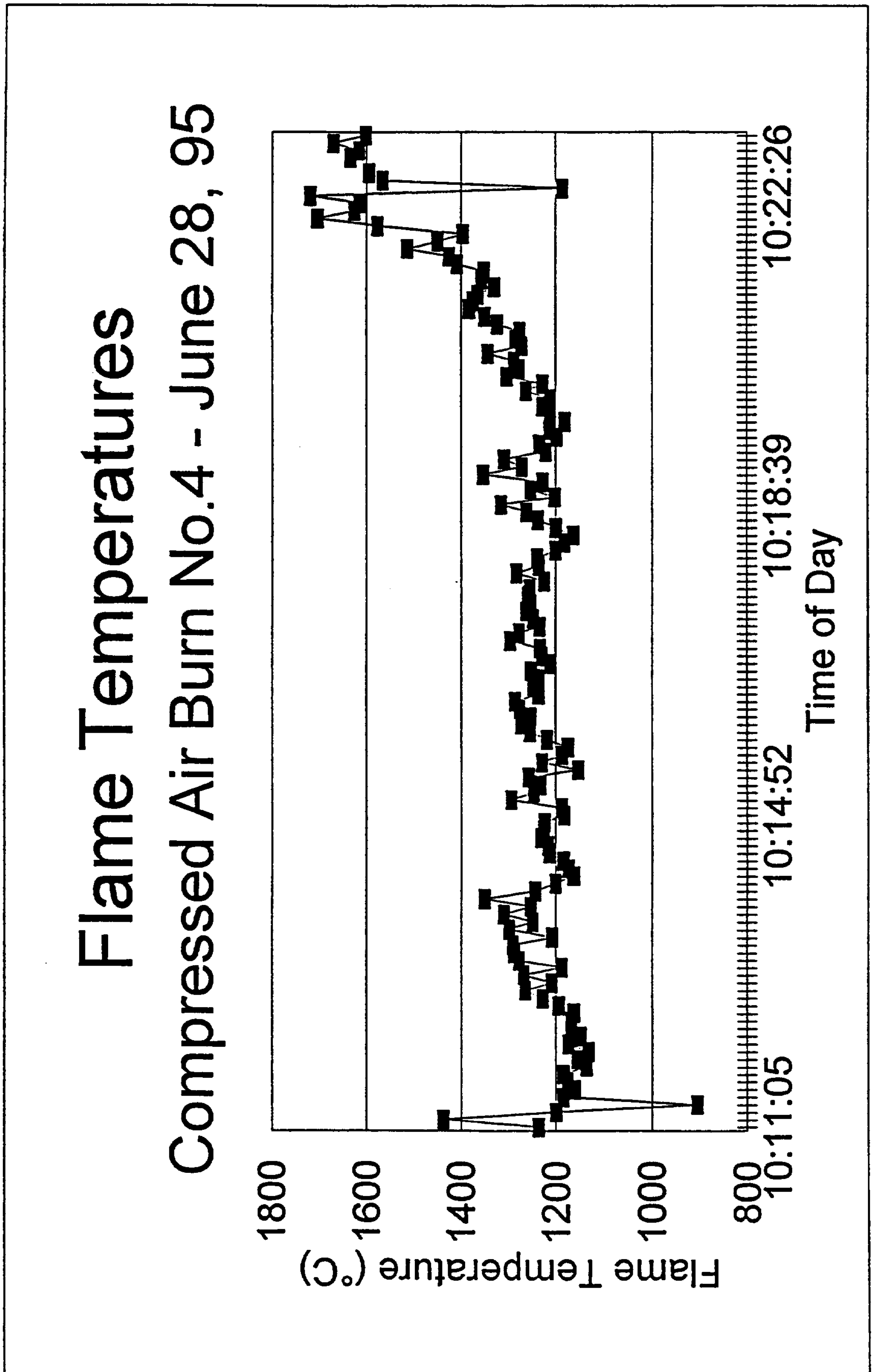
1800
1600
1400
1200
1000
800
600
16:35:42
16:39:29
16:43:16
16:47:03
Time of Day


Flame Temperatures
Compressed Air Burn No.3 - June 28, 95
1825.5
1217
608.5
Flame Temperature (°C)
9:32:07
Time of Day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Compressed Air Burn No.4 - June 28, 95
Flame Temperature (°C)
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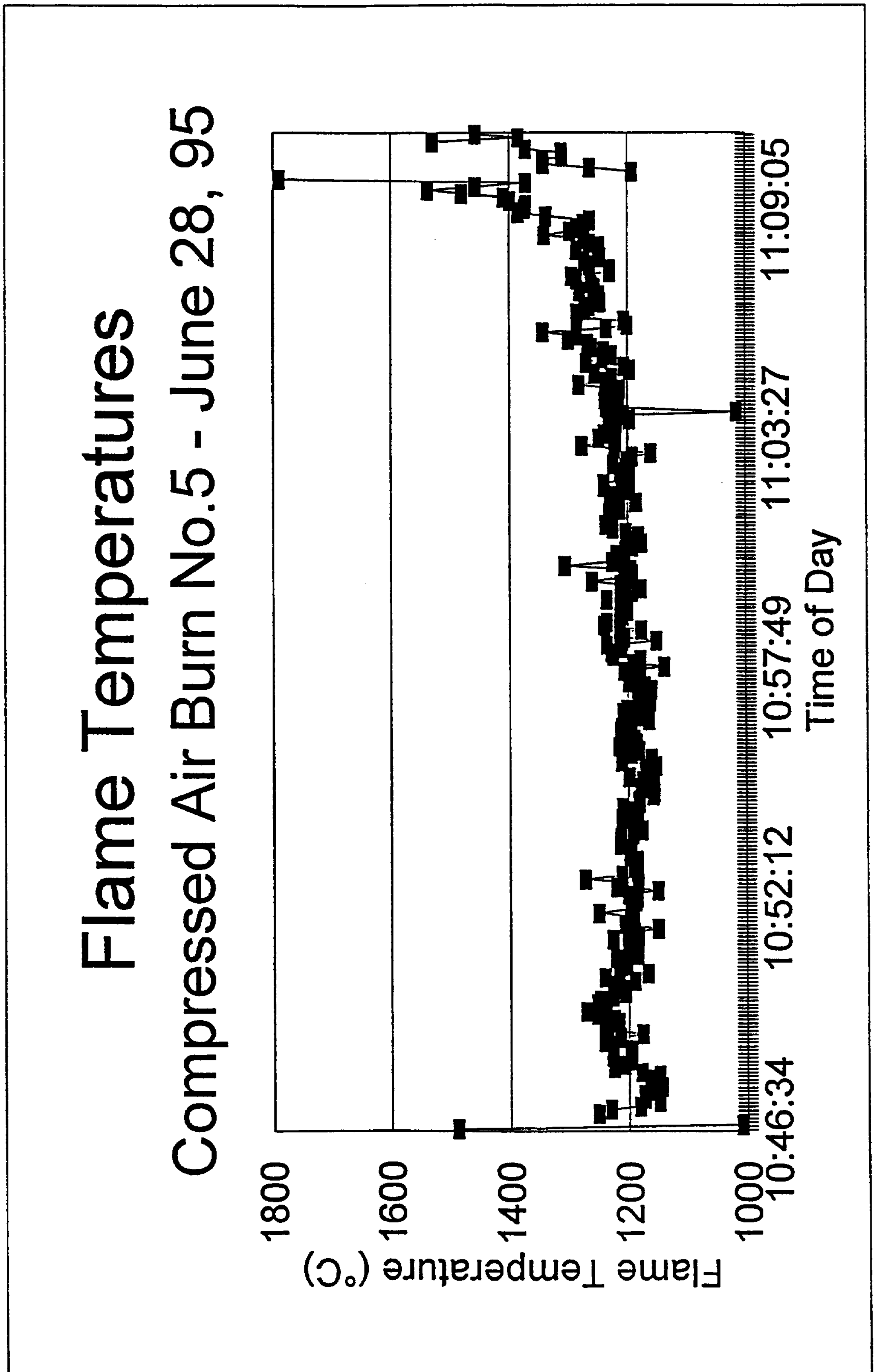
1600
1400
1200
1000
800
10:11:05
10:14:52
10:18:39
10:22:26
Time of Day


Flame Temperatures
Compressed Air Burn No.5 - June 28, 95
Flame Temperature (°C)
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1600
1400
1200
1000
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10:52:12
10:57:49
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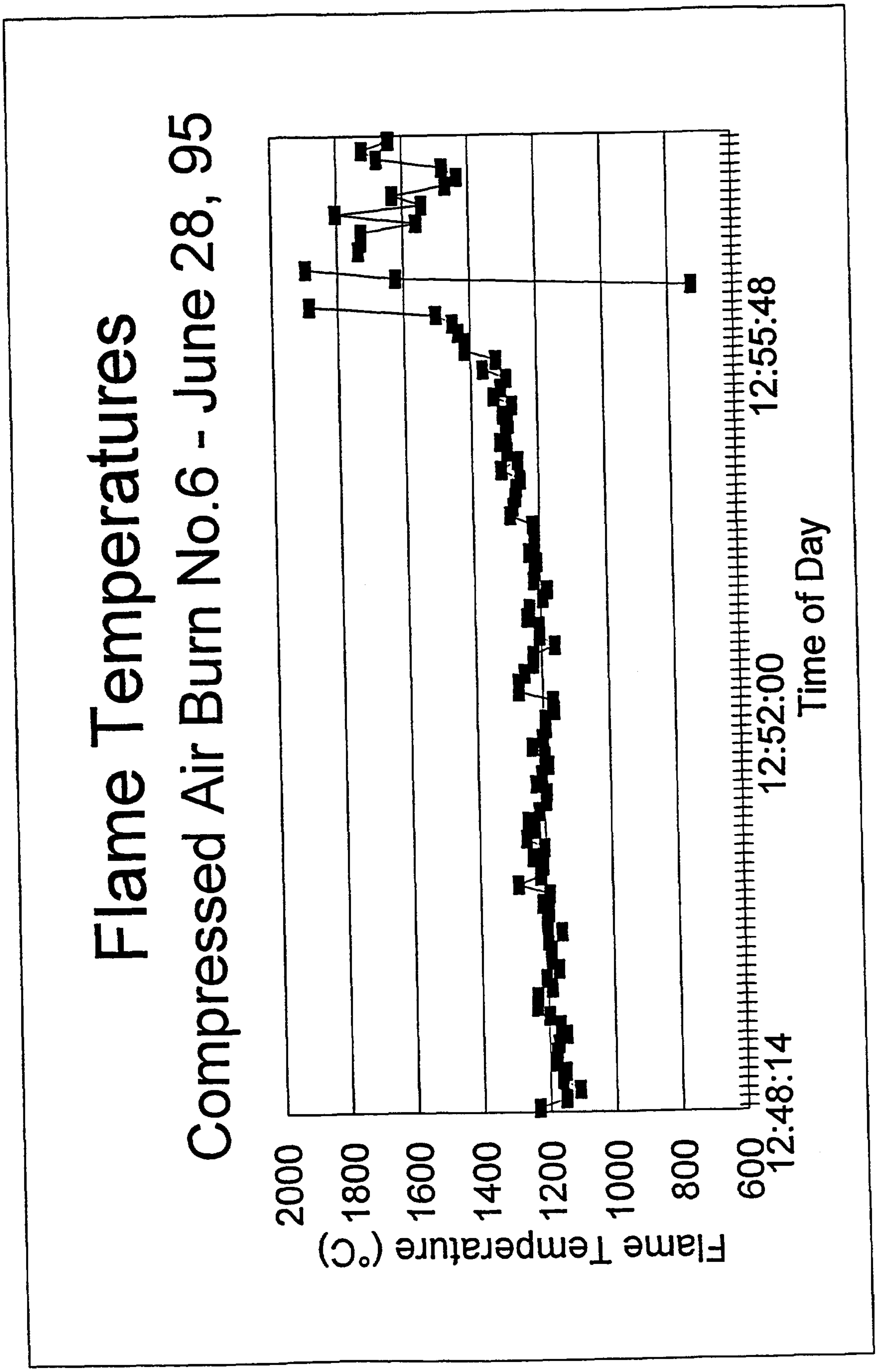
11:09:05
Time of Day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Compressed Air Burn No.6 - June 28, 95
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1800
1600
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1200
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800
600
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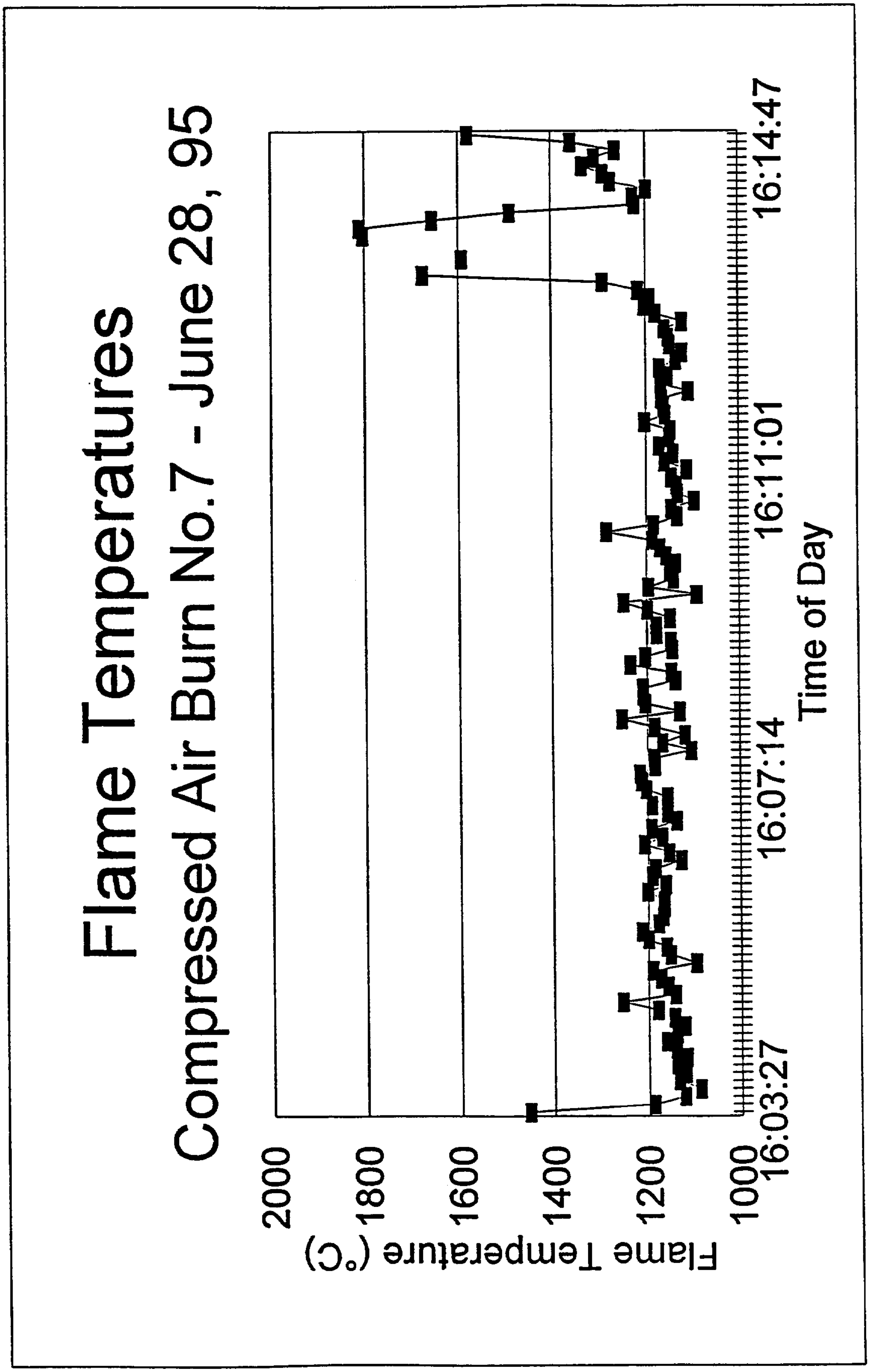
12:55:48
Time of Day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Compressed Air Burn No.7 - June 28, 95
Flame Temperature (°C)
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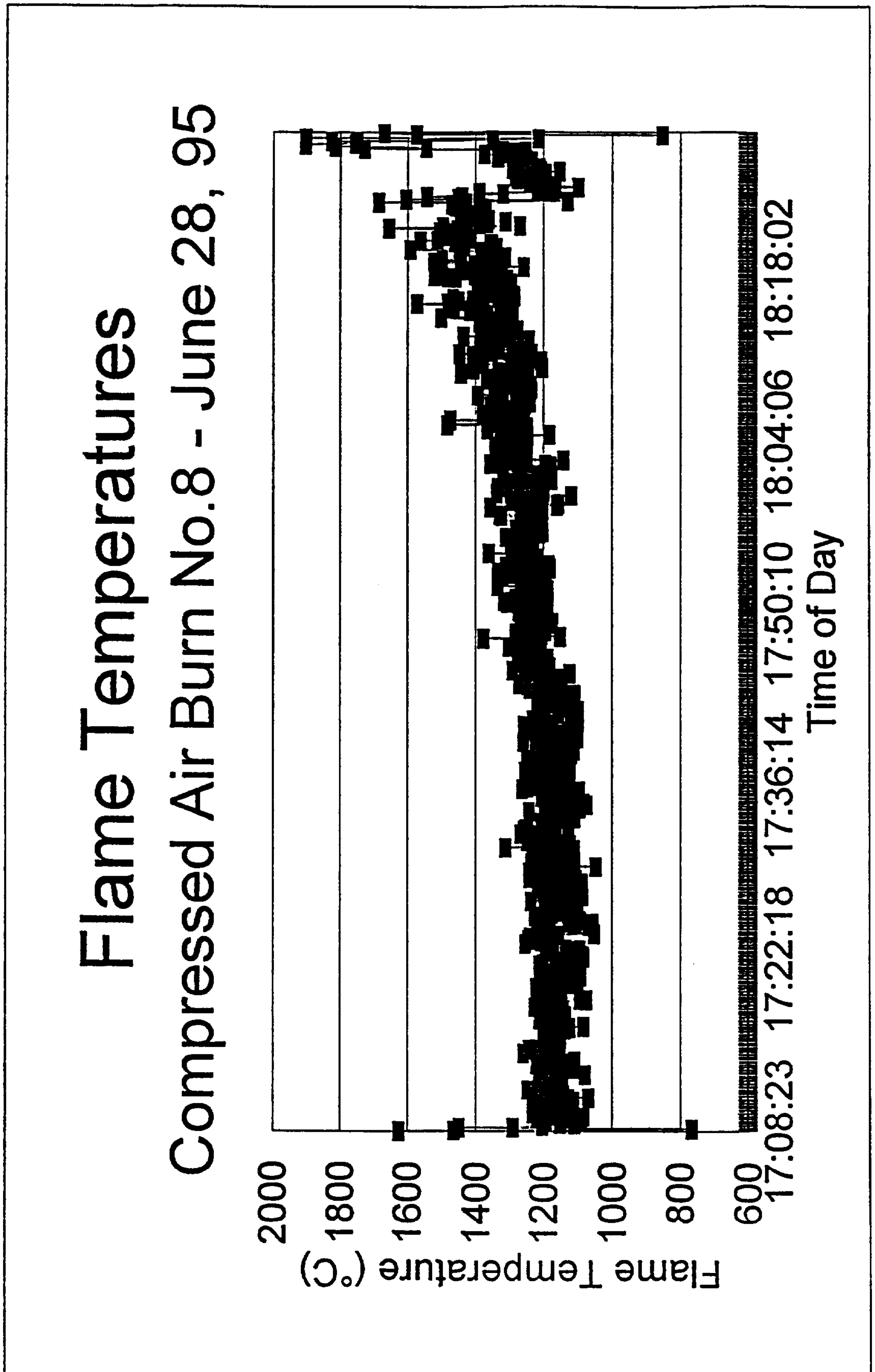
1800
1600
1400
1200
1000
16:03:27
16:07:14
16:11:01
16:14:47
Time of Day



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Compressed Air Burn No.8 - June 28, 95
Flame Temperature (°C)
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1800
1600
1400
1200
1000
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600
17:08:23
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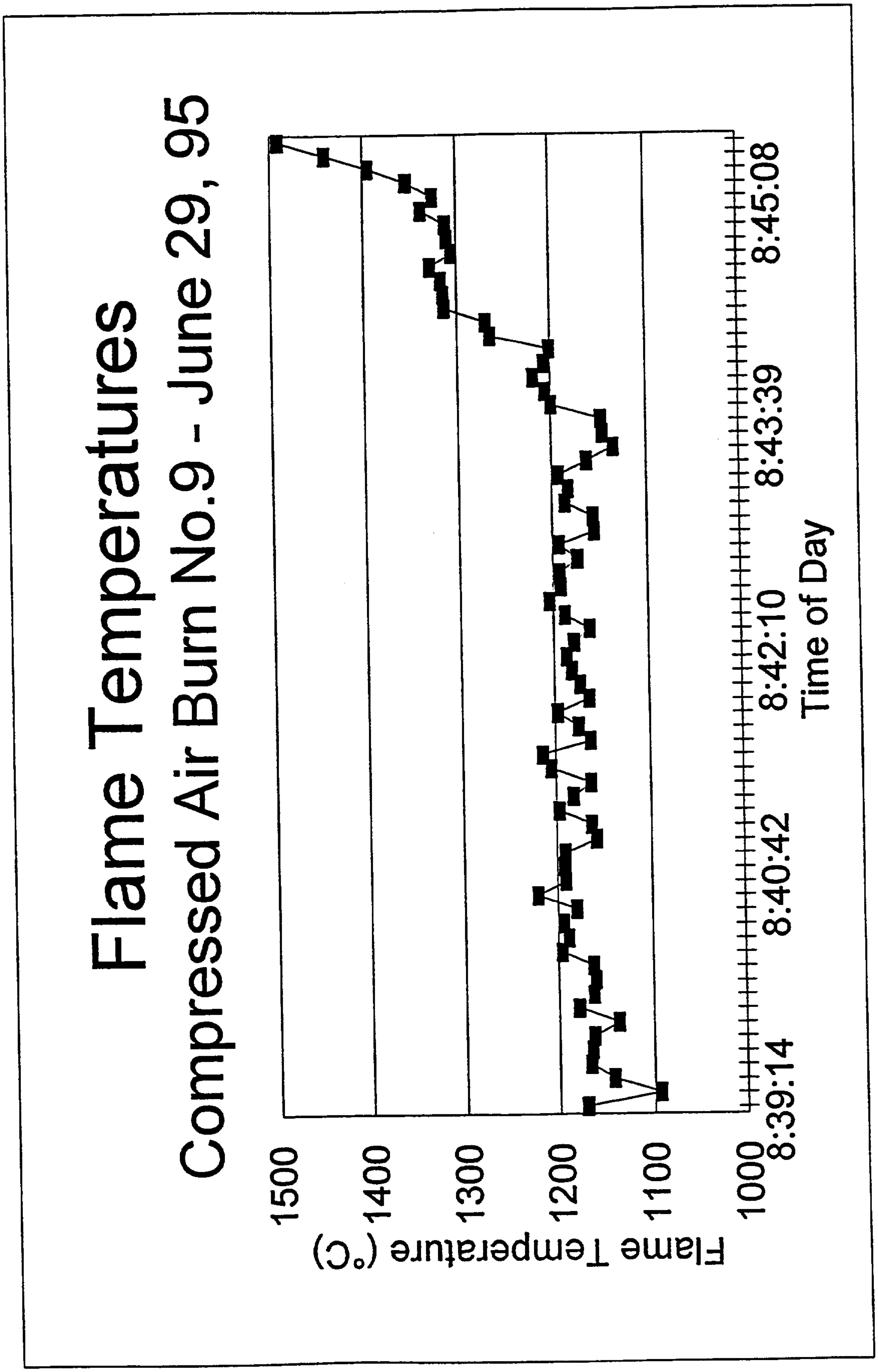
17:36:14
17:50:10
18:04:06
18:18:02
Time of Day


Flame Temperatures
Compressed Air Burn No.9 - June 29, 95
Flame Temperature (°C)
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1400
1300
1200
1100
1000
8:39:14
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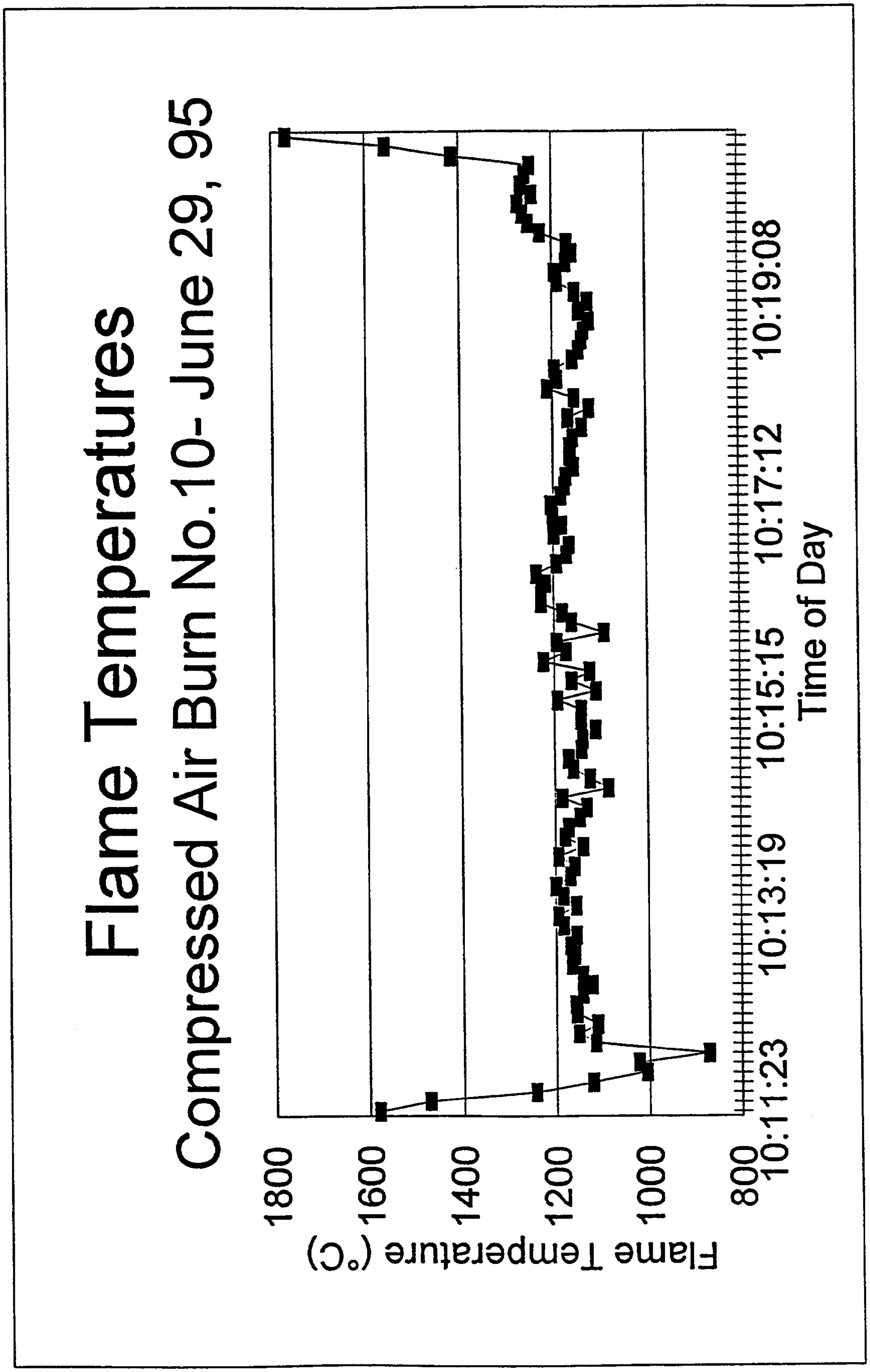
8:45:08
Time of Day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Flame Temperature (°C)
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800
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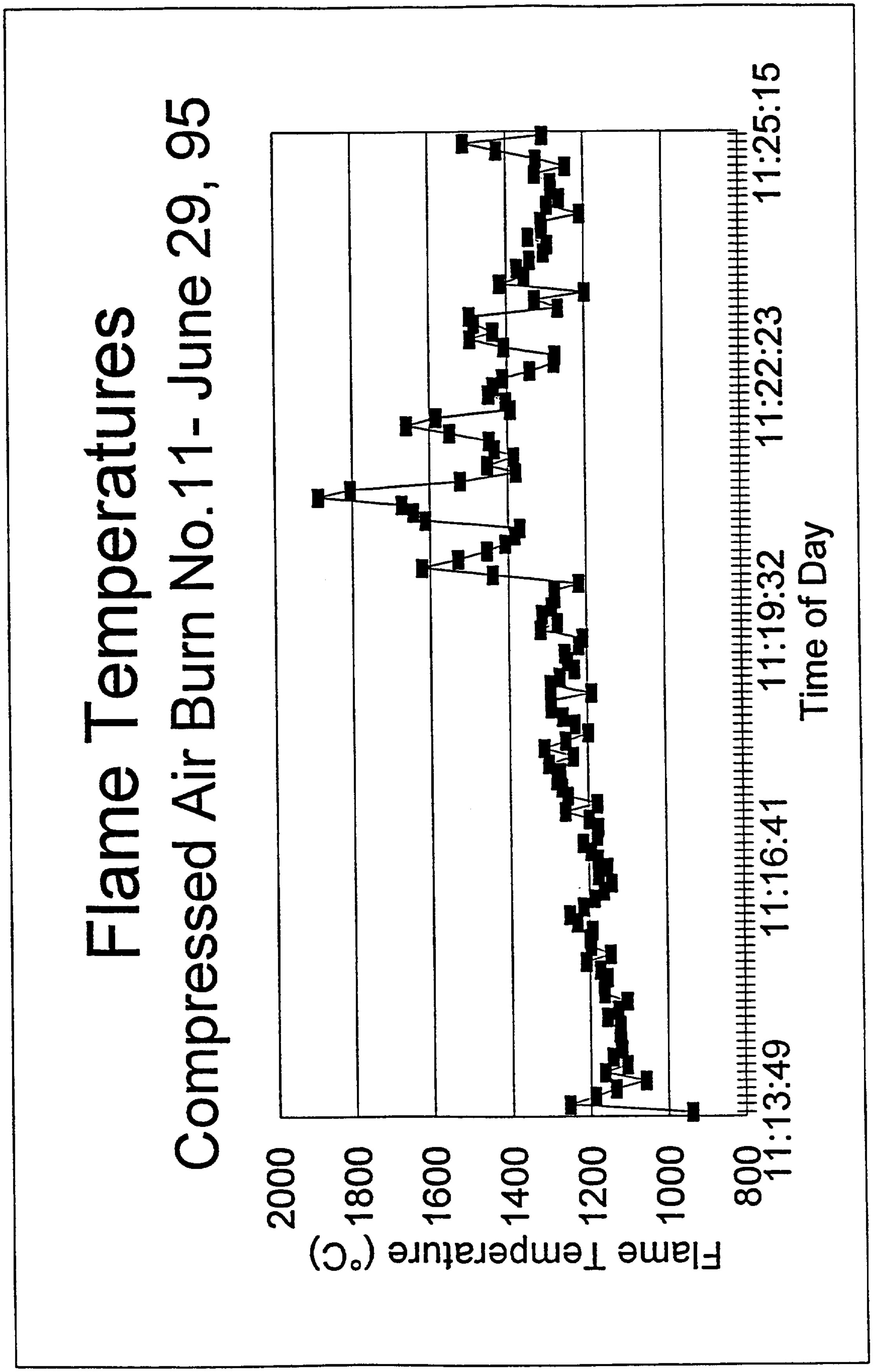
10:19:08
Time of Day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Compressed Air Burn No.11- June 29, 95
Flame Temperature (°C)
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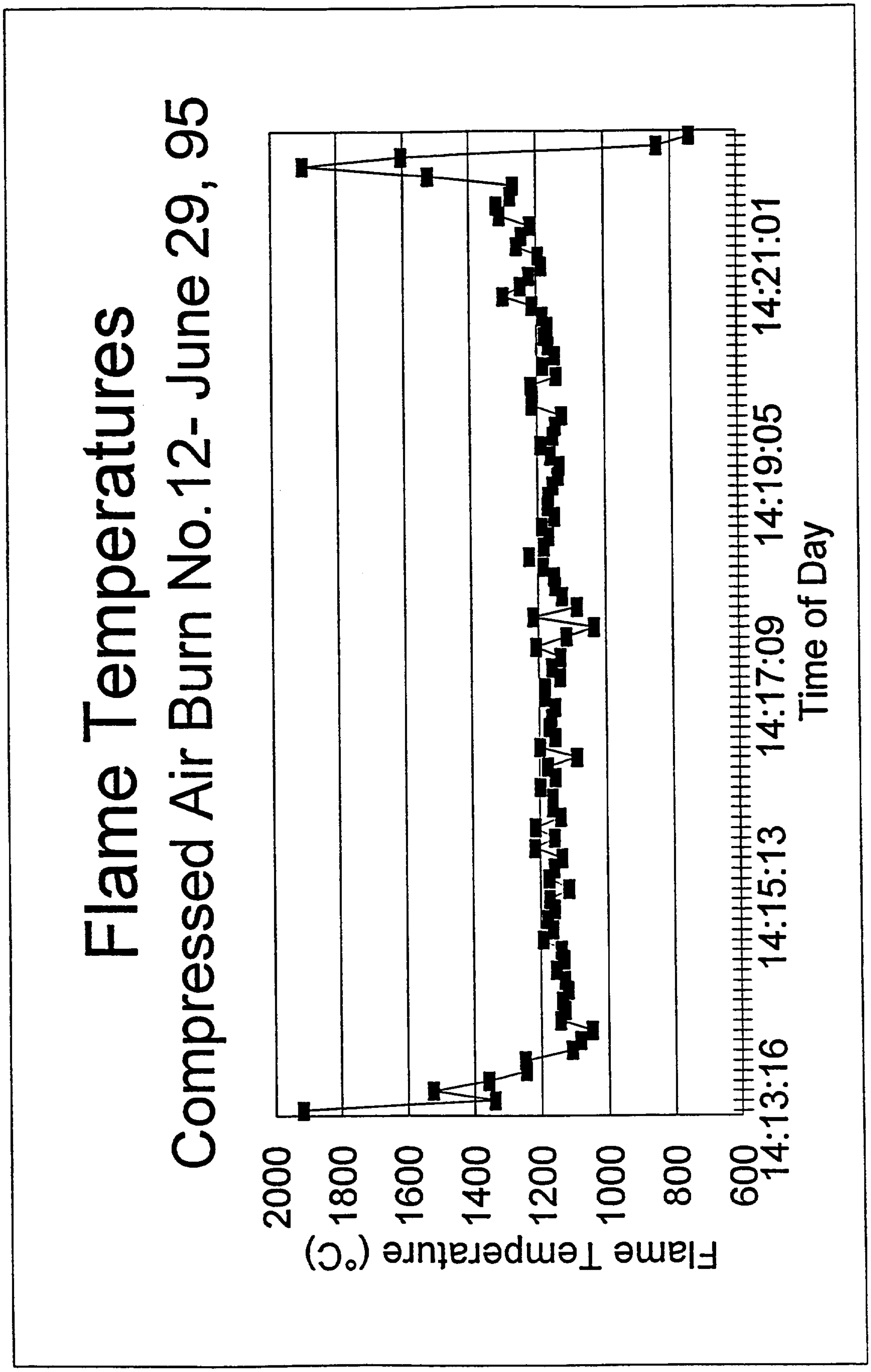
Time of Day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Compressed Air Burn No.12- June 29, 95
Flame Temperature (°C)
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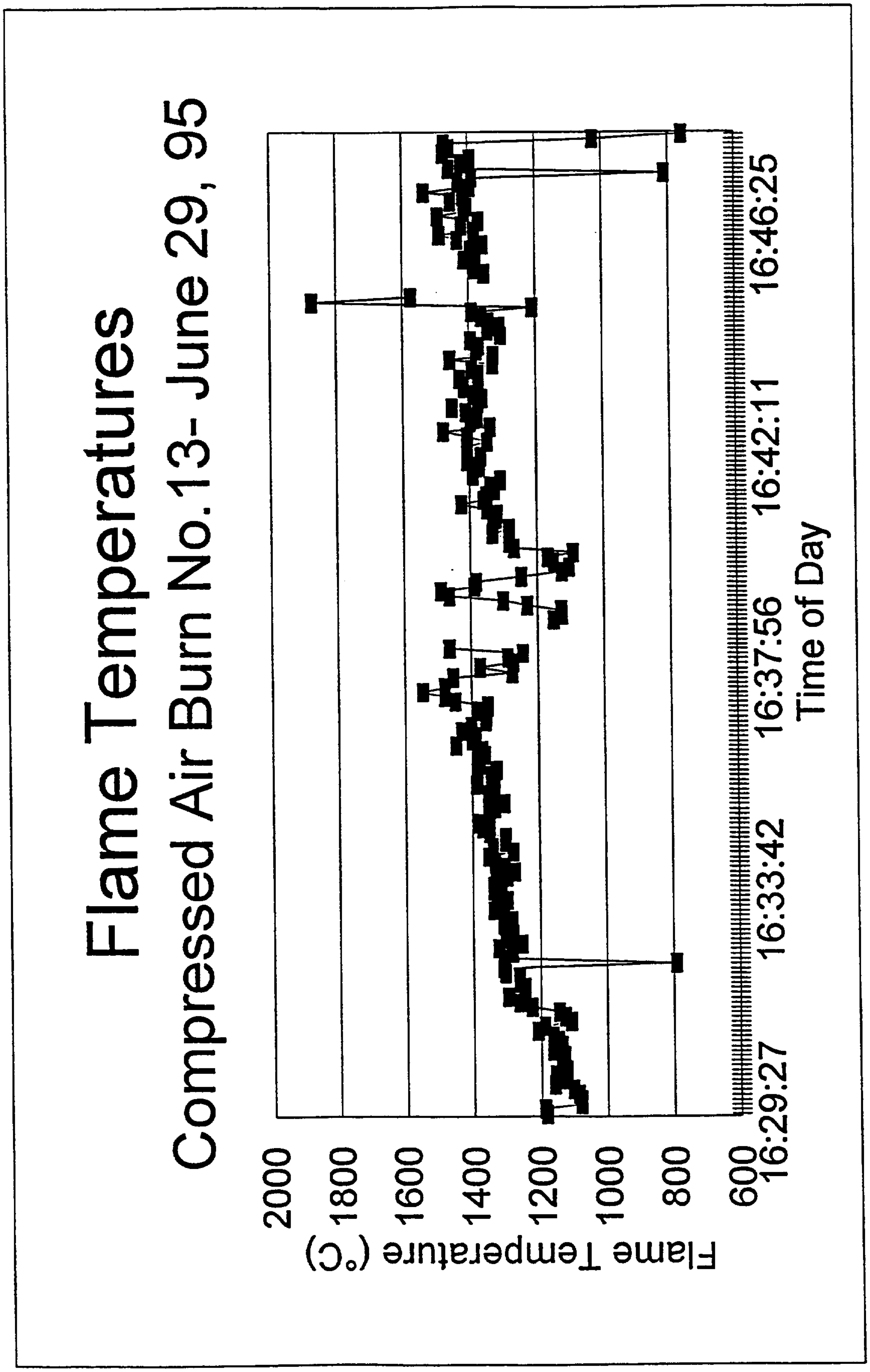
Time of Day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Flame Temperature (°C)
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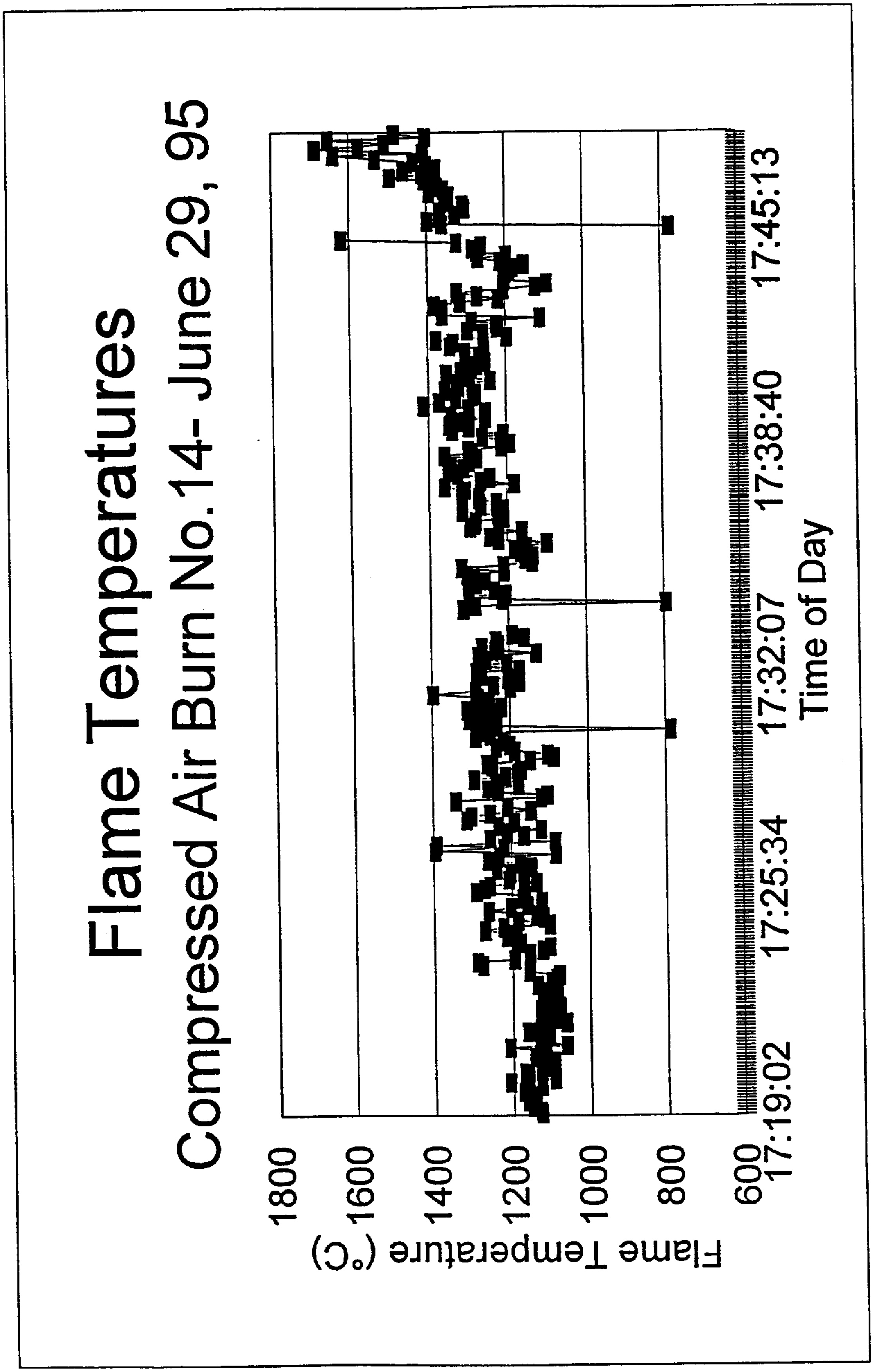
16:46:25
Time of Day



Flame Temperatures
Compressed Air Burn No.14- June 29, 95
Flame Temperature (°C)
1800
1600
1400
1200
1000
800
600
17:19:02
17:25:34
17:32:07
17:38:40
17:45:13
Time of Day

Appendix C

Spill Igniter Delivery System (SIDS) Development Report

C.1.0 Introduction

The purpose of the Spill Igniter Delivery System (SIDS) development is to provide industry a safe, readily accessible, and reliable method for igniting marine crude oil spills. To date, the SIDS development has included the design, fabrication, and demonstration of a half scaled prototype SIDS unit. The scaled prototype SIDS unit was developed by Oceaneering Technologies (OTECH), based on the MSRC Applied Engineering staff's concept. The concept has been guided by MSRC technical reports and studies investigating conditions required to ignite oil spills for in-situ burning. This development report documents the design requirements, component selections, test results of the prototype SIDS, and recommends steps to be included in the development of an operational model.

C.2.0 SIDS Design

C.2.1 Design Requirements

The SIDS concept is based on the empirical observation that a sufficient amount of burning area (one square meter) and time (ten minutes) will ensure ignition of the surrounding slick. The SIDS prototype is a half linear scaled model that covers 1/4 square meter with liquid fuel. The model is required to maintain a burning liquid fuel level of 3 mm for a total of ten minutes. The concept includes a method for concentrating the burning liquid fuel prior to coming in contact with the surrounding slick. The model is also required to be self-contained and include a safely operated time delayed ignition system. The final system is desired to be light-weight, 1-2 person deployed, disposable, and self-righting.

C.2.2 Design Selection

The remaining components of the SIDS prototype model not covered in the above requirements include: fuel type, fuel storage and injection, fuel regulation method, ignition device, delay device, and ballasting/stability. Due to the limited time available for initial development, the prototype's individual components were selected based on availability for the function they serve and do not represent the actual size or weight of the desired final components.

C.2.2.1 Fuel Type

The fuel selected is a 50/50 mixture of gasoline and diesel. This selection was based on the report, "Emulsifiers and Modified Heli-torch Fuels to Enhance In-Situ Burning of Emulsions", by S.L. Ross Environmental Research Ltd. The report indicates that a 50/50 mixture of gelled gasoline and diesel offers higher initial radiation to its surroundings, and sustains a burn for a reasonable duration with moderate heat transfer to underlying fluids. Gelled fuel benefits the Heli-torch application by reducing the surface area and evaporation rate of the fuel as it is dispersed. Since the SIDS unit continuously disperses fuel into and closed to a controlled area, the benefits of gelled fuel were determined to be unnecessary.

C.2.2.2 Fuel Storage and Injection

Two fuel storage and injection concepts were selected and developed. The first concept (SIDS 1) utilized an off-the-shelf fuel piston accumulator for fuel storage and fuel injection. The second concept (SIDS 2) utilizes a hose ring for fuel storage and the same 2.5 gallon piston accumulator for fuel injection. Both concepts are illustrated in section 2.3, Summary of Prototype Igniter Designs. SIDS 2 concept injects fuel by displacing the fuel in the hose with water stored in the accumulator. For both concepts, a nitrogen bottle with a low pressure regulator supplies 5 to 10 psi of non-flammable pressure to the gas side of the accumulator. The nitrogen pressure disperses the fuel by displacing the fuel or water in the accumulator. Downstream of the accumulator the fuel can be injected into the area through nozzles or faucet type openings. The nozzles atomize the fuel to increase its volatility and flammability if needed. The placement of the fuel outlet serves as a method of containing and sustaining the burning liquid fuel with in a 1/4 square meter area.

C.2.2.3 Fuel Regulation

A needle valve located downstream of the accumulator provides flow control. The fuel flow can be adjusted to maintain the required 3 mm per minute fuel depth. The needle valve includes a locking knob to lock the desired flowrate.

C.2.2.4 Ignition Devices

Several possible ignition devices identified during the expedited research include: hot wire, glow coils, high energy sparkers, piezo-electric sparkers, electric squibs, model rocket igniters, and blasting caps. The three igniting devices tested to date include the hot wire, piezo-electric sparkers, and electric squibs. Electric squibs are commonly used to detonate explosives due to their ability to emit a substantial amount of intense energy when electrically activated. Operating observations concluded that the piezo-electrics were unreliable and not worth further testing. Preliminary ignition tests concluded that:

- hot wire temperatures tested were inadequate to ignite the fuel and
- squibs were successful in igniting the fuel.

A hood was also constructed to be placed over the dispersed fuel to collect volatiles around the igniting device to encourage fuel ignition (See Figure C.1).

C.2.2.5 Time Delay

The prototype system utilizes two time delays located in the controls box (Figure C.1): fuel delay and ignition delay. The fuel delay postpones the time between placing the apparatus and opening the solenoid valve allowing fuel flow. The second delay (ignition delay) enables the fuel thickness to reach 3 mm thick before ignition. An electrical time delay relay is the self-contained method that was used in the model to delay the ignition of the fuel. The selected time delay relays require a 12 volt battery to operate. The delays may be set at any desired time from .1 second to 3,100 minutes. The delay to begin fuel dispersion is set at 2 minutes and the squib is set to ignite 90 seconds later. A safety-lock switch mounted inside the SIDS apparatus is utilized to begin the time delays.

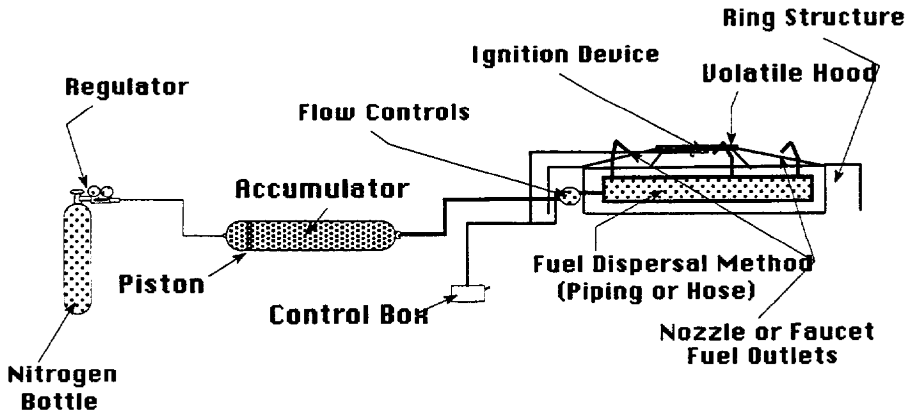


Figure C.1 Basic SIDS prototype schematic and components

C.2.2.6 Ballasting and Stability

The design of the prototype SIDS did not concentrate on system ballasting and stability. The purpose of this phase of the SIDS development was to validate the SIDS concept and does not include a complete ballasting or stability method. OTECH is confident in providing a final system which has a stable, self-righting design ballasted to the desired water level.

C.2.3 Summary of Prototype Igniter Designs

The two variations of the prototype system are very similar to each other. The variation of the systems are on the storage and dispersal methods of the fuel. On each variation the dispersal method of the fuel can be further altered by placing or removing nozzles at the fuel outlets.

C.2.3.1 SIDS 1: Fuel Piping With/Without Nozzles

The first SIDS concept, SIDS 1, (shown in Figure C.2) stores the 2 gallons of 50/50 gasoline and diesel fuel mixture in the piston accumulator. When the nitrogen pressure is increased to 5 - 10 psi, the piston presses the fuel from the fuel outlets into the center of the ring.

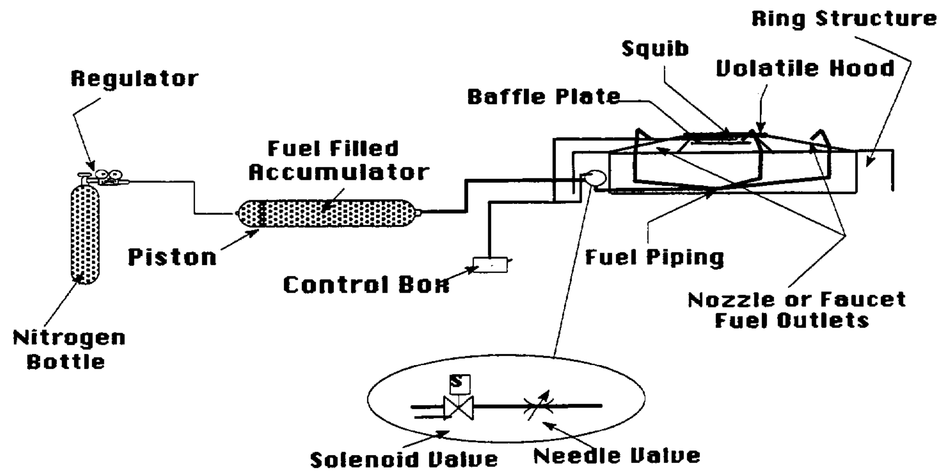


Figure C.2 SIDS 1 prototype igniter design

C.2.3.2 SIDS 2: Hose Containing Fuel With/Without Nozzles

The second SIDS concept, SIDS 2, (shown in Figure C.3) stores the 2 gallons of 50/50 gasoline and diesel fuel mixture in the hose. Water stored in the accumulator displaces the fuel from the fuel outlets when nitrogen pressure is placed on the piston.

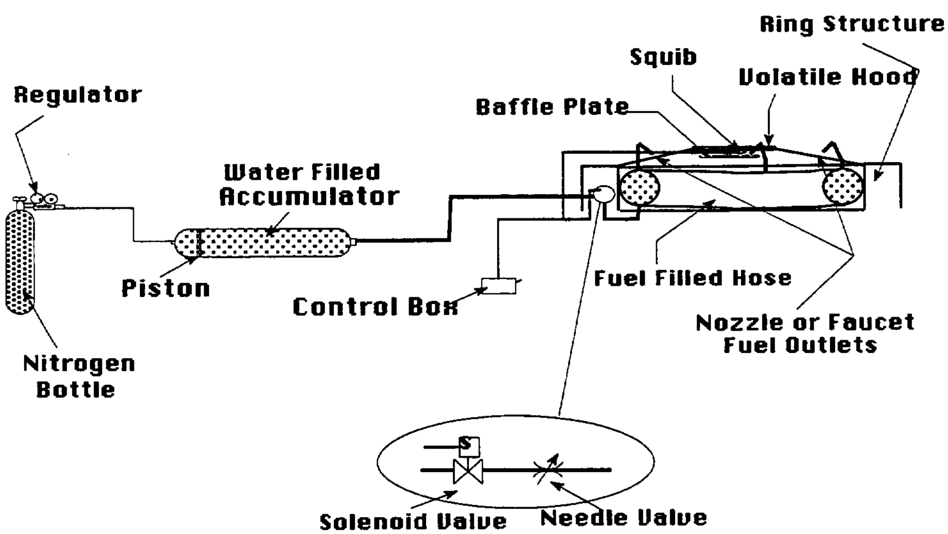


Figure C.3 SIDS 2 prototype igniter design

C.2.3.3 Safety

Several safety features are designed within the systems to ensure safety in operating the system. These safety measures are specific to the design of the test model but similar measures will be used in the future. The basic requirements are safety during storage, activation, ignition, and combustion control. Additional operational precautions were taken to ensure safe operations during prototype testing.

- The prototype system's ignition source (squib) is contained separately and is the last item installed in the apparatus.
- The safety-lock switch that initiates the time delay relays must be lifted while being switched eliminating accidental initiations.
- The fuel is dispersed by a piston pressured by nitrogen (non-flammable) at a low pressure.
- The fuel storage devices are purged with nitrogen prior to filling with fuel.

C.3.0 Oceaneering Technologies Facility Tests

C.3.1 Preliminary Tests and Calibration

The ignition devices tested include the hot wire and the electric squib (A piezo-electric device was examined but was not judged to be worth including in the ignition tests). The preliminary tests were conducted by placing a layer of fuel (50/50 gasoline and diesel mixture) in a 1.5 ft X 1.5 ft X 4 in pan (Figure C.4). Water placed around the pan maintained low fuel temperatures and served as a heat sink during burns. Both igniting devices were placed in the hood approximately 2-3 inches above the layer of fuel in the pan.

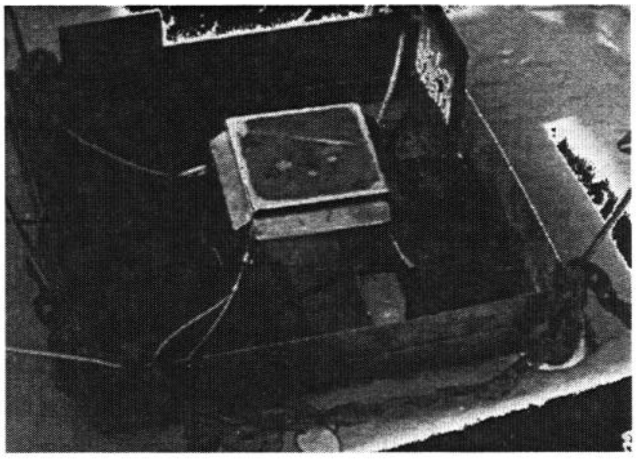


Figure C.4 *Preliminary igniter test set up*

Several preliminary ignition tests were conducted to determine the ignition subsystem to be used. The hot wire utilized a special material (Chromel) used to achieve extreme temperatures. The two temperatures tested to ignite the fuel were approximately 200°F and 400°F. The temperatures of the hot wire were maintained for a duration greater than one minute without success. The second igniter devices (electric squib) was placed in the igniter hood after the hot wire attempts. After contacting the squib to a power source (12 volt battery), the squib successfully ignited the pan of fuel (Figure C.5).

Figure C.5 *Successful ignition of fuel with electric squib*

The fuel dispersal rate was calibrated by increasing the flow through the needle valve until a flow rate maintaining a slick thickness of 3 mm per minute was achieved.

C.3.2 Ignition Tests

After the electric squib was identified as a successful igniting device, several ignition tests were conducted to identify the sensitivity of igniting the fuel mixture. Prior to the elimination of gelled fuel, a squib ignition test was conducted to determine if igniting a gelled fuel added any difficulties. The test was set up the same as the preliminary tests describe above (Figure C.4). The squib was successful in igniting the slightly gelled gasoline and diesel mixture. A third test was conducted to determine if fuel added to a water surface would have any difficulties igniting. Two attempts in igniting the 50/50 fuel mixture on approximately 1 inch of water with the electric squib were unsuccessful. The squib was positioned differently on each attempt, first vertically and then horizontally. The igniter hood was modified to include a baffle plate located approximately 2 inches below the hood's top surface. The baffle plate is a perforated sheet metal used to reduce the blow of the squib on the surface of the fuel. The next ignition test with the baffle plate succeeded in igniting the fuel on the water surface.

C.3.3 System Tests

The fuel dispersion system was tested with water to test the operation of the accumulator, solenoid valve, piping, and nitrogen prior to using the system to ignite fuel. The complete SIDS 1 unit with nozzles (including the ignition and fuel dispersion systems) was the final system tested at OTECH facilities. The test was conducted in a tank of water approximately 1.5 feet deep. The test was initiated by manually contacting the solenoid and squib electrical leads to the battery with the proper delays. The test proved to be successful in igniting and dispersing the fuel. Observations during the test conclude that the atomization of the nozzles is too great and causes the fuel to burn at the nozzles rather than on the water surface.

C.4.0 Diesel Fuel Pool Ignition Tests

The SIDS 1 (without nozzles) igniter was demonstrated and tested twice during the Mesoscale In-Situ Burn Air Jet Aeration Test at the Southwest Research Institute's Department of Fire Technology Remote Test Site located in D'Hanis, Texas. Each demonstration was set up in the same manner (shown in Figure C.6) and both proved to be successful.

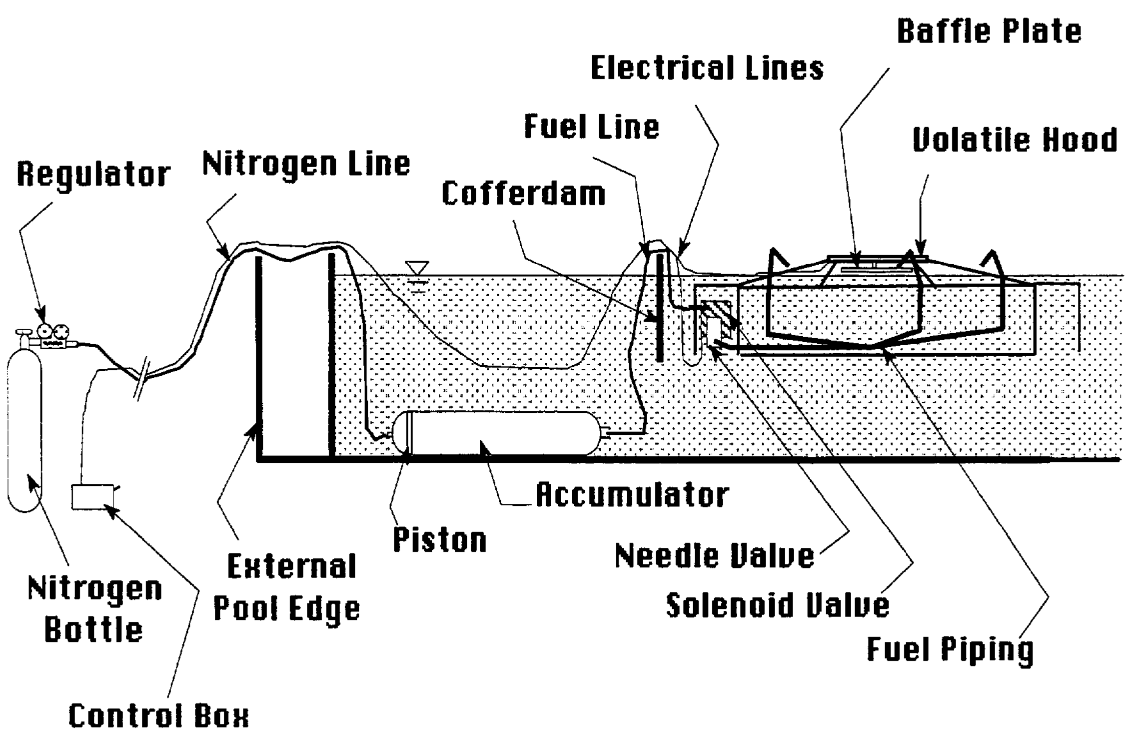


Figure C.6 Diesel fuel pool ignition demonstration set up of SIDS 1 prototype.

The system was positioned in the south-east corner of the pool inside the cofferdam prior to the addition of diesel fuel in the pool. The system was placed on four concrete blocks to avoid unnecessary delays for trimming of the system. The previously filled accumulator was placed outside the cofferdam at the bottom of the pool. A U-shaped piping system covered with ceramic fiber protection was used to shield the fuel line from the fire. A total of four electrical lines ran from the corner of the pool to approximately 60 feet away from the pool. The first test utilized the electronics by initiating the system with the switch. The second test was initiated manually in the same manner as the system test conducted at OTECH's facilities. The first test used a 2 minute delay prior to dispersing the fuel and an additional 90 second delay before igniting the squib. Observations of both tests suggest that the 1/4 square meter of area and the ten minute duration of fuel dispersion may not be needed to ignite the surrounding slick. The dispersed fuel mixture quickly ignited the surrounding diesel within at least 25 seconds. The duration of the fuel dispersion was also undetectable due to the limited visibility through the surrounding fire.

Since the variation of the systems (SIDS 1 and SIDS 2) are only on the storage and dispersal methods of the fuel it was decided that the SIDS 2 unit would not be demonstrated. It was of more interest to successfully demonstrate SIDS 1 twice rather than have one success per system. It can be assumed that the systems would have been equally successful due to the similarities in the ignition systems.

A second set of informal tests were conducted to determine the squib's capabilities in igniting a ceramic fiber pad containing gasoline. Two tests were conducted in the pool on a small (approximately 1/4 square foot) ceramic fiber pad. The failure of the first test was attributed to the lack of volatiles left in the gasoline poured on to the ceramic fiber pad. The second test was successful when fresh gasoline was added to the pad. The success of the test suggests that possible modifications could be made to the current SIDS design.

C.5.0 Conclusions

The demonstration of the prototype SIDS 1 unit has successfully validated the spill igniter concept. The main factors that contributed to the success of the concept were observed as:

- the SIDS remains stationary in the pool after ignition,
- igniter fluid remains in contact with the surrounding diesel,
- the SIDS relies on igniting a more volatile fuel (gasoline) rather than igniting diesel or crude oil,
- the ignition device is in close contact to fresh volatiles, and
- the igniter fluid and surrounding fuel is protected from the blast of the ignition device

It should also be noted that the demonstration's success could be attributed to the location of the unit in the pool. The cofferdam may have blocked the wind from directly blowing over or through the unit. A simple modification can easily reduce the SIDS's possible wind sensitivity. The tests demonstrated other additional modifications can also improve the system. The second set of tests suggest that pads could be added to center of the unit to increase the burn time if needed. The demonstration also concluded that the size of the prototype was more than sufficient to ignite the surrounding diesel fuel.

C.6.0 Recommendations

OTECH recommends further development of the SIDS concept into a unit ready for operation in in-situ burning practices. A fully self-contained, self-righting, SIDS can provide industry a safe, easily accessible, reliable method for igniting in-situ burns of marine spills. Suggested modifications to the SIDS prototype include:

- simpler, smaller, specifically built fuel storage and dispersal system,
- addition of a perforated plate covering the sides of the unit to reduce possible wind sensitivity,
- the installation of two squibs in series for redundancy,
- eliminate the requirement of 3 mm per minute flowrate for 10 minutes by adding a flammable pad (similar to ceramic fiber) to aid in the duration and reliability of the burn, and
- coating the underlying exterior sides of the pads with silicone can prevent the pads from absorbing underlying water

Prior to development of the final SIDS, OTECH recommends further investigation/discussion in the following:

- the similarities in the flammability characteristics of diesel and briefly weathered crude oil before concluding the size of the SIDS concept can be reduced,
- the burn rate of igniter fuel contained in the flammable pad before eliminating the 3 mm per minute fuel flowrate requirement, and
- the importance of fire containment for igniting a briefly weathered crude oil spill.

The successful development of the SIDS prototype in less than a few weeks testifies to the viability of the concept.