Development of a Protocol for Testing Fire-resistant Oil Containment Boom in Waves and Flames

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Summary

A near full-scale screening test was developed for fire-resistant boom. The test evaluates a boom's durability and its ability to contain oil following an *in situ* burn. The procedure involves cyclical exposure of the boom to waves and fire. Recent experience with refractory-fabric-based booms have shown them to be fragile and unable to contain thick pools of hot oil. This test simulates the heat and mechanical stresses of an *in situ* burn without the environmental problems of burning crude oil or the costs of testing offshore. The draft protocol was tested on a section of fire-resistant boom obtained from the Canadian Coast Guard. The boom was first stressed under tension for two hours in 0.9 m waves. Then, the boom was deployed in a U-configuration in an outdoor wave tank, where it was exposed continuously to waves and current. Propane gas, from and underwater bubbler system, was burned in the pocket of the boom, for one hour out of every two, to simulate the collection and burning phases of an *in situ* burn. Finally, the boom was returned to the indoor tank for another two hours in 0.9 m waves, and then inspected for damage. The boom used in the testing of the protocol was the same model as the one used in the Newfoundland Offshore Burn Experiment (NOBE). It suffered damage similar to that of the boom in the sea trial, although not as severe or in as short a time. This indicates that the protocol reproduces the correct stresses, but that they are lower in intensity. Further development is scheduled for the summer of 1997.

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1. Introduction

1.1 Background

Since the late 1970s, when fire-resistant booms were first proposed and developed in North America (Purves 1978, Buist et al. 1983, Spiltec 1986), there has been an urgent need to conduct burn tests with fire-resistant booms in waves. Fire testing of these booms in quiescent conditions has been carried out, and much has been learned from these tests (Buist et al. 1983, Spiltec 1986, S.L. Ross 1983, Allen and Fischer 1988, Alaska Clean Seas 1991, S.L. Ross 1995, McCarthy 1996); however, this type of testing has its limitations. The combined effect of exposure to water, wave action and high temperature flames is known to cause much more rapid boom failure in both metallic (Buist et al. 1983) and refractory fabric booms (Fingas et al. 1995) than would be predicted from quiescent-condition tests.

In the early 1980s, some early fire-resistant boom designs were tested at the Oil and Hazardous Materials Simulated Environmental Test Tank (OHMSETT) (Buist et al. 1983, Borst 1983); however, the exposure time to fire was limited to a few minutes (i.e., the time it took to tow the boom the length of the tank).

Several burn tests with fire boom have been conducted offshore: one at Spitsbergen (Allen 1990); one in Alaska (Allen 1990); one during the Newfoundland Offshore Burn Experiment (NOBE- Fingas et al. 1995) and one in the English channel (Allen 1996). All involved booms constructed from refractory textile material. In the first two of these tests, wave conditions were calm and a single burn was carried out. In each instance no damage to the booms was reported (Allen 1990 and 1991). The offshore test, during NOBE, involved two individual burns; during the second of these burns, in 0.5 m waves, the boom suffered severe damage (Fingas et al. 1995).

It has been theorized for some time (Dome 1981, Roberts and Chu 1978) that the combination of water, intense heat and mechanical flexure (from wave action) would cause mineral, ceramic or synthetic-based refractory textiles to rapidly self-abrade. It remains to be seen whether this problem has been solved with recent design changes, such as protective coatings on the individual fibres of the fabric and mechanical strengthening of the overall boom structure through the incorporation of stainless steel wire mesh and load-bearing members (Burkes 1994). Another problem recently discovered (S.L. Ross 1995, McCarthy 1996) is that at least one design of high temperature textile fire boom becomes significantly permeable to oil when exposed to a fire with a large slick thickness (i.e., 17 cm). The oil thicknesses at which leakage has been observed during these tests is on the lower end of what might be expected in a boom under tow. This phenomenon may be one of the reasons why substantial amounts of burning was observed on the downstream side of the fire boom during the NOBE trials (Fingas et. al 1995).

Realistic, inexpensive testing is needed in both waves and high-temperature flames for extended time periods to evaluate any fire boom system's capabilities and limitations before expensive testing at sea.

1.2 Objective

The objective of this project was to develop a near-full-scale screening test protocol for the effectiveness and durability of fire-resistant oil containment boom that incorporates simultaneous testing in waves and flames. The ability of boom exposed to fire to contain thick, hot oil and to survive extended exposure to wave action prior to and after exposure to flames was also to be determined. The flame test was to be relatively simple and inexpensive to carry out in a wave tank, even possibly at sea, without producing any visible air or water pollution while simulating full-scale *in situ* burning heat loads.

1.3 Approach

In order to conduct nearly full-scale fire boom tests in a safe and environmentally acceptable manner, propane gas or natural gas was to be burned in the pocket of a section of fire-resistant oil containment boom to simulate full-scale heat loads from an oil slick fire. This approach offered the advantages of:

- easy fire control and safety (by merely adjusting or stopping the flow of gas via a tank-side valve);
- no contamination of the water in the test tank with an oil product; and, no visible or noxious emissions. Both natural gas and propane will burn to completion with little or no soot generation (Bruzstowski and Aziz 1977, S.L. Ross 1984, Blackmore and Summers 1982) with a properly designed delivery system.

The concept for the fire test system was an underwater bubbler that distributed gas in the boom pocket in a 0.5 to 1 m-wide area beside the section of the boom to be exposed to flame. The design of the underwater gas distribution system was based on experimental work (Bruzstowski and Aziz 1977) that modelled the burning of gas from a subsea blowout and developed equations relating gas flow, water depth and flammability using natural gas and propane bubble plumes in test tanks. Similar concepts have been used to construct fire training facilities for the US Navy and other fire-fighting organizations. At these, propane is bubbled through a gravel bed covered with shallow water to produce a continuous flame over a large area. The flame is controllable via a series of valves. Little smoke is produced when the flames stabilize after a short ignition period.

This project was carried out in consultation with the researchers at the National Institute for Standards and Technology's (NIST) Building and Fire Research Laboratory (BFRL) who were working on: quantifying the external radiant fluxes at a fire's periphery produced by propane, diesel fuel and crude oil flames; and, developing small-scale exposure tests for short portions of fire-resistant boom.

1.4 Goals

The specific goals of the study were to:

- conduct a detailed literature review on the heat flux at the periphery of gas and liquid petroleum fires (i.e. where a boom would be situated);
- conduct wave tank tests with small-scale gas fires on water fed by an underwater bubbler system;
- conduct tests in a large wave basin with mid-scale gas fires on water fed by an underwater bubbler;
- select the best gaseous fuel for the purposes of the test program and design a suitable underwater bubbler system;
- develop the preliminary test protocols;
- outfit and instrument separate wave basins and/or flumes for wave endurance tests, simultaneous wave and flame tests, and thick oil containment tests; and,
- put one fabric-based fire-resistant boom through the entire test series using the preliminary test protocols.

1.5 Report Contents

This report has been divided into 8 sections. Section 2 describes the results of the literature review. Section 3 details the small-scale studies of propane and natural gas flames from single and multiple underwater bubble plumes. Section 4 presents the design of the underwater propane distribution system and its shakedown tests in an outdoor wave basin. Section 5 describes the test protocols developed and details the equipment and techniques used to subject a section of fire-resistant boom to the protocols. Section 6 describes the results of the tests. Section 7 presents the conclusions arising from the study and the recommendations for future work to improve the protocols.

2. Literature Review

One of the first tasks of the project was to conduct a literature review on the subject of the heat flux at the periphery of a pool fire of liquid or gaseous hydrocarbons. The purpose was to find information on total heat fluxes (i.e. both convective and radiative combined) from *in-situ* or pool fires of petroleum fuels to a barrier at the edge of the fire in order to define the magnitude of the flux required to simulate such fires with other fuels. The services of the Canada Institute for Scientific and Technical Information were used to conduct a computerized literature search of the following databases over the time spans indicated:

Energy Science and Technology	1974 to June 1996
EI Compendex Plus	1970 to August 1996
NTIS	1964 to September 1996
Energyline	1970 to December 1993
Enviroline	1975 to June 1996
Pollution Abstracts	1970 to August 1996
Wilson Appl. Sci and Tech Abstracts	1983 to May 1996

The FIREDOC system maintained by NIST was also accessed. The search resulted in several hundred "hits", of which about 40 were deemed relevant and reviewed.

Neill et al. (1970) reported total heat fluxes to a small, cylindrical water boiler immersed in flames above 12-inch and 18-inch diameter JP-4 fires as 9,600 and 19,500 BTU/hr·ft^2 (30 and 60 kW/m^2) respectively. The heat flux from a cluster of 6-inch pools of burning JP-4 (with a fire area equivalent to an 18 inch diameter pool) was reported as 31,000 BTU/hr·ft^2 (100 kW/m^2); the enhanced aeration of the combustion zone permitted by the cluster layout greatly increased the heat flux. For the 18-inch JP-4 fire they estimated that 50% of the heat flux was due to radiation and 50% due to convection. They also calculated that the convective heat transfer coefficient from a hot, luminous flame to a cold surface would be on the order of 3.5 to 4 BTU/hr·ft^2·°F (6 to 7 W/m^2·°C). They estimated that the total heat flux to an immersed object from an optically thick JP-4 fire (given as 80 inches, or 2 m, thick) would be 31,000 $BTU/hr \cdot ft^2$ (100 kW/m^2).

Russell and Canfield (1973) reported on radiant heat fluxes to a large horizontal cylinder immersed in flames at a height of 4 feet (1.2 m) above an 8 x 16 ft (2.4 x 5 m) JP-5 pool fire. The radiometers used were specifically designed to eliminate convective heat flux. The highest mean radiant heat fluxes reported were in the range of 15 $BTU/ft^2 \cdot s$ (40 kW/m^2).They measured maximum flame temperatures on the order of 900°C; these occurred on the downwind side of the cylinder.

Steward and Mitsoulis (1983) measured the radiant heat flux at various distances from the center of 15 cm diameter pool fires of various liquid fuels. The measurement locations were both beneath and outside of the flames in the plane of the fuel surface. They showed that the peak radiant heat flux occurs at the edge of the pan containing the burning fuel. The measured heat flux was approximately 1 $cal/cm^2 \cdot s$ (40 kW/m^2) for methanol and propanol fires.

Longenbaugh and Matthews (1986) measured heat fluxes in a large (9 x 18 m) JP-4 fire on water in a pan. One of the transpiration radiometers (specifically designed to eliminate convective heat transfer) used was placed at the edge of the pan, approximately 1.2 m above the fuel surface, looking into the center of the fire. The mean radiative flux reported for this radiometer (averaged over 18 to 28 seconds) was 115.6 kW/m^2 at 24 minutes, 62.2 kW/m^2 at 27 minutes, and 59.4 kW/m^2 at 28 minutes. Thermocouples placed at the edge of the pan recorded flame temperatures of approximately 400°C; thermocouples 1.5 m inside the flames recorded temperatures of 800° to 1000°C.

Mudan and Croce (1988) give the following for large fires (large in comparison to the heated surface - i.e., a boom containing a large oil slick on fire) where the flames are optically thick and have emissivities near 1. The heat flux to a thermally thin vertical surface being impinged by the flame is given by:

$$q_{total} = \sigma(\alpha_s T_f^4 - \varepsilon_s T_s) + h_a(T_f - T_a) \quad (1)$$

where q_{total} ≡ total heat flux to the vertical surface (W/m^2)

σ ≡ Stefan-Boltzman constant

= 5.67×10^{-8} $W/m^2 \cdot K^4$

α_s ≡ absorption coefficient of the surface

ε_s ≡ emissivity of the vertical surface

h_a ≡ convective heat transfer coefficient from flame to vertical surface

≈ $1.31\ (T_f - T_s)^{1/3}$ $W/m^2 \cdot K$

T_f = actual flame temperature [as opposed to a radiative flame temperature] (K)

T_s = temperature of vertical surface (K)

T_a = ambient temperature (K)

Khater et al. (1989) measured the heat flux from small (4- to 9- cm diameter) pool fires of LPG (30% propane and 70% butane). The radiometer was placed at the height of the lip of the pan at various distances from the edge. Extrapolating their data back to the lip yielded a heat flux (presumed to be solely radiative) of approximately 15 kW/m^2. The maximum heat flux was found to occur above the lip of the pan. The authors presumed that this was due to changing values of the view factor.

Nakos and Keltner (1989) reported on experiments to measure the radiative and convective portions of the heat flux to an object immersed in a 9 x 18 m JP-4 pool fire. The measured radiative heat fluxes in the fire ranged widely over the period of the tests, generally from 50 to 200 kW/m^2 and averaged about 100 kW/m^2. The calculated total heat flux ranged from 50 to 250 kW/m^2 and averaged approximately 120 to 130 kW/m^2, with the convective component making up 10 to 20% of the total (average of 15 kW/m^2). They reported the surface temperature of a steel plate in the fire as ranging from 900 to 1100°C.

Hayasaka et al. (1992) used high-speed thermography to measure the radiance distribution and fluctuations from 2.7 x 2.7 m pool fires of heptane, kerosene and Arabian crude oil. Their data suggests that the overall irradiance (measured at a distance from the edge of the pan of L/D = 5) is highest for heptane and lowest for crude oil. The point of highest mean radiance from the flames was found to be in their center at 0.5D above the fuel surface for heptane and at about 0.2D for kerosene and crude oil. Multiplying their reported mean radiance values per solid angle (given in $kW/m^2 \cdot sr$) by 4π yields maximum mean radiant fluxes of 185 kW/m^2 for heptane, 175 kW/m^2 for kerosene and 163 kW/m^2 for crude oil. Koseki (1993) reported on using the thermography technique at a 15 x 15 m diameter Louisiana crude oil fire. The maximum irradiance measured with this large fire was 127 kW/m^2 at the base of the flame, which corresponded to a temperature of 950°C, assuming a flame emissivity of 1.

Gritzo et. al (1995) reported on experimental measurements of radiative heat flux to large objects immersed in flames from a 19-m diameter JP-8 pool fire during very windy conditions. The object was a 3.7-m diameter horizontal steel cylinder (simulating an aircraft fuselage) positioned at the downwind edge of the fire. The wind speed was 10.2 m/s. In these conditions, the combustion produced very high temperatures (>1400°C), melting Inconel thermocouples and wire, and several parts of the test pan that had survived numerous previous JP-8 fires in calmer conditions. The measured heat fluxes to the cylinder ranged from 100 to greater than 250 kW/m^2 with the highest fluxes occurring near the bottom of the cylinder on the leeward side. The measured fuel consumption rate and heat flux to the fuel surface were not unusual for this type of fire.

Guénette and Wighus (1996) reported on heat flux measurements to a 1-m diameter vertical steel cylinder in a 15-m diameter Statfjord crude oil pool fire on ice. Winds were 0 to 2 m/s. The maximum heat flux measured was at 6.8 m above the surface and averaged (over 32 seconds) 220 to 230 kW/m^2. The average heat flux at a height of 1.8 m was 130 kW/m^2. Flame temperatures ranged from 600 to 1300°C

3. Small-scale Gas Burns

Small-scale burns using natural gas and propane were conducted in the wind/wave tank at the S L Ross laboratory. The purpose was as follows:

i) determine whether propane or natural gas was the best fuel for the test protocol;
ii) identify the parameters, such as fuel flow rate and fire diameter, that allowed for a smokeless burn;
iii) determine the desired size, shape and heat flux of the fire for the final burner system;
iv) determine the configuration of the full scale underwater propane bubbler; and,
v) test the data acquisition systems.

3.1 Methods

The wind/wave tank (Figure 3-1) measures 1.2 x 1.2 x 11 m and was filled with water to a depth of 85 cm. The burns were performed in the section of tank underneath the fume hood, which was connected to a 200 m^3/min (7000 cfm) fan to exhaust all smoke and combustion gases.

3.1.1 Natural Gas Tests

The natural gas was supplied from a 2.5 cm i.d. pipe tapped into the gas main at the S.L. Ross laboratory. The flow of gas was regulated by a ball valve installed at the end of the pipe, upstream of the bubbler, and was measured by timing the rotation of the gas company meter. The outlet for the natural gas underwater bubbler was a 2 cm (0.75 in.) i.d. 90° elbow, or "ell", attached to the end of a plastic feed hose from the 2.5-cm (1 in.) pipe. The ell was clamped to a submerged frame with the outlet facing down to prevent the hose from filling with water. The outlet could be raised and lowered in depth, although the natural gas delivery pressure of 2 kPa (8 to 9 in. of H_2O) restricted the maximum depth of the nozzle to 15 cm (6 in.) below the surface of the water. Holes much smaller than one inch could not be used since the supply

Four Medtherm model 64-20-20 total heat flux transducers (0 to 200 kW/m^2 with $\pm 3\%$ FS accuracy) were obtained, each with its own factory calibration curve. Each of the four was used to measure the heat flux from a propane radiant heater at full flow at various distances from the hot element. One of the heat flux transducers was set aside and never used in experiments. The other three that were used in experiments were periodically checked against the reference transducer with the propane heating element. This ensured that the heat flux measurements were consistent throughout the small- and large-scale tests.

The underwater bubblers were constructed from lengths of 1.3 cm (0.5 in.) i.d. copper pipe. Small holes of various diameters were drilled in the copper pipe(s) at different locations to permit the generation of a variety of gas bubble plume sizes and geometries. The bubbler was positioned 45 cm (18 in.) beneath the surface of the water. The heat fluxes from the fires were measured by a heat flux transducer placed 5 cm above the surface of the water at the expected periphery of the flames. Flame temperatures were recorded with a Type "K" thermocouple placed in the expected location of the flames. Output signals from the pressure transducer, the heat flux transducer and the thermocouples were fed to an Advantech PCLD789 Amplifier and Multiplexer Board connected to an Advantech PCL711B analog/digital card in an IBM-compatible personal computer.

Some difficulty was encountered at higher gas flow rates with the flow of propane decreasing as the cylinders cooled. As gaseous propane was drawn off the top of the cylinder, liquid propane evaporated to replace it. The heat of vaporization lost resulted in the liquid propane and the cylinder cooling, and the vapor pressure dropping. In turn, this resulted in a drop in gas flow rate. For example, with one propane cylinder feeding one 1.6 mm diameter hole in the bubbler, the line pressure dropped from 95 to 70 kPa (14 to 10 psig) over the 6 minute duration of the test.

This was partially overcome by using more propane cylinders (up to four at a time) so that the evaporative cooling was spread over a larger mass of liquid propane. Still, the propane cylinders had to be warmed, from time to time, by running hot water over them. Keeping the propane cylinders in a warm circulating bath (i.e., improving the heat transfer between the cylinders and their surroundings) would be one solution to this problem, although care would have to be taken to ensure the water temperature was kept moderate so that the cylinders were not overheated. This was not necessary for these tests since they were all of short duration. For larger scale tests, however, where gaseous propane was to be drawn directly from the cylinder, this would have to be considered. The full-scale system discussed in Section 4 was fitted with vaporizers that used gas-fired heaters to evaporate the liquid (i.e., supply the heat of vaporization) and maintain a constant feed pressure and temperature.

3.2 Results

The raw data for all the tests may be found in Appendix 1.

3.2.1 Natural Gas

Natural gas test burns were conducted with the gas outlet positioned at three depths of approximately 3, 5 and 10 cm below the surface of the water. Table 3-1 presents the flow and heat release rates achieved during the natural gas runs. The heat release rate was calculated by multiplying the gas flow rate by the estimated net heat of combustion for natural gas of 50 kJ/g.

Table 3-1: Results of small-scale burns with natural gas

Nozzle Depth (cm)	Gas Flow Rate (g/s)	Approximate Heat Release Rate (kW)
3	1.23	61
5	1.06	53
10	0.62	31

In all cases, the flames were very transparent and unstable. The gas flow rate was highly dependent on the depth of the outlet and, rather than being dispersed in a fine cloud like the propane gas plumes discussed below, the bubbles were large and burst violently at the water's surface. Figures 3-2 through 3-4 show the heat flux from the natural gas fires, as measured by a radiometer placed at the flames edge, 15 cm from the surface of the water. The heat flux ranged from 1 to 3 W/cm^2 (10 to 30 kW/m^2) for the 1.28 g/s fire; from 1 to 5 W/cm^2 for the 1.1 g/s fire; and from 1 to 6 W/cm^2 for the 0.6 g/s fire. The unusually low heat flux measured for the 1.23 g/s fire was due to poor positioning of the radiometer; for the shallower depths the burn diameter at the water surface was much smaller and the radiometer was located a significant distance from the edge of the flame. The short measurement time for the 0.6 g/s fire was due to the fire extinguishing after 1.5 minutes because the fuel flow rate was too low. For comparison, Figure 3-5 shows the heat flux measured from a 40-cm diameter diesel fire, burning at a rate of 2.47 g/s. In this case the total heat flux ranges from 3 to 7 W/cm^2 during the steady burning phase.

It became clear that the standard delivery pressure for natural gas would be insufficient to supply enough fuel for the full-scale tests. Furthermore, the low delivery pressure precluded its use at the desired water depth of a boom skirt. If natural gas was to be used as a fuel, a source of liquified natural gas (LNG) would be needed. Only lab-grade LNG was available, which would have been prohibitively expensive to use in larger-scale tests. As well, natural gas has a much lower net heat of combustion per unit volume of gas than propane so a greater volume would have to be used to generate the same heat release rate. For these reasons natural gas was not considered further as a fuel for the larger-scale test program.

3.2.2 Propane

Numerous tests were run, varying hole size, number of holes, and hole layout, in order to develop a basis for the design of an underwater bubbler system for the large-scale tests. All tests were run with the copper pipe header submerged to a depth of 45 cm (18 in.).

The first test involved one 1.6-mm diameter hole in the copper pipe fed by one propane cylinder. The results of this test are shown in Table 3-2. The heat release rate was calculated using an estimated heat of combustion of 50 kJ/g.

Figure 3-2: Total heat flux from 1.3 g/s natural gas fire

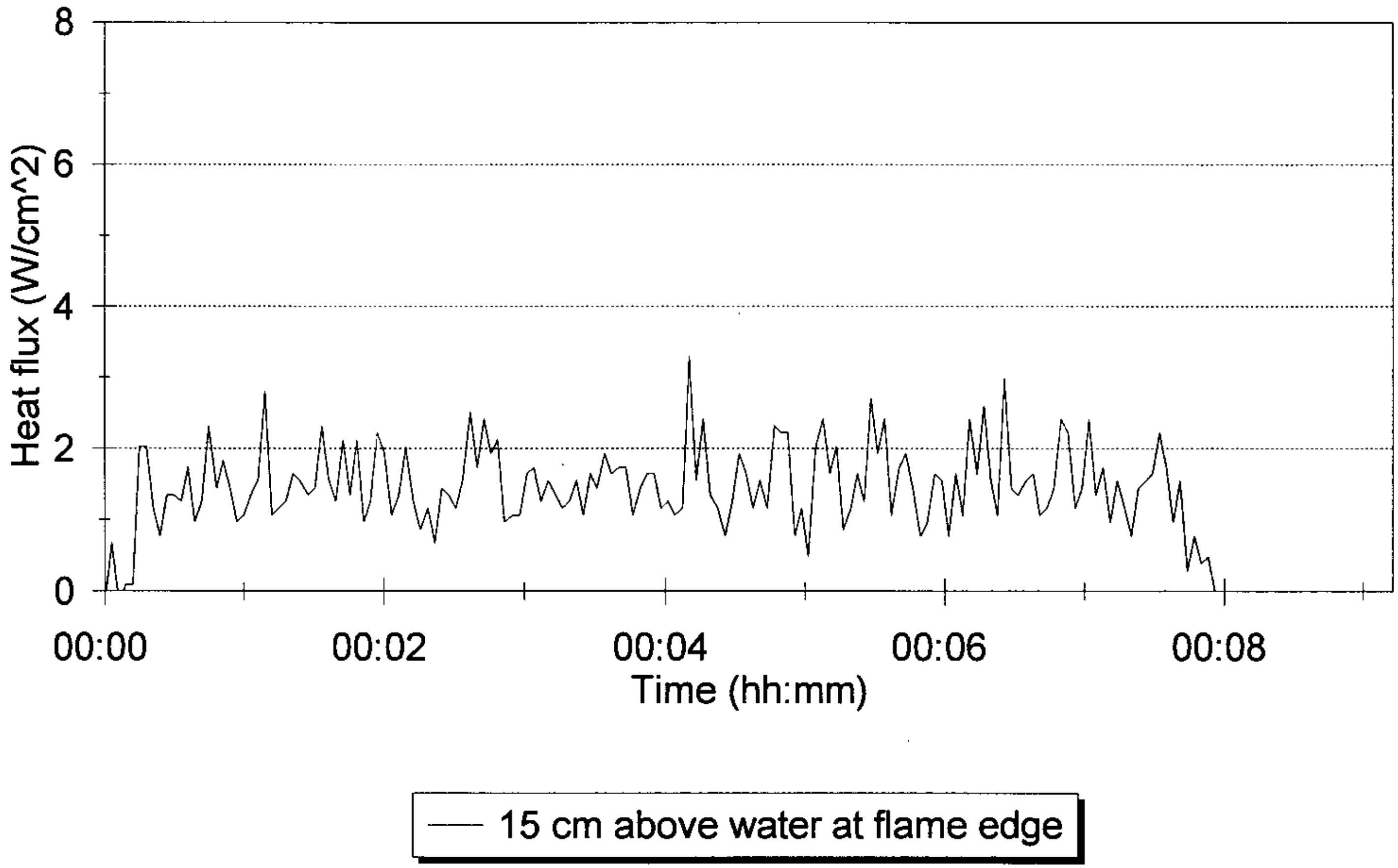


Figure 3-3: Total heat flux from 1.1 g/s natural gas fire

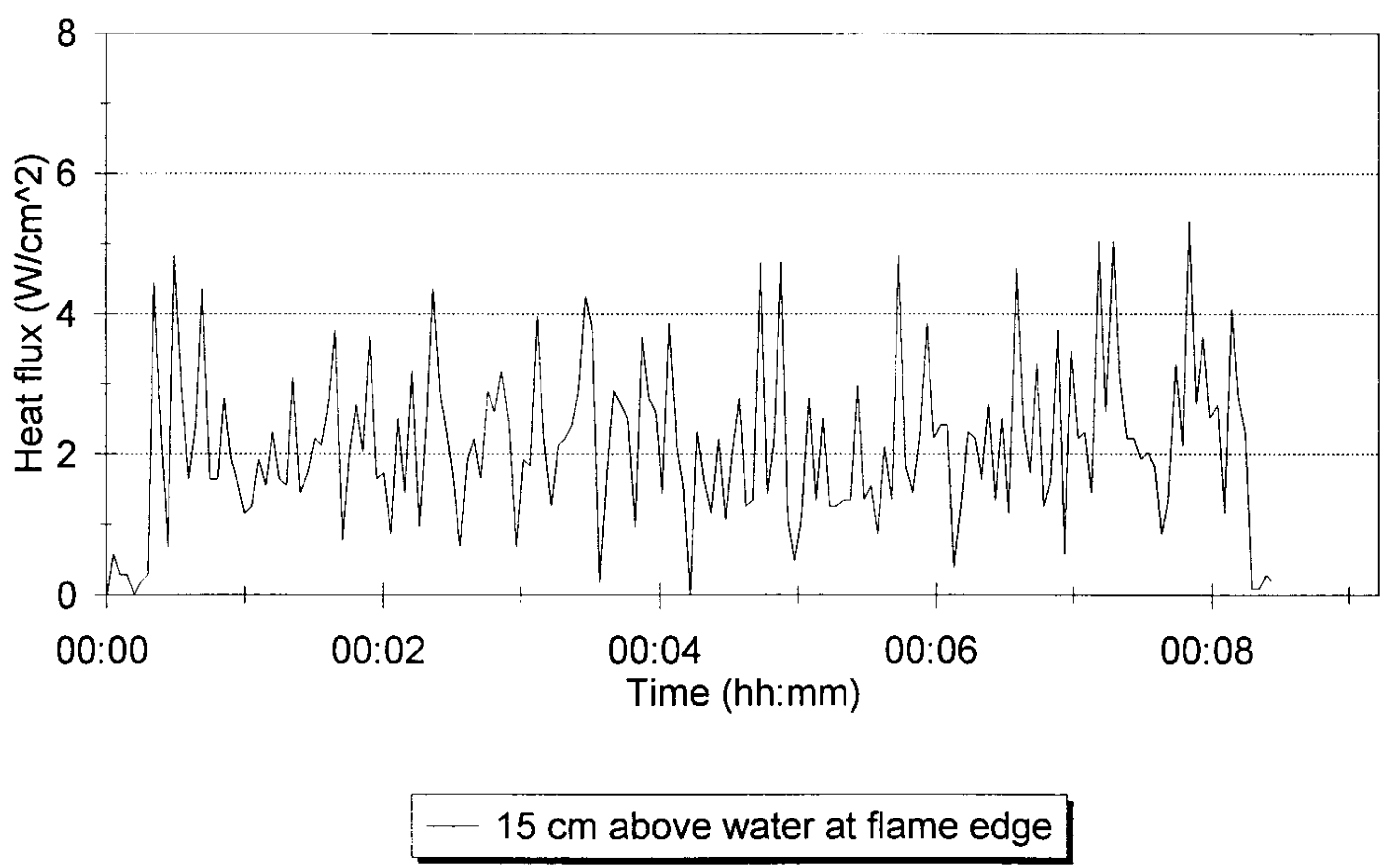


Figure 3-4: Total heat flux from 0.6 g/s natural gas fire

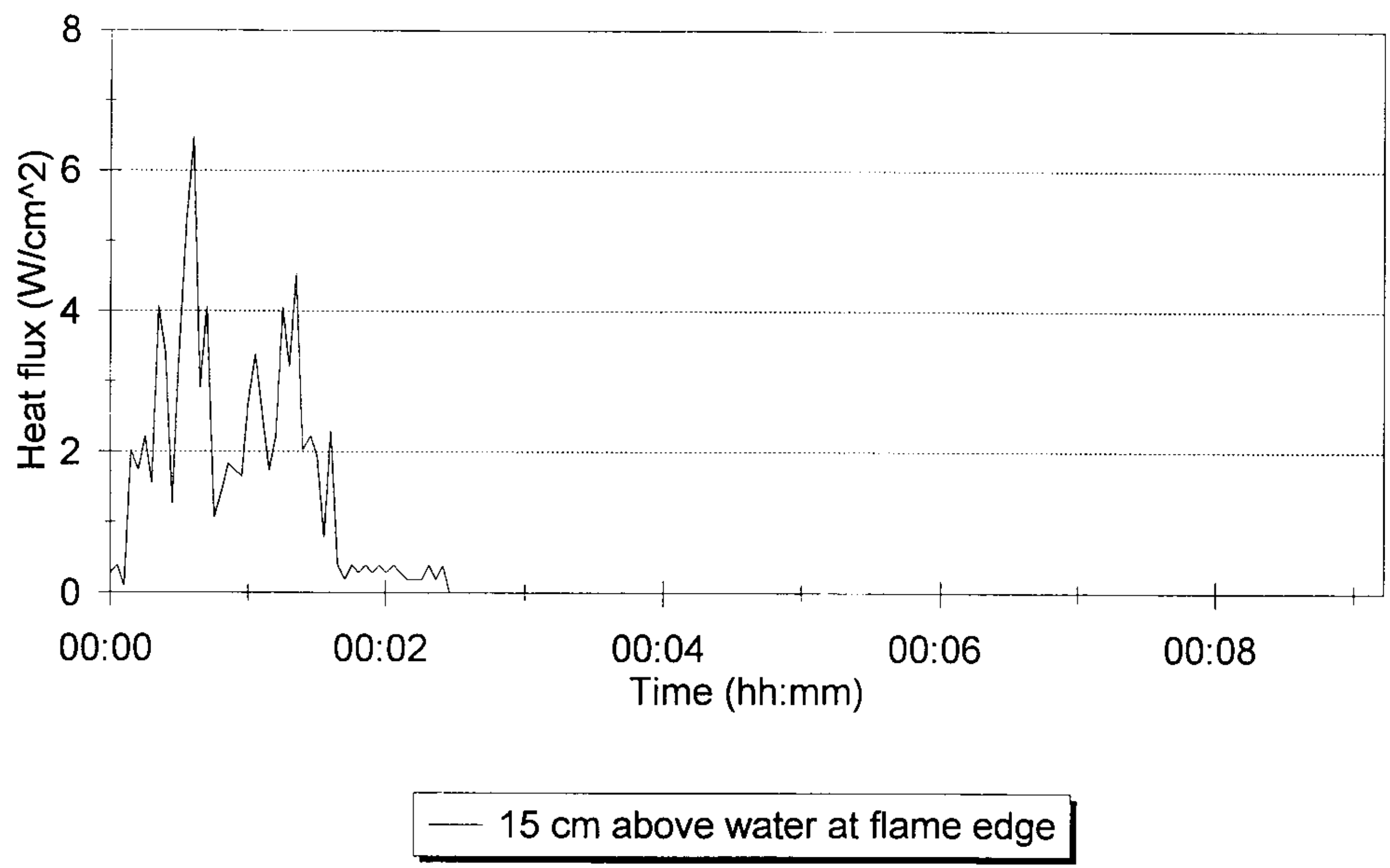


Figure 3-5: Total heat flux from 2.47 g/s diesel fire

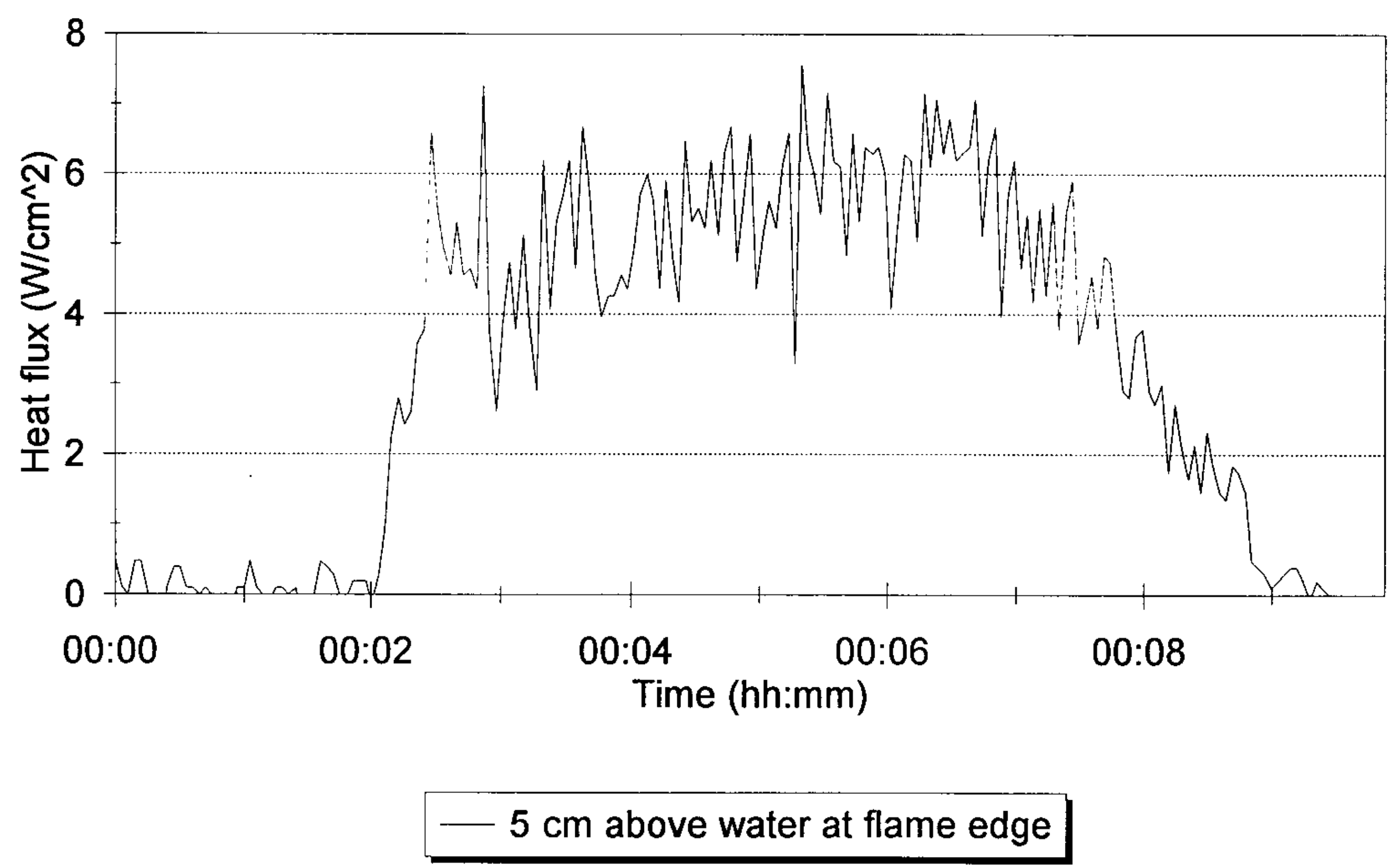


Table 3-2: Results of small-scale burn with one hole fed by one cylinder

Elapsed Time (min)	Line Pressure (kPa gauge)	Gas Flow Rate (g/s)	Heat Release Rate (kW)
1	89.6	1.08	54
2	82.7	1.08	54
3	75.8	0.92	46
4	68.9	0.92	46
5	68.9	0.83	42
6	68.9	1.00	50

This configuration produced a stable, smokeless flame 35 to 40 cm in diameter and 75 to 80 cm in height. The average flow rate of propane was 0.97 g/s. The valve on the propane cylinder was completely open and the gas was running at full flow. Evaporative cooling of the liquid propane in the cylinder caused a steady drop in pressure over the six minutes of the test. This flow rate was lower than desired so the next four tests (see Appendix 1) varied propane feed parameters (pressure, flow, number of cylinders) to determine an experimental setup that would provide stable flames over a suitable measurement time.

It was determined that the best setup used two propane cylinders to feed the one 1.6 mm hole. Table 3-3 presents the results of this test.

Table 3-3: Results of small-scale burns with one 1.6-mm hole fed by two cylinders

Elapsed Time (min)	Line Pressure (kPa)	Gas Flow Rate (g/s)	Heat Release Rate (kW)
1	200.0	1.95	98
2	193.0	1.92	96
3	193.0	1.92	96
4	206.8	1.97	99
5	193.0	1.93	97

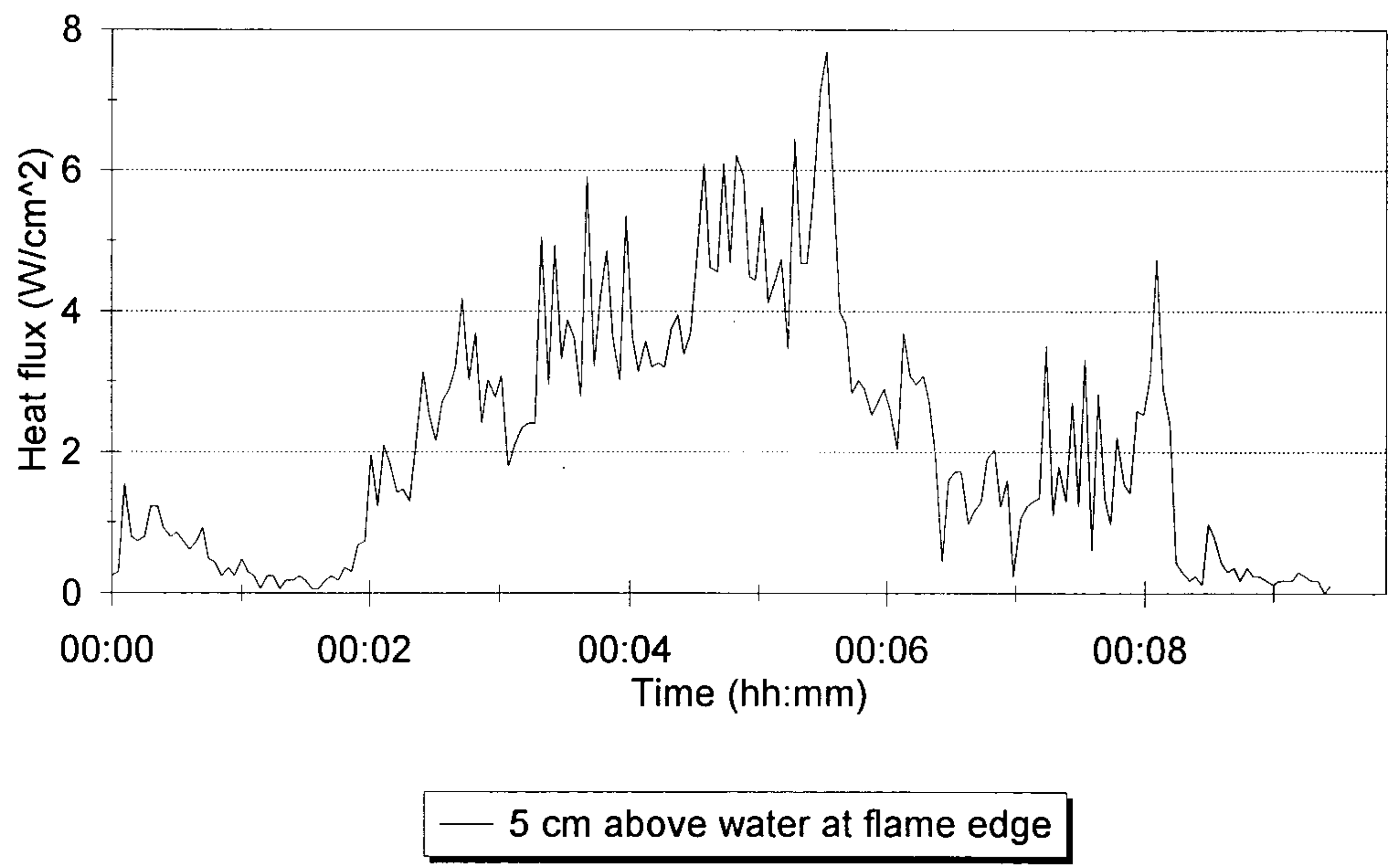
With two propane cylinders on line, it was possible to maintain a steady, higher pressure over the time frame of the test. This resulted in a higher average flow rate of 1.94 g/s and produced a stable, steady flame with just a hint of soot. The flame base was 50 cm in diameter and the flames reached 100 cm in height. The dimensions of this flame and the fact that little smoke was produced appeared promising and 2 g/s per hole eventually became the basis for the full-scale design. Figure 3-6 shows the heat flux for this test. The heat flux varied considerably over the duration of the test, ranging from 2 to 12 W/cm^2 (20 to 120 kW/m^2). This large variation was likely a result of the flame being blown about by the air flow induced by the exhaust fan. Sometimes the transducer was "looking" at a full flame diameter while at other times the air had moved the flames, and the radiometer was "seeing" only part of the flame. The base of the flame also wandered a small amount due to movements in the underwater bubble plume. This would move the edge of the flame towards and away from the heat flux transducer.

The next step was to try two 1.6-mm holes at once. A second hole was drilled in the copper pipe, spaced 40 cm from the first. This spacing allowed for some overlap between the bubble plumes at the surface to ensure that there was a continuous flame base. Several scoping tests were run before good data could be obtained (see Appendix 1). The results of the good test, using two propane cylinders to feed the two holes, are presented in Table 3-4.

Table 3-4: Results of small-scale burns with two holes and two cylinders

Elapsed Time (min)	Line Pressure (kPa)	Total Flow Rate (g/s)	Flow Per Nozzle (g/s)	Total Heat Release Rate (kW)
1	137.9	2.78	1.39	139
2	124.1	2.59	1.30	130
3	117.2	2.55	1.28	128
4	110.3	2.40	1.20	120
5	103.4	2.36	1.18	118
6	99.9	2.29	1.15	115
7	93.1	2.20	1.10	110

Figure 3-6: Total heat flux from one hole



Initially there was good overlap between the bubble plumes. The flames were steady and smoke free, measuring 40 to 45 cm wide, 85 to 90 cm long and 95 cm high. As the propane cylinders cooled, the pressure and flow rate dropped until there was a noticeable space between the two flames. It became clear that the flow rate must be kept above about 1.3 g/s per nozzle in order for the 40 cm spacing to provide a continuous flame region. Figure 3-7 shows the heat flux from the test. The heat fluxes ranged from 2 to 7 W/cm^2. The heat flux transducer was "looking" through a 70 cm path length of flame for these readings. The readings are considerably more steady with the two holes than those for the test with only one. This test was repeated, this time using 3 propane cylinders to feed the two 1.6 mm holes. The results are given in Table 3-5.

Table 3-5: Results of small-scale burns with two holes and three cylinders

Elapsed Time (min)	Line Pressure (kPa)	Total Flow Rate (g/s)	Flow Per Nozzle (g/s)	Total Heat Release Rate (kW)
1	168.9	2.97	1.49	149
2	151.6	2.87	1.44	144

The flames were slightly taller (at 100 cm) due to the higher flow rate per nozzle. Flame coverage was good. A third 1.6-mm hole was then drilled 40 cm from the second. The results of this run are presented in Table 3-6.

Table 3-6: Results of small-scale burns with three holes and three cylinders

Elapsed Time (min)	Line Pressure (kPa)	Total Flow Rate (g/s)	Flow Per Nozzle (g/s)	Total Heat Release Rate (kW)
1	158.5	4.34	1.45	217
3	141.3	4.08	1.36	204
5	124.1	3.78	1.26	189
7	103.4	3.44	1.15	172
9	89.6	3.22	1.07	161

As with the previous tests with one tank per hole, the initial flow was sufficient to provide even flame coverage, but it soon decreased as the cylinders cooled. Figure 3-8 shows the heat flux from the fire. As expected, the heat flux was higher than the test with two holes, and was quite

Figure 3-7: Total heat flux from two holes with two tanks

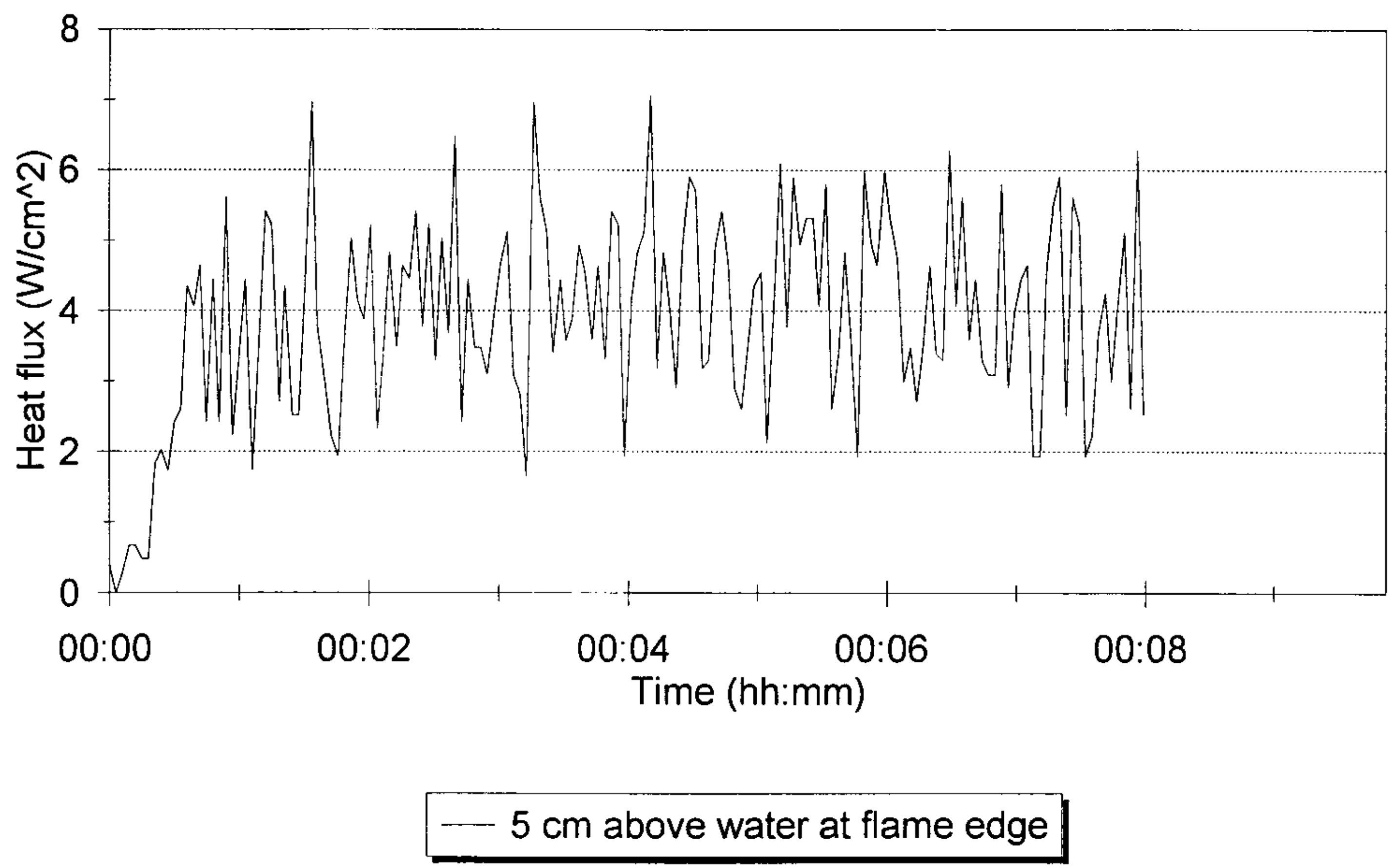
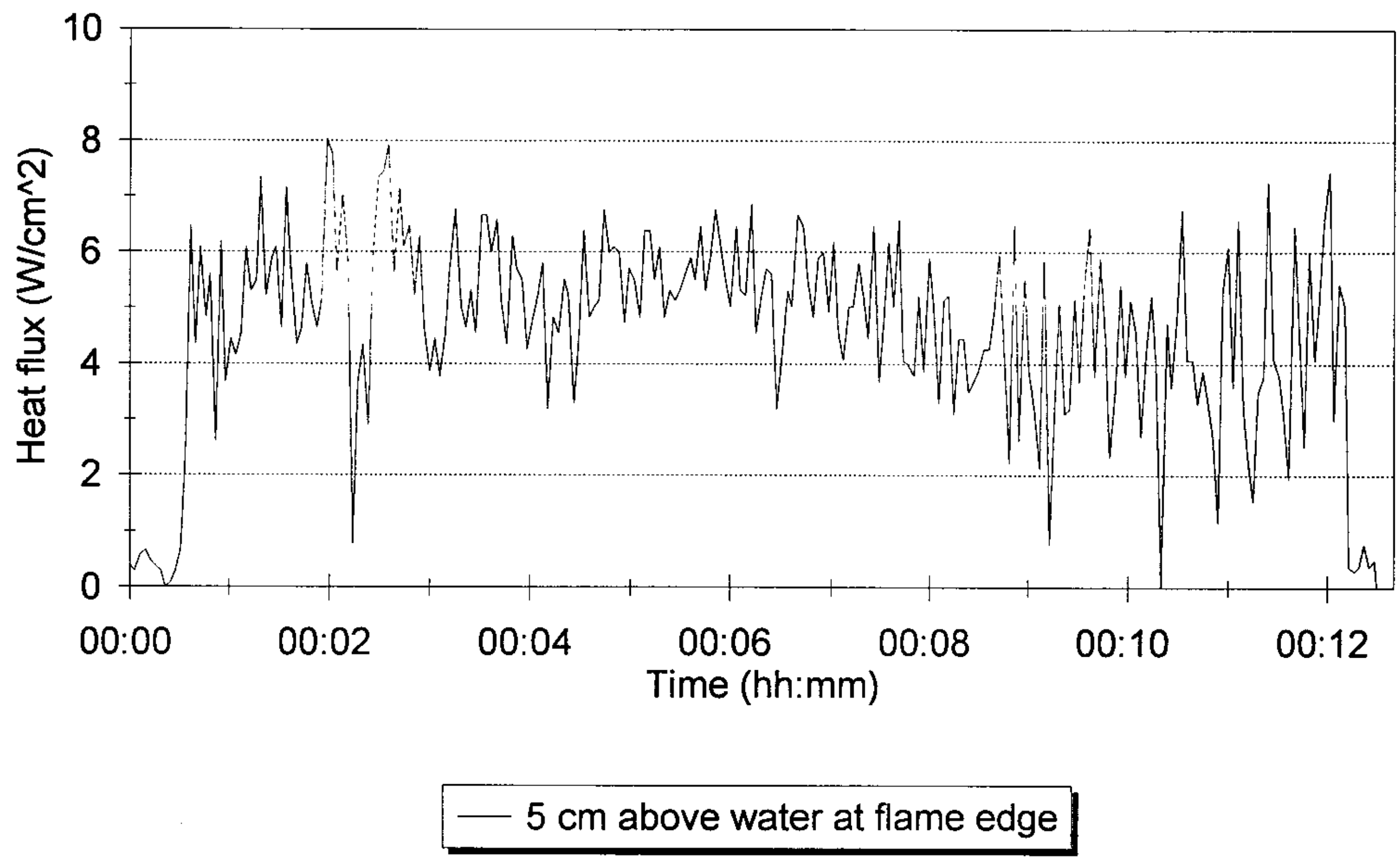


Figure 3-8: Total heat flux from three holes with three tanks



similar to that produced by the small diesel fire (see Figure 3-5). The variability in readings increased near the end of the test as the flow rate dropped and the flames became weaker and more susceptible to the turbulence from the exhaust fan.

At this point, different geometric layouts of the holes were tested, namely a triangle with 40 cm long sides with holes at the points; a square with 40 cm long sides; and, an "X" layout, similar to the five on a die. Table 3-7 gives the results for the triangle fed by three propane cylinders. Figure 3-9 shows the heat flux measured by the transducer looking from the point of the triangle towards the middle of the base. The results are very similar to those obtained for three holes in a line (see Figure 3-8).

Table 3-7: Results of small-scale burns with three holes in a triangle and three cylinders

Elapsed Time (min)	Line Pressure (kPa)	Total Flow Rate (g/s)	Flow Per Nozzle (g/s)	Total Heat Release Rate (kW)
1	212	5.58	1.86	278
3	179	4.64	1.55	232
5	141	3.74	1.25	187
7	106	3.25	1.08	54
9	89.6	3.18	1.06	53

Table 3-8 gives the results for the four holes at the corners of a square. In this case three cylinders are feeding the system. The measured heat flux, with the transducer looking from the middle of one side of the square to the other side, is shown in Figure 3-10. The heat fluxes for this test were slightly lower than for the triangular configuration (see Figure 3-9) because of the reduced fuel flow per nozzle.

The final configuration tested was an "X". The results are given in Table 3-9 and Figure 3-11. The heat fluxes ranged from 2 to 6.5 W/cm^2 (20 to 65 kW/m^2). These were somewhat lower than the three hole configurations due to the lower flow rates per hole achievable. The flames produced at the beginning of the test were continuous over the entire area. As the pressure dropped, the flame broke into five separate burns. The five-hole bubbler was subjected to waves

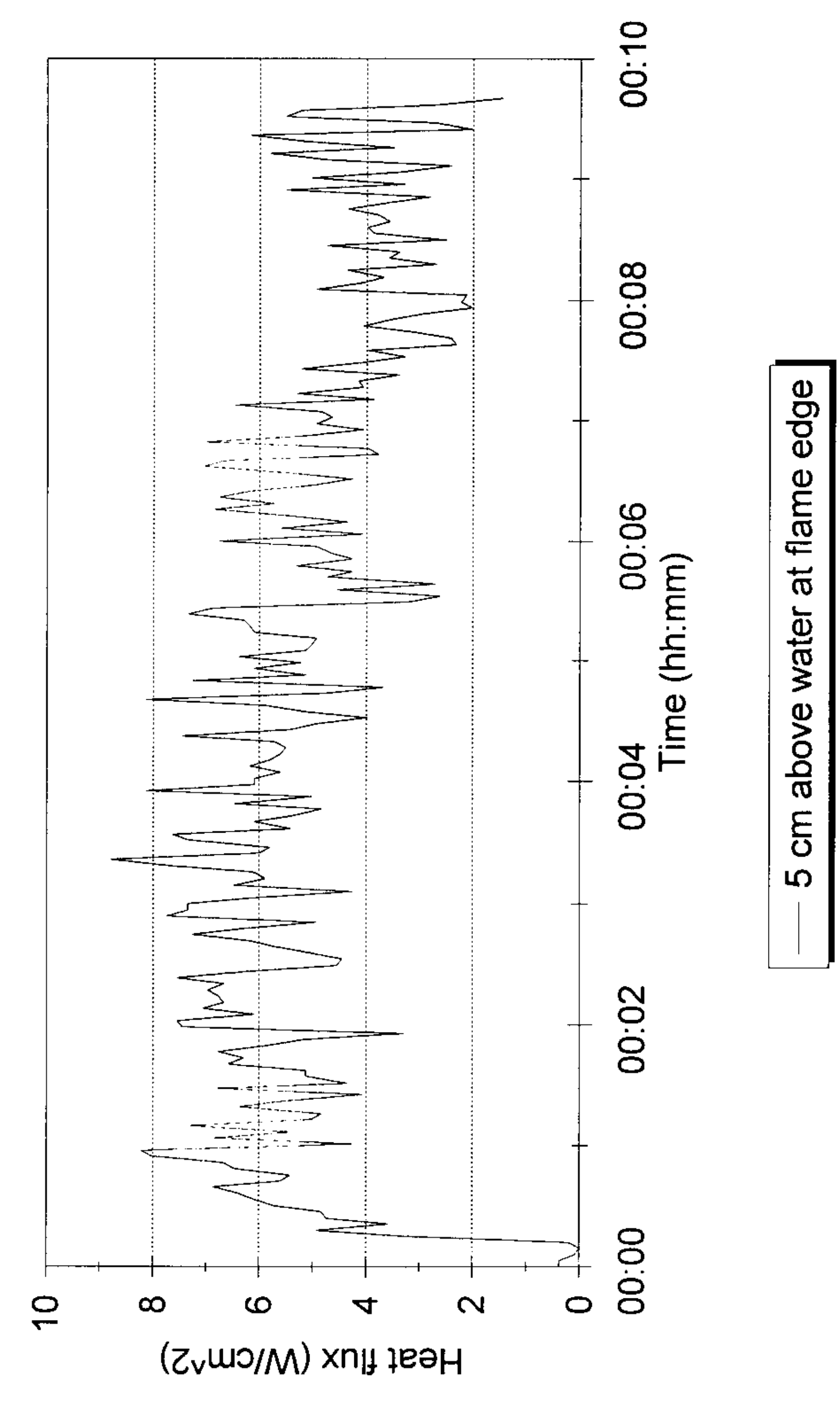


Figure 3-9: Total heat flux from three holes in a triangle

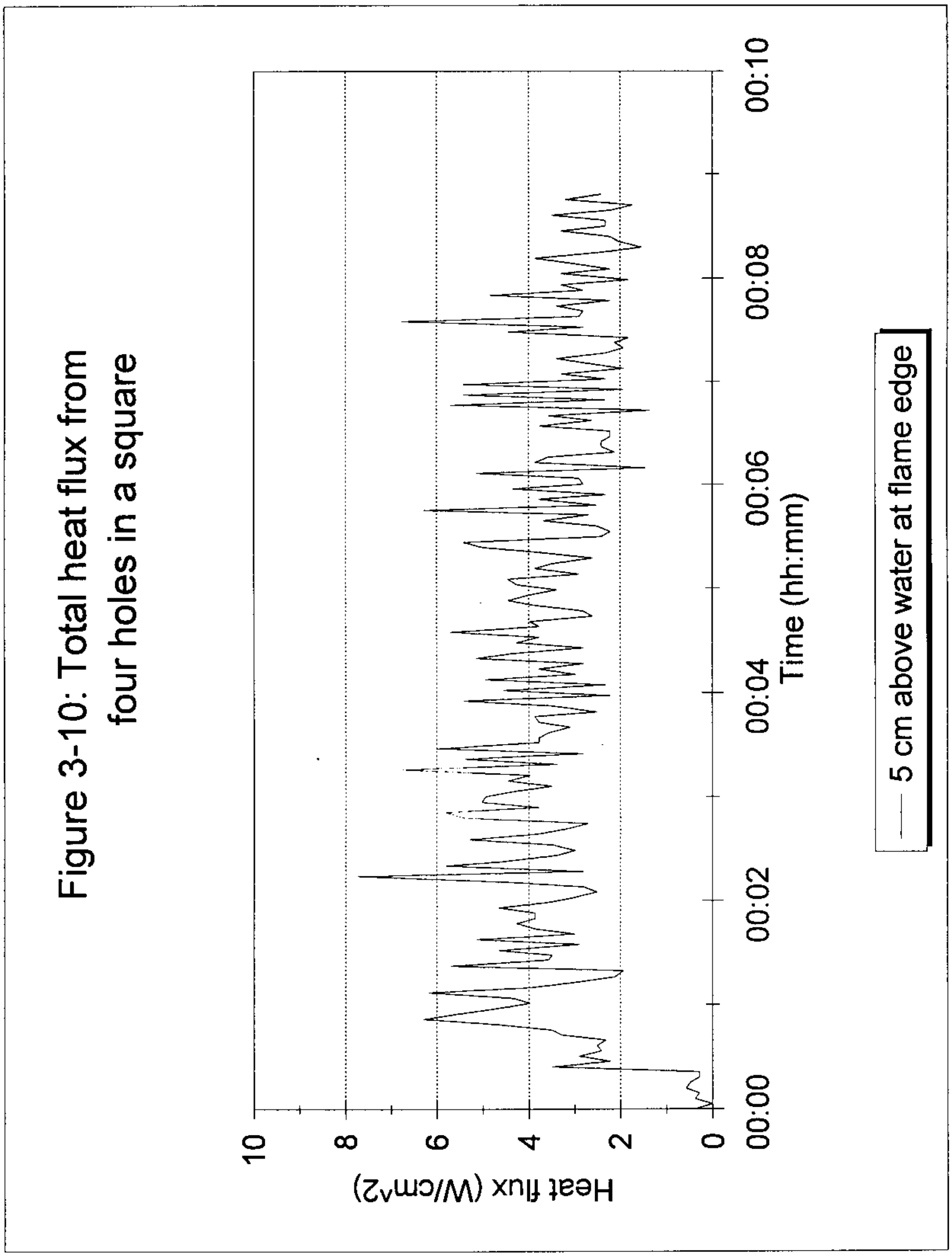


Figure 3-10: Total heat flux from four holes in a square

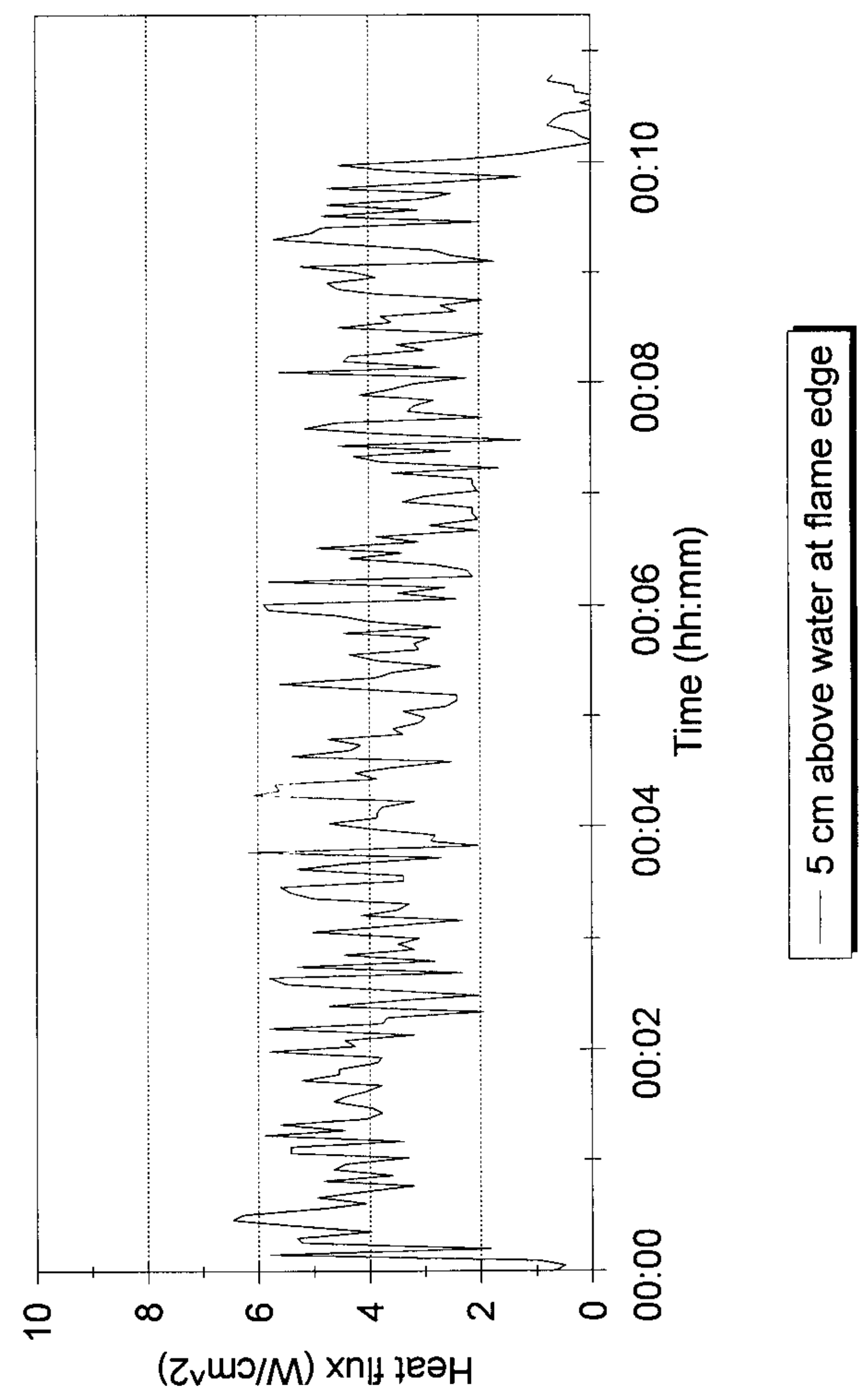


Figure 3-11: Total heat flux from five holes in an "X"

and current. The current was generated by an electric trolling motor, rated at 24 lb. thrust, installed about 1 m from the bubbler. The current moved the bubbles about 5 cm downstream, but had no other measurable effect on the flame. The waves measured 10 cm in height, with a 2 s period. The waves expanded and contracted the flame region as they passed through, which resulted in some surging in flame height at the same frequency as the waves.

Table 3-8: Results of small-scale burns with four holes in a square and three cylinders

Elapsed Time (min)	Line Pressure (kPa)	Total Flow Rate (g/s)	Flow Per Nozzle (g/s)	Total Heat Release Rate (kW)
1	130	4.78	1.20	239
3	110	4.36	1.09	218
5	89	3.94	0.99	197
7	69	3.43	0.86	43
8	62	3.26	0.82	41

Table 3-9: Results of small-scale burns with five holes in an "X" fed by four cylinders

Elapsed Time (min)	Line Pressure (kPa)	Total Flow Rate (g/s)	Flow Per Nozzle (g/s)	Total Heat Release Rate (kW)
1	134.4	5.77	1.15	289
3	110.3	5.15	1.03	258
5	93.1	4.63	0.93	232
7	82.7	4.41	0.88	220

Based on the small-scale burns, it was decided that the "X" configuration provided a good flame size and heat flux for the large-scale tests. The flow rate for the "X" configuration tests had been a little low and an increase to 2 g/s per hole seemed reasonable. It was felt that this would produce an acceptable heat flux with little smoke. The spacing of 40 cm between holes in underwater pipes worked well in terms of overlap between the bubble plumes, producing a continuous flame base. Based on this it was decided that the pipes and holes in the final bubbler system would be spaced according to Figure 3-12. The design of this bubbler is discussed next.

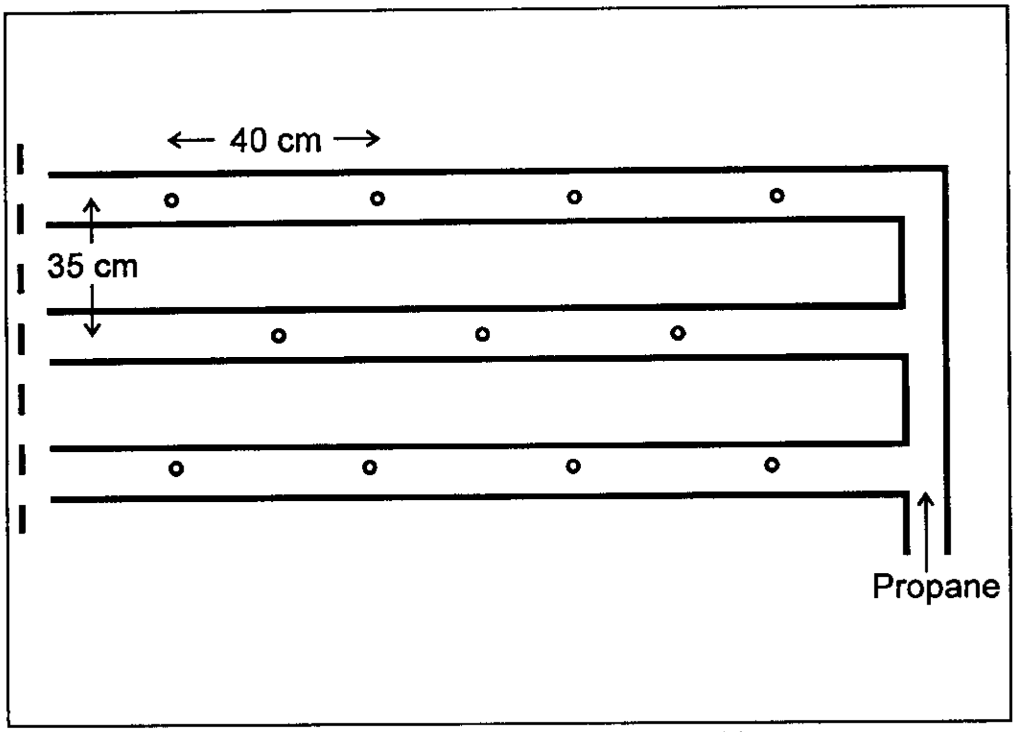


Figure 3-12: proposed hole spacing for full-scale bubbler

4. Bubbler System Design And Shakedown Tests

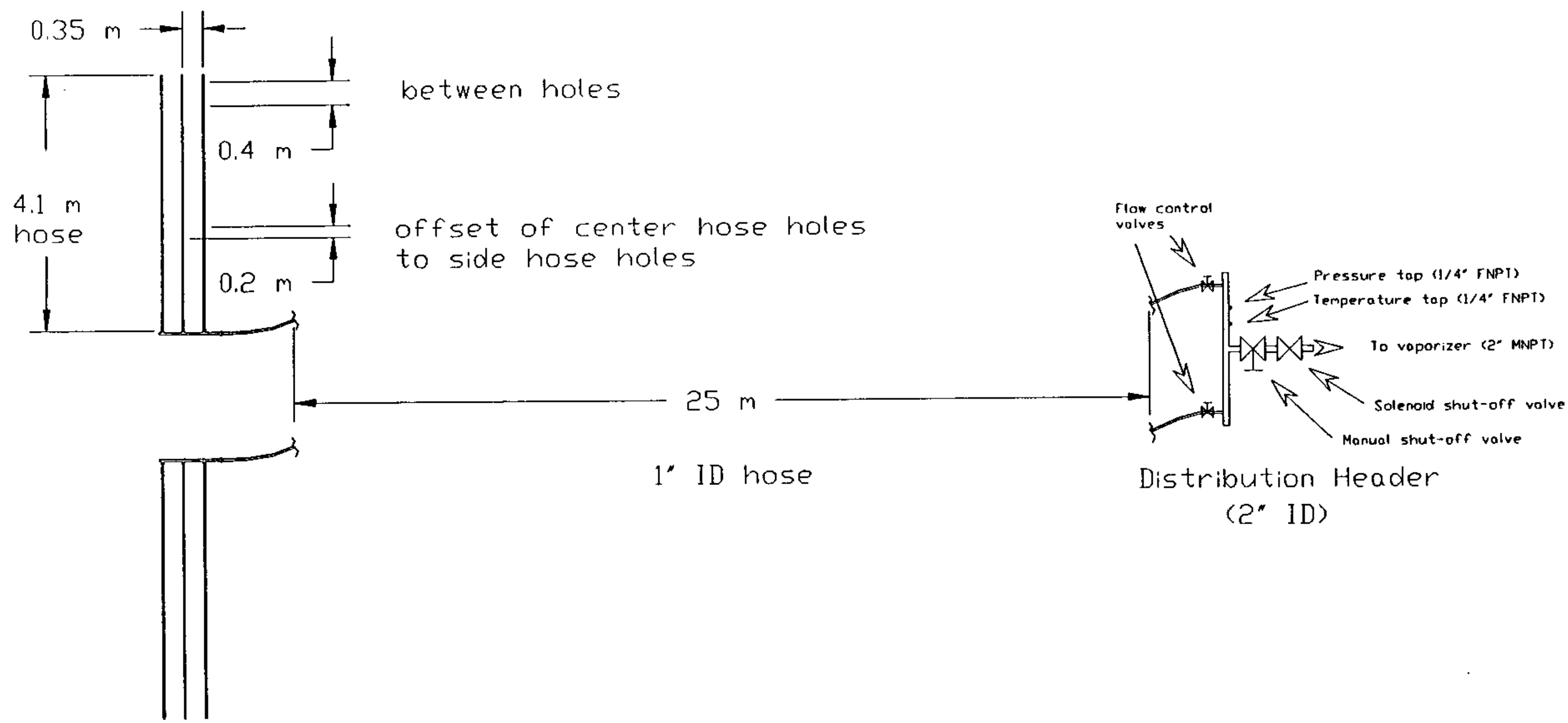
This part of the project involved design of the underwater gas bubbler system, and the gas supply, ignition and control system for the fire tests.

4.1 Propane Gas Underwater Bubbler System

The purpose of the bubbler system was to provide heat flux from a continuous flame area along a length of fire-resistant oil containment boom. The heat flux was to be equivalent to that produced by a burning crude oil slick. The bubbler system had to maintain a fixed position (in both depth and separation) and a stable bubble plume configuration relative to the test section of boom while it was exposed to waves and current. The system also had to be safe to operate, simple to control, easy to shut off in an emergency, be an approved gas burning device, and generate no visible emissions.

Based on the results of the lab investigations described in Section 3, gaseous propane was selected as the fuel source to allow for the maximum possible control. A mathematical flow analysis was used to determine the sizing of the bubbler system. The details may be found in Appendix 2. The basis for this analysis was the need to provide 2 g/s of gaseous propane from a series of holes, in an "X" configuration, submerged about 50 cm (18 in.) underwater. The flames generated were to cover an area approximately 1 m wide directly against the test section of the boom along an 8 m length.

A flexible, underwater propane bubbler, made in two units, each with its own 2.5-cm (1-in.) feed hose was designed. A schematic is given in Figure 4-1 and the completed unit is shown in Figure 4-2. Each underwater unit was made of three sections of 4.1 meter long, 2-cm (0.75-in.) i.d. hose connected to a 2.5-cm header pipe. The header pipe was fed from a 2.5-cm (1-in.) hose connected to a distribution header mounted on the propane vaporizer at the side of the tank (see Figure 4-3). The three 2-cm i.d. hoses were held parallel, 35 cm apart, and had 3-mm holes



Bubbler Assemblies
- 1" ID headers
- 3/4" ID hose
- 3 mm holes on 40 cm centers
- hoses spaced 35 cm apart
- holes in center hose offset 20 cm

FIGURE 4-1

Bubbler and Propane Distribution	
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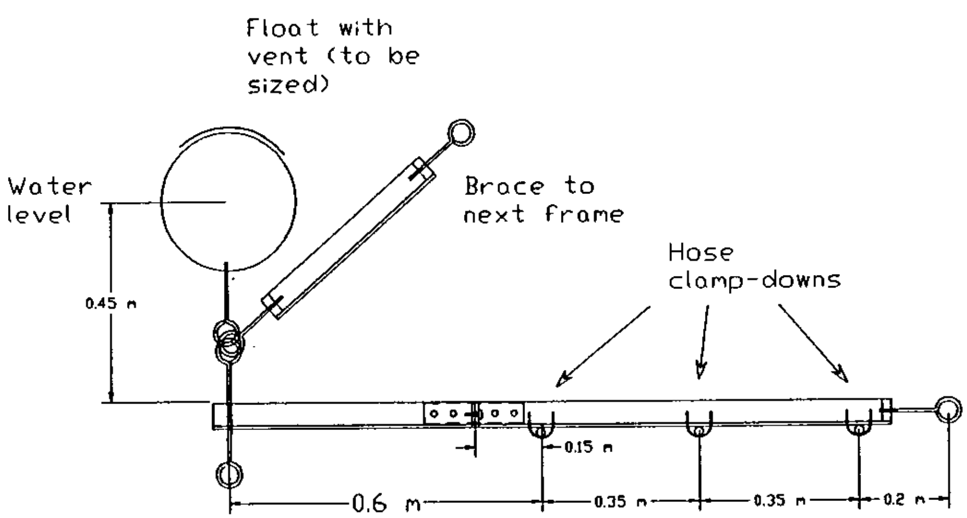
September 18, 1996	Drawn by: Jake Morrison

in their underside spaced 40 cm apart. The holes in the center hose were offset 20 cm from those in the side hoses to create the "X" configuration.

The three 2-cm hoses were held in place using a framework of aluminum bars (see Figure 4-4). One end of each of the aluminum bars was connected to the ballast/tension chain at the bottom of the skirt of the boom. A hole was cut in the chain pocket fabric to expose a link and the aluminum bar was attached to the exposed link using a snap connected to an eye attached to the end of the bar. This allowed the frame to pivot while attached to the boom skirt. The other end of the frame was supported by metal floats connected by rings and snaps so that it would freely follow the waves. Four frames held each bubbler unit; the 2-cm hoses were clamped at the design separation distances to the bottom of the frames using "U" bolts. One set of frames was built such that the other could be added to it to make a 2-m wide flame. The spacing between floats was maintained by braces between the float connection point on adjacent frames. Specific construction details may be found in Appendix 3.

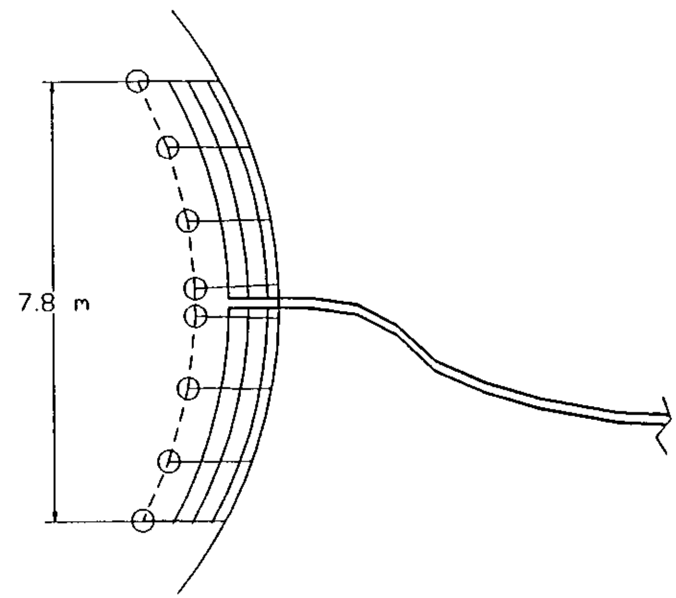
The two bubbler units were designed as mirror images so that, when deployed, the header pipes at the end of each unit would be next to each other in the center of the bubbler system. This simplified the deployment of the 2.5 cm feed hoses that supplied propane from the tank-side vaporizers. Each 2.5 cm feed hose from the side was ballasted with short lengths of steel reinforcing bar so as to remain underwater at all times.

The propane supply system consisted of a 6000-L storage tank (Figure 4-5) that fed liquid propane through steel pipe to a bank of three vaporizers (each with a nominal propane supply rate of 2.3 MW or 8 million BTU/hr) connected in parallel. The vaporizers supplied gaseous propane through regulators at 140 kPa gauge (20 psig) to a 5-cm (2-in.) pipe. A 5-cm ball valve at the end of this pipe controlled the flow of propane to the distribution header (see Figures 4-1 and 4-2). From here the flow to each bubbler unit was controlled by two 2.5-cm (1-in.) ball valves. Taps were also provided in the distribution header for a pressure transducer or gauge, and a thermocouple.



A Bubbler Frame

- Approx. 2" x 1" aluminum angle
- Welded end piece with 5/16 hole for boom attachment
- Self-closing hook on threaded shaft for boom attachment.
- Jointed float attachment rod with ring on end for weights
- Four of the frames made in two pieces to attch to the other four frames to provide for six sparger hoses wide by 4 m length



Framing Layout

FIGURE 4-4

Gas Bubbler Framing

An aluminum angle with metal float, self-closing boom attachment and gas hose clamps. Four of the eight frames break down for attachment to the other four frames for width doubling.

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An ignition pilot light was provided on each bubbler unit. This consisted of 1 m of 1.3-cm (0.5-in.) copper pipe in an L-shape clamped to an aluminum frame such that the end of the copper pipe extended above the water surface (see Figure 4-2). The copper pipe had many small (1.6-mm) holes drilled in it, both above and below the waterline, to ensure a steady flow of propane in wave action. The copper pipe was wrapped in Fibrefrax refractory batting to diffuse the propane flow from the holes and provide a large, stable flame in wind. Each igniter was independently fed propane from a 9-kg (20-lb.) propane cylinder at the side of the test tank. The pilots were manually ignited prior to each test.

The underwater propane bubbler was constructed to code by International Code Systems of Markham, ON and connected to the propane supply system by ICG Propane of Toronto, ON. The system met all the regulatory requirements for an outdoor propane burning device. For safety, a technician attended the valves located on the vaporizers for the entire duration of each burn test. As well, propane gas detectors with audible alarms were placed at all four corners of the tank.

4.2 Bubbler Shakedown Test

A shakedown test of one of the bubbler units was conducted to assess the shape and stability of the flames produced. One end of the bubbler was attached to a weighted wooden spar suspended beneath two 55-gallon steel drums held at the appropriate position in the tank using wire cables (Figure 4-6). The pilot was lit from a small boat using a propane soldering torch attached to the end of a metal pole (Figure 4-7) and then the propane supply was turned on (Figure 4-8). The propane pilot and the bubbler system functioned well in both calm conditions, and with waves and current. The flames generated covered an area of the water surface approximately 4 m x 1 m, and were approximately 1 to 2 m high. The flame burned very cleanly and produced no visible smoke. The flame radiation level at the side of the tank was quite low; it was just detectable on bare skin. The flame did not seem to be adversely affected by either waves or current, although the current did move the flame back behind the supporting drums. This was presumably in response to the current drag on the hoses, aluminum angle and wooden spar. The framing and bubbler system suffered no visible damage from the test, and appeared in perfect working order afterwards. The pilot assembly needed to have a subsurface float installed to help it remain upright. The valving system on the vaporizer train allowed quick and positive control and shut-off for the flame from the side of the tank.

5. Large-scale Test Methods And Draft Protocol

This section describes the equipment and techniques used to subject a section of fire boom to the test protocol. It begins with a summary of the protocol followed by a description of the boom used for the tests. This is followed by a discussion of the methods used to: i) test the boom's durability in large waves prior to exposure to flames; ii) test the boom in waves, flames and current simultaneously; iii) retest the boom's durability in large waves after exposure to flames; and finally, iv) test the booms ability to contain thick slicks of low viscosity oil.

5.1 Test Protocol Summary

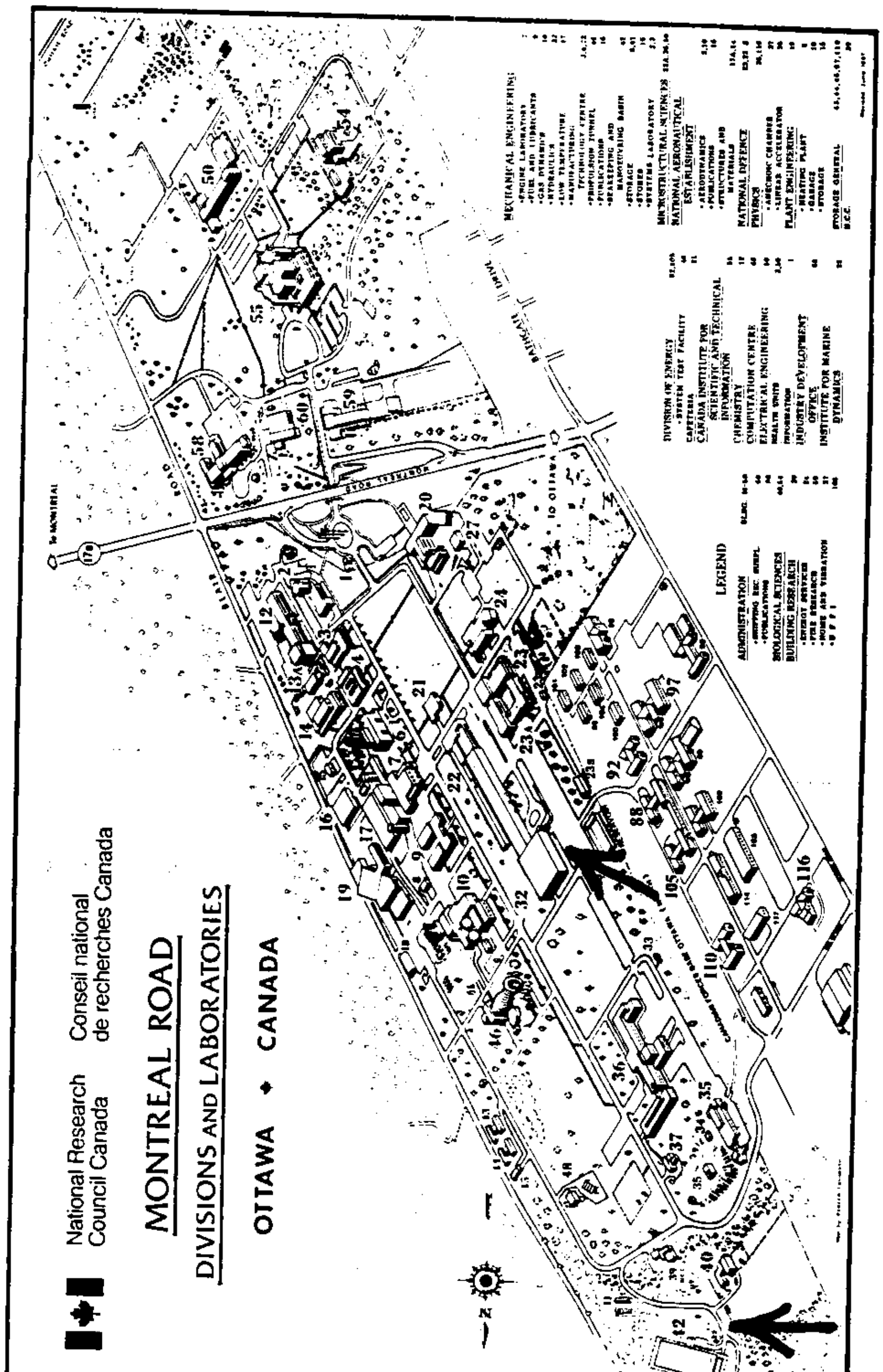
The test protocol involved four discrete stages, comprising: a pre-burn wave stress test; burn tests in waves, current and flames; post-burn wave stress tests; and, thick oil containment tests. A complete draft test protocol, including detailed procedures, may be found in Appendix 4.

The tests were conducted at two locations on the Montreal Rd. Campus of the National Research Council of Canada (NRC) in Ottawa (see Figure 5-1). The Wave Research Flume, where the wave stress tests were carried out, is located in Building M-32, the site of the Canadian Hydraulics Centre (CHC). The static tank for low-viscosity oil containment testing was also to be located there. The Outdoor Maneuvering Basin (Building M-42), site of the wave/flame tests, is located on the northern edge of the campus.

5.1.1 Pre-burn Wave Stress Test

The pre-burn wave testing involved stressing the fire boom in large waves in CHC's indoor Wave Research Flume (WRF) for a period of two hours. The boom was installed longitudinally in the WRF and tensioned by a winch (see Figure 5-2). The tension load imposed was to simulate that expected for a 150 m (500 foot) length of the boom deployed at sea in 1 m waves in a 0.25 m/s (0.5 knot) current. Short-period waves about 1 m high were to be generated in the

Figure 5-1 location of tanks (NRC map)



WRF and used to accelerate axial bending and flexing of the test boom and its refractory fabric, as would happen to a real boom over a much longer time period.

After the test, the boom section was extracted from the WRF and its sacrificial plastic covering carefully removed so that the internal, fire-resistant components could be examined non-destructively. Removal of this covering would not affect the subsequent performance of the boom, since the cover is intended to burn up on exposure to flames. Particular attention was paid to the appearance of the refractory material and structural members, and the presence of any loose fibres inside the plastic covering.

5.1.2 Burn Test in Waves and Current

Figures 5-3 and 5-4 show the general layout of the test equipment in the Outdoor Maneuvering Basin. This is described in more detail in a later section. One 15-m section of fire-resistant boom (see below for details) were placed in the middle of two 15-m (50-ft) sections of conventional containment boom to form an overall boom length of 45 m (150 ft). Flames were generated along the middle 8 m (25 ft) of the fire boom. The width of the flames was approximately 1 m (3 ft). In general, the protocol was to subject the test section of boom to cycles of a combination of flames, waves and current of one hour duration, followed by one hour of wave and current action with no flame. On completion of these tests, once a full 6000 L of propane had been burned, the boom was removed from the tank, inspected and returned to the WRF.

5.1.3 Post-Burn Wave Stress Test

This test involved stressing the fire-resistant boom again in large waves in the WRF for a period of two hours. The boom was re-installed longitudinally in the WRF and tensioned by a winch as described above. The test conditions were as described for the pre-burn stress test. After this test, the boom section was extracted from the WRF and examined carefully. Particular attention was to be paid to the appearance of any visible refractory material and structural components.

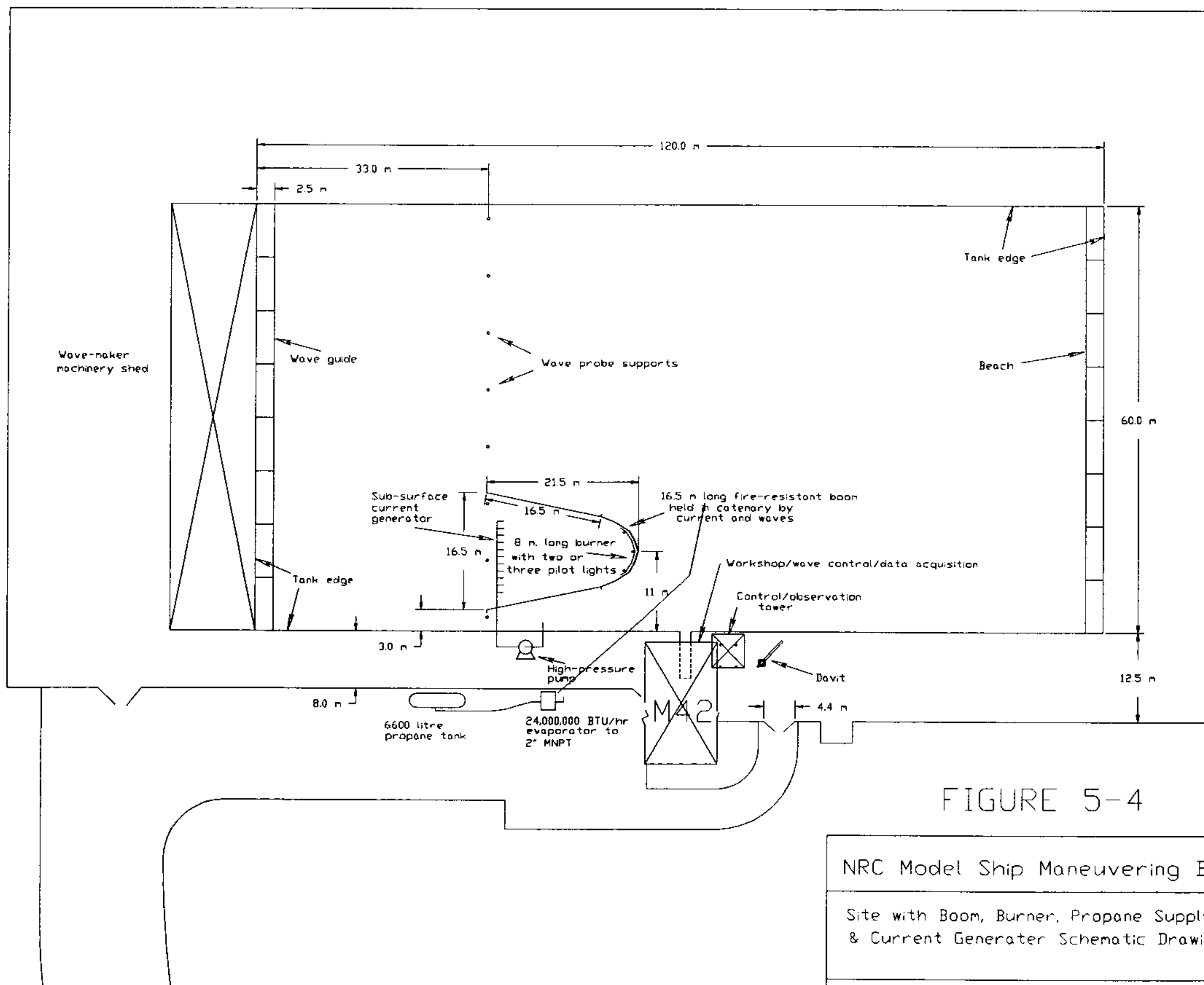


FIGURE 5-4

NRC Model Ship Maneuvering Basin

Site with Boom, Burner, Propane Supply & Current Generater Schematic Drawings

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5.1.4 Static Thick Oil Containment Test

This final test was to involve assessing the capability of the boom to contain thick slicks of low viscosity oil, simulating a layer of burning oil in the pocket of a boom under tow. A 4.5-m (15-ft) diameter 1-m (36-in.) deep portable tank was obtained for this portion of the testing. It was to be set up inside the CHC. A section of the test boom, consisting of three float lengths, that had been exposed to the propane flames was to be clamped in a triangle and floated in the tank. A thick layer of low viscosity, dyed vegetable oil was to be poured onto the water surface contained by the three sections and the leak rate of oil through the boom measured by monitoring the decrease in contained slick thickness (as measured with a "cookie cutter" sample) over time.

Due to the degradation of the test section of boom over the first three stages of the test protocol, this final test was not employed. Instead, at the end of the post-burn wave stress test, dye was placed on the water in the WRF on one side of the boom and blown against the boom to check its permeability.

5.2 The Test Boom

The section of fire-resistant boom utilized for this test (Figure 5-5) was one that had been deployed at the Newfoundland Offshore Burning Experiment (NOBE - Fingas et al. 1995), but never exposed to flames. The section used had been stored by the Canadian Coast Guard (CCG) in St. John's, NF in a sealed ISO container since the NOBE trials. The CCG kindly donated it for use. Using this boom offered a unique opportunity to benchmark the test protocol: the boom being tested had failed during a full-scale *in situ* burn at sea in a known manner after an accurately measured period of exposure to flames and waves in a well-documented environment. On receipt of the boom from St. John's, a section was refurbished; the connectors at each end had been damaged and were replaced. At one end, the fabric and stainless steel mesh near the connector had been torn and one of the float units had come out of the segment. As such, the connector was re-attached to the segment, but with only one floatation unit inside. This reduced along the centerline of the 2 m wide, 2 m water depth, 97 m long Wave Research Flume inside CHC's laboratory, between vertical posts spaced 17 m (55.8 ft) apart. Figure 5-6 shows the boom being prepared for testing. The up-wave end of the boom was attached to the first post, located 45 m from the wave machine, by means of a cable to a load cell, pulley and winch system (Figure 5-7). The down-wave end of the boom, 62 m from the wave machine, was attached to the second post by a shackle. A winch near the load cell enabled the floating boom to be stretched and a pre-tension to be set.

A 19 m long wave absorber at the far end of the flume, made up of 28 vertical sheets of expanded metal of varying porosity and spacing, absorbed over 95% of the energy of the waves arriving at the end of the flume. The floating boom itself represented a small enough blockage that the waves retained much of their progressive nature, rather than becoming simply a series of standing waves. As a result, there was a net transport velocity near the surface created by the waves which caused tension in the boom considerably greater than the pre-tension.

Figure 5-8 shows the boom being subjected to regular progressive waves with a period of 3.66 seconds, and a wave height of 0.8 m (2.6 ft). The boom was exposed to waves for a total of 2 hours during this stage of the test protocol. The wave generator consists of a computer-controlled wave board driven by a double hydraulic actuator system which can continuously vary the ratio of the motion of the top of the wave board relative to the bottom from full flapper to full piston mode. This enables the correct reproduction of kinematics for deep water as well as shallow water waves. A capacitance-wire type wave probe was located 19 m from the wave board. The calibration for this probe may be found in Appendix 5, and is representative of the calibration of the wave probe also used in the outdoor wave basin for the burn tests. A Neff A/D converter and VAX computer data acquisition system sampled the wave probe and load cell outputs at 20 samples per second.

The boom tension was measured by a 8,900 N (2,000 lb.) capacity model 1110-AF Interface pancake load cell. Its calibration curve is in Appendix 5. (This calibration is also typical of the calibration of the two 22,000-N (5,000-lb.) load cells used in the outdoor basin burn tests).

After the test, the sacrificial plastic outer covering of the boom was removed, exposing the fire-resistant fabric, wire mesh and refractory material (see Figure 5-9), and examined for damage.

5.4 Methods used for the Test in Waves, Flames and Current

The fire boom was next placed in the basin and the propane bubbler assembly was attached to the chain in the skirt along the middle 8 m (25 ft) of the fire boom. The fire boom section was then attached to two 16.5-m sections of conventional boom in a catenary, and exposed to flames, waves and current in the Outdoor Ship Maneuvering Basin at the National Research Council in Ottawa. Figures 5-10 to 5-15 show the basin, setup and testing. The basin is 3.3 m (10.8 ft) deep, 61 m (200 ft) wide, and 122 m (400 ft) long. A pneumatic wave machine on one end uses eight blowers and a system of valves to force air into and draw it out of inverted chambers near the water surface (see Figure 5-10). This forces the water surface to fall and rise, and waves to be propagated from beneath the chambers. Both period and amplitude can be controlled, and sinusoidal waves up to 0.6 m (2 ft) in height can be generated.

At the other end of the basin is a short sloping perforated beach/absorber. It is very inefficient for long or large waves, and as a result, after a few minutes, standing waves start to be set up in the basin due to reflected energy from the end wall. These waves can easily exceed a meter in height at certain frequencies. The envelope of wave heights in the basin for long duration tests has nodes and anti-nodes, such that at any one location in the basin, one may encounter only small waves, only large waves, something in between, or something with slowly varying amplitude. In other words, measurements of waves at any one location in the basin are not necessarily representative of the average waves in the basin. Early shakedown trials determined that, for these boom tests, waves of nominal 2.5 second period and 0.6 m amplitude would provide sufficient motion and flexing of the boom for the purposes of the protocol demonstration.

A 1 m long capacitance wave probe was mounted on an existing post 33 m from the wave generator, and 6 m upstream of the 16.5 m wide opening to the boom (see Figure 5-11). A current generation system was installed by crane just at the mouth of the boom. Figures 5-11 and 5-12 show the 6 m long rig which consists of three 3 inch diameter pipes each fitted with 18 nozzles. The top bank of nozzles was 0.4 m below the still water surface, and the next two rows were 0.2 and 0.4 m respectively below the top row. The flow to each row was controlled by a gate valve located near the 25 kW, high pressure pump. Two 450 kg concrete lintels were fitted to the base of the frame to resist the overturning moment caused by the reaction force of the jets from the nozzles. At maximum flow of over 100 L/s, (which was not needed for these tests), a reaction force of 66 kg could be produced from the 54 nozzles, each 1.3 cm (0.5 in.) in diameter discharging 2 L/s. As these jets expand, they entrain surrounding water and create a current approximately 6 m wide and 1 m deep, in the region of the boom pocket. At full flow from the pump, a current of 0.6 m/s was observed. Unfortunately, this magnitude of current dampened the wave height and boom motions near the pocket, and it was decided to carry out most of the testing with reduced flow to the nozzles such that the current was only 0.2 m/s. This was sufficient to maintain the shape of the deployed boom catenary (Figure 5-13). In fact, even with the current shut off, the waves alone were found to generate a net transport current sufficient to maintain the catenary. Under wind conditions opposing the waves, it is possible that the catenary might not have been maintained. However, the test protocol required the winds, if any, to be with the waves in order to angle the flames against the boom material. In future tests, the current generation system may not be necessary.

Each end of the boom was attached to a 22,000-N (5,000-lb.) model 1110-AF Interface load cell and float, and a 1-cm (3/8-in.) diameter wire rope used to moor the boom to the end wall of the basin. As well, a 3-mm (1/8-in.) diameter cable was stretched across the basin at right angles to the current and used to keep the boom ends from wandering laterally, but free to move longitudinally under the action of waves and current. A test showed negligible effect of this cable on the loads measured by the load cells. Again, data acquisition from the load cells and wave probe was done using a Neff A/D converter and VAX computer sampling at 20 Hz. The NRC GEDAP software package was used to acquire, analyze and present the measured data.

The propane supply, distribution and bubbler system was described in Section 4. The flow of liquid propane to the vaporizers was measured using a Dynasonics series 300 ultrasonic Doppler flowmeter (accuracy dependant on fluid; repeatability of $\pm 0.1\%$ FS) with the analog signal displayed on a meter and converted to digital for recording on a PC. A calibration curve for the flow meter with water may be found in Appendix 6. The total amount of propane used was determined from the delivery ticket; the tank was completely drained during the flame tests. The propane flow meter did not function very well, and its data was not used to determine fuel flow. A gauge, in units of percent of capacity, on the propane supply tank was used to estimate the amount of fuel burned for each test run. The delivery ticket from the supplier showed a total of 6117.5 L of propane in the tank; based on the total time the bubbler was operated (always with the valves full open) the average propane flow was 407 kg/hr. The temperature and pressure of the gaseous propane (i.e., downstream of the evaporator) were monitored at the distribution header for the 2.5-cm (1-in.) propane supply lines using the pressure gauge and themocouples described in Section 3.

The total heat flux at the middle of the boom pocket was measured using two Medtherm heat flux transducers, as described in Section 3. A raft, constructed from 6"x 6" lumber and steel framing was used to support the radiometers and thermocouples (Figure 5-14). The transducers were mounted side-by-side, about 15 cm (6 in.) apart approximately 60 cm (2 ft) above the still water surface. The raft was loosely tethered to the boom at one of the vertical stiffeners, with the transducers looking into the flames at a position corresponding to the back side of the boom (see Figure 5-15). The flame temperature was measured using Type K themocouples, also described in Section 3. The signals were carried back to the data acquisition computer (see Section 3 for details) located inside the tank-side building using long leads submerged beneath the water. Cooling water for the heat flux transducers was provided through a plastic garden hose fed from a tap in the building.

A video camera was located in the control tower looking down on the test setup in the basin. Continuous VHS video was taken during all tests for archival purposes. In addition, a hand-held

8-mm video camera was used to document specific activities during the test program, including boom inspections. As well, 35-mm slides and photographs were taken.

For the first two days of testing the boom was exposed to one hour of flames and waves, then one hour of waves alone. The waves were either nominally 0.3 m high with a 1.4 second period or nominally 0.6 m high with a 2.5 second period. This protocol was changed for the last two days of testing to involve approximately two hour burns in waves with no intervening periods of waves alone. During the tests in the basin, propane was burned at an average rate of 13.3 L/min (407 kg/hr) over a water surface area of approximately 8 m^2 to give a power of 5.7 MW (19.3 million BTU/hr) and a unit heat release rate of 0.7 MW/m^2. This was slightly less than the design level of 0.8 MW/m^2. The boom was examined after each exposure to flame.

Figure 5-16 shows the boom flexing in the waves. Figure 5-17 shows the boom in waves and flames. During the periods with no flames, the burned boom section continued to be subjected to flexing and wear. Over a two day period, in excess of 8.5 hours of 0.6 m, 2.5 s waves were run (12,000 waves). On completion of this portion of the testing, the boom was removed from the tank, closely inspected for damage, then returned to the Wave Research Flume.

5.5 Post-burn Wave Stress Test Methods

The burned boom section was reinstalled in the Wave Research Flume and stressed for 130 minutes (2130 waves) in 0.8 m high, 3.66 s waves. Figure 5-18 shows the burned boom being tested in waves. In this post-burn case, it was decided to increase the pre-tension in the mooring to 900 N (200 pounds) before starting the waves. It was anticipated that this would cause greater stresses and damage to the boom material as the tighter boom attempted to conform to the wave surface, and would be more representative of the mooring loads it would be subjected to while being slowly towed in the field. Periodically, the test was paused and the boom re-tensioned to 900 N (200 lb.).

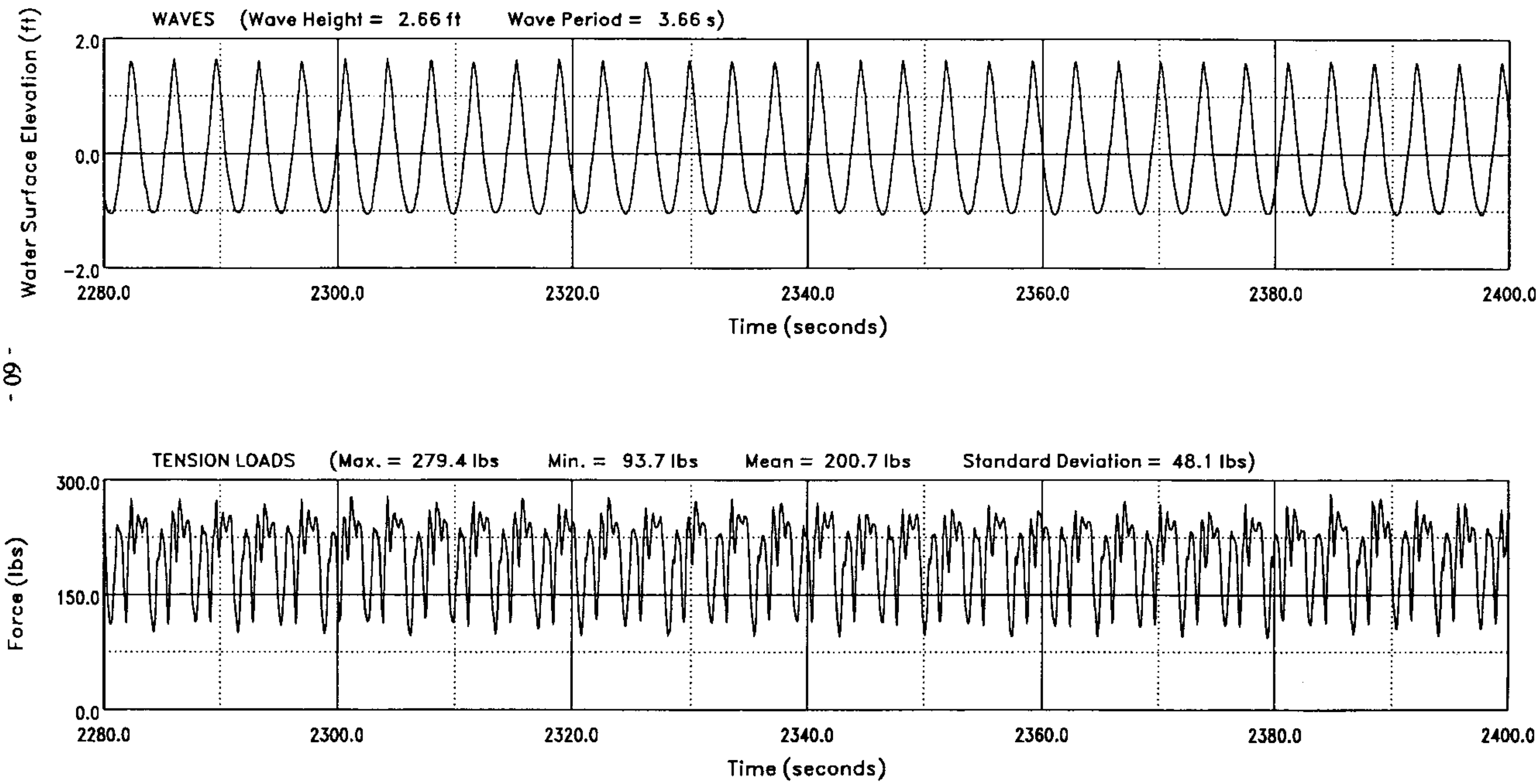
6. Large-scale Test Results And Discussion

This section summarizes and discusses the results of the large-scale tests in the Wave Research Flume and the Outdoor Maneuvering Basin. Full data sets may be found in the Appendices.

6.1 Pre-burn Wave Stress Test

The first test in the protocol involved stressing the fire boom section (with the sacrificial cover intact) in waves in the WRF for 2 hours (see Figures 6-1 and 6-2). A pre-tension of only about 180 N (40 lb.) was applied to the boom section because the posts in the Flume were too close together. The tension loads measured in the wave tests varied from 180 to 2,600 N (40 to 575 pounds), well within the calibrated range of the load cell. The waves were run for 120 minutes. This subjected the boom to 1,970 wave cycles of flexing. Boom tensions in waves varied from a minimum of 360 N (80 lb.) to a maximum of 1,100 N (250 lb.), with a mean of 800 N (180 lb.). Figure 6-3 shows a measurement of the waves, which were quite regular, and the resulting tension loads for a two minute time-select, taken from a longer record. The complete set of records may be found in Appendix 7, including a table listing the characteristics of each run. Examination of the boom after the tests revealed no visually apparent damage. After this, the sacrificial plastic outer covering of the boom was removed down to the water line, exposing the fire-resistant fabric, wire mesh and refractory material (see Figure 6-4). In general, the boom was in good condition. The stainless steel mesh was undamaged, except in an area that had been previously repaired. The refractory fabric material was slightly abraded in a few places (see Figure 6-5), but it was uncertain whether this was as a result of the wave stress tests or from the boom's deployment during NOBE. The internal flotation units were undamaged and still fully contained in their packaging of stainless steel and plastic sheeting cover. The skirt, stiffeners and connectors had suffered no further damage as a result of the wave stress tests.

Figure 6-3: Typical time series results for the pre-burn tests



6.2 Tests in Waves, Current and Flames

Figures 6-6 and 6-7 show the boom tests being conducted in the Outdoor Manuevering Basin. The first day of testing (Nov 6, 1997) involved exposing the boom to 60 cm x 2.5 s waves and 0.2 m/s current for one hour then turning on the propane fire for an additional hour.

Figure 6-8 shows a typical time series output of the waves and the two mooring loads. Note that in comparison to the tests in the indoor Wave Research Flume, which resulted in high tension loads with the boom moored tightly (e.g., up to 2,550 N or 575 lb. for the post-burn test in which the boom was pretensioned to 900 N or 200 lb.), the tension loads on the three-times-longer catenary in the outdoor basin tests are small. This is because it was not possible to apply a pre-tension to the moorings. When the current and/or waves were running, the tension loads only increased to about 90 N (20 lb.), plus or minus 50 N (10 lb.). Even with such low drag loads being created on the boom, the catenary shape was maintained.

The existing current generator setup did have the capability to create higher current and greater drag on the boom, but as previously noted, this was found to cause a significant reduction in wave action and motion of the boom. For this reason, it was decided to operate mostly with the low current to permit more motion in the boom pocket. Appendix 8 summarizes the wave and mooring load results. Only a selection of some of the runs are provided. It can be seen how non-uniform the wave behavior is at the location of the wave probe due to reflected waves.

The propane gas burned very cleanly with continuous, steady flames of 1 to 2 m height over the entire 8 x 1 m area. No visible air emissions were observed. For the hour that the flames were on, the average liquid propane flow rate was 13.3 L/min, or 407 kg/hr, giving a total heat release rate of 5.7 MW (19.3 million BTU/hr), slightly lower than planned. The average propane flow per hole in the bubbler was 1.7 g/s, again slightly lower than the target 2 g/s. The average heat release rate per unit water surface area was 0.7 MW/m^2, compared to 1.76 MW/m^2 for Alaska North Slope crude and 2.34 MW/m^2 for diesel *in situ* fires (McGrattan et al. 1997).

Figure 6-8: Typical time series results for waves and tension loads

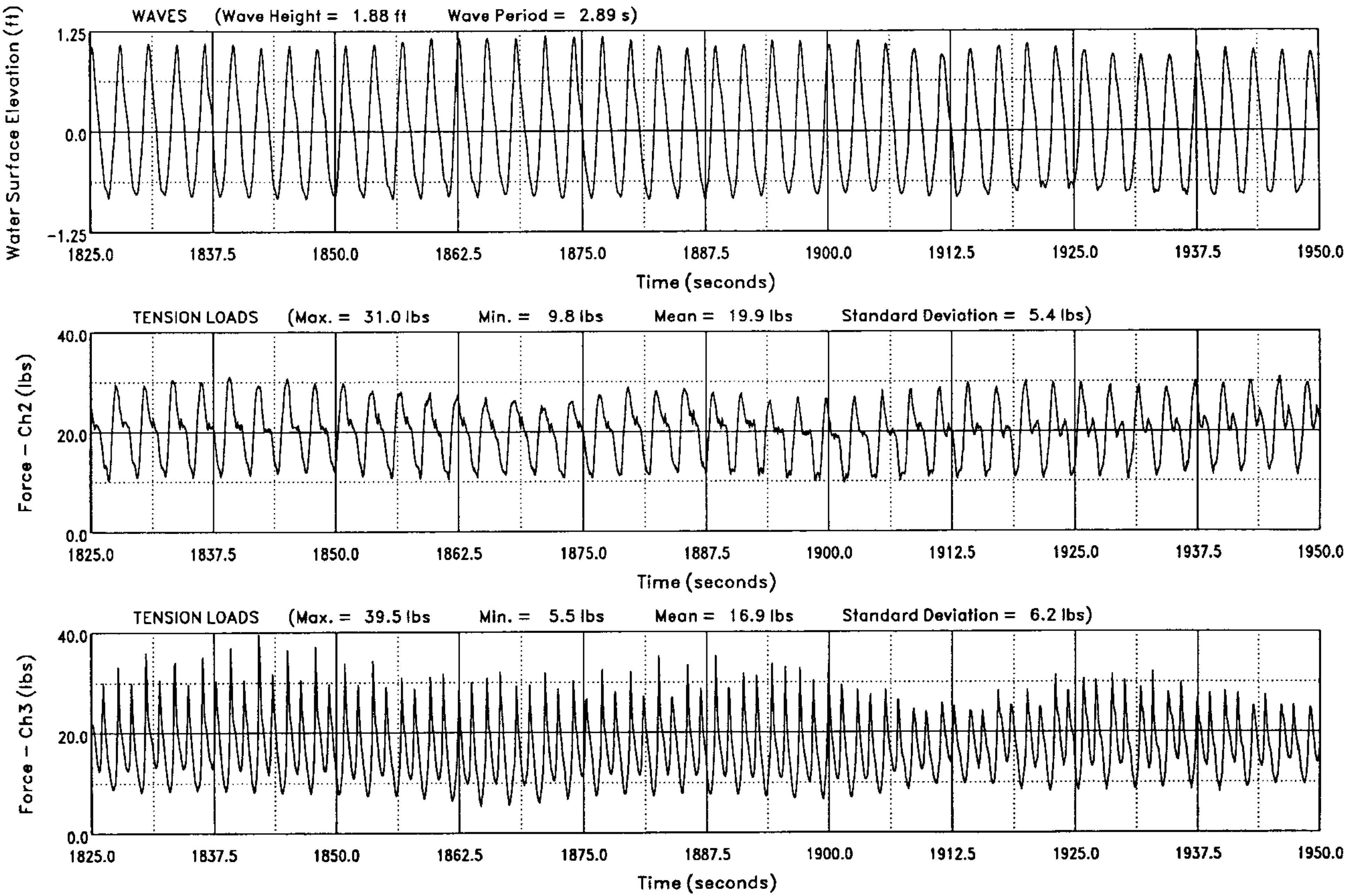


Figure 6-9 shows the output from the two total heat flux transducers, or radiometers, for this first hour of testing in flame. It was apparent that something was wrong with the test setup: the readings swung wildly over a large range and highly negative readings were obtained. It was eventually discovered that this was caused by the data acquisition system making contact with the stainless steel mesh of the fire boom, which was connected by the steel mooring cables, etc to ground. Further evidence of this was the fact that the thermocouples would not read correctly for this run. The instrument raft and its connection to the fire boom were modified for subsequent tests in order to overcome this problem; however, for future tests the heat flux and thermocouple data acquisition system need to be re-designed.

The morning after the test in waves, current and flame, the condition of the boom was visually assessed *in situ* from a small boat. Although there was some charring evident on the surface of the boom facing the fire, the boom appeared to be in good shape (see Figure 6-10), and the next test run was started.

For the second test, on November 7, 1997, the waves were set at 0.6 m x 2.5 s for one hour, then the propane fire was started and run for 61 minutes. For this test, the wind was blowing from the east, toward the wave generator, and angled the flames away from the boom (see Figure 6-11). This resulted in very low heat flux readings from the transducers (see Figure 6-12) and very low temperatures recorded by the one functioning thermocouple (Figure 6-13). This reinforced the necessity for fire boom testing to be conducted with the wind blowing the flames towards the boom. The low heat flux measured also underlined the need to reposition the transducers to midway up the fire side of the boom. As noted above, this would require a redesign of the data acquisition system. About halfway through this test it was realized that the cooling water for the heat flux transducers had not been turned on; this necessitated their replacement and recalibration after this test.

The next day, the boom was reinspected. Significant charring was noted in the areas above the wave splash zone on the fire side of the boom (see Figures 6-14 and 6-15) and some abrasion was noted near the vertical stiffeners.

Figure 6-9: Heat flux for test run 1

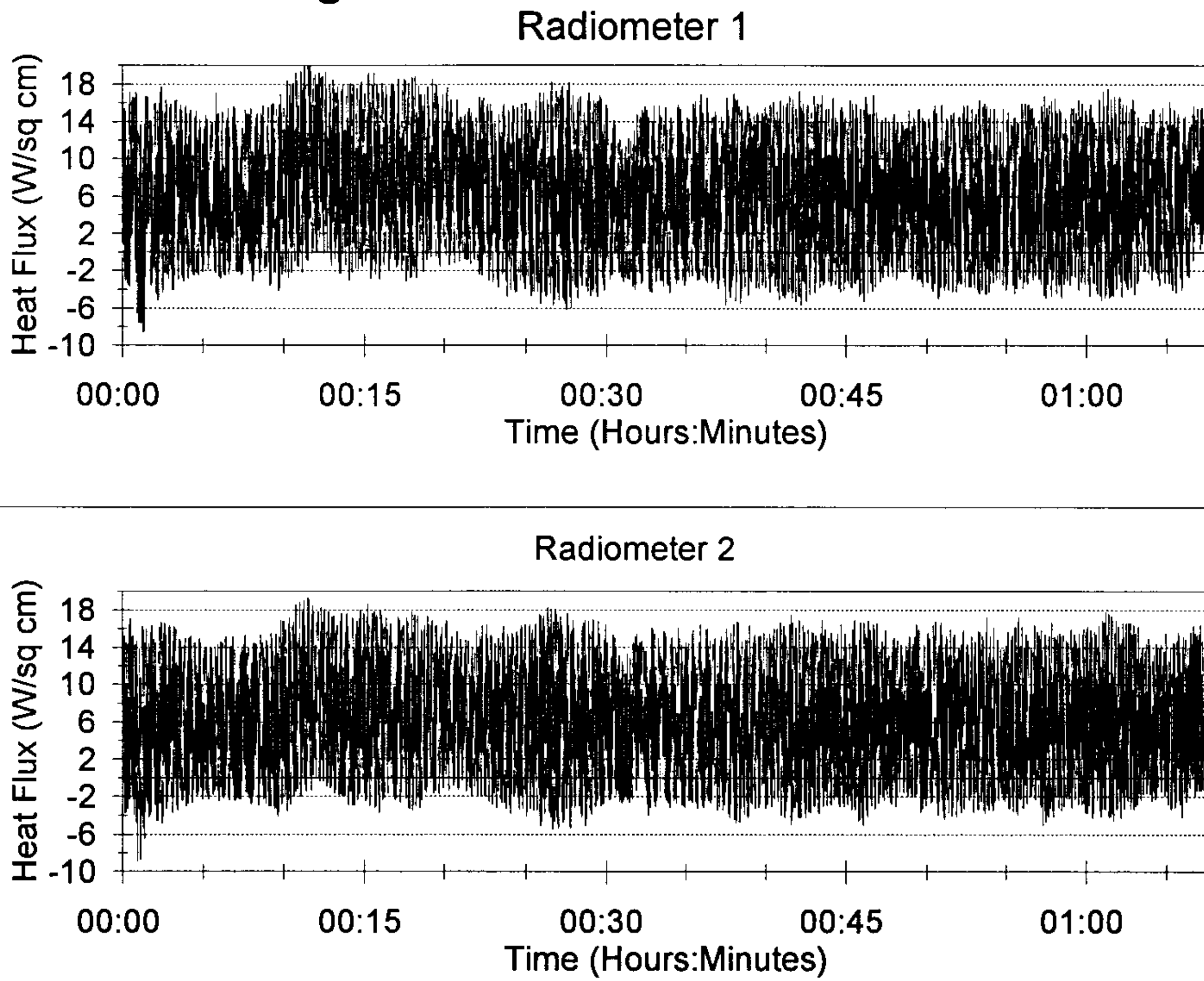
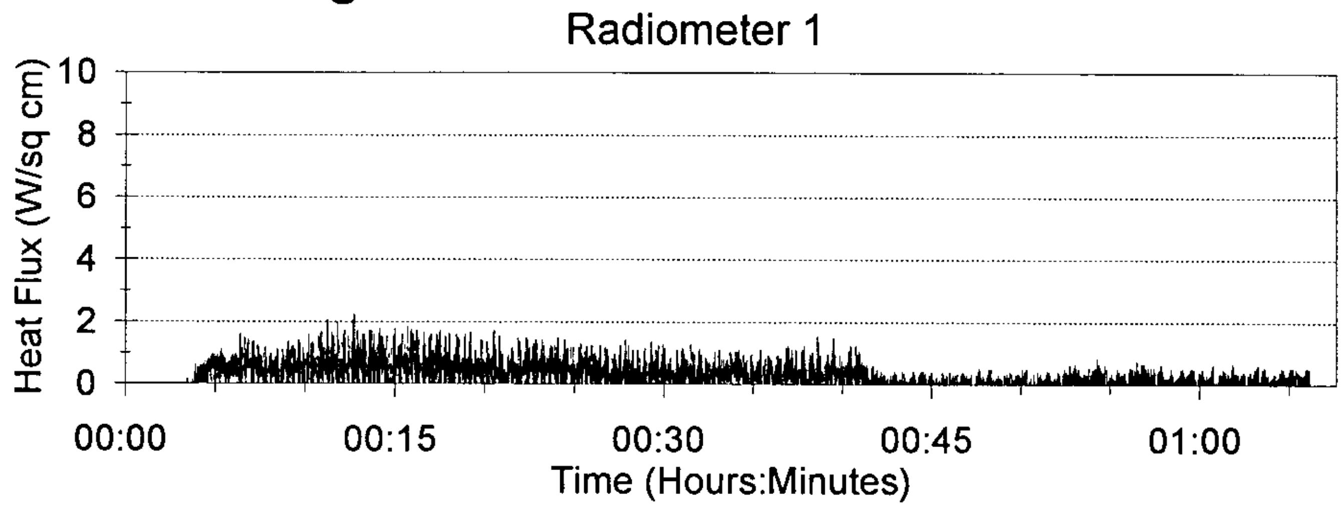


Figure 6-12: Heat flux for test run 2



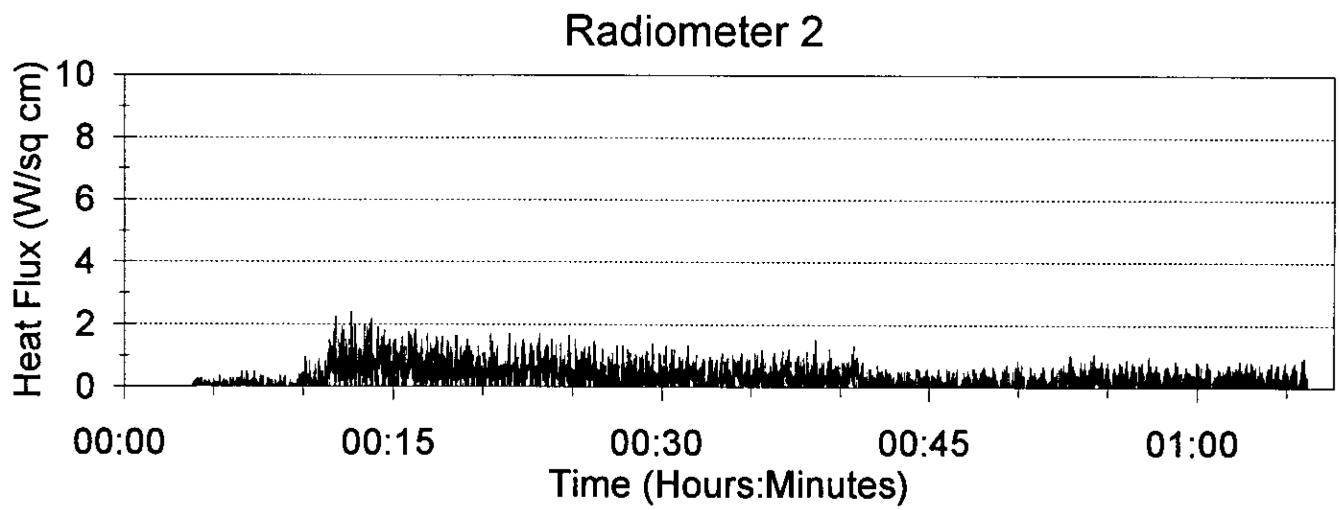
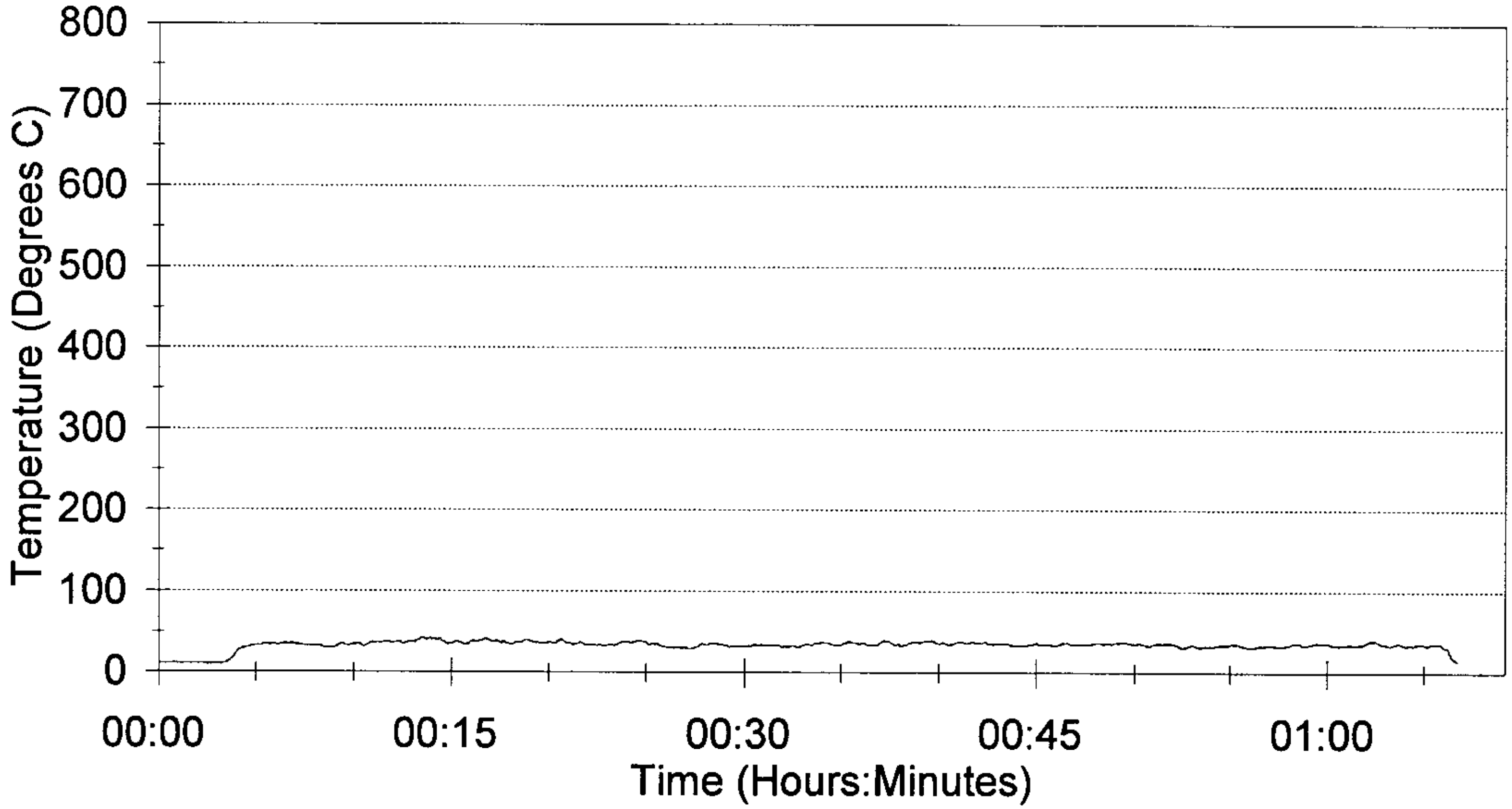


Figure 6-13: Record of temperature above boom for test run 2

Sensors not properly set



On November 8, 1997 two test runs were conducted. In the morning the wave generator was set to produce 0.3 m x 1.4 s waves for one hour. Figure 6-16 shows a short record of these waves. At the end of this hour the propane fire was ignited and the waves increased to 0.6 m x 2.5 s. The heat flux transducer and thermocouple outputs are given in Figures 6-17 and 6-18 respectively. For this run the wind was blowing lightly from the northwest, angling the flames generally across the boom pocket. The transducers recorded heat fluxes ranging from 0 to 7 W/cm^2 (0 to 70 kW/m^2) averaging about 2 W/cm^2 in this situation. The thermocouple temperature ranged from 100 to 800°C. At the end of this test run the waves were shut off to allow replacement of one of the load cells on the boom mooring cables.

After the load cell had been changed the waves were restarted and, in order to make up lost time, it was decided to immediately restart the propane fire. After about 10 minutes of testing, the instrument raft broke free from the boom and data recording was stopped. The test run continued for a full 63 minutes. Figure 6-19 shows the data from the heat flux transducer and Figure 6-20 shows the thermocouple temperature for the first ten minutes of this test. After the instrument raft was reattached, the test was continued for another 103 minutes of burning. The heat fluxes and thermocouple temperatures for this period are given in Figures 6-21 and 6-22 respectively. The winds were still from the northwest for this period, which explains the lower-than expected heat flux readings.

The next day the boom was inspected. The charring had increased and significant abrasion and ablation of the refractory fabric was noted, especially in the vicinity of the vertical stiffeners (Figure 6-23 and 6-24).

The final fire test on November 12, 1997 ran for 85 minutes in 0.6 m x 2.5 s waves, until the propane supply tank was empty. This time the wind was from the west and angled the flames toward the instrument raft. Figure 6-25 shows the output from the heat flux transducers for the final test in flames. In this case the wind was blowing the flames toward the instrument raft, and on occasion the heat flux transducers were briefly immersed in flame. It is evident from Figure 6-25 that the heat flux measured for this test run was higher than for others (discounting the first

Figure 6-16: Typical time series results for waves and tension loads

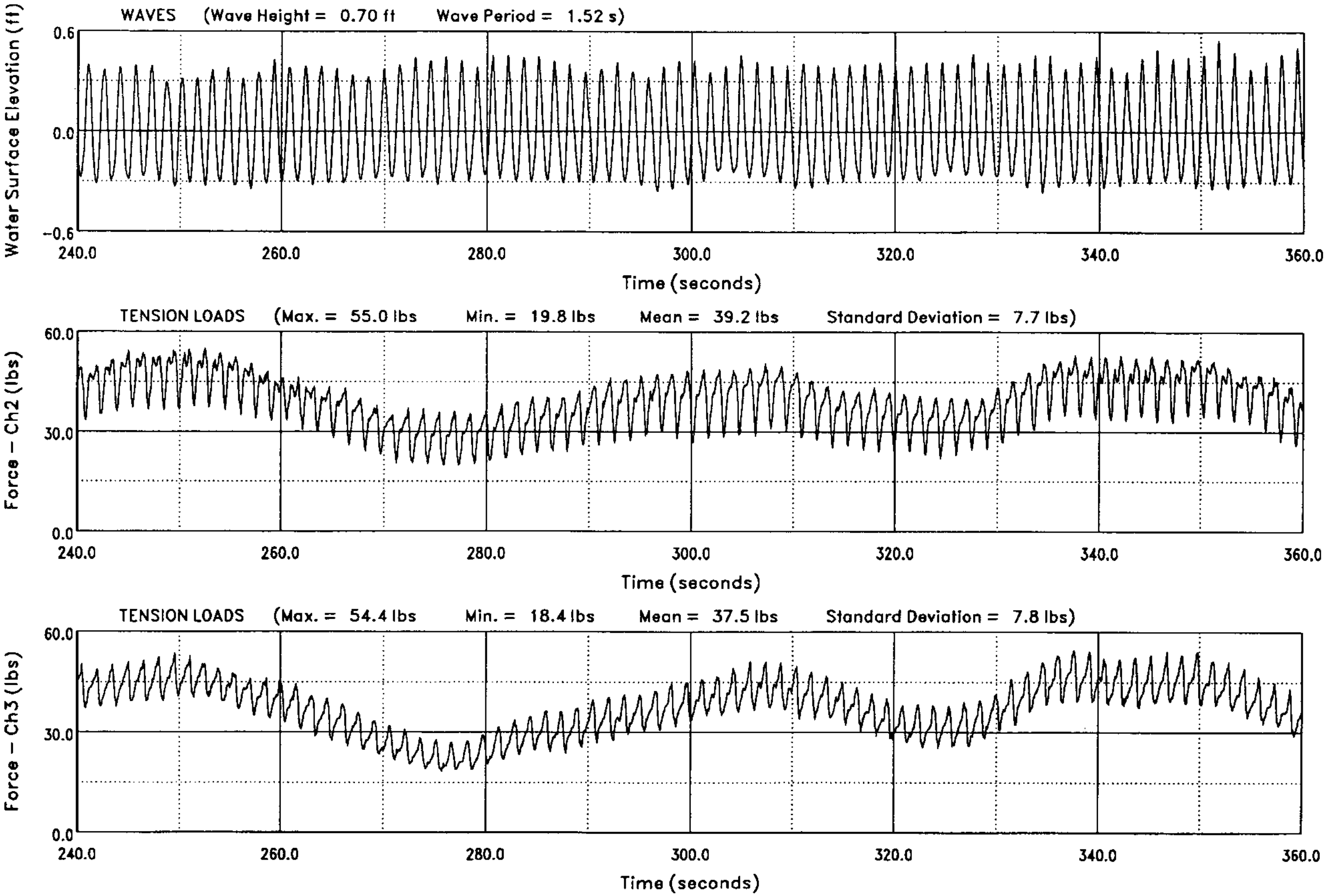


Figure 6-17: Heat flux for test run 3

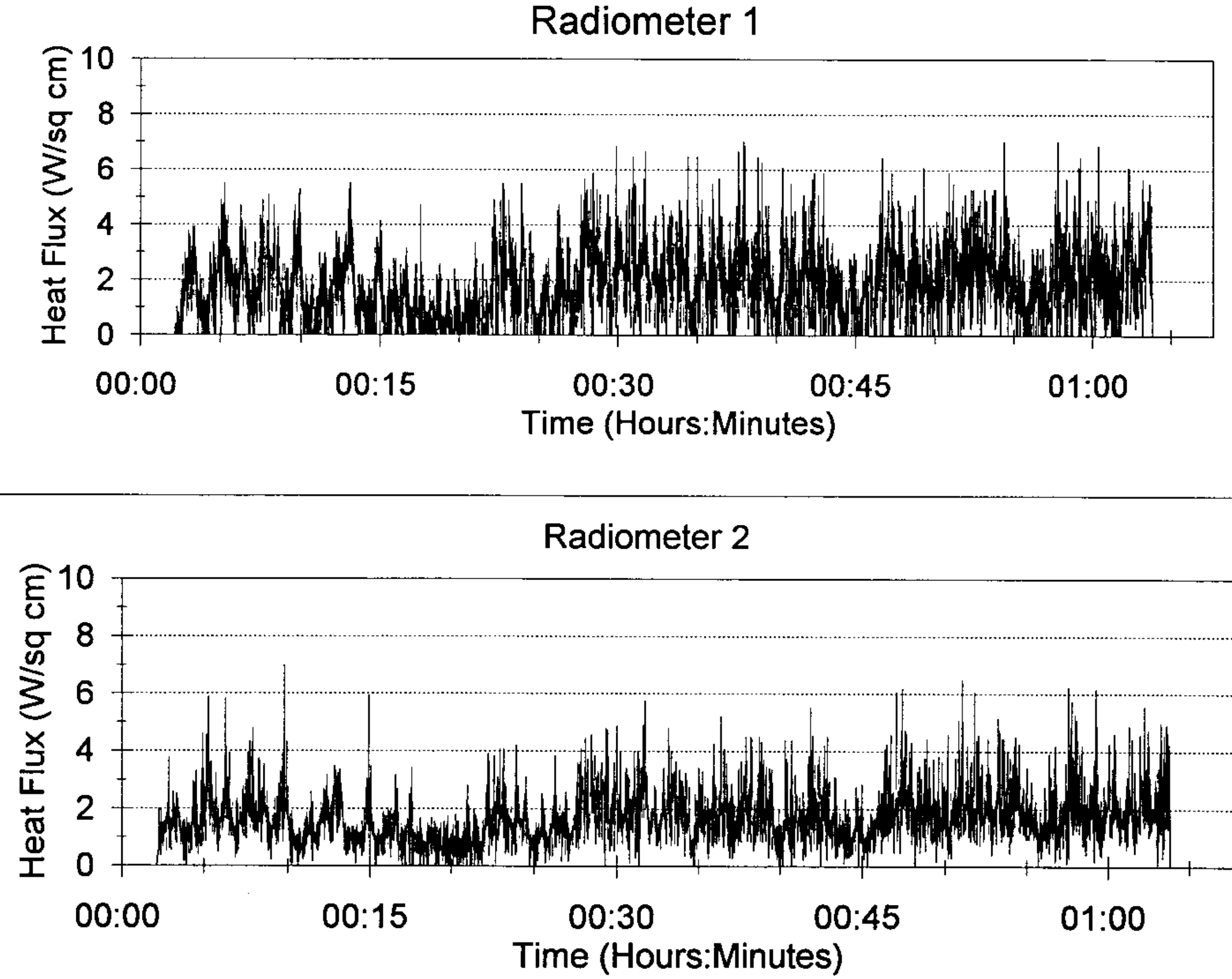


Figure 6-18: Record of temperature above boom for test run 3

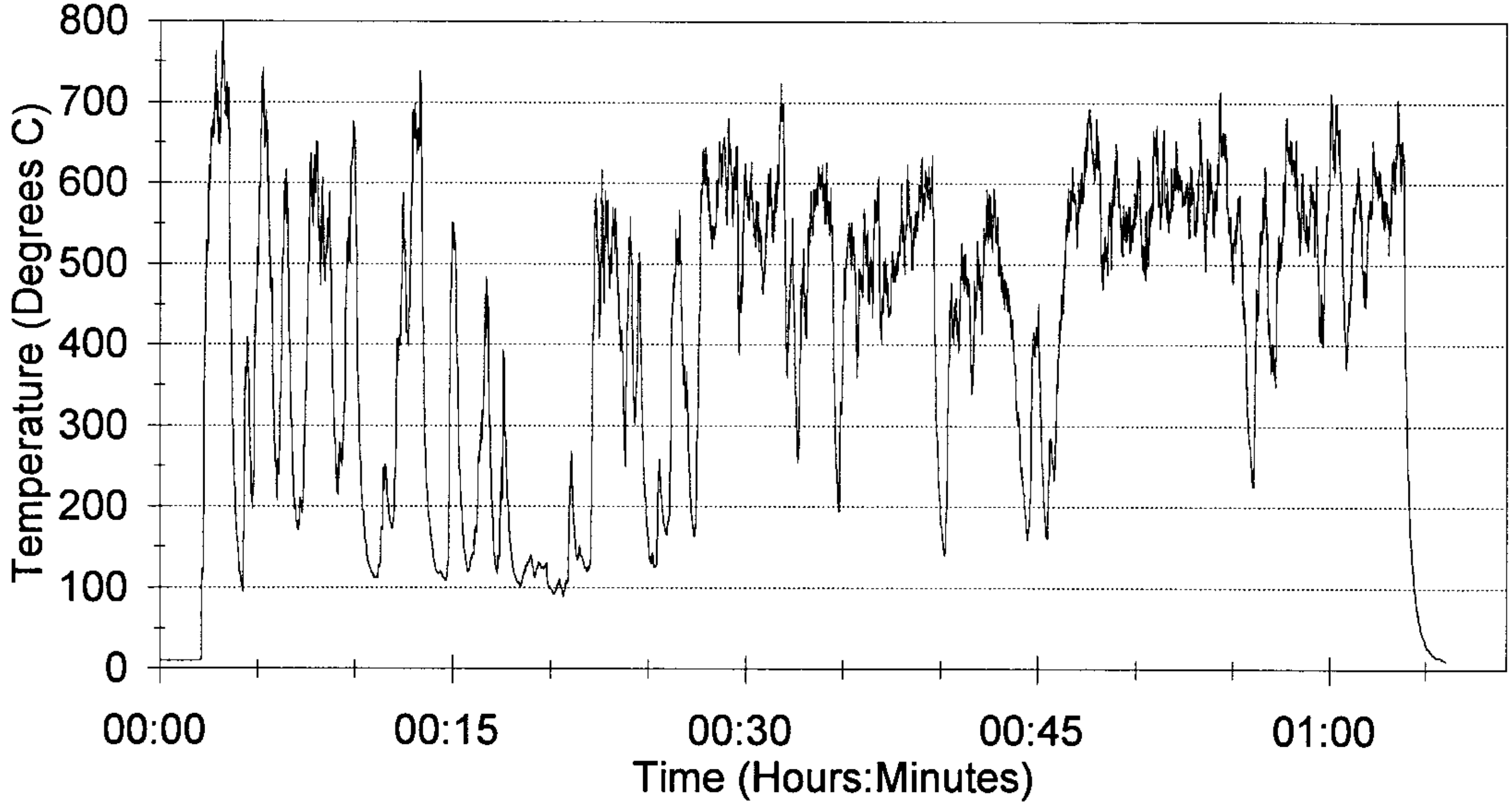
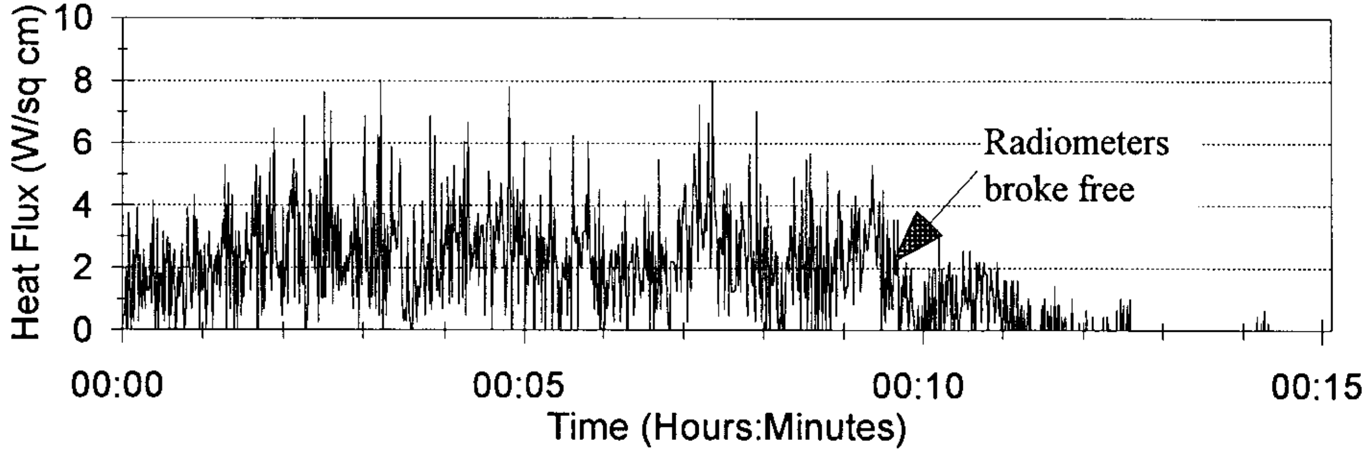


Figure 6-19: Heat flux for test run 4a

Radiometer 1



Radiometer 2

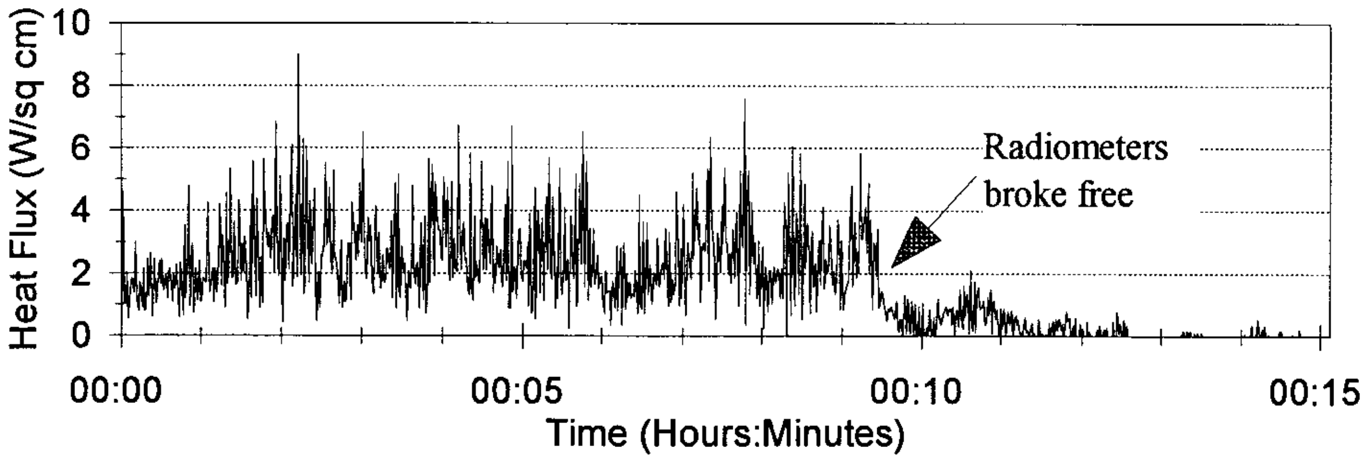


Figure 6-20: Record of temperature above boom for test run 4a

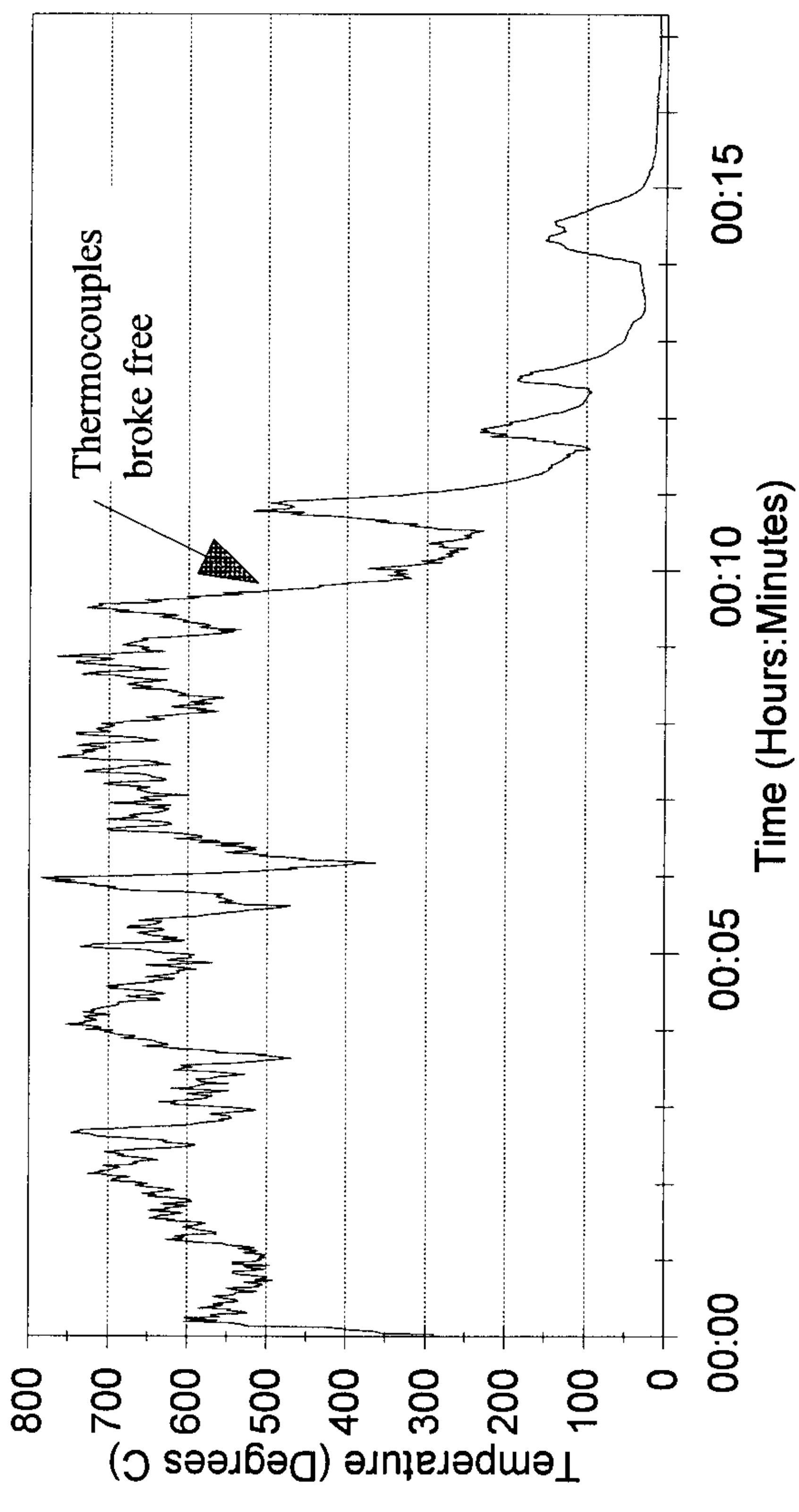
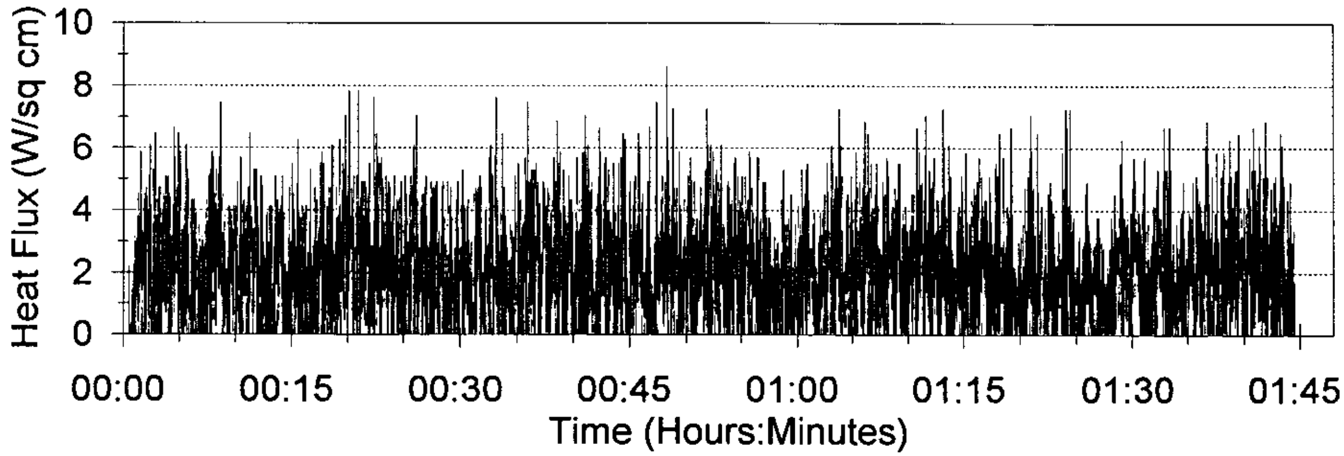


Figure 6-21: Heat flux for test run 4c

Radiometer 1



Radiometer 2

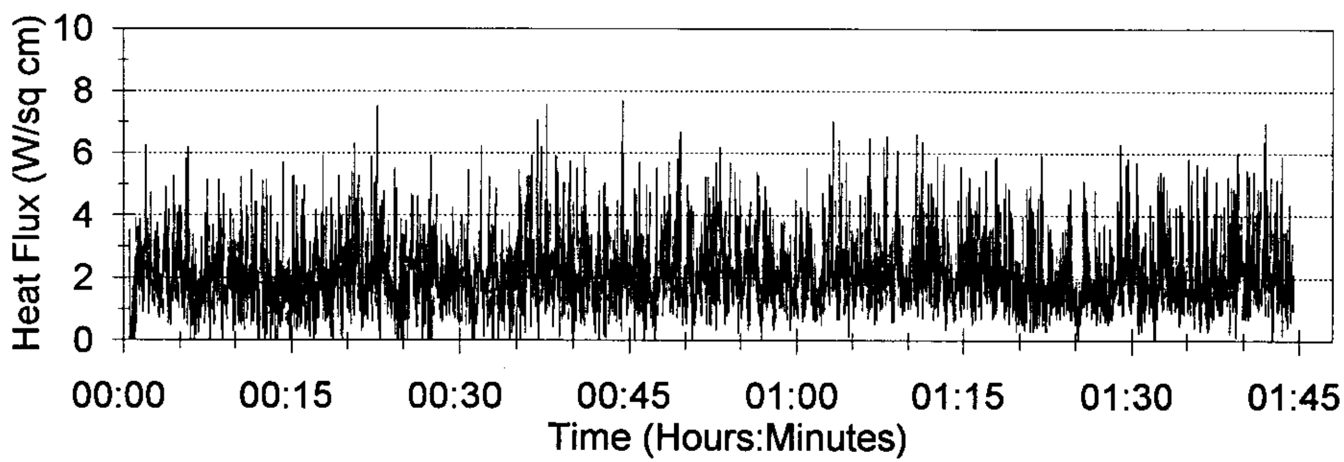
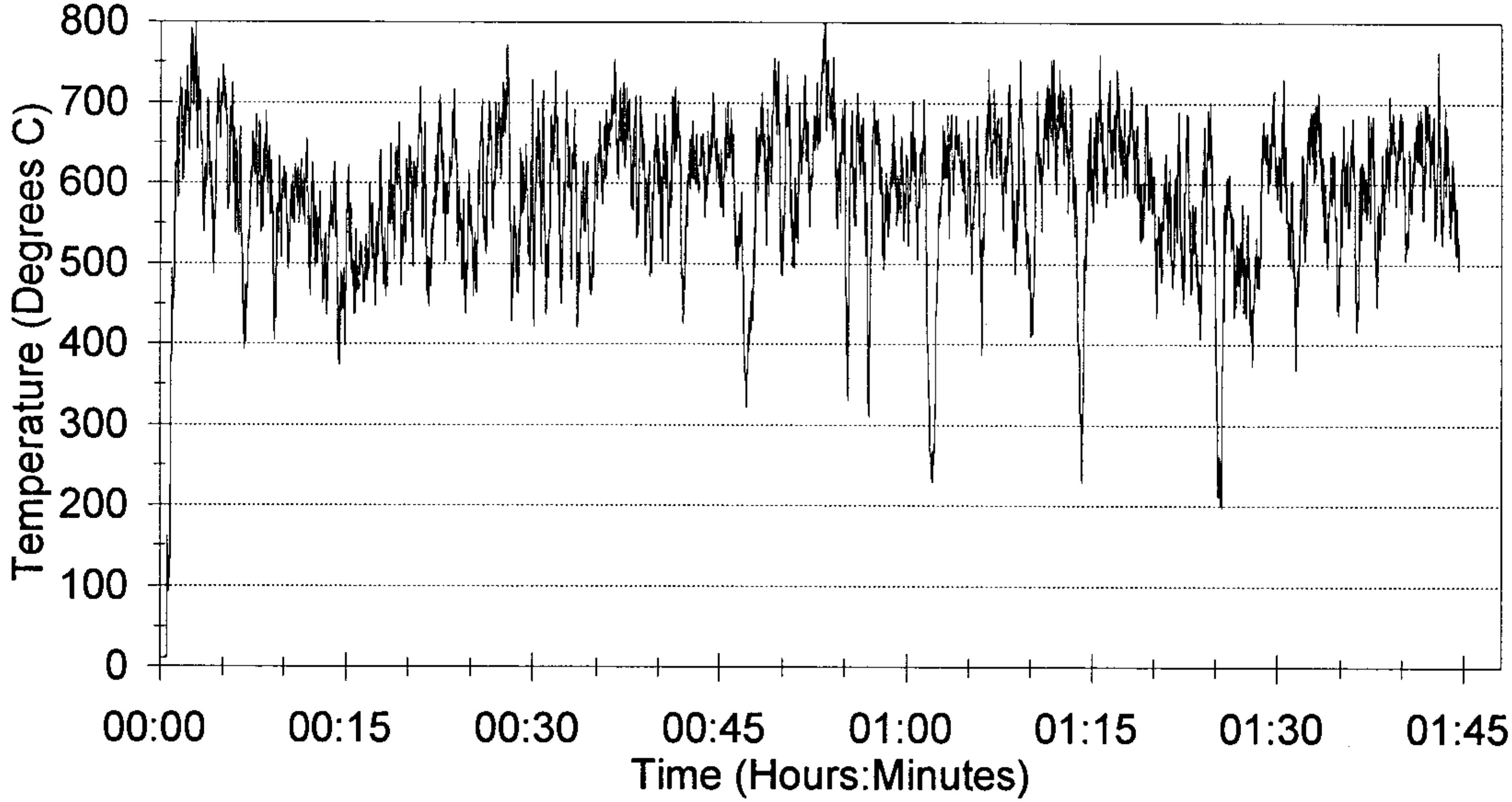
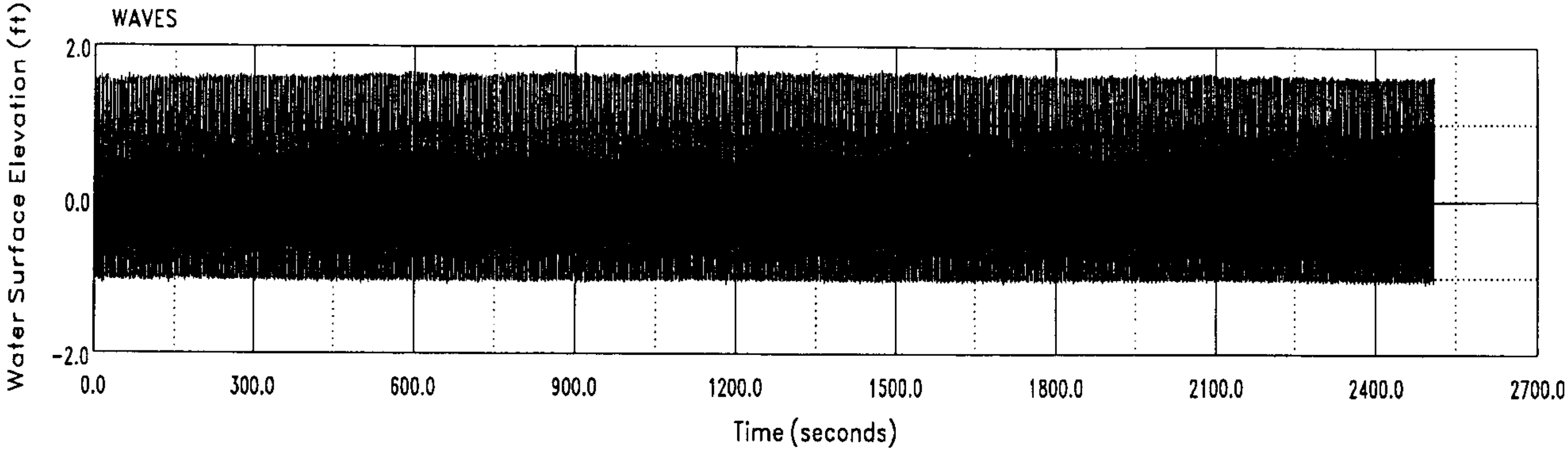
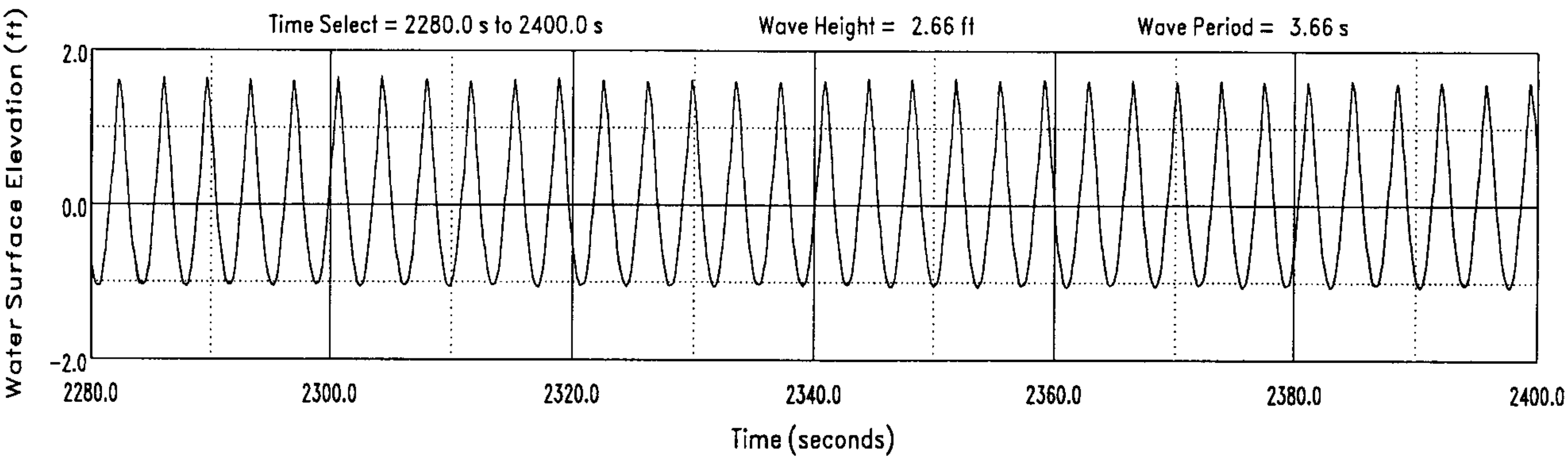


Figure 6-22: Record of temperature above boom for test run 4c

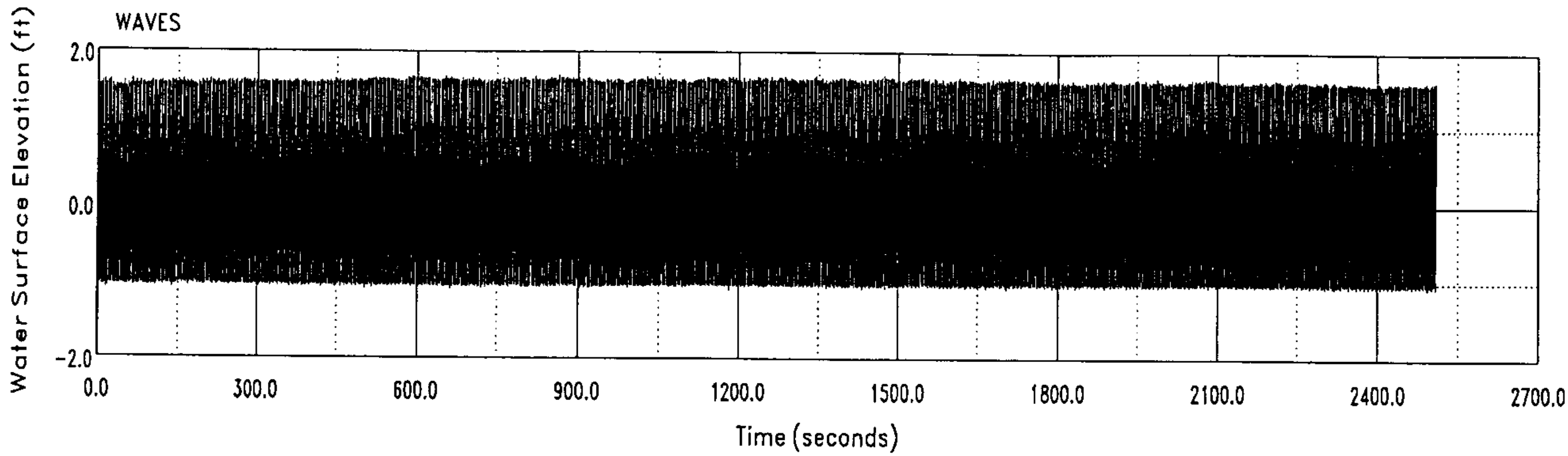


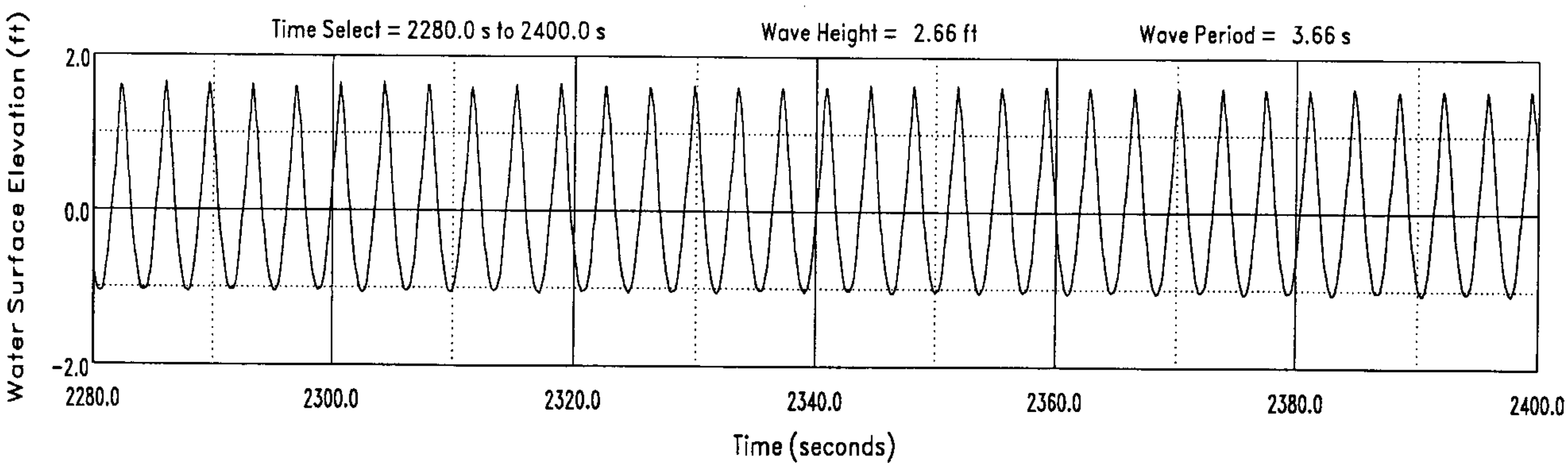
Test Number : nov5_testb_h0p80_t3p66_p





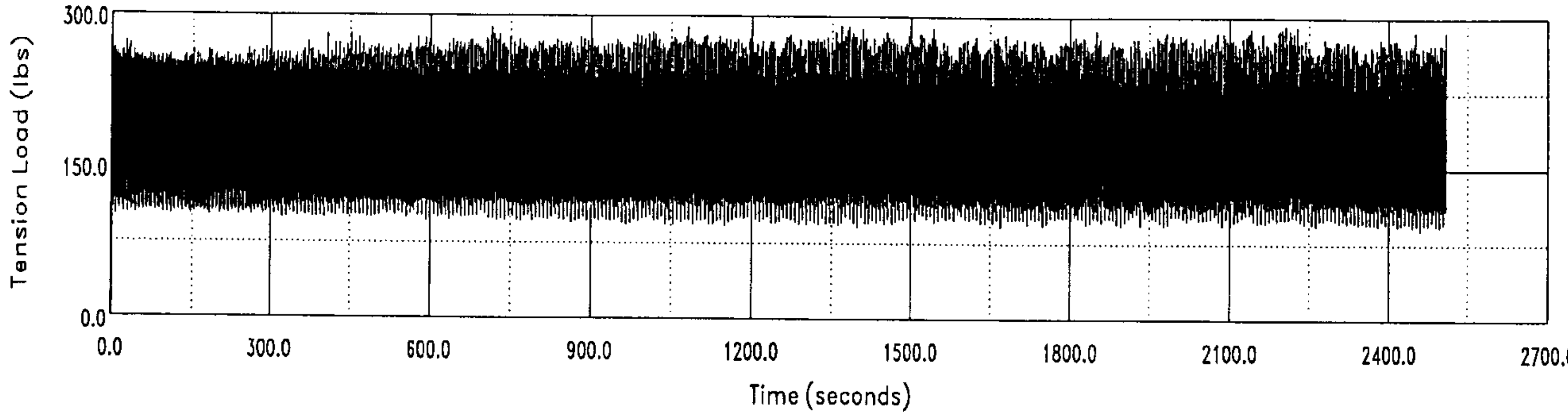
Test Number : nov5_testb_h0p80_t3p66_p



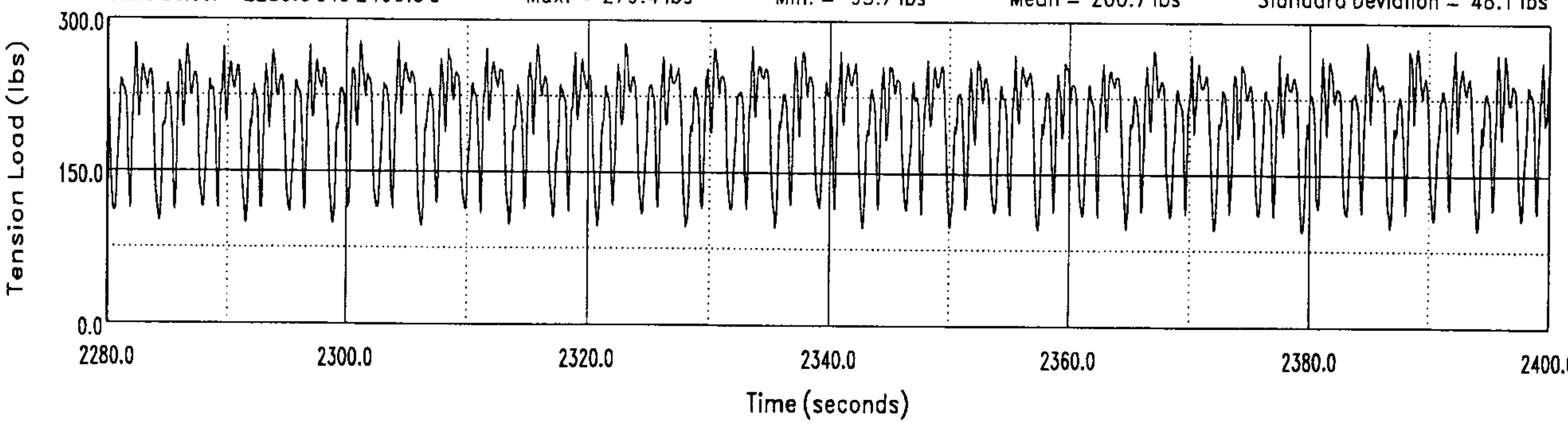


Test Number : nov5_testb_h0p80_t3p66_p

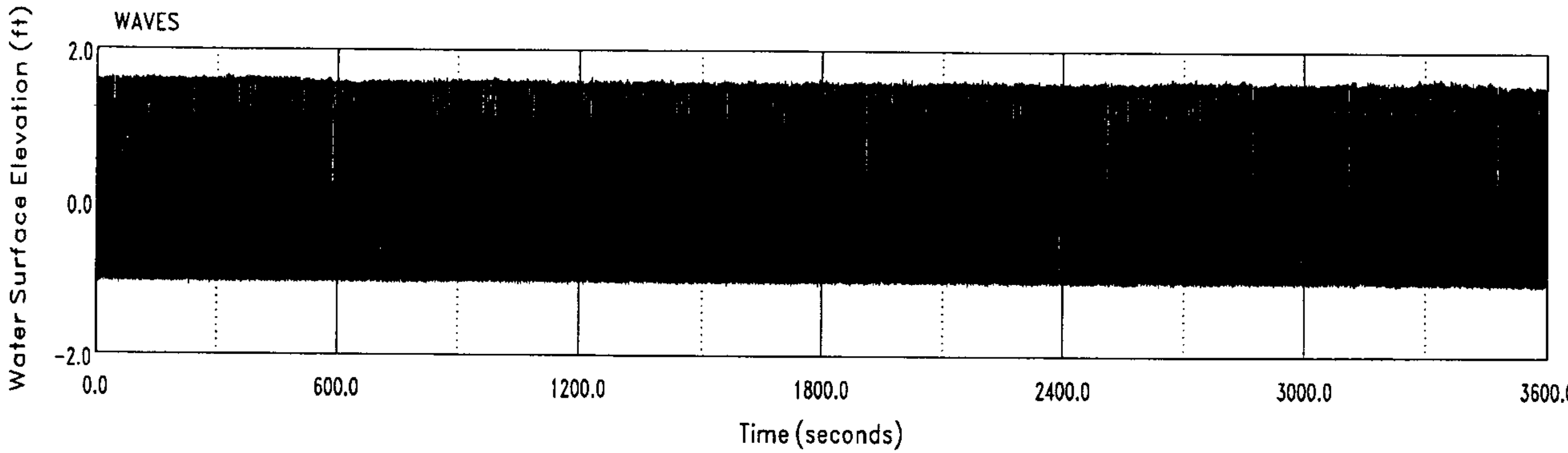
(Wave Height = 2.66 ft, Wave Period = 3.66 s)

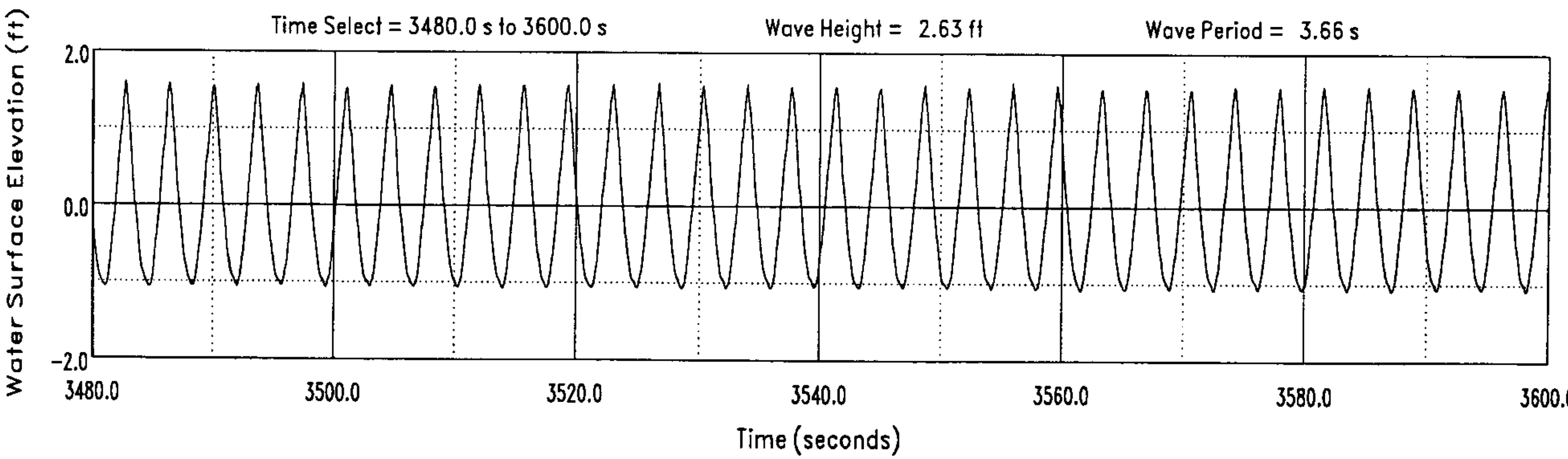


Time Select = 2280.0 s to 2400.0 s   Max. = 279.4 lbs   Min. = 93.7 lbs   Mean = 200.7 lbs   Standard Deviation = 48.1 lbs



Test Number : nov5_testc_h0p80_t3p66_p





Appendix 8

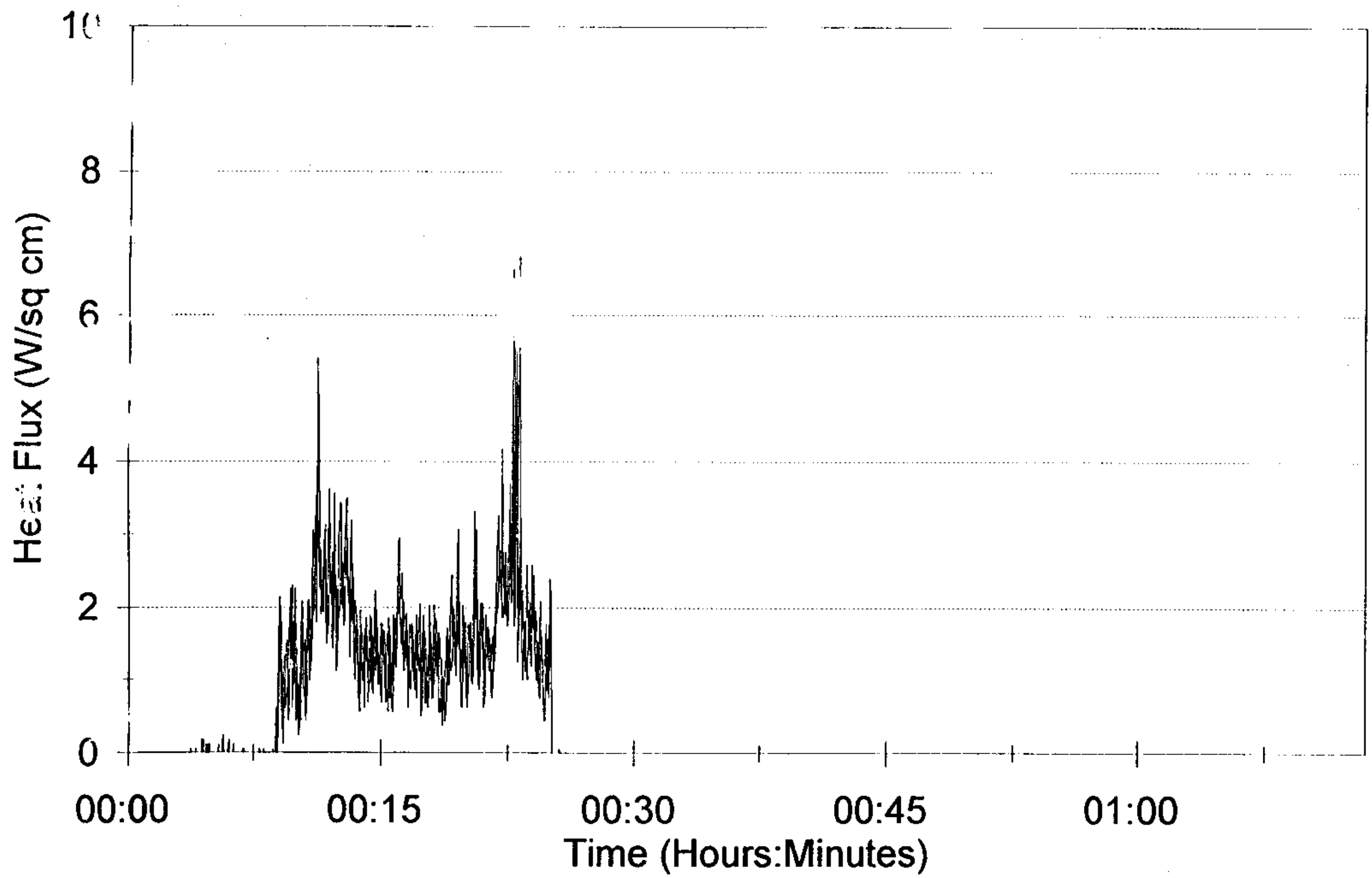
Records from Burns in Waves and Current

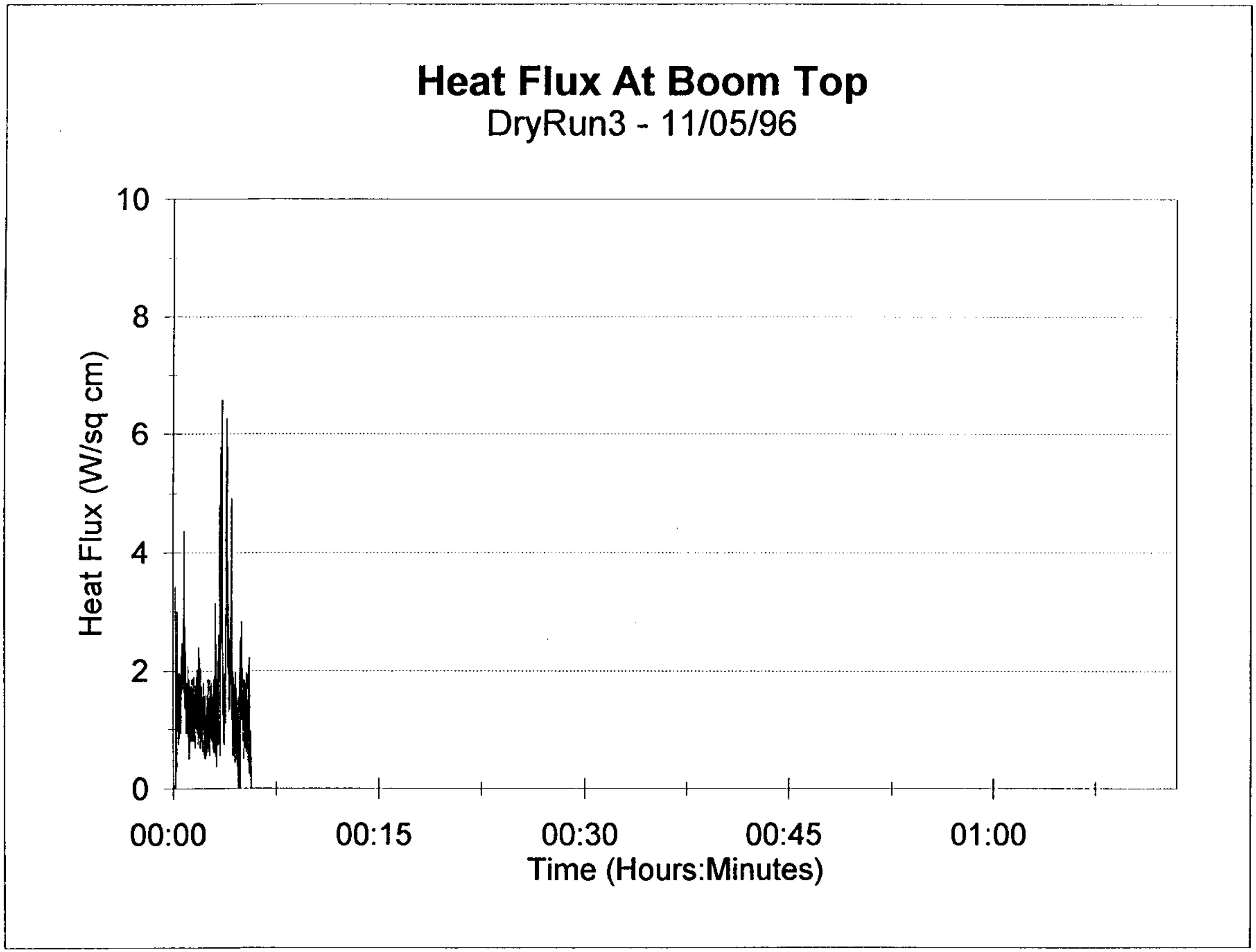
MMS-96-51 - Log of significant data recording events

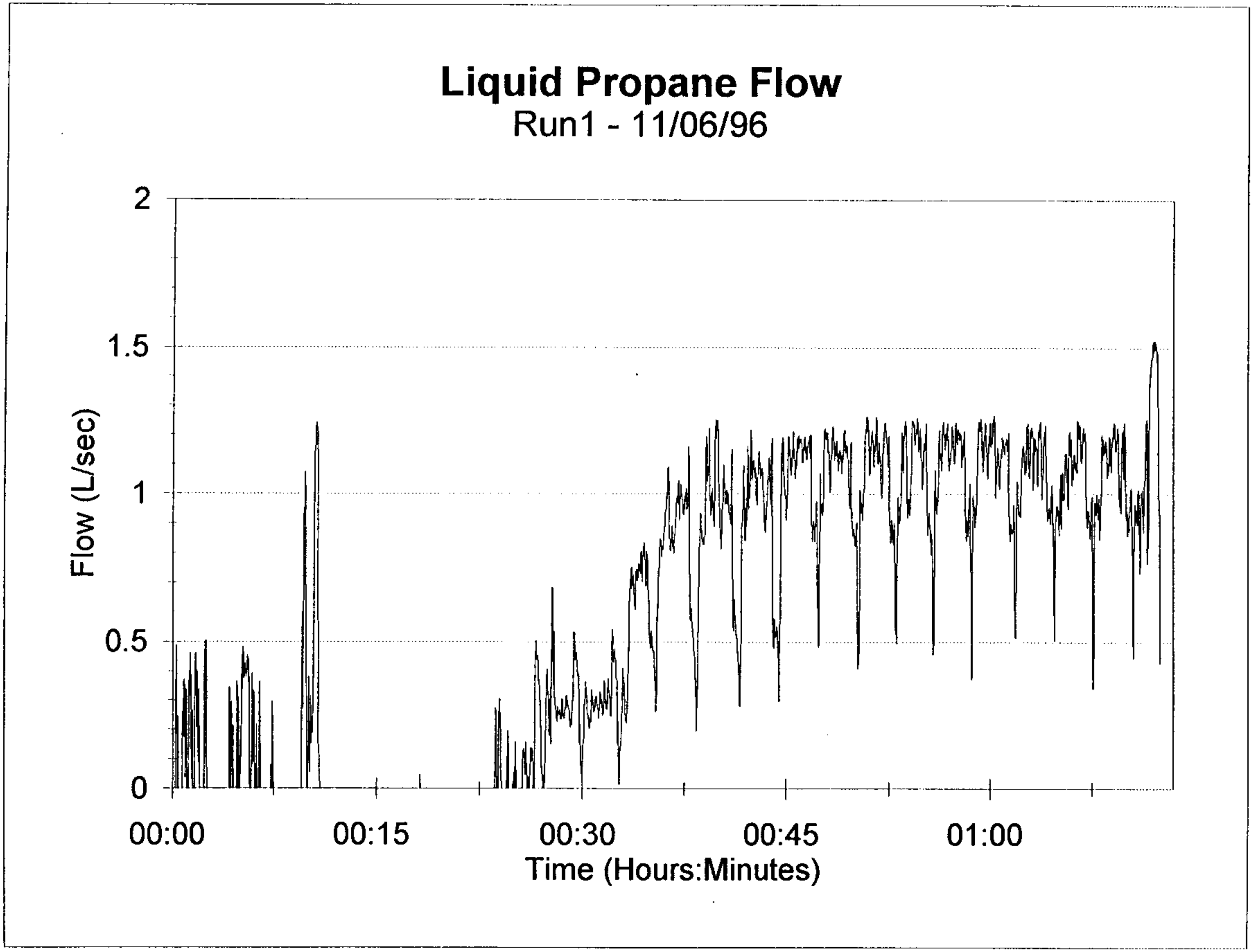
Data Log	Date	Comments	Radiometers			Propane	Thermocouples					
			96961	96962	96964	Header Pressure	Gas	Air	Boom1	Boom2	Boom3	Boom4
	04-Nov-96	Received boom										
	05-Nov-96	In Wave Research Flume										
Run1	06-Nov-96	Start burn at 4:03 - one hour	Rad1	Rad2		Manual	Manual	Manual	Unused	Unused	Unused	Unused
Run2	07-Nov-96	Start burn at 4:02 . Off at 5:03. No water to Rads for 40 min?	Rad1	Rad2		Manual	Manual	Manual	Unused	Unused	Unused	Unused
		@4:02				19	10.4					
		@4:16				18	29.5					
		@4:32				19	32.2					
		@4:57				19	33					
Run3	08-Nov-96	Changed Rad, set up welded TCs, burn at 12:00. Off at 1:01	Rad1		Rad2	Manual	Manual	Manual	Welded TC	Welded TC	Unused	Welded TC
		@12:18				19	27					
		@12:44				19	32.9					
Run4a	08-Nov-96	Start burn at 1:56, off at 2:59. Raft loose at 2:10	Rad1		Rad2	Manual	Manual	Manual	Welded TC	Welded TC	Unused	Welded TC
		@2:01				19	16.7					
		@2:49				19	32.3					
Run4c		Restart burn at 3:24, off at 5:07										
		@3:27				19	25.3					
		@4:41				19	33					
Run5	12-Nov-96	Start burn at 10:10. Off at 11:35	Rad1		Rad2	Manual	Manual	Manual	Welded TC	Welded TC	Unused	Welded TC
		@10:12				19	8.3					
		@10:21				19	16.6					
		@11:06				18	30.1					
		@11:14				18	30.3					
		@11:24				18	30.6					
		@11:30				17	31.9					
		@11:33				15	34					
		@11:35				12	36					

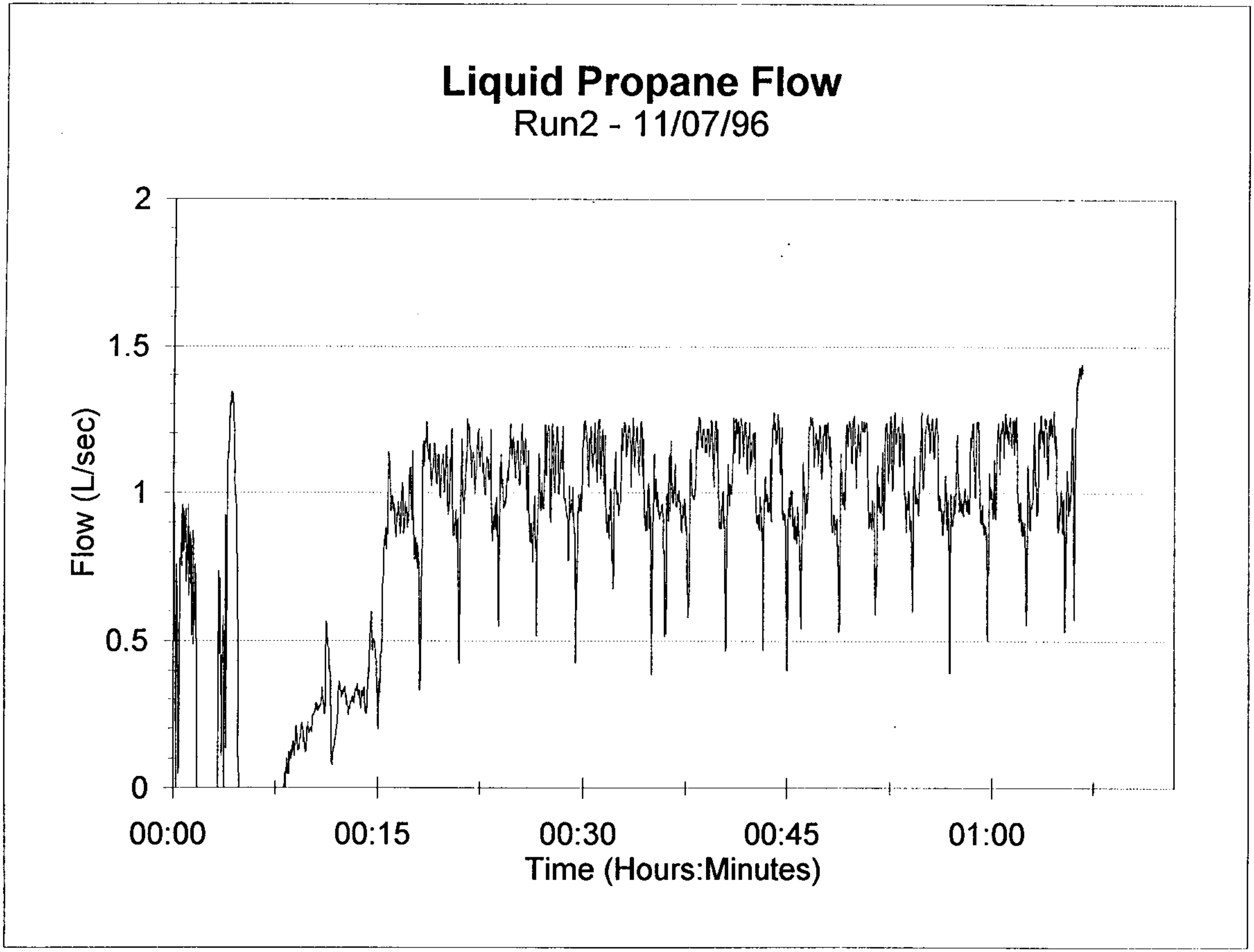
Heat Flux At Boom Top

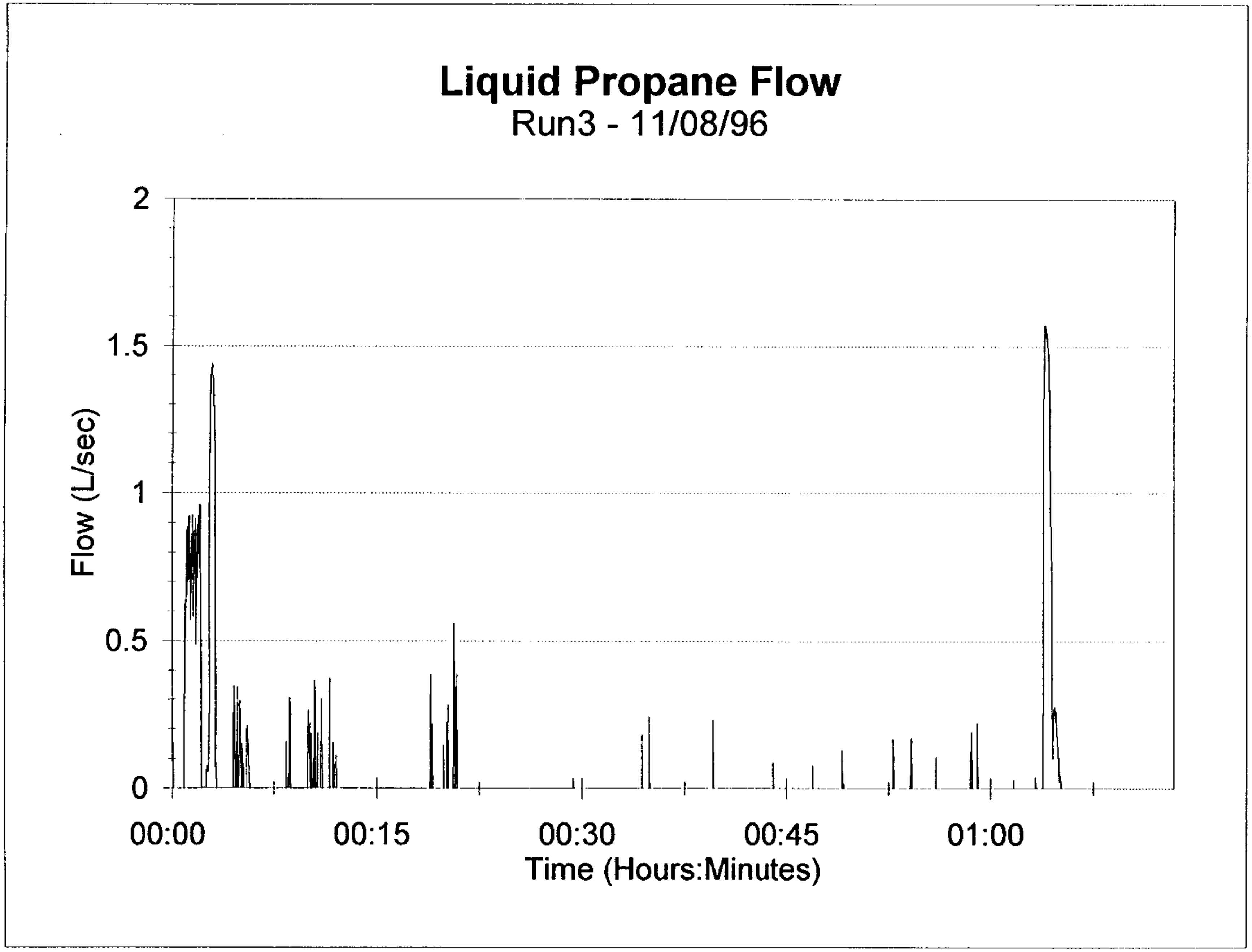
DryRun2 - 11/05/96

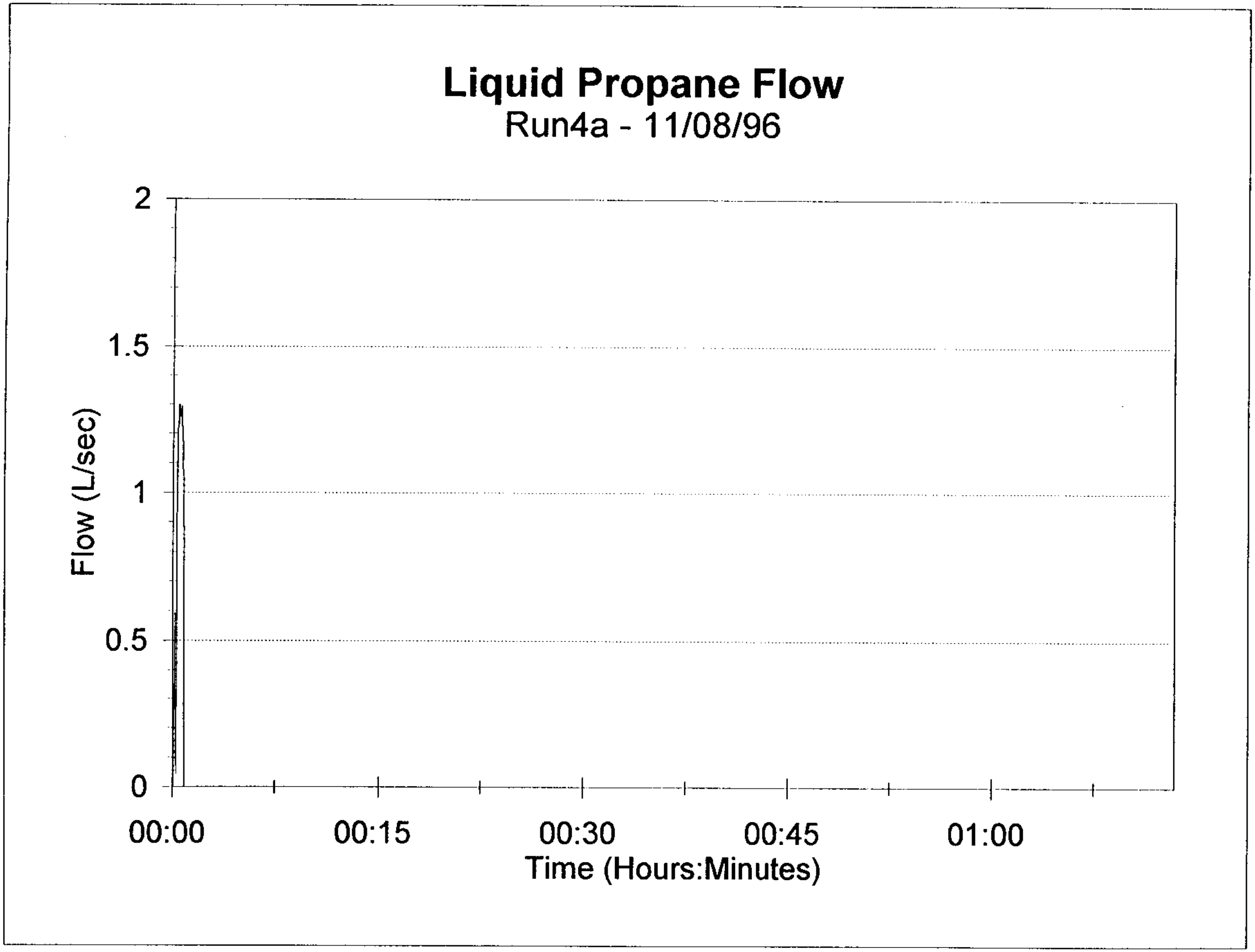


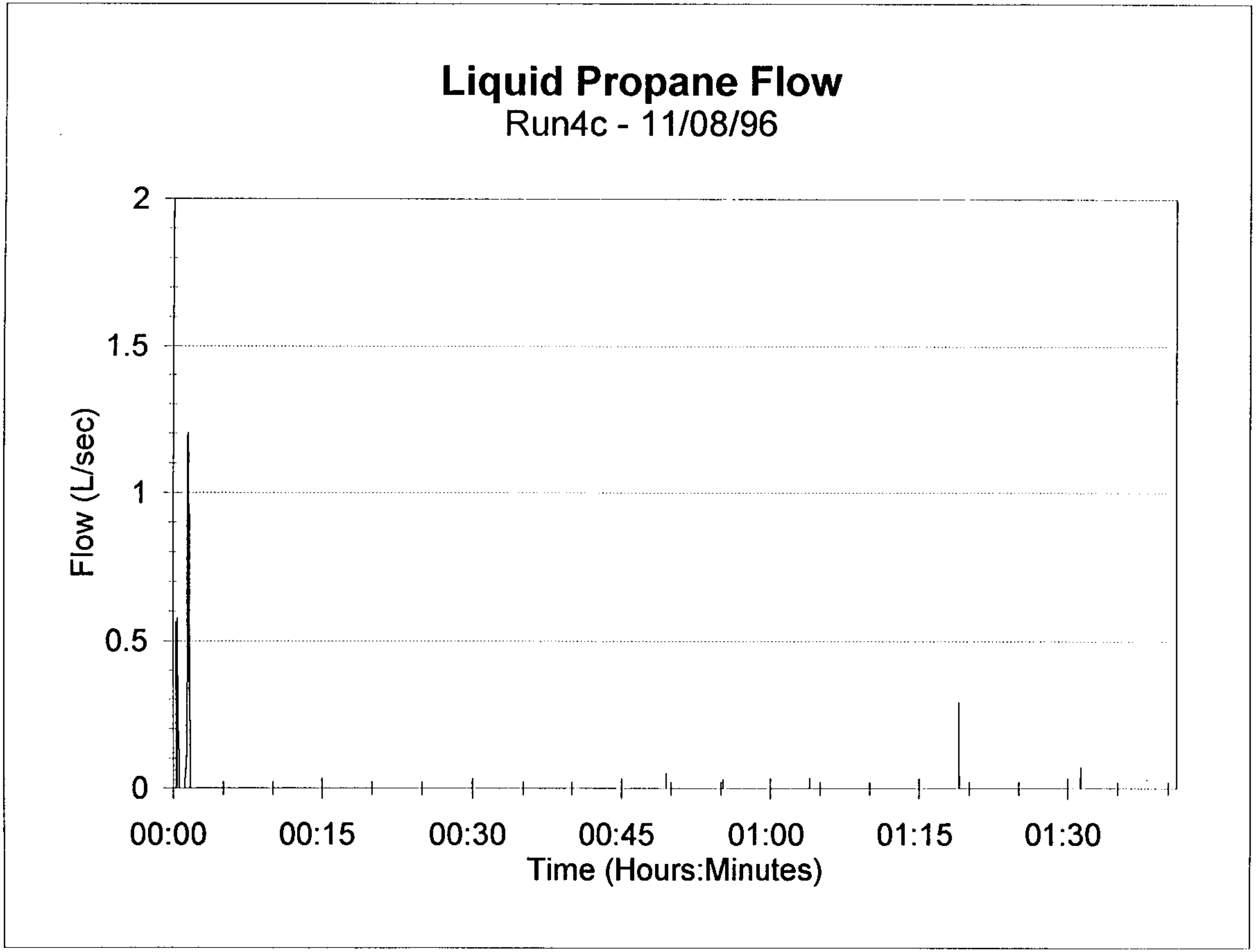

Heat Flux At Boom Top
DryRun3 - 11/05/96
10
8
6
4
2
0
Heat Flux (W/sq cm)
00:00
00:15
00:30
00:45
01:00
Time (Hours:Minutes)

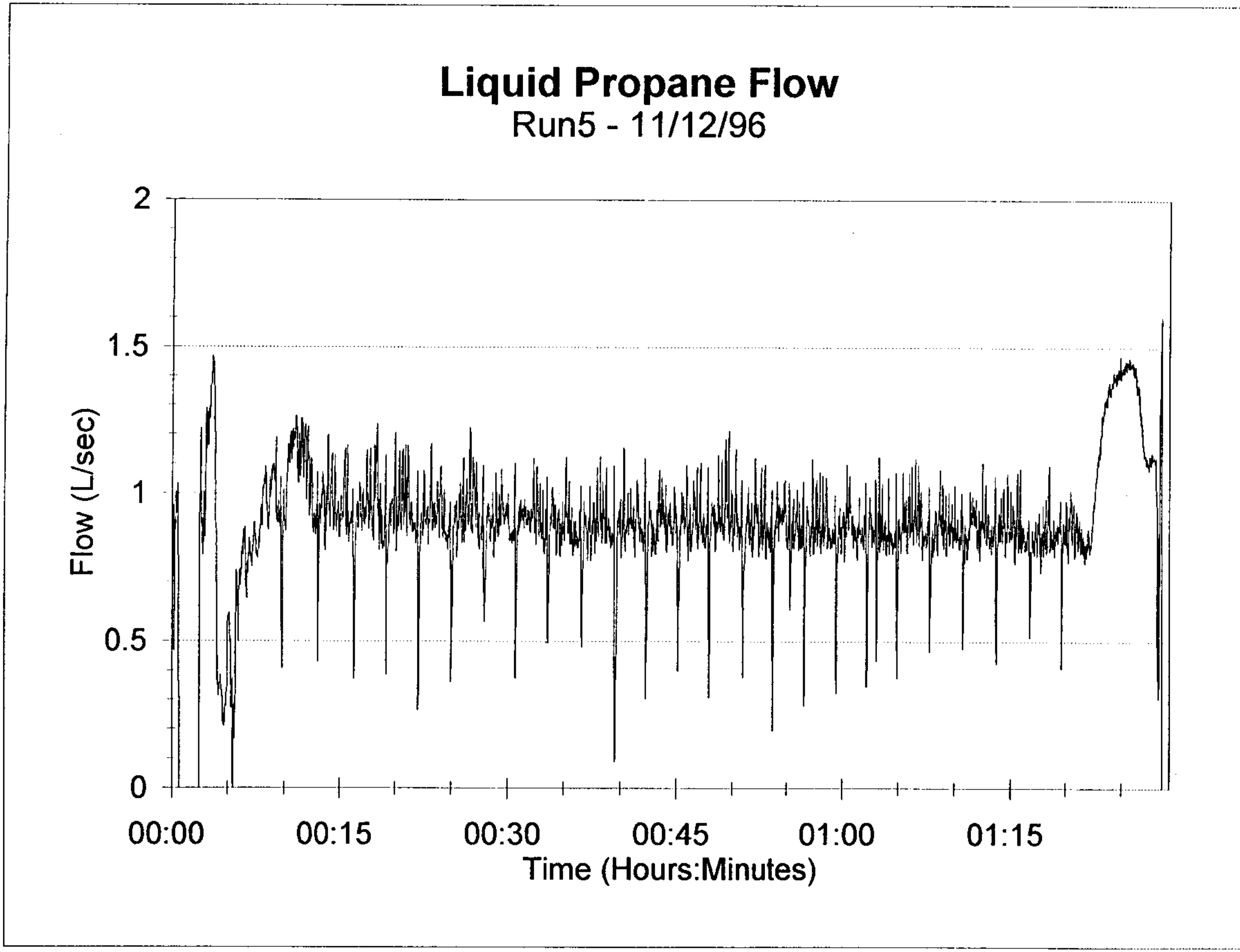

Liquid Propane Flow
Run1 - 11/06/96
Flow (L/sec)
2
1.5
1
0.5
0
00:00
00:15
00:30
00:45
01:00
Time (Hours:Minutes)

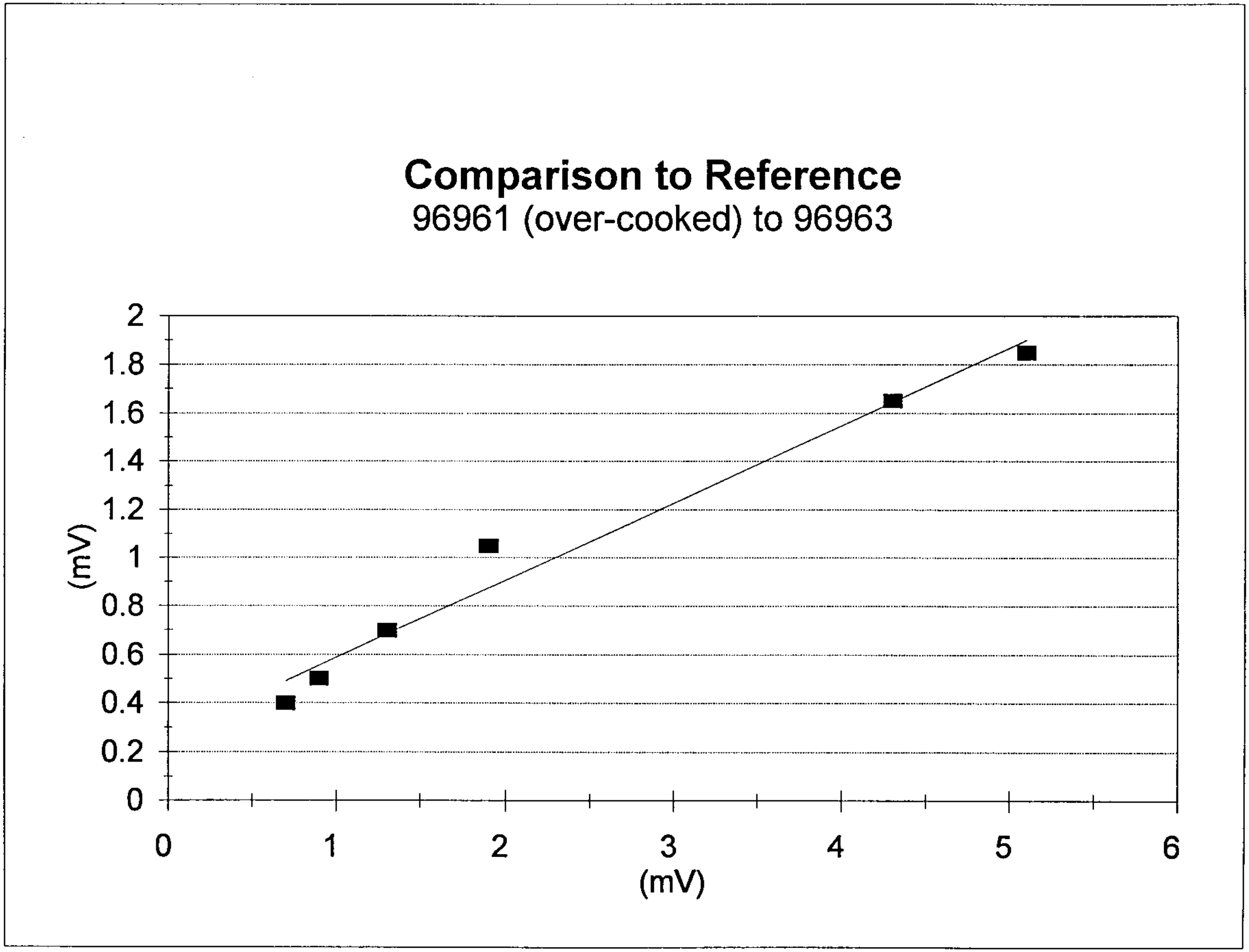

Liquid Propane Flow
Run2 - 11/07/96
Flow (L/sec)
2
1.5
1
0.5
0
00:00
00:15
00:30
00:45
01:00
Time (Hours:Minutes)


Liquid Propane Flow
Run3 - 11/08/96
Flow (L/sec)
2
1.5
1
0.5
0
00:00
00:15
00:30
00:45
01:00
Time (Hours:Minutes)


Liquid Propane Flow
Run4a - 11/08/96
2
1.5
1
0.5
0
Flow (L/sec)
00:00
00:15
00:30
00:45
01:00
Time (Hours:Minutes)


Liquid Propane Flow
Run4c - 11/08/96
Flow (L/sec)
2
1.5
1
0.5
0
00:00
00:15
00:30
00:45
01:00
01:15
01:30
Time (Hours:Minutes)


Liquid Propane Flow
Run5 - 11/12/96
2
1.5
1
0.5
0
Flow (L/sec)
00:00
00:15
00:30
00:45
01:00
01:15
Time (Hours:Minutes)


Comparison to Reference
96961 (over-cooked) to 96963
(mV)
(mV)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6

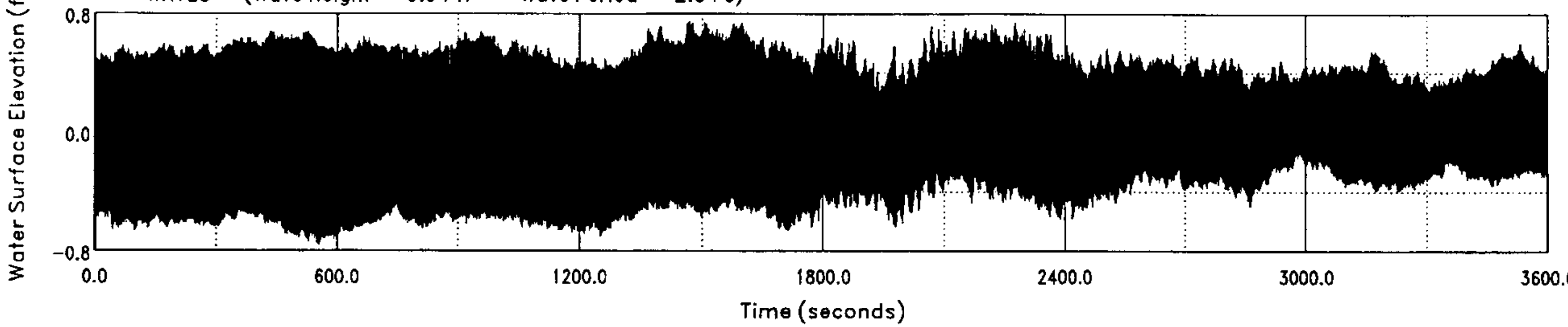
Test Number	Duration of Test (s)
NOV08_LARGE_LCUR_001	3600
NOV08_LARGE_LCUR_002	3600
NOV08_LARGE_LCUR_003	3600
NOV08_LARGE_LCUR_004	3600
NOV08_SMALL_HCUR_001	3600
NOV12_LARGE_001	3600
NOV12_LARGE_002	1500

On the following pages, time series results are provided for tests NOV08_LARGE_LCUR_003 and NOV08_SMALL_HCUR_001.

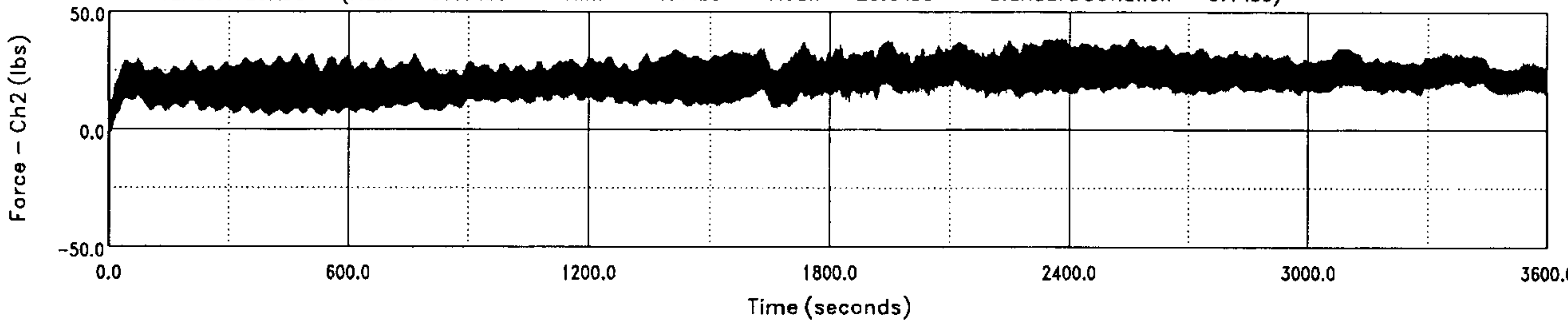
NOTE :
(a) LARGE means large waves (nominally 0.6 m, 2.5 s);
(b) SMALL means small waves (nominally 0.3 m, 1.4 s);
(c) LCUR means low currents (nominally 0.2 m/s);
(d) HCUR means high currents (nominally 0.6 m/s).

Test Number : NOV08_LARGE_LCUR_003

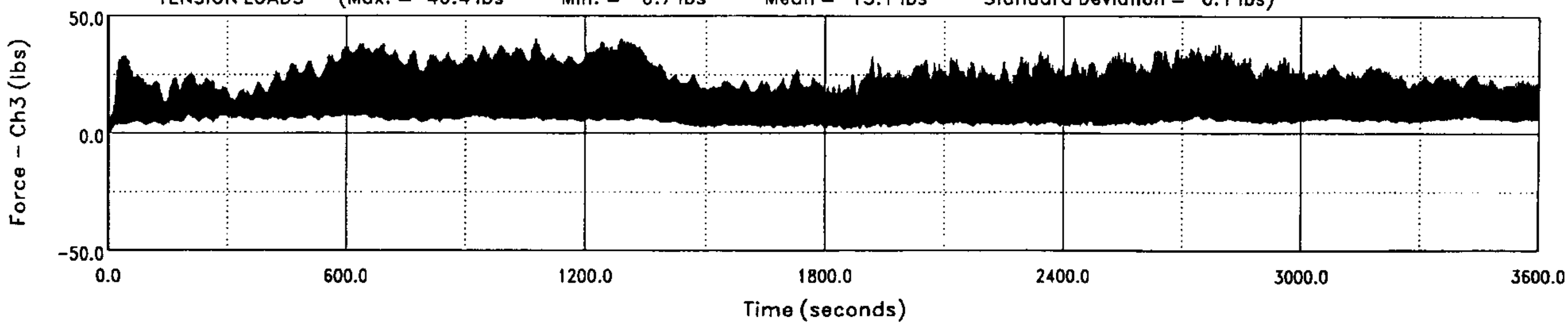
WAVES (Wave Height = 0.94 ft Wave Period = 2.54 s)



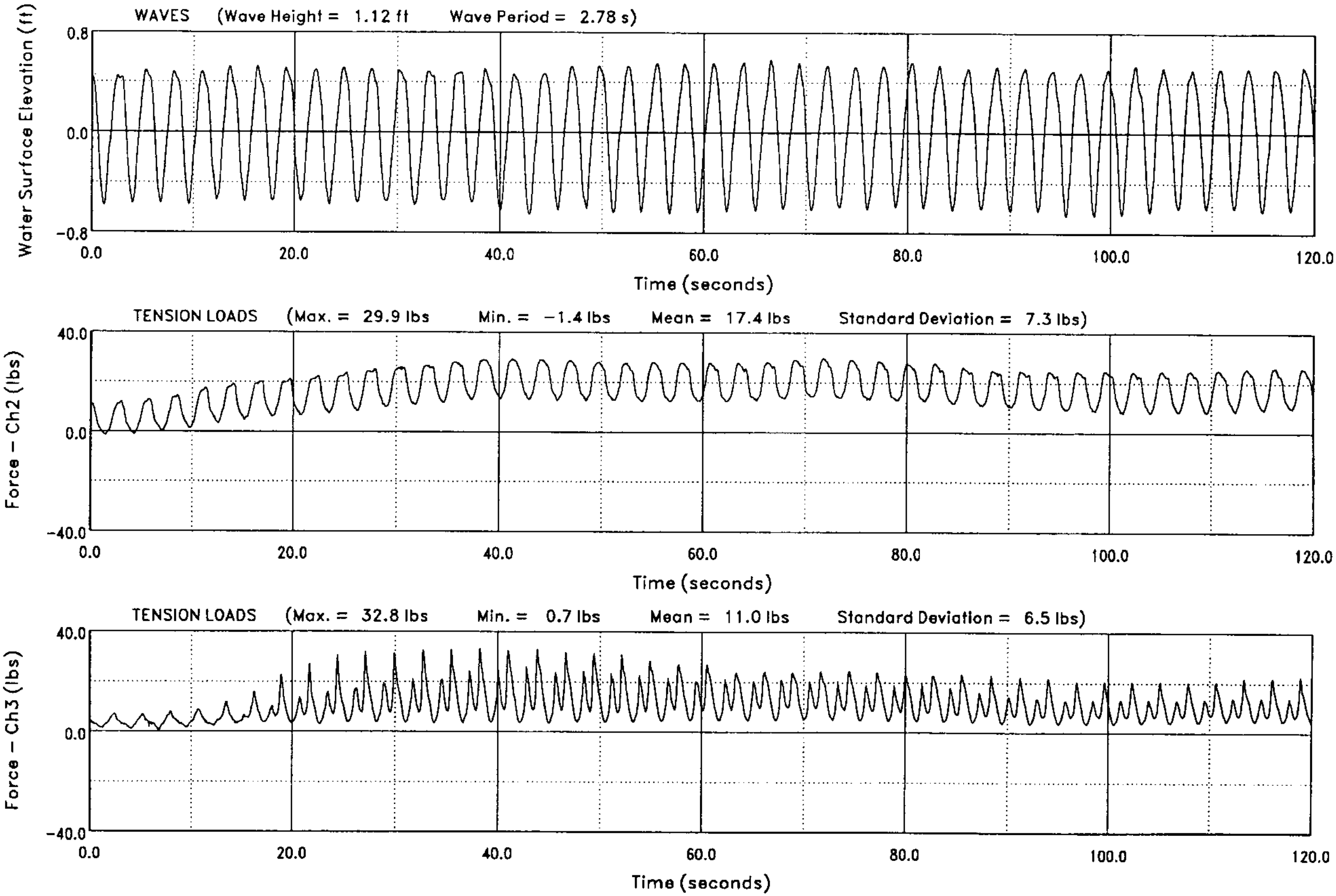
TENSION LOADS (Max. = 39.0 lbs Min. = -1.4 lbs Mean = 20.6 lbs Standard Deviation = 6.1 lbs)



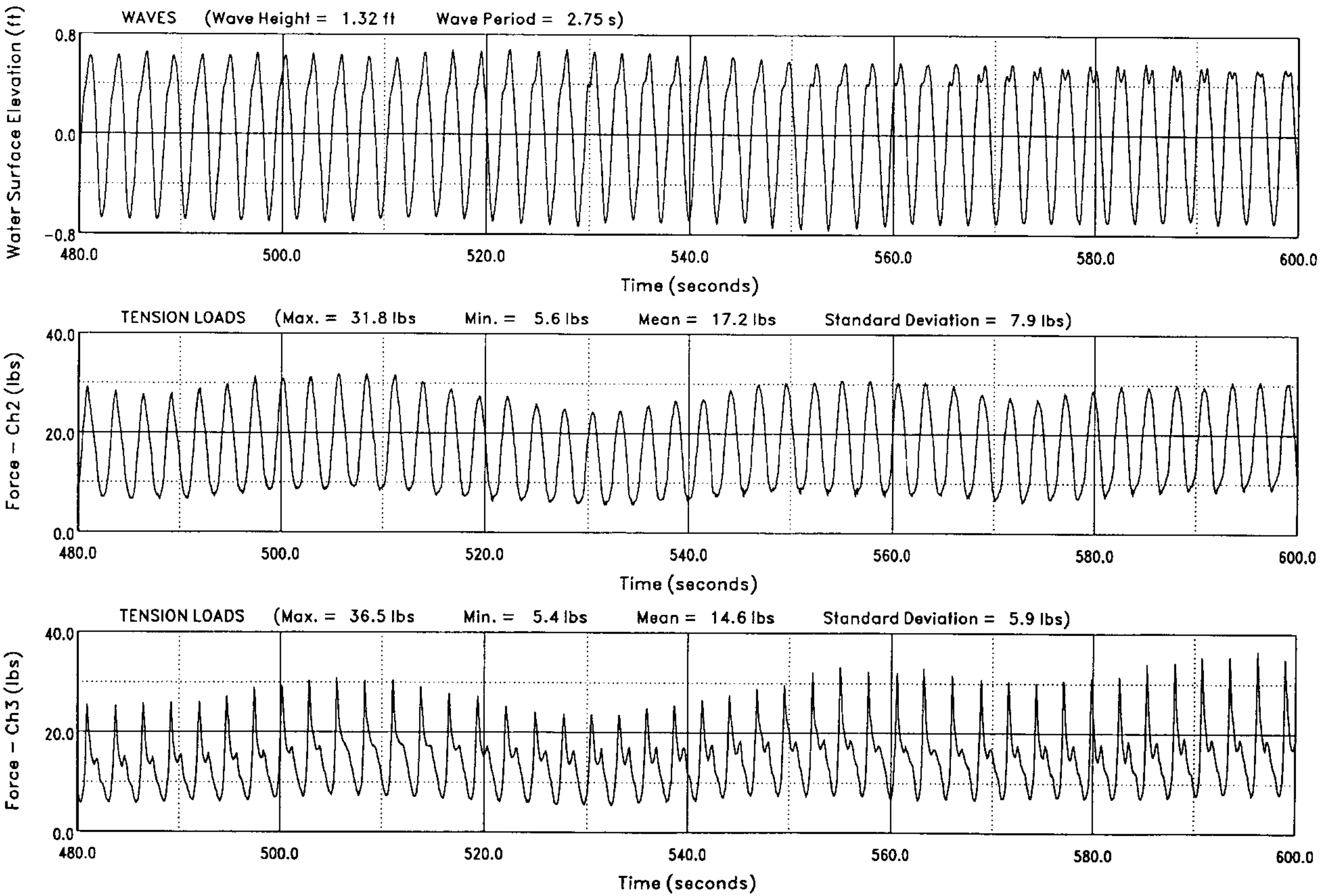
TENSION LOADS (Max. = 40.4 lbs Min. = 0.7 lbs Mean = 13.1 lbs Standard Deviation = 6.1 lbs)



Test Number : NOV08_LARGE_LCUR_003

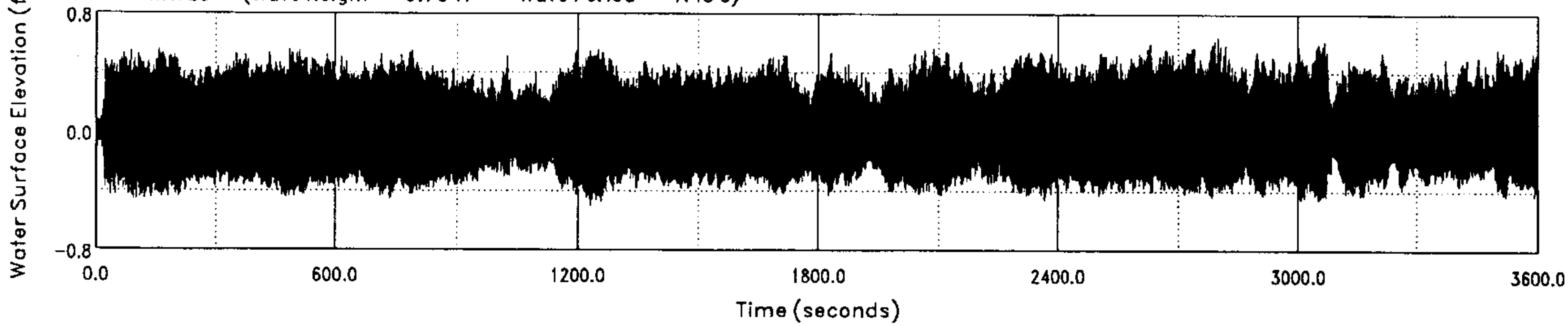


Test Number : NOV08_LARGE_LCUR_003

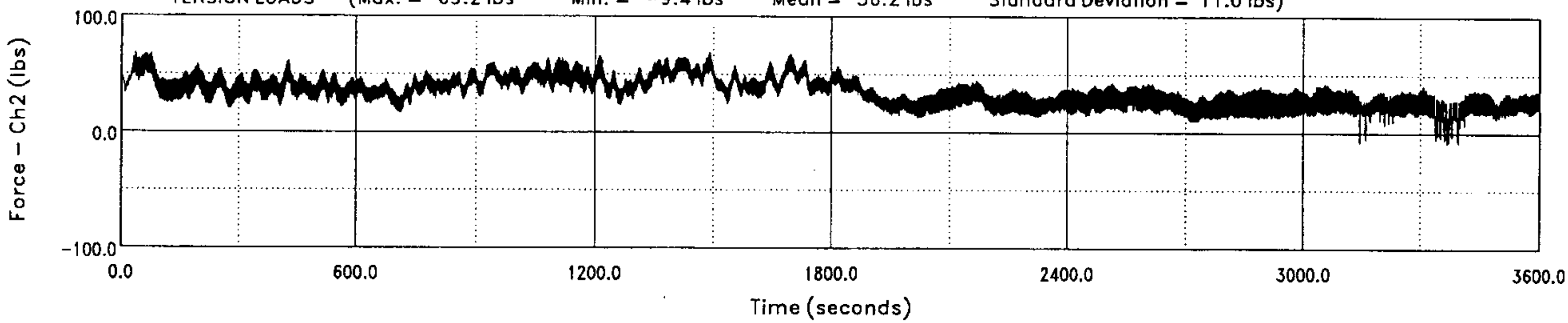


Test Number : NOV08_SMALL_HCUR_001

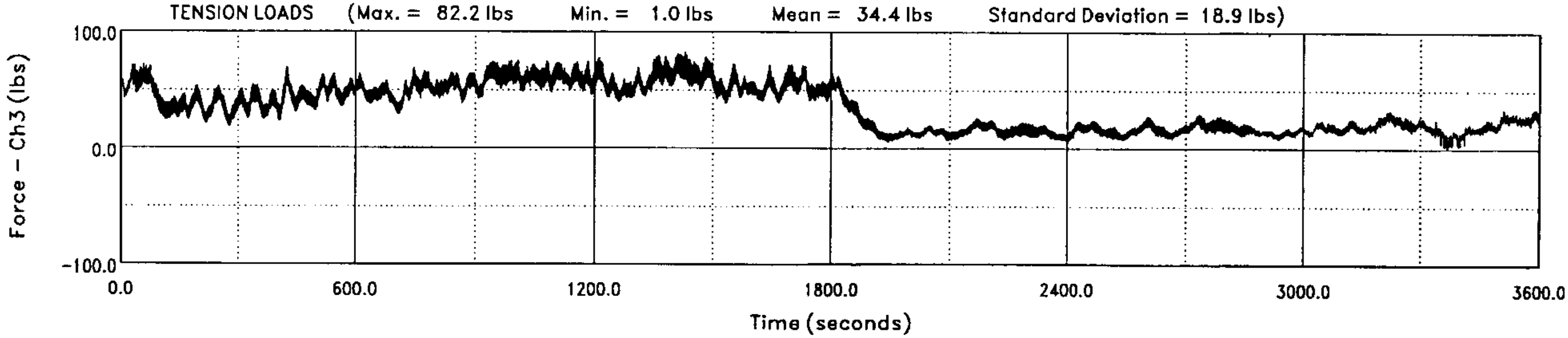
WAVES (Wave Height = 0.73 ft Wave Period = 1.45 s)

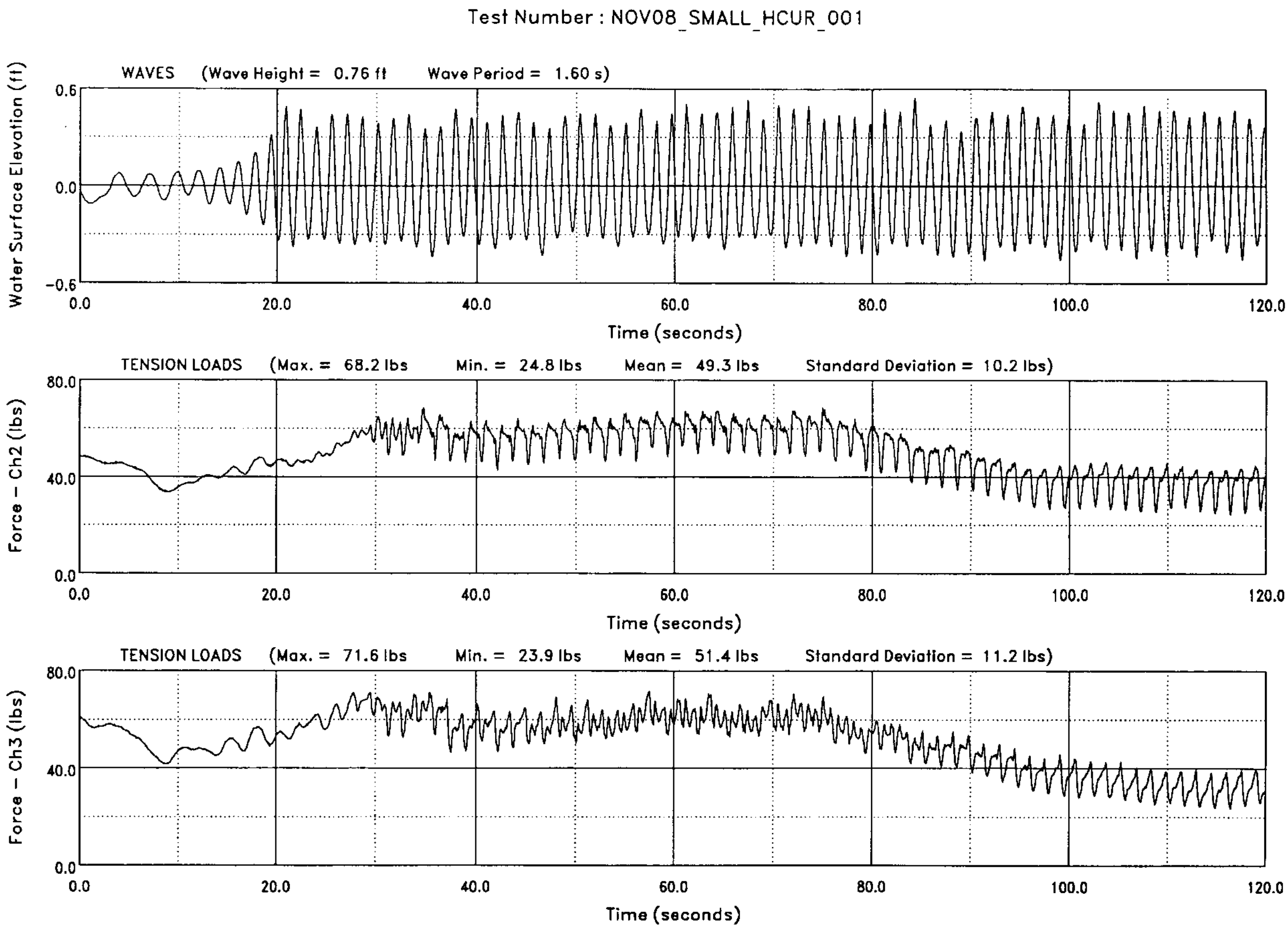


TENSION LOADS (Max. = 69.2 lbs Min. = -9.4 lbs Mean = 36.2 lbs Standard Deviation = 11.0 lbs)

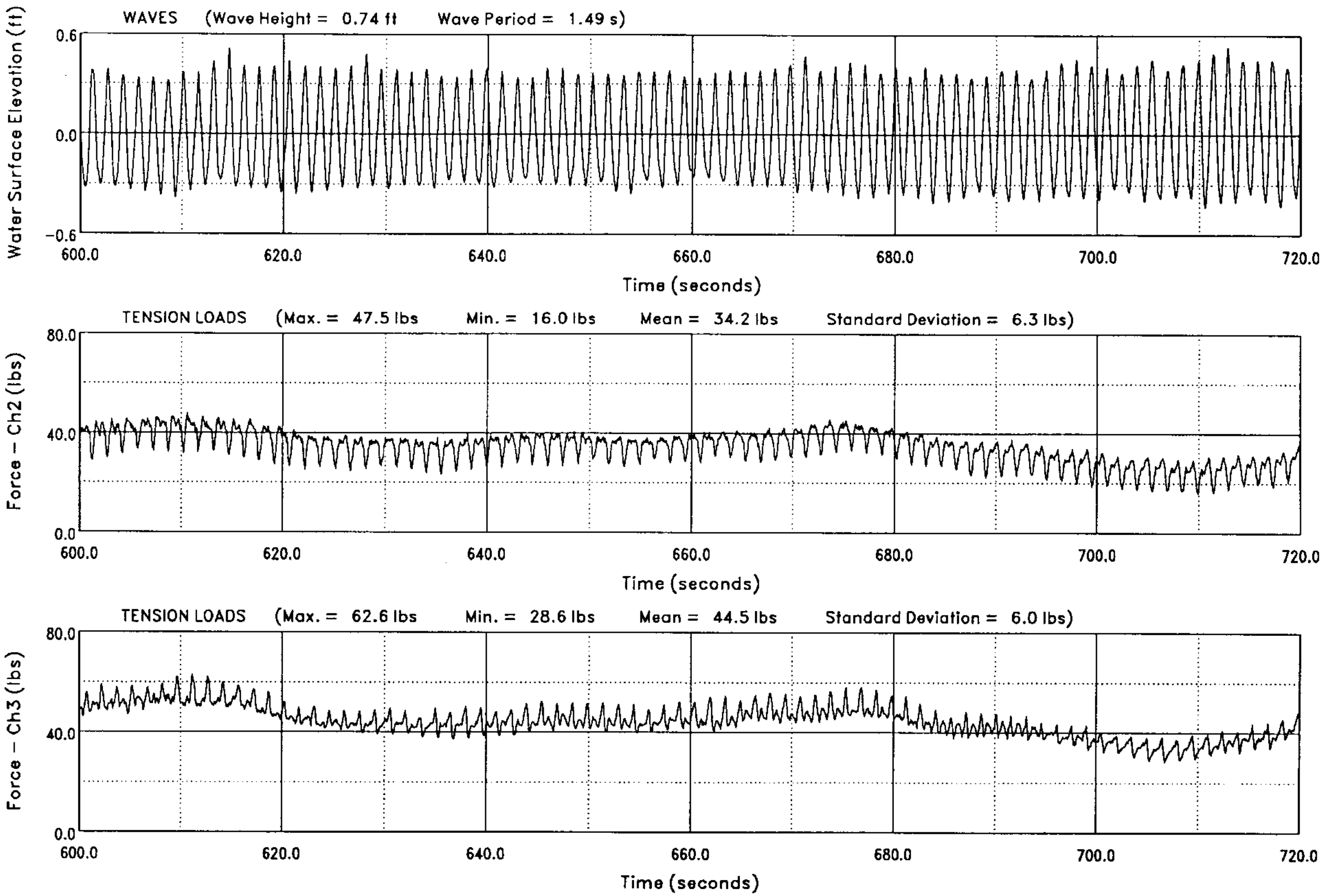


TENSION LOADS (Max. = 82.2 lbs Min. = 1.0 lbs Mean = 34.4 lbs Standard Deviation = 18.9 lbs)




Test Number : NOV08_SMALL_HCUR_001
WAVES (Wave Height = 0.76 ft Wave Period = 1.60 s)
Water Surface Elevation (ft)
0.6
0.0
-0.6
0.0
20.0
40.0
60.0
80.0
100.0
120.0
Time (seconds)
TENSION LOADS (Max. = 68.2 lbs Min. = 24.8 lbs Mean = 49.3 lbs Standard Deviation = 10.2 lbs)
Force - Ch2 (lbs)
80.0
40.0
0.0
Time (seconds)
TENSION LOADS (Max. = 71.6 lbs Min. = 23.9 lbs Mean = 51.4 lbs Standard Deviation = 11.2 lbs)
Force - Ch3 (lbs)
80.0
40.0
0.0
Time (seconds)

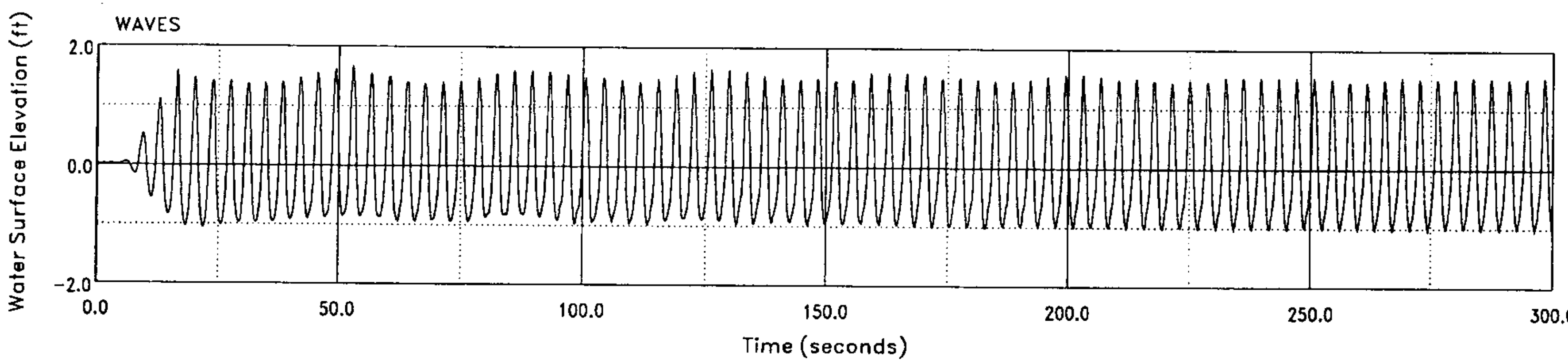
Test Number : NOV08_SMALL_HCUR_001

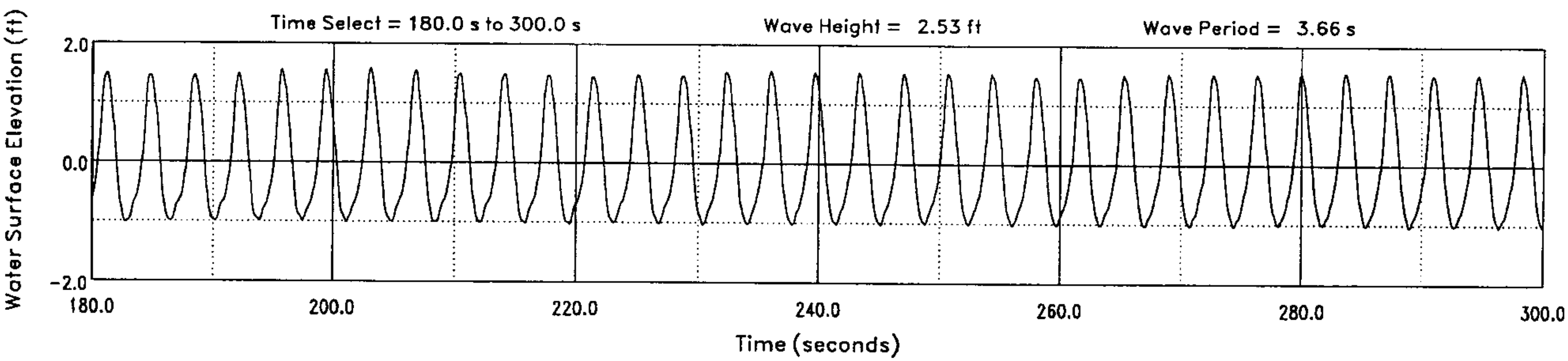


Appendix 9

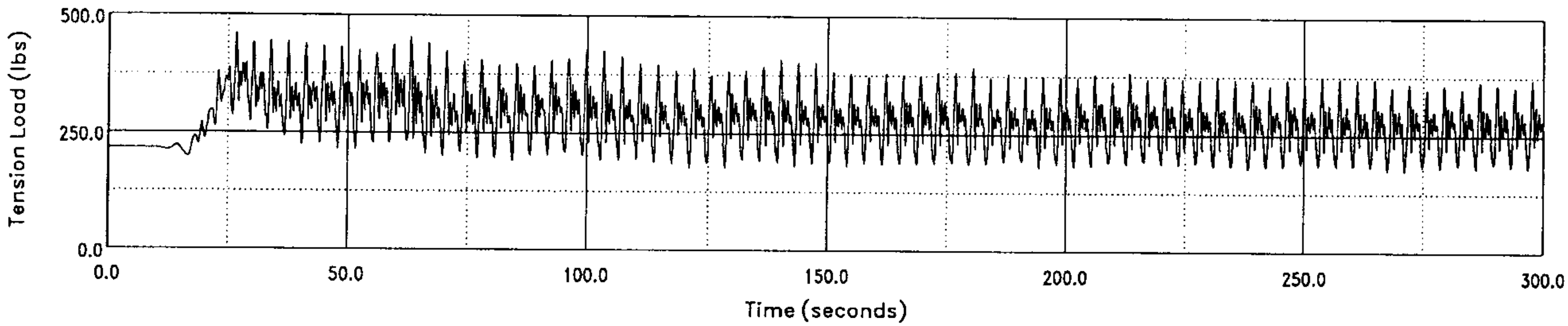
Records from Post-burn Wave Stress Test

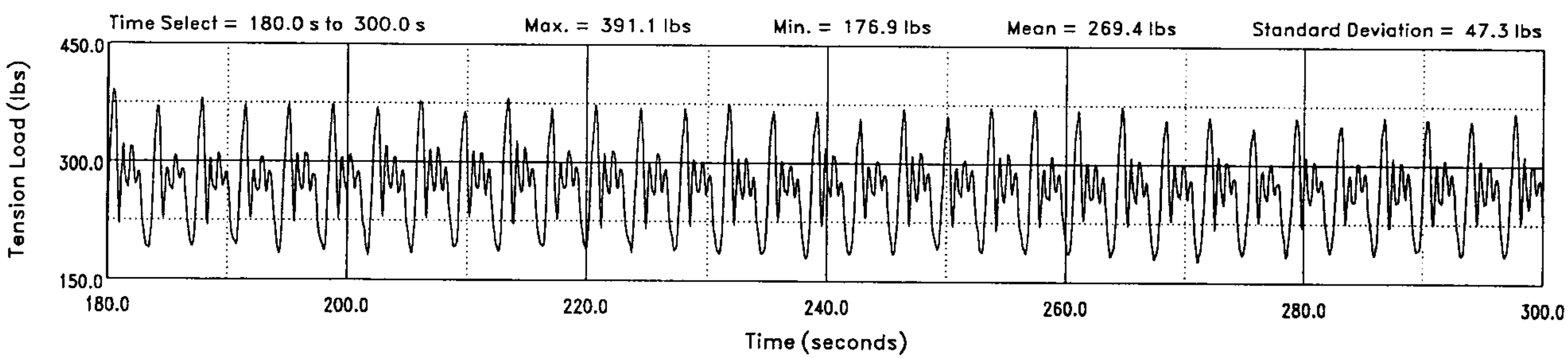
Test Number : nov13_testa_h0p80_t3p66_p



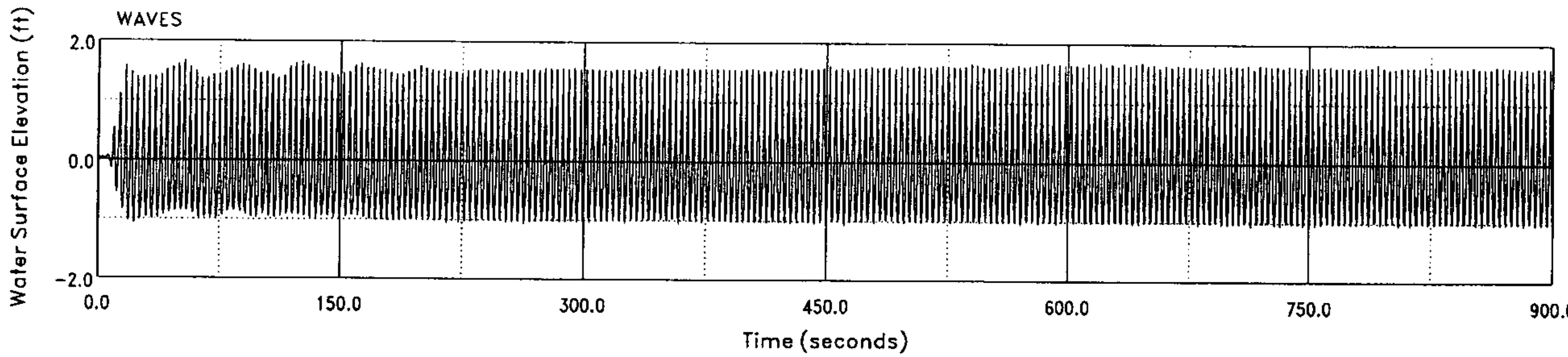


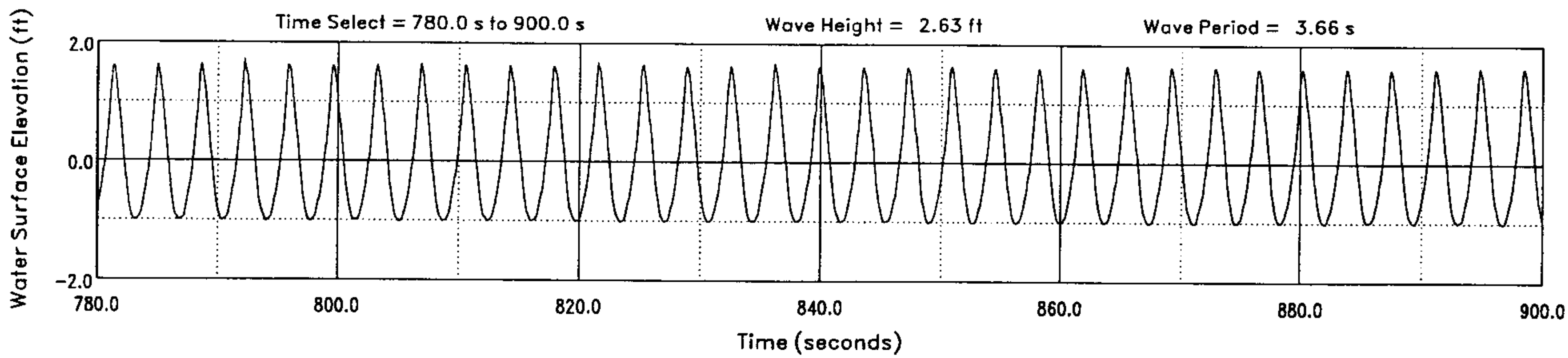
Test Number : nov13_testa_h0p80_t3p66_p
(Wave Height = 2.53 ft, Wave Period = 3.66 s)



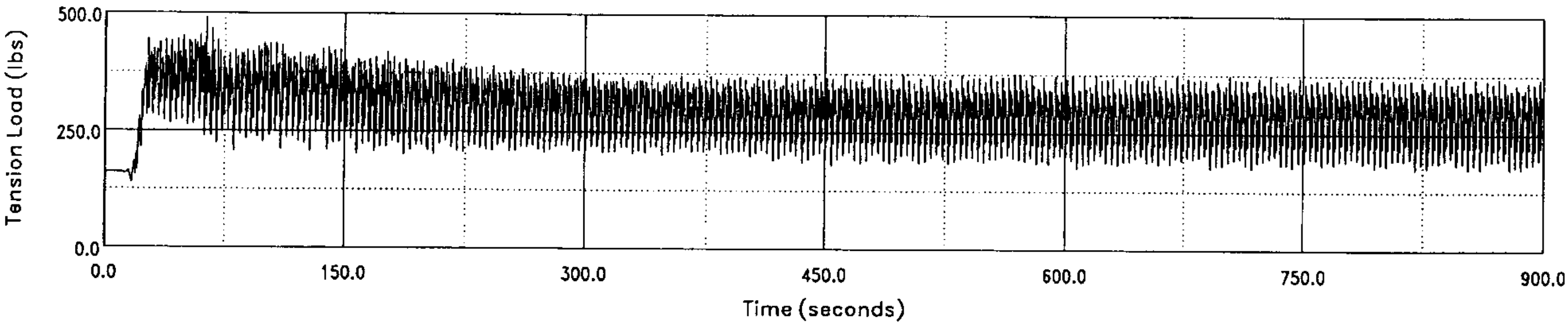


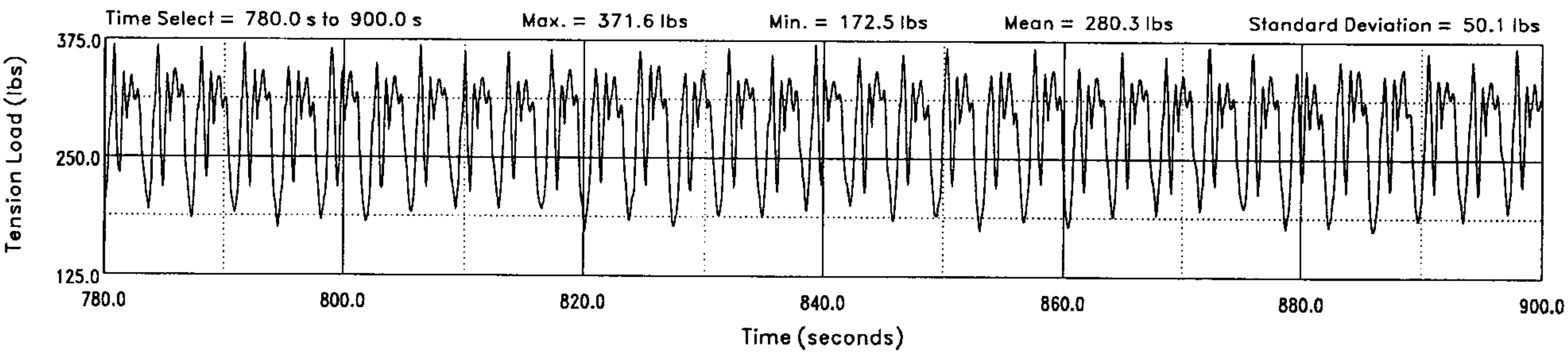
Test Number : nov13_testb_h0p80_t3p66_p



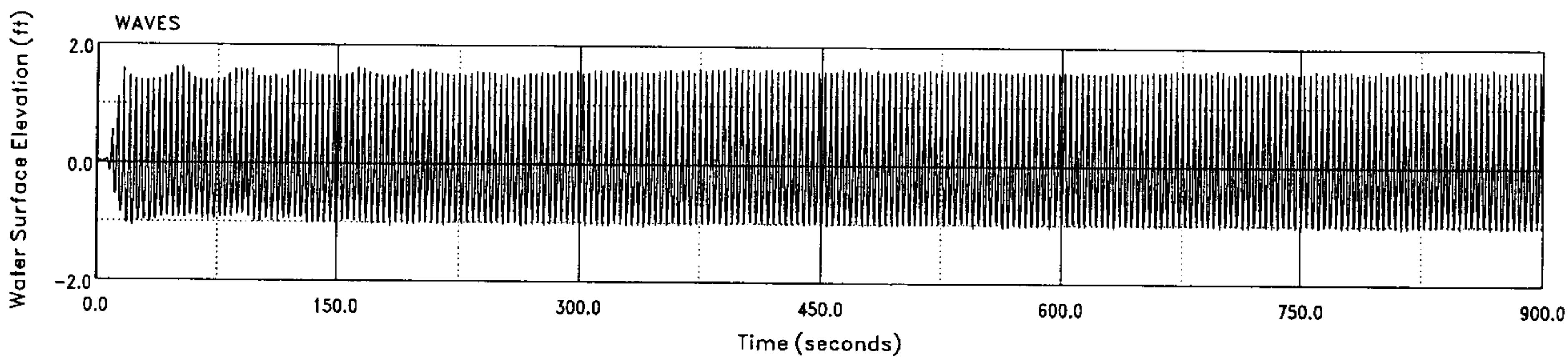


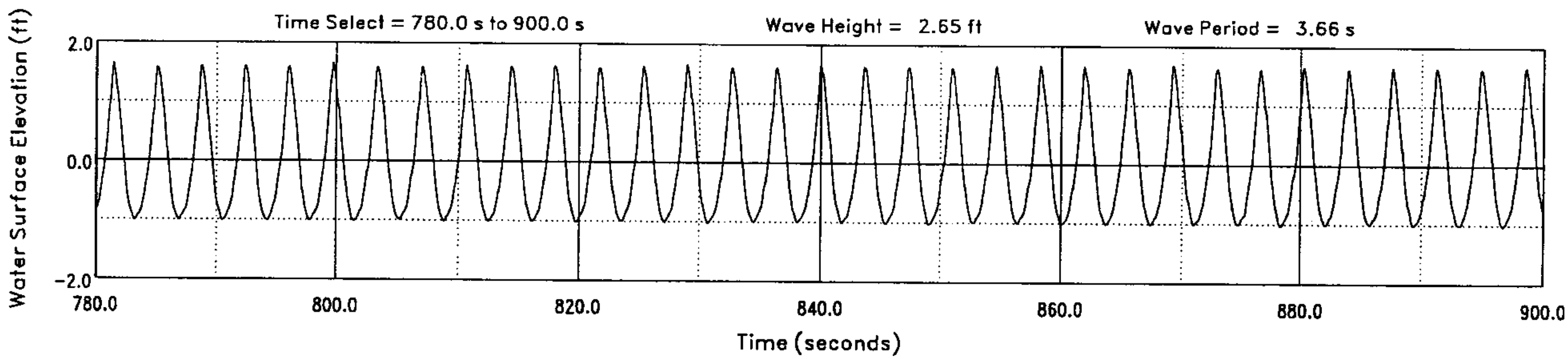
Test Number : nov13_testb_h0p80_t3p66_p
(Wave Height = 2.63 ft, Wave Period = 3.66 s)



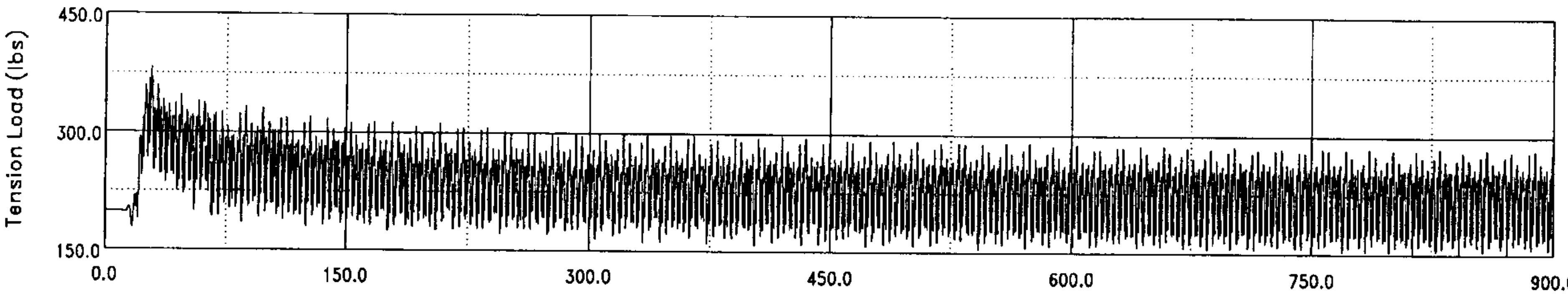


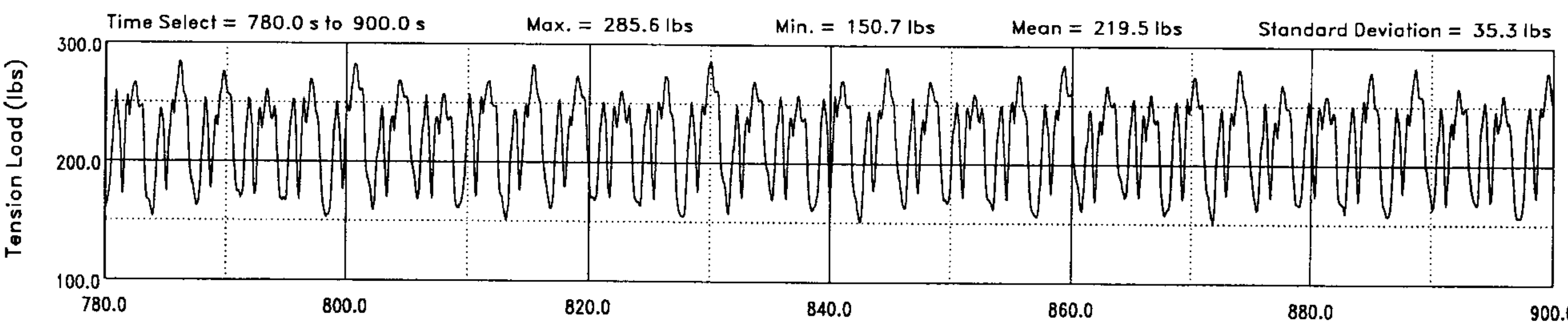
Test Number : nov13_testc_h0p80_t3p66_p



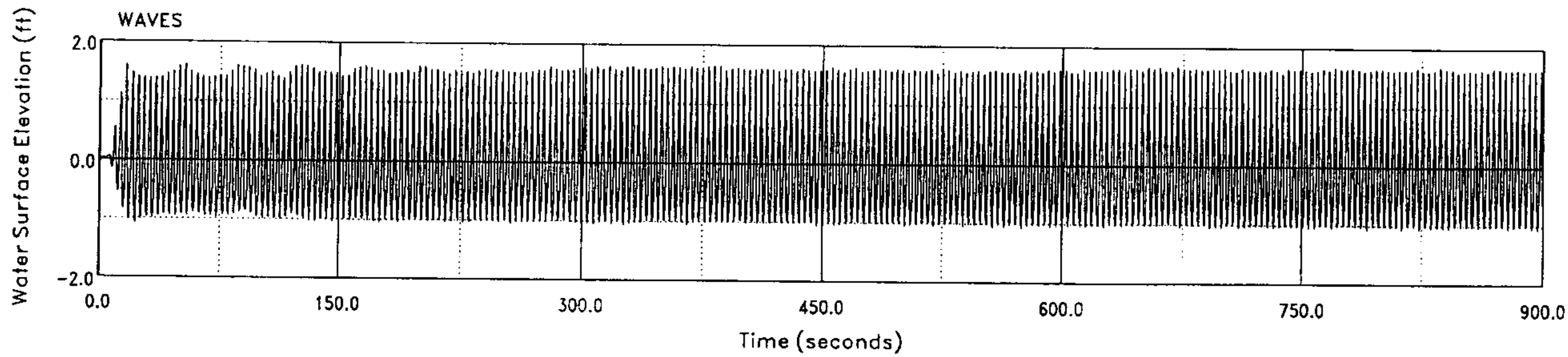


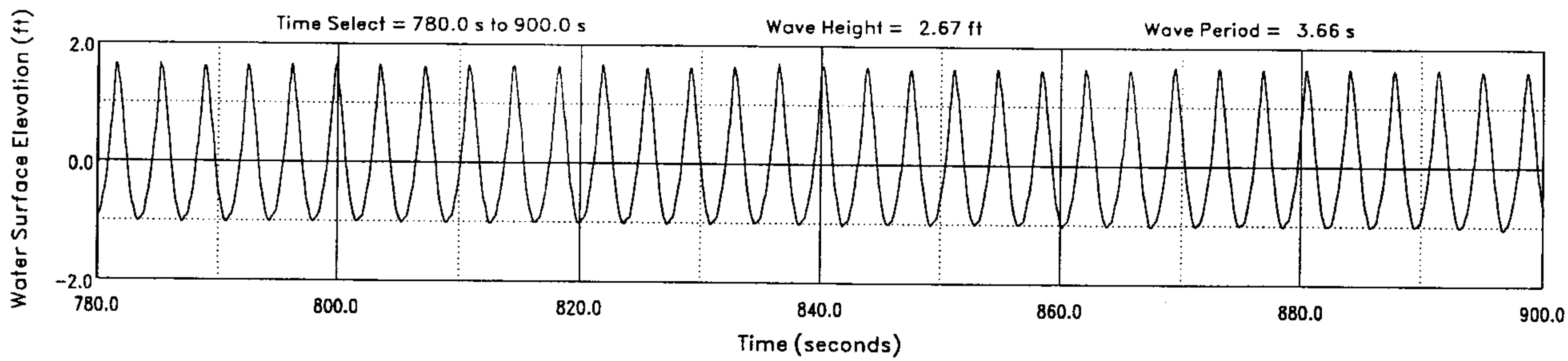
Test Number : nov13_testc_h0p80_t3p66_p
(Wave Height = 2.65 ft, Wave Period = 3.66 s)





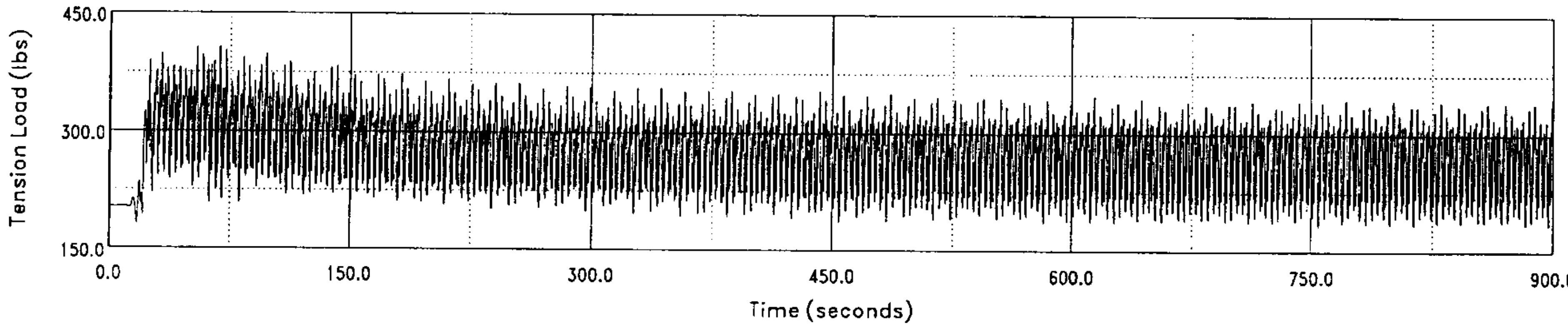
Test Number : nov13_testd_h0p80_t3p66_p

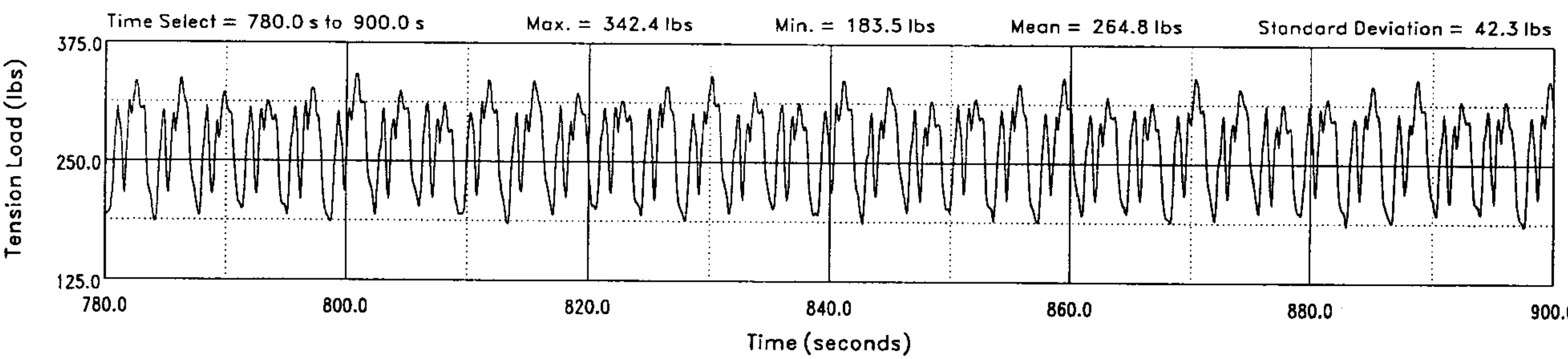




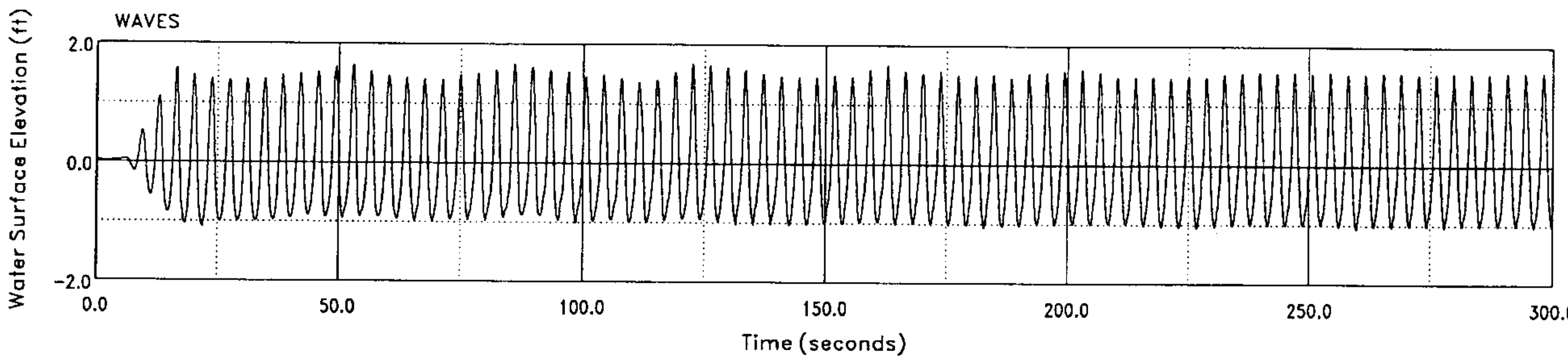
Test Number : nov13_testd_h0p80_t3p66_p

(Wave Height = 2.67 ft, Wave Period = 3.66 s)

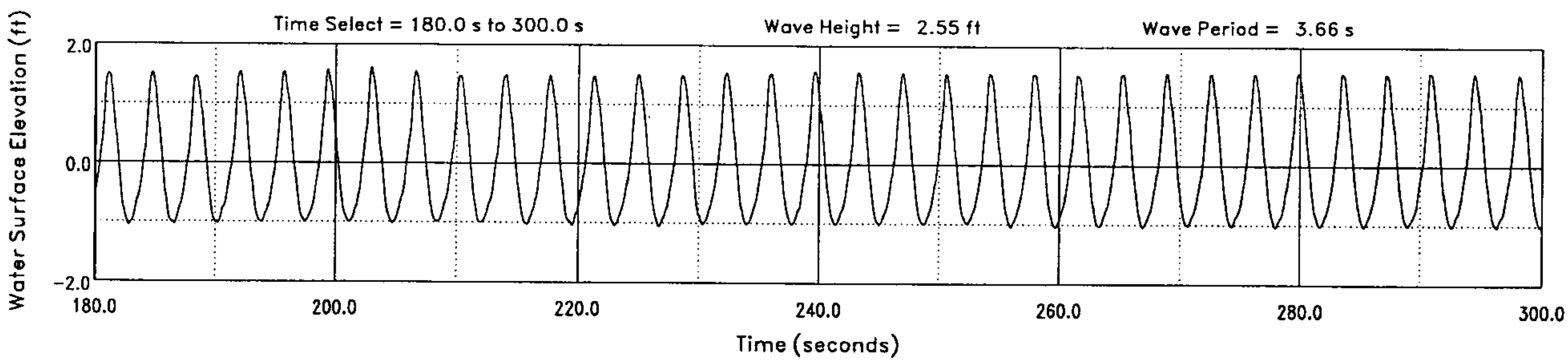




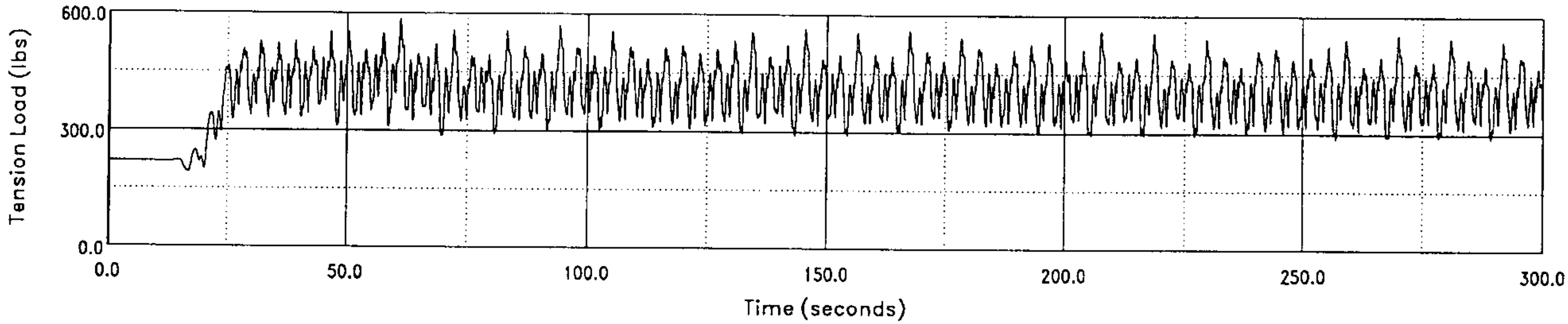
Test Number : nov13_teste1_h0p80_t3p66_p

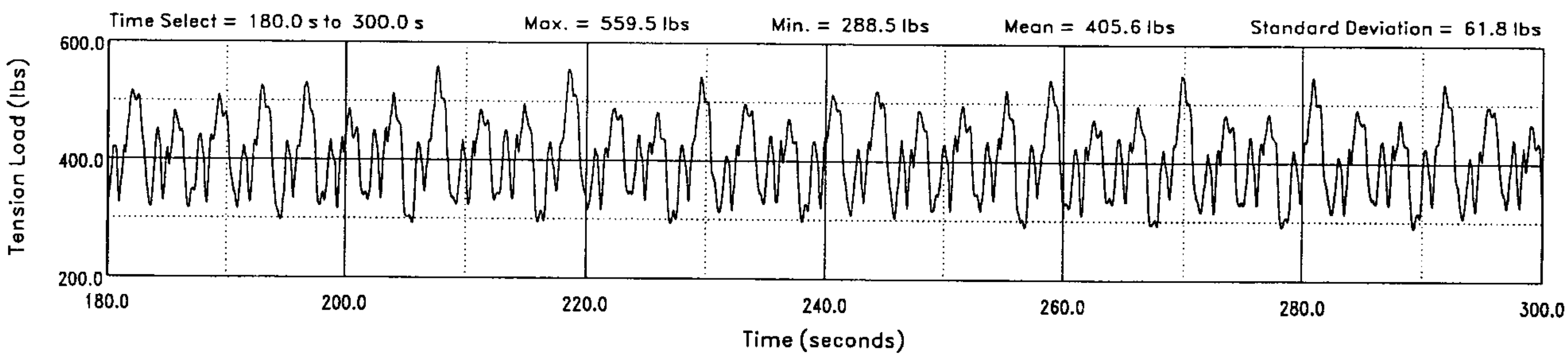


Time Select = 180.0 s to 300.0 s
Wave Height = 2.55 ft
Wave Period = 3.66 s

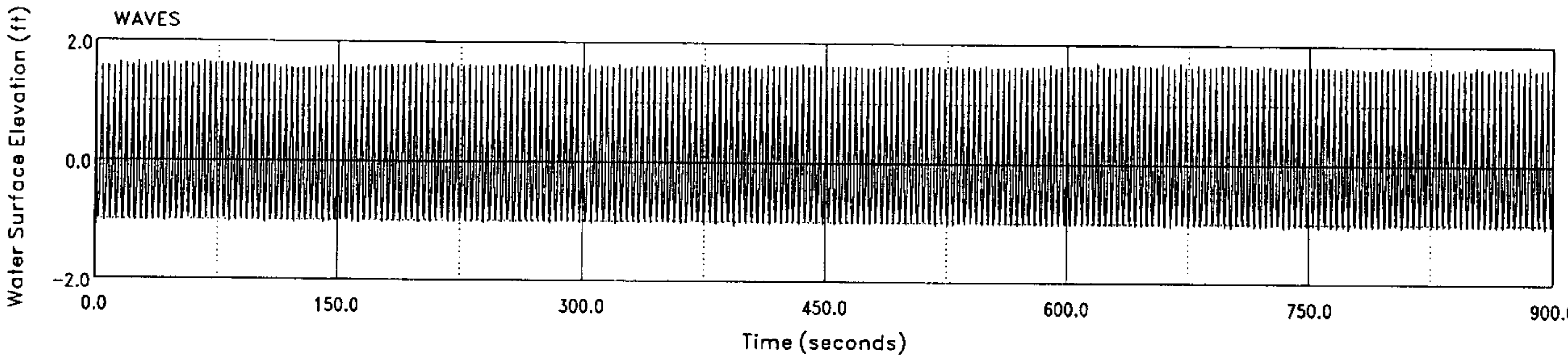


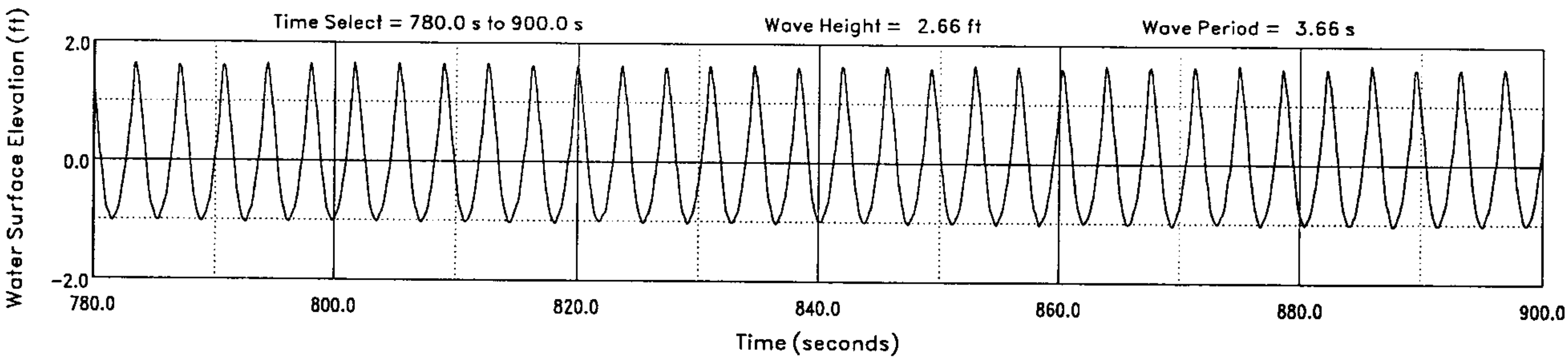
Test Number : nov13_teste1_h0p80_t3p66_p
(Wave Height = 2.55 ft, Wave Period = 3.66 s)



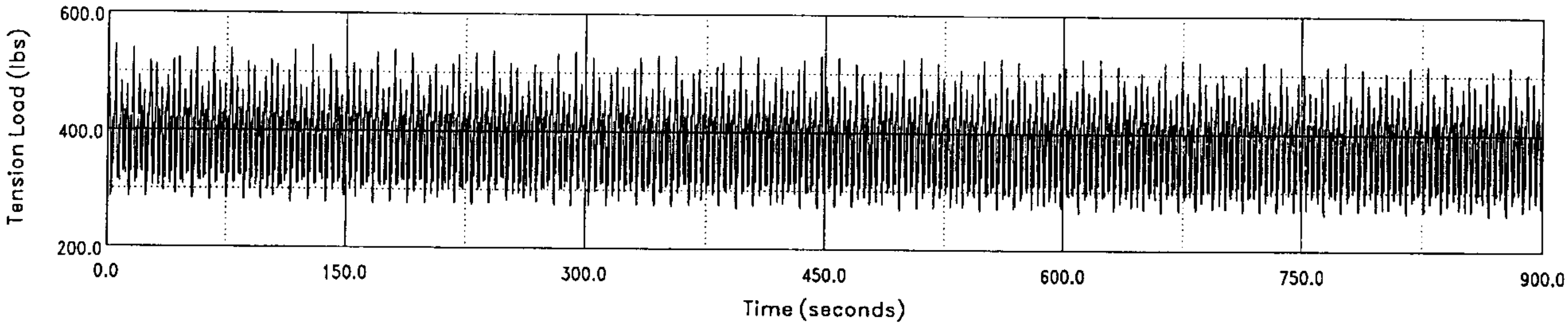


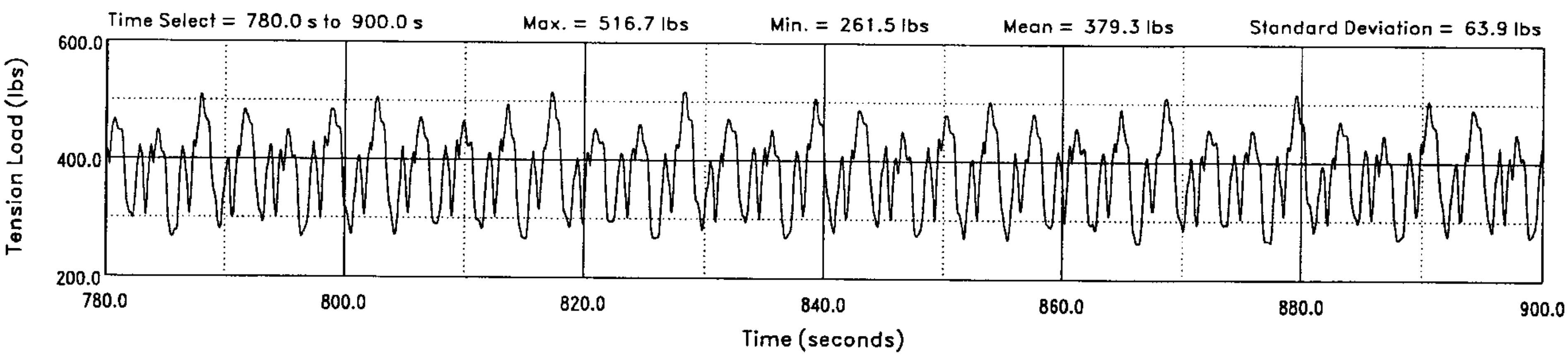
Test Number : nov13_teste2_h0p80_t3p66_p



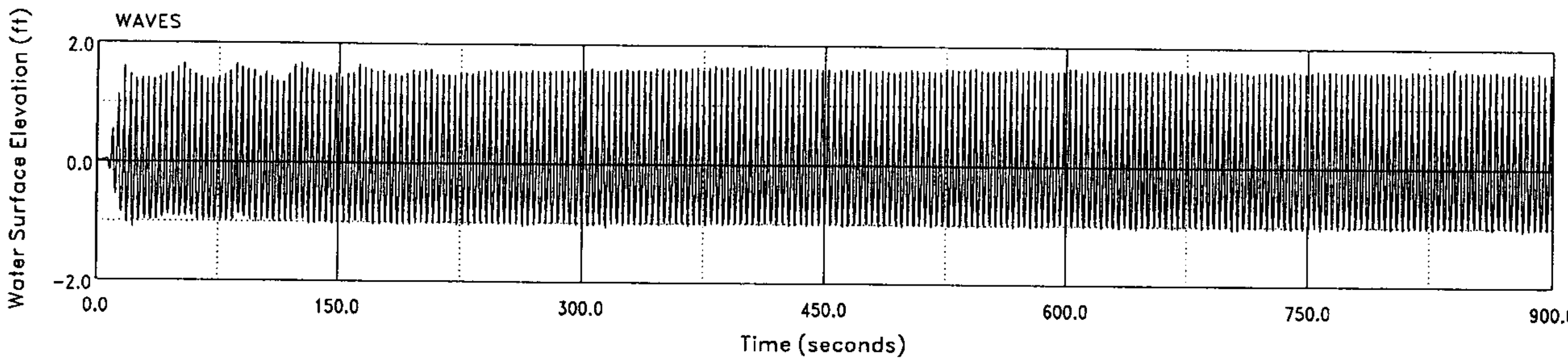


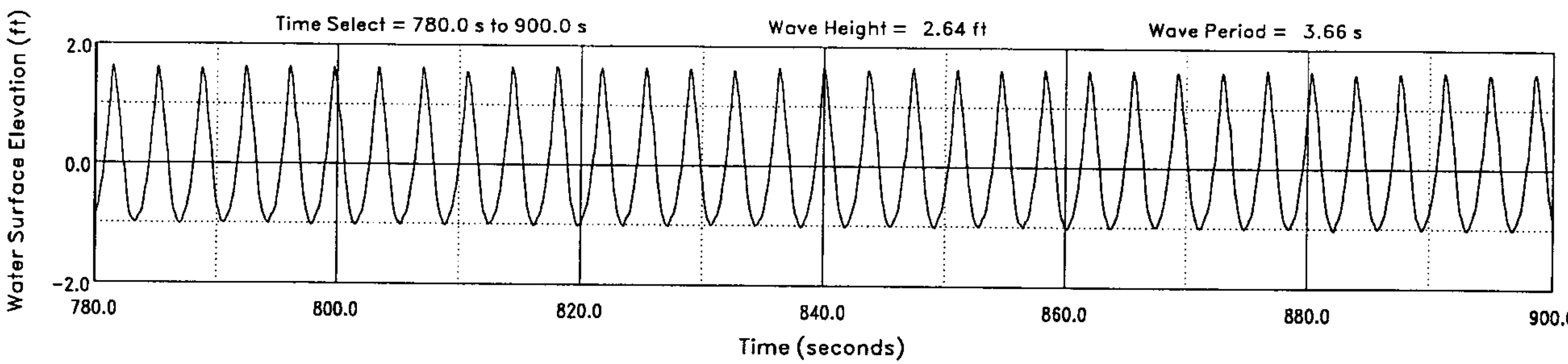
Test Number : nov13_teste2_h0p80_t3p66_p
(Wave Height = 2.66 ft, Wave Period = 3.66 s)



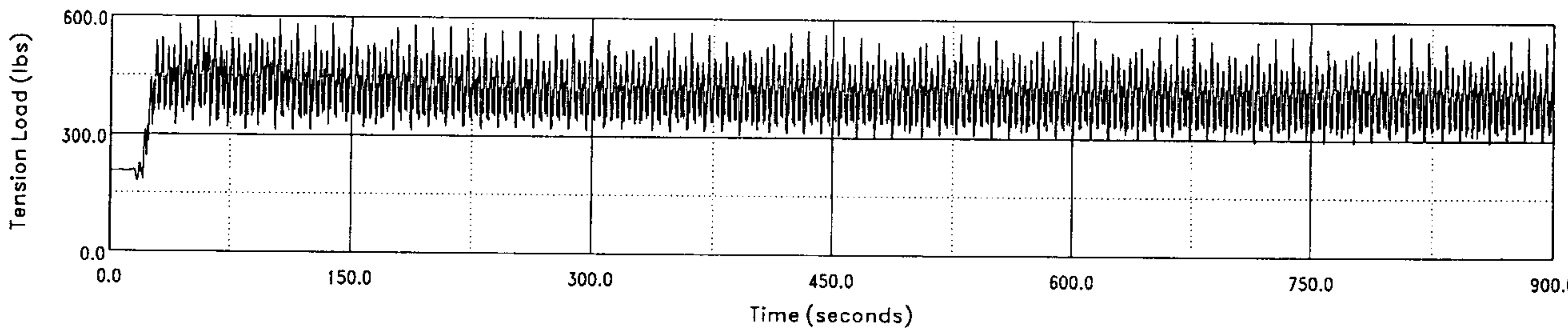


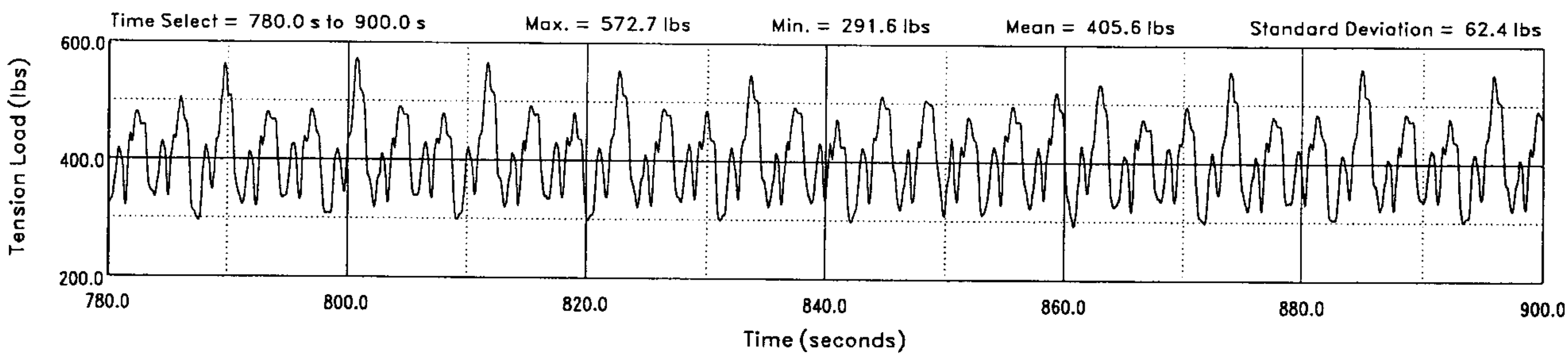
Test Number : nov13_testf1_h0p80_t3p66_p





Test Number : nov13_testf1_h0p80_t3p66_p
(Wave Height = 2.64 ft, Wave Period = 3.66 s)





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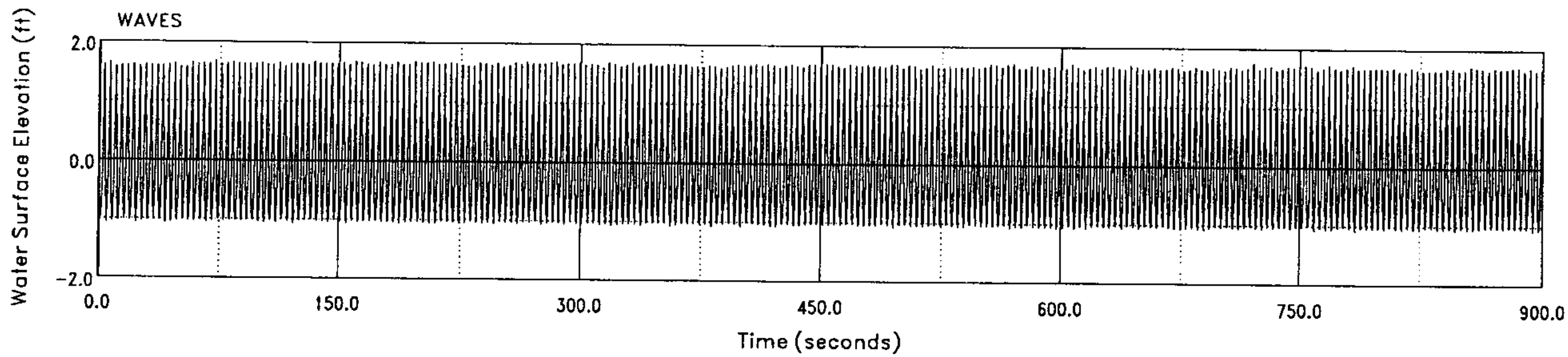
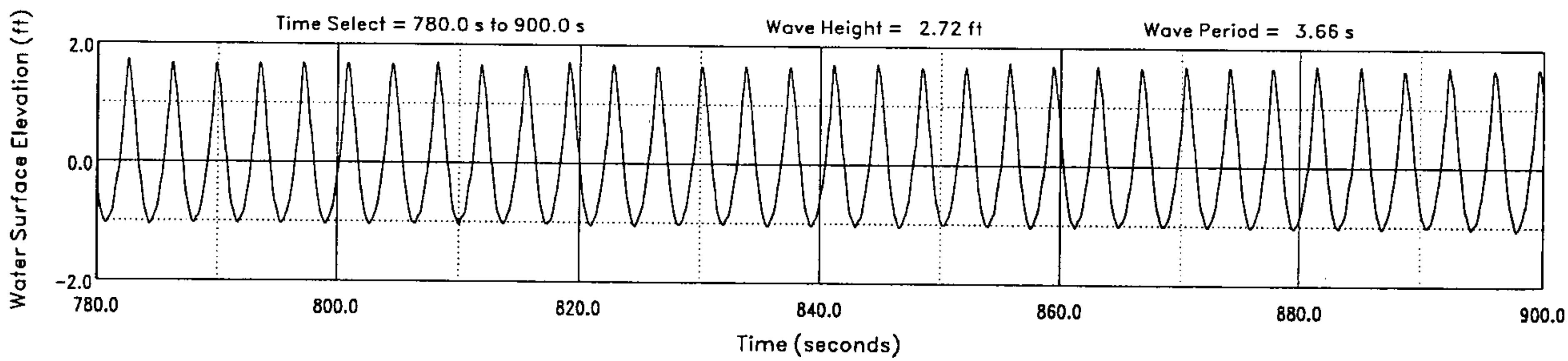
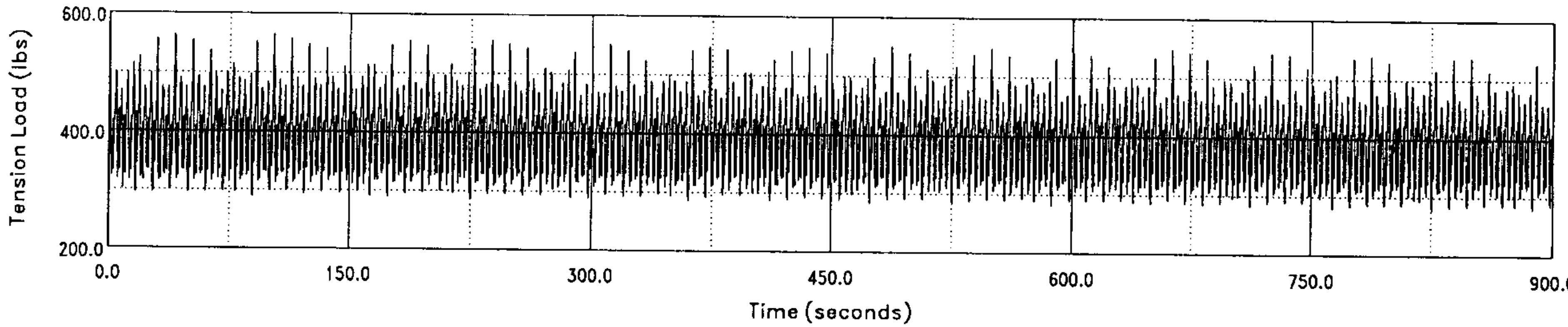
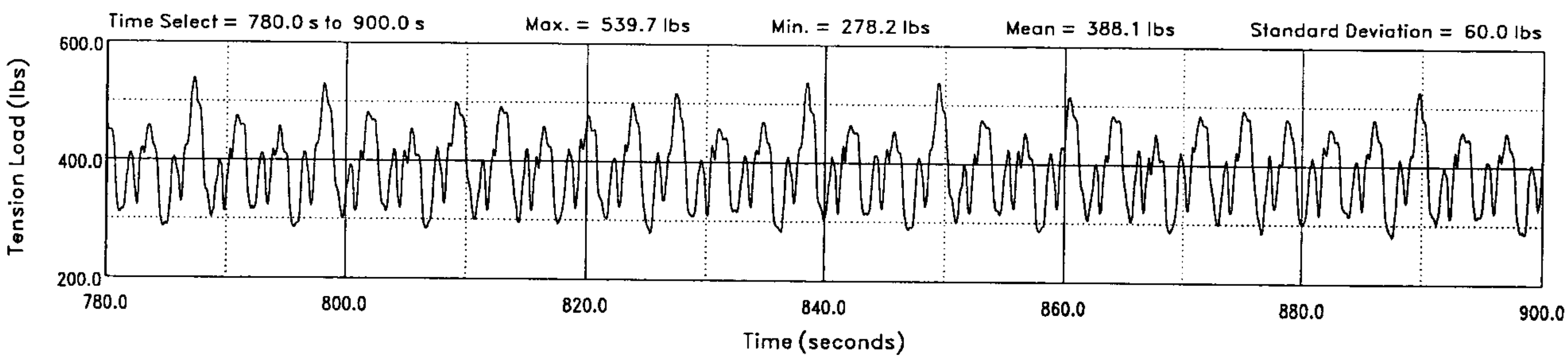


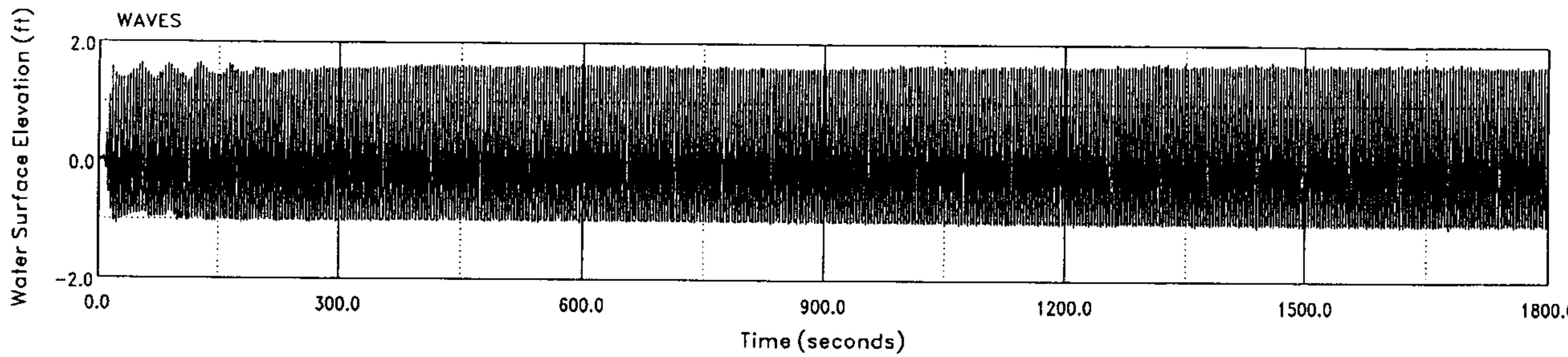


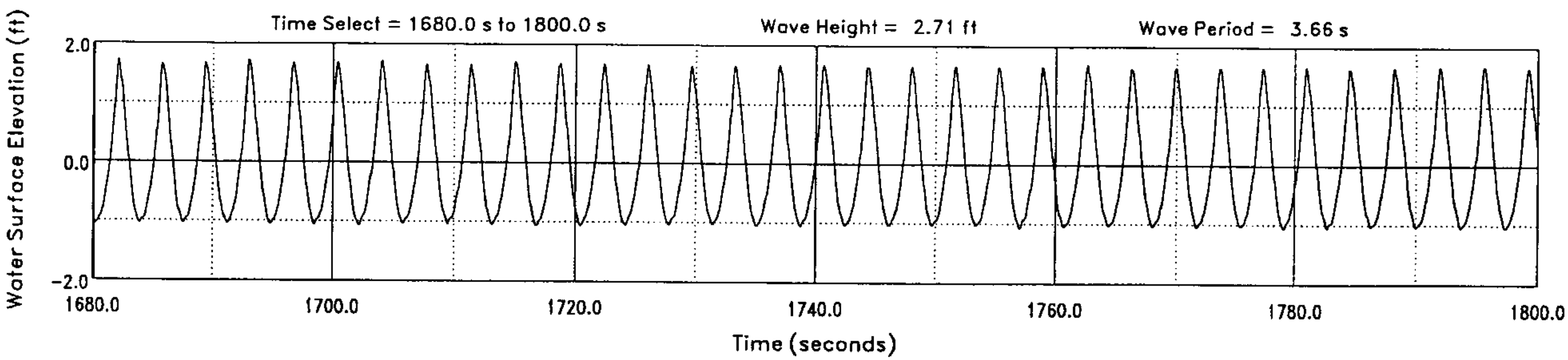
Test Number : nov13_testf2_h0p80_t3p66_p
(Wave Height = 2.72 ft, Wave Period = 3.66 s)



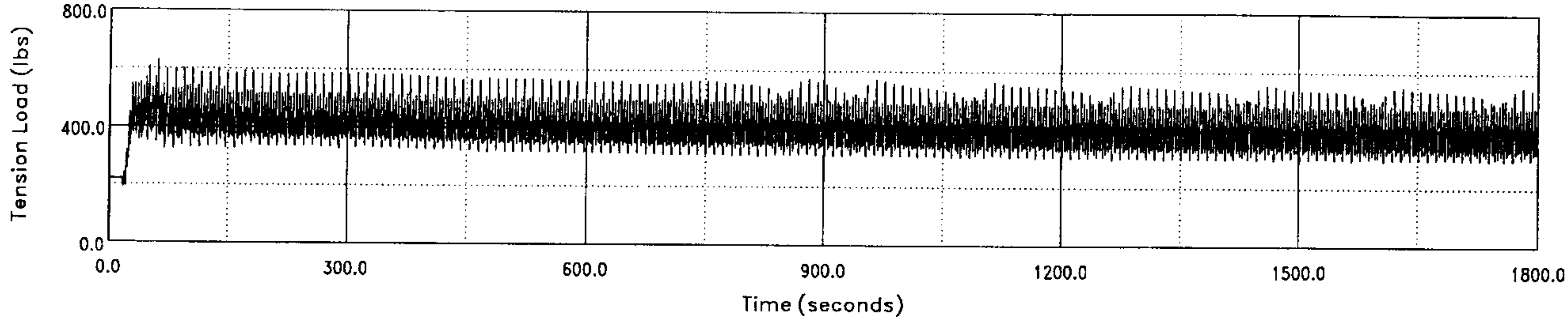


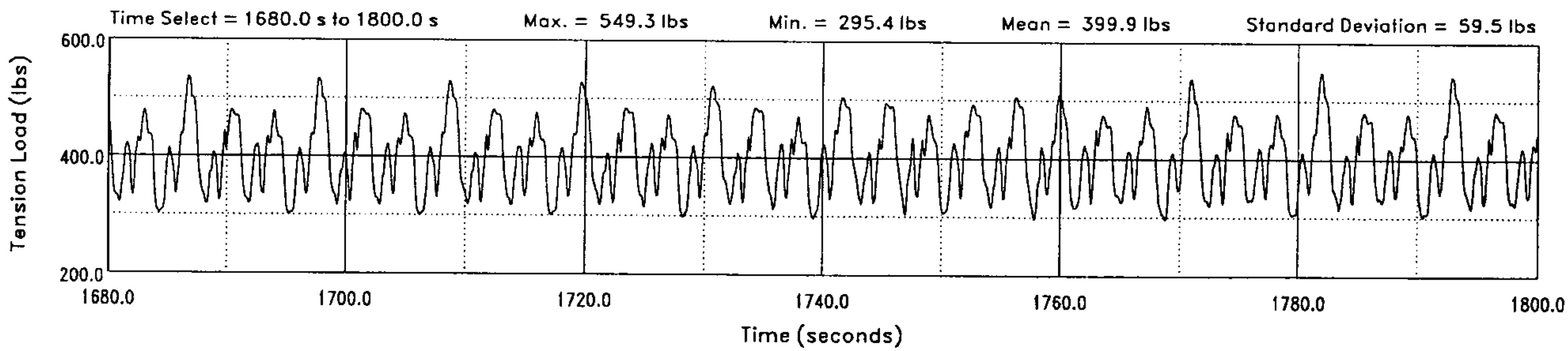
Test Number : nov13_testg_h0p80_t3p66_p





Test Number : nov13_testg_h0p80_t3p66_p
(Wave Height = 2.71 ft, Wave Period = 3.66 s)





test's heat flux data as incorrect). The heat flux ranged from 0 to 9.5 W/cm^2 (0 to 95 kW/m^2). It is also clear that the location of the transducers needs to be changed to better measure the heat flux impinging on the fire side of the boom surface. Figure 6-26 shows the temperature of the thermocouple for this last run. The placement of thermocouples in future tests to measure the temperature of the boom material needs to be reassessed as well.

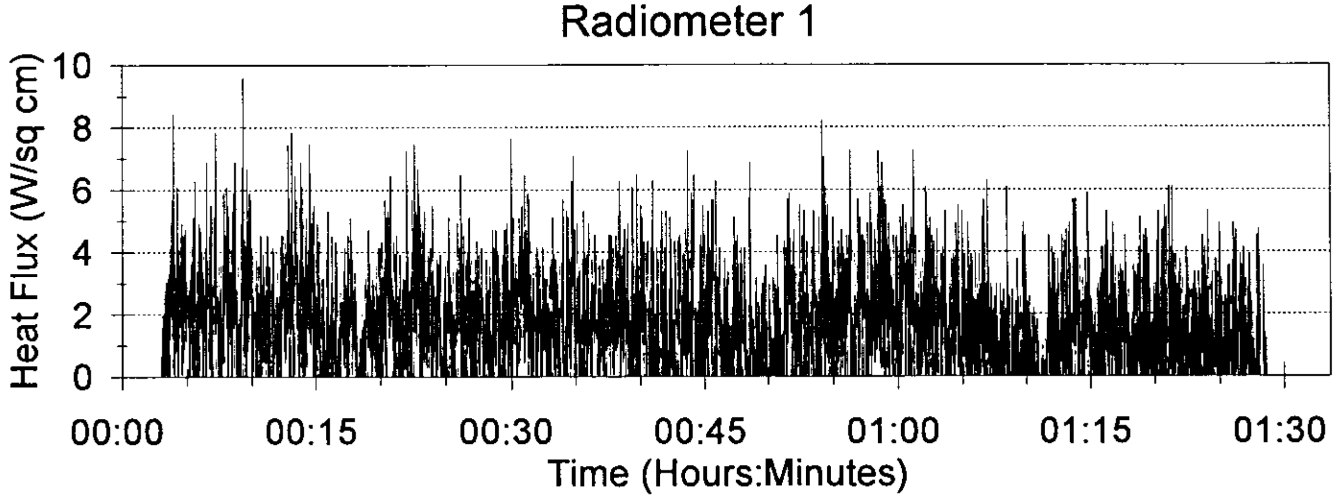
On completion of the tests the boom was inspected. At the end of the approximately 7 hours of flame exposure it was visually apparent that the boom was beginning to suffer significant degradation. The refractory fabric had worn through at several vertical stiffeners (Figure 6-27), and the entire surface exposed to flame had been charred. The boom sail material had begun to sag at the vertical stiffeners, to the point where the top of the stiffeners were almost underwater (Figure 6-28). After this inspection the boom was removed from the basin and replaced in the WRF for the final wave stress tests.

6.3 Post-burn Wave Stress Test

The boom was returned to the WRF for a final 2-hour wave stress test. The mooring posts in the WRF had been moved farther apart and the desired pre-tension of 900 N (200 pounds) could be achieved. The test was stopped periodically and the boom re-tensioned to 900 N (200 pounds) because the stainless steel mesh carrying the longitudinal load in the boom began to fail and the boom stretched. Figure 6-29 shows part of the time series of the waves and tension loads acting on the boom. The forces measured by the load cell varied between approximately 1,350 and 2,550 N (300 and 575 lb.) each wave cycle with a mean of just over 1,800 N (400 lb.).

Appendix 9 contains a table listing relevant characteristics of each run as well as extensive time series of the tension loads, plus a short segment to which analysis was applied. Again, the waves were very regular with time, with a height of 80 cm and period of 3.66 s.

Figure 6-25: Heat flux for test run 5



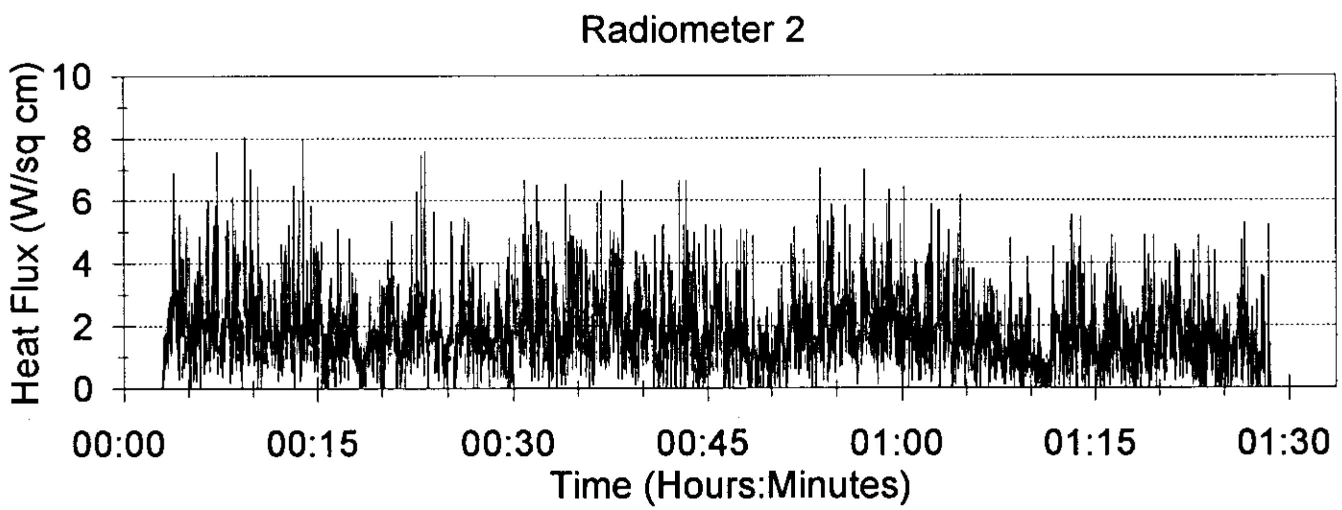


Figure 6-26: Record of temperature above boom for test run 5

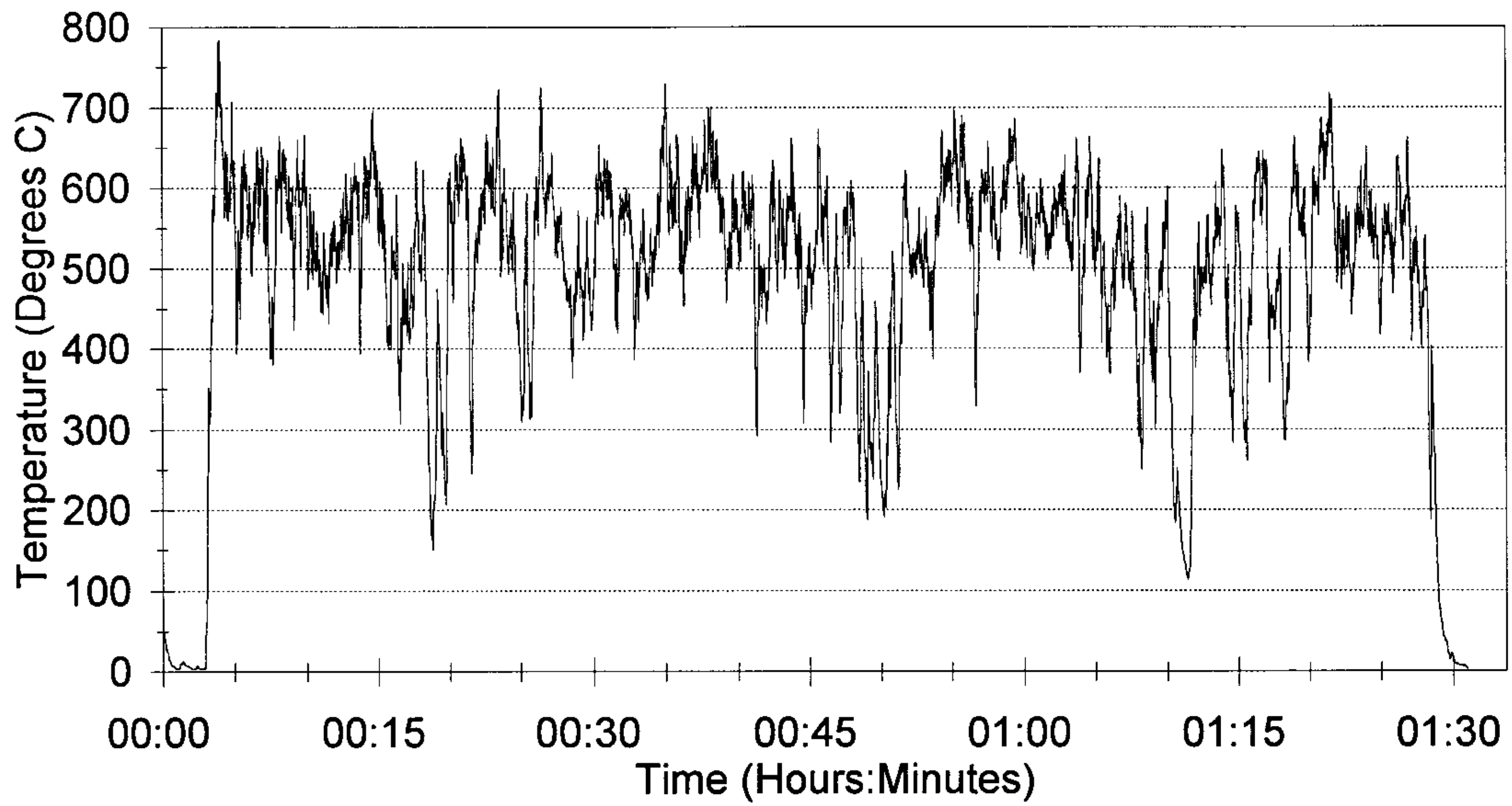
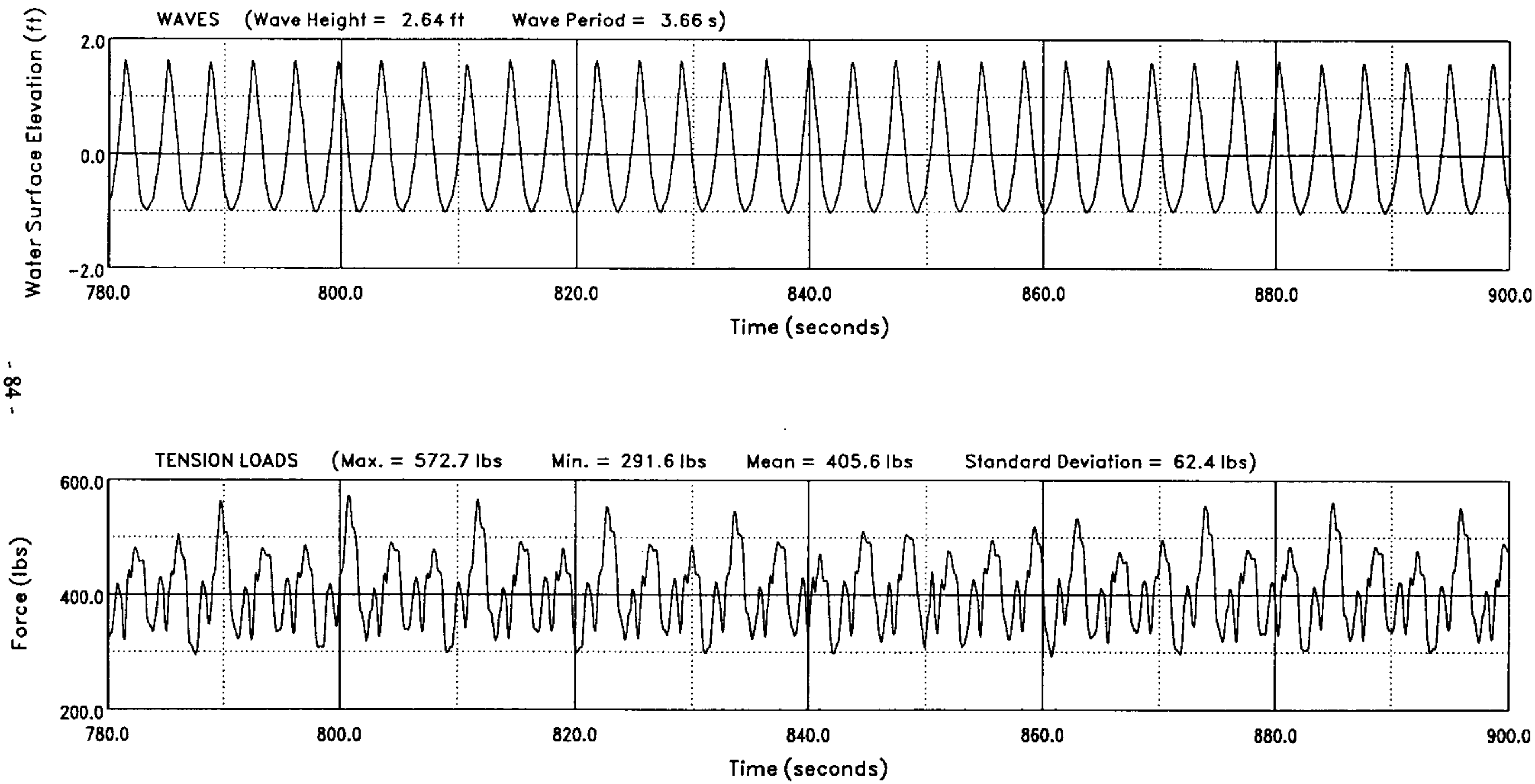


Figure 6-29: Typical time series results for the post-burn test



After the two hour test period had elapsed, the boom was examined carefully. Considerable degradation of the refractory fabric had occurred in the areas that had been exposed to flames (Figure 6-30) and several portions of the stainless steel mesh had failed (Figure 6-31). Failed fabric, wire mesh and voids in the refractory material were so evident (Figure 6-32) that it was deemed unnecessary to test the boom section for its ability to retain thick, low viscosity oil in a separate test. While still in the Flume, water containing a soluble dye was blown against one side of various sections of the boom using a small compressed air stream directed at the water surface. It was observed that the dyed water moved quickly though the boom in areas that had suffered severe degradation of the refractory fabric. This was generally at the vertical stiffeners between float segments (Figure 6-33); however, it was also observed to occur in the middle of a badly worn float segment as well. It should be noted that the dyed water did not penetrate the boom in undegraded areas of the boom and was contained on one side.

6.4 Comparison with Boom Damage at NOBE

In August 1993, 212 m of the same boom as tested here was used to contain the burning oil at the Newfoundland Offshore Burning Experiment (NOBE). These burns were conducted 45 km offshore of St. John's, Newfoundland in 0.5 m waves with 8-11 km/hr winds (OSIR, August 19, 1993; NOBE Newsletter September 1993). Two discreet burns were conducted. The first involved 48.3 m^3 of slightly weathered Alberta Sweet Mixed Blend (ASMB) crude oil burned over a 1.5 hour period. Initially, some splash over of the oil was observed; however, most of this oil was reportedly retained in the stagnation zone aft of the boom and subsequently ignited and burned by the main fire. At the end of the first burn, the boom was inspected. As shown in Figure 6-34, some signs of fatigue in the stainless steel mesh were observed at a point about 10 cm from the vertical stiffeners and some of the refractory fabric was missing; however, the boom was considered fit enough for a second burn (NOBE Newsletter September 1993).

One hour and 15 minutes into the second burn several flotation sections from the boom came loose, oil began to leak rapidly and the oil pumping was stopped. After the fire had stopped (28.9 m^3 had burned) the boom was again inspected. A prototype section of the boom that incorporated a middle tension member (the boom tested here did not have this member) had lost 3 flotation sections and a number of other sections were completely missing refractory fabric near the vertical stiffeners (see Figure 6-35, NOBE Newsletter September 1993; Raloff 1993). Photos (Raloff 1993) of the damage to the boom after NOBE are strikingly similar to the damage observed as a result of these tests. Anectdotal accounts from the crew that recovered the burned sections of the boom after the experiment confirmed that the damage to the floats, mesh and refractory fabric of the NOBE boom was severe.

The boom tested in the Flume and Basin suffered degradation similar to that of the boom at NOBE, although not as intense or in as short a time. By the end of the draft test protocol the boom had been exposed to propane flames for approximately 7 hours and waves for approximately 13 hours (4 hours in the Wave Research Flume with 0.8 m x 3.7 s waves; and, 1 hour with 0.3 m x 1.4 s and 8 hours with 0.6 m x 2.5 s waves in the Outdoor Manuevering Basin). It was charred and had lost significant amounts of refractory fabric to the combined effects of heat and abrasion; particularly, but not exclusively, in the vicinity of the vertical stiffeners (Figures 6-36 and 6-37). As well, some of the structural components had started to fail. The test boom section would not have contained oil after the tests. This indicates that the draft test protocol reproduces the correct stresses (both mechanical and heat); but, that they need to be increased in intensity to better simulate real *in situ* burning conditions.

6.5 Improvements to the Draft Test Protocol

It is recommended that the protocol be amended and re-tested. In particular, three areas of improvement are suggested: i) increasing the heat flux to the boom; ii) conducting more representative heat flux measurement; and, iii) carrying out the flame exposure tests with the boom section mechanically pretensionsed.

Heat release rates for *in situ* oil fires on water range from 1.76 MW/m^2 for ANS crude to 2.34 MW/m^2 for diesel fuel. The heat release rate for a liquid propane fire on water, as tested by NIST at the USCG test site in Mobile, was about 1.6 MW/m^2. The burning of liquid propane on water at this rate did result in some smoke being generated. The heat release rate for the draft protocol fire boom tests reported here using propane gas was about 0.7 MW/m^2. This heat release rate, a direct function of the flow rate of propane, was kept intentionally low in order to avoid smoke production from the fire for these initial protocol tests. The test boom could be subjected to a more rigorous environment by increasing the flow rate of gaseous propane by up to a factor of three (to 2.1 MW/m^2). The addition of combustion air, either by bubbling or from compressed air jets, could further increase heat flux to the boom, while maintaining a nearly-smokeless burn.

The fire data acquisition system needs to be revised. The heat flux transducers should be mounted at the mid-way point of the surface of the boom facing the fire and the thermocouples should be imbedded in the boom surface material. The grounding problem with the stainless steel mesh of the boom needs to be solved. In addition, a better method for measuring the propane flow rate to the bubbler needs to be devised.

The exposure of the appropriately pre-tensioned test boom to waves in the WRF after the boom tests appeared to accelerate the degradation of the boom. Consideration should be given to mechanically pre-tensioning the test boom section to 900 N (200 lb.) during the fire tests in waves to see if this causes more rapid deterioration; the loads imposed by the current on the boom deployed in a "U" in the basin were far lower than would be expected in a full-scale deployment offshore. Pre-tensioning would also make the protocol better suited to many other test tanks where the generation of a current is not readily possible.

Measurement of the waves at one location near the mouth of the boom provided little information about the motions of the boom in the burn pocket, which may be important for defining the flexing and wear of the boom materials. In future test protocols, the waves should be measured nearer the apex of the boom. However, if a wave probe was to be installed inside the pocket, it could not withstand the flames; if it was located behind the pocket, it would be in the lee of the boom and show lower waves; and if off to one side of the apex, would again be in the lee of the boom. A pressure cell wave sensor resting on the bottom of the tank directly beneath the boom apex, would be able to measure the surface motions of the boom and yet be unaffected by the flames. Alternatively, accelerometers mounted on the lee side of the boom itself could be used to measure the boom motions.

The 22,000 N (5,000 lb.) capacity load cells were oversized for the surprisingly low mooring loads, and the 90 N (20 lb.) tensions measured in the Basin were perhaps approaching the limit of what could be expected from these cells. Knowing this, future tests should use lighter, lower capacity cells. However, in future tests, it may not be necessary to monitor the mooring loads at all since they are so small, and it is doubtful if the information could be used to quantify the stresses in the boom as it flexes in the region with flames.

Waves alone provided a sufficient transport current, or circulation, in the basin to maintain the catenary shape of the boom. If further control of the shape is needed, a system of several light ropes or cables leading from the pocket to the end of the tank could suffice. Thus, a complex and costly current generation system should not be required for future tests unless needed to keep any floating unburned liquid fuel from propagating upwave away from the burning pocket.

In the Wave Research Flume, a tensioning winch should be provided at each of the mooring posts. The mooring posts should be spaced farther apart to ensure that sufficient pre-tension can be applied to a test boom without overly restricting the motion of the ends of the boom by their proximity to the mooring point on the posts.

7. Conclusions And Recommendations

7.1 Conclusions

Recent experiences with refractory-fabric-based fire-resistant oil containment booms have shown them to be less durable than desired under field conditions and unable to contain thick pools of burning oil for long periods of time. A test protocol being developed simulates the heat and mechanical stresses of an open-water *in situ* burn without the problems of burning crude oil in test tanks or the costs and challenges, such as obtaining permits, associated with testing offshore. The draft protocol was tested using a section of fire-resistant boom at the facilities of the Canadian Hydraulics Centre of the National Research Council in Ottawa. The boom was first stressed under tension for two hours in an indoor flume using 0.8 m high waves with a period of 3.67 seconds. Then, the boom was deployed in a U-configuration in an outdoor wave tank, where it was subjected continuously to a current (variable from 0.2 to 0.6 m/s) and to waves (either 0.3 m high with a 1.4 second period or 0.6 m high with a 2.5 second period). Propane gas, from an underwater bubbler system, was burned in the pocket of the boom to simulate the oil collection and the combustion phases of *in situ* burning operations. Heat fluxes and flame temperatures were measured. Finally, the boom was returned to the indoor tank for another two hours exposure to the 0.8 m waves.

The boom was periodically inspected for damage throughout the test program and its progressive degradation recorded. The boom used in the testing of the protocol was the same as the one used in the Newfoundland Offshore Burn Experiment. The test section of boom suffered degradation similar to that of the identical boom in the offshore trial, although not as severe or in as short a time. By the end of the test protocol the test section of boom was charred and had lost significant amounts of refractory fabric to the combined effects of heat and abrasion, particularly, but not exclusively, in the vicinity of the vertical stiffeners. As well, some of the structural components had started to fail. The boom section would not have effectively contained oil. This indicates that the protocol reproduces the correct stresses (both mechanical and heat), but that they need to be increased in intensity to better simulate real *in situ* burning conditions.

7.2 Recommendations

It is recommended that consideration be given to conducting further testing next year at the NRC facilities to refine the test protocols. Suggested revisions to the protocol include:

1. Increasing, by up to a factor of three, the propane flow rate over the same fire area in the pocket of the boom in order to achieve heat release rates similar to those expected from an oil fire. The addition of combustion air into the fire zone, to increase heat fluxes, should also be researched. This would be done to see if higher heat loads, causing more and faster degradation in the boom, can be achieved while maintaining no visible air emissions. It would also be ideal to be able to "benchmark" the tests to the NOBE boom failure by causing the boom to fail in about the same time frame as occurred at sea with a crude oil fire.

2. Improving the data acquisition aspects of the protocol, particularly heat flux, boom surface temperature, boom tensional loads and propane flow rate; and,

3. Testing long (50 foot) pre-tensioned linear sections of boom engulfed in flames in the Outdoor Maneuvering Basin, both parallel to and, at angles to the larger waves.

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Appendix 1

Small-scale Laboratory Burn Test Data

Test # 1

Mass Cyl. (kg)	Pressure (psig)	Temp. (°C)	Elapsed Time (min)	Mass Flow (g/min)	Flowrate @Gauge (L/min)	Flowrate @Nozzle (L/min)	Accumulator (L/min)	Flowrate @Nozzle (scfm)
16.105	14.0	22.2	0					
16.040	13.0	22.2	1	65	18.66	35.53	16	1.28
15.975	12.0	22.2	2	65	19.35	35.53	18	1.28
15.920	11.0	22.2	3	55	17.00	30.07	16	1.08
15.865	10.0	22.2	4	55	17.67	30.07	16	1.08
15.815	10.0	22.2	5	50	16.39	27.33	16	0.98
15.755	10.0	22.2	6	60	19.67	32.80	17	1.18

Note: temperature was not recorded accurately

Test #2

Mass Cyl. (kg)	Pressure (psig)	Temp. (°C)	Elapsed Time (min)	Mass Flow (g/min)	Flowrate @Gauge (L/min)	Flowrate @Nozzle (L/min)	Accumulator (L/min)	Flowrate @Nozzle (scfm)
15.565	30.0	22.2	0					
15.470	28.0	22.2	1	95	17.60	51.93	16	1.87
15.375	26.0	22.2	2	95	18.45	51.93	20	1.87
15.290	24.0	22.2	3	85	17.33	46.47	13	1.67
15.210	22.0	22.2	4	80	17.18	43.73	17	1.57
15.130	21.0	22.2	5	80	17.89	43.73	16	1.57
15.055	20.0	22.2	6	75	17.25	41.00	16	1.47

Note: temperature was not recorded accurately

Test #3

Mass Cyl. (kg)	Pressure (psig)	Temp. (°C)	Elapsed Time (min)	Mass Flow (g/min)	Flowrate @Gauge (L/min)	Flowrate @Nozzle (L/min)	Accumulator (L/min)	Flowrate @Nozzle (scfm)
14.120	55.0	13.9	0					
13.965	48.0	12.7	1	155	18.39	84.73	17	3.04
13.830	45.0	12.7	2	135	17.29	73.80	16	2.65
13.710	40.0	12.7	3	120	16.44	65.60	15	2.36
13.590	35.0	11.6	4	120	17.98	65.60	18	2.36
13.500	32.0	11.8	5	90	14.58	49.20	15	1.77

Test #4

Mass Cyl. (kg)	Pressure (psig)	Temp. (°C)	Elapsed Time (min)	Mass Flow (g/min)	Flowrate @Gauge (L/min)	Flowrate @Nozzle (L/min)	Accumulator (L/min)	Rotameter	Flowrate @Nozzle (scfm)
12.775	9.5	25.3	0						
12.675	9.0	24.9	1	100	34.13	54.67	27	136	1.96
12.605	8.0	24.5	2	70	24.64	38.27	28	133	1.37
12.540	7.0	24.2	3	65	23.88	35.53	24	129	1.28
12.470	6.1	24.0	4	70	26.84	38.27	24	126	1.37
12.405	6.0	23.8	5	65	25.51	35.53	24	120	1.28
12.335	5.1	23.6	6	70	28.13	38.27	24	117	1.37
12.275	4.9	23.6	7	60	24.78	32.80	24	113	1.18
12.220	4.5	23.6	8	55	23.06	30.07	21	110	1.08
12.165	4.0	23.6	9	55	23.61	30.07	22	107	1.08

Test #5

Mass Cyl. (kg)	Pressure (psig)	Temp. (°C)	Elapsed Time (min)	Mass Flow (g/min)	Flowrate @Gauge (L/min)	Flowrate @Nozzle (L/min)	Accumulator (L/min)	Rotameter	Flowrate @Nozzle (scfm)
11.945	31.0	27.5	0					130	
11.840	31.0	27.2	1	105	18.93	57.40	10	130	2.06
11.705	32.0	26.9	2	135	24.05	73.80	20	130	2.65
11.605	31.5	26.7	3	100	17.70	54.67	16	130	1.96
11.525	14.0	26.6	4	80	17.56	43.73	17	100	1.57
11.470	12.0	26.6	5	55	16.32	30.07	14	100	1.08
11.415	11.5	26.7	6	55	17.09	30.07	17	100	1.08
11.350	12.0	26.7	7	65	20.20	35.53	19	100	1.28
11.300	4.0	26.7	8	50	18.11	27.33	18	70	0.98
11.270	4.0	26.9	9	30	13.19	16.40	13	70	0.59

Test 6

Holes: 1 Tanks: 2
Mass of propane used (kg) 0.76

Time (min)	Gas Temp. (°C)	Accumulato (L/min)	Pressure (psig)	Rotameter Reading (cfm)	Flow Rate (scfm)	Flow Rate (g/s)	Total Flow (scf)	Total Mass (kg)	Accumulato Flow Rate (scfm)	Total Flow (scf)	Total Mass (kg)
2	25.7	19	29	1.50	2.06	1.95	12.30	0.70	1.96	9.19	0.52
3	25.6	17	28	1.50	2.03	1.92			1.71		
4	25.4	18	28	1.50	2.03	1.92			1.81		
5	25.3	18	30	1.50	2.08	1.97			1.90		
6	25.2	18	28	1.50	2.04	1.93			1.81		

Note: Rotameter readings for this test are not accurate.

Test 7

Holes: 2 Tanks: 2
mass of propane used (kg) 0.70

Time (min)	Gas Temp. (°C)	Accumulato (L/min)	Pressure (psig)	Rotameter Reading (cfm)	Flow Rate (scfm)	Flow Rate (g/s)	Total Flow (scf)	Total Mass (kg)	Accumulato Flow Rate (scfm)	Total Flow (scf)	Total Mass (kg)
1	25.7	30	15	2.10	2.37	2.25	14.62	0.83	2.10	13.21	0.75
2	25.6	28	14	2.00	2.22	2.10			1.89		
3	25.5	32	13	2.00	2.18	2.07			2.09		
4	25.3	31	11.5	2.00	2.13	2.01			1.92		
5	25.3	30	10.5	1.90	1.98	1.87			1.78		
6	25.1	31	10	1.85	1.91	1.81			1.81		
7	25	29	9	1.80	1.82	1.72			1.62		

Test 8

Holes: 1 Tanks: 2
mass of propane used (kg) 0.81

Time (min)	Gas Temp. (°C)	Accumulato (L/min)	Pressure (psig)	Rotameter Reading (cfm)	Flow Rate (scfm)	Flow Rate (g/s)	Total Flow (scf)	Total Mass (kg)	Accumulato Flow Rate (scfm)	Total Flow (scf)	Total Mass (kg)
1	23.6	19	29	1.35	1.86	1.76	14.78	0.84	1.97	12.58	0.71
2	23.3	15	27	1.35	1.82	1.72			1.49		
3	23.5	16	39	1.50	2.29	2.17			2.04		
4	23.3	12	39	1.50	2.29	2.17			1.53		
5	23.1	15	38	1.45	2.19	2.07			1.88		
6	22.9	16	37	1.45	2.17	2.06			1.97		
7	22.9	14	36.5	1.45	2.16	2.05			1.70		

Test 9

Holes: 2 Tanks: 2
mass of propane used (kg) 1.10

Time (min)	Gas Temp. (°C)	Accumulato (L/min)	Pressure (psig)	Rotameter Reading (cfm)	Flow Rate (scfm)	Flow Rate (g/s)	Total Flow (scf)	Total Mass (kg)	Accumulato Flow Rate (scfm)	Total Flow (scf)	Total Mass (kg)
1	23	32	14	2.20	2.46	2.32	17.64	1.00	2.18	15.69	0.89
2	22.9	31	13	2.10	2.30	2.18			2.04		
3	22.9	31	12	2.10	2.26	2.14			1.97		
4	22.9	31	12	2.05	2.21	2.09			1.97		
5	22.8	30	12	2.05	2.21	2.09			1.91		
6	22.7	31	11	2.00	2.11	2.00			1.90		
7	22.7	31	11	2.00	2.11	2.00			1.90		
8	22.6	31	10	1.90	1.97	1.86			1.82		

Test 10

Holes: 2 Tanks: 2
mass of propane used (kg) 1.00

Time (min)	Gas Temp. (°C)	Accumulato (L/min)	Pressure (psig)	Rotameter Reading (cfm)	Flow Rate (scfm)	Flow Rate (g/s)	Total Flow (scf)	Total Mass (kg)	Accumulato Flow Rate (scfm)	Total Flow (scf)	Total Mass (kg)
1	23.3	35	21	2.40	2.99	2.83	16.35	0.93	2.97	14.77	0.84
2	23.2	32	19	2.40	2.90	2.75			2.56		
3	23.1	31	18	2.30	2.74	2.59			2.41		
4	23.1	32	16.5	2.30	2.68	2.53			2.37		
5	22.9	31	16	2.20	2.54	2.40			2.26		
6	22.9	31	15	2.20	2.50	2.36			2.19		

Test 16

Holes: 2 Tanks: 2
mass of propane used (kg) 0.95

Time (min)	Gas Temp. (°C)	Accumulato (L/min)	Pressure (psig)	Rotameter Reading (cfm)	Flow Rate (scfm)	Flow Rate (g/s)	Total Flow (scf)	Total Mass (kg)	Accumulato Flow Rate (scfm)	Total Flow (scf)	Total Mass (kg)
1	24.5	35	20	2.40	2.94	2.78	18.13	1.03	2.87	16.47	0.93
2	24.4	32	18	2.30	2.73	2.59			2.48		
3	24.4	32	17	2.30	2.69	2.55			2.40		
4	24.2	31	16	2.20	2.54	2.40			2.25		
5	24.1	31	15	2.20	2.49	2.36			2.18		
6	24.1	32	14.5	2.15	2.42	2.29			2.21		
7	23.9	31	13.5	2.10	2.32	2.20			2.07		

Test 17

Holes: 3 Tanks: 2
mass of propane used (kg) 1.21

Time (min)	Gas Temp. (°C)	Accumulato (L/min)	Pressure (psig)	Rotameter Reading (cfm)	Flow Rate (scfm)	Flow Rate (g/s)	Total Flow (scf)	Total Mass (kg)	Accumulato Flow Rate (scfm)	Total Flow (scf)	Total Mass (kg)
1	24.7	45	12	3.00	3.22	3.05	23.56	1.34	2.84	20.71	1.17
2	24.5	45	11.5	3.00	3.19	3.02			2.79		
3	24.4	46	11.5	3.00	3.19	3.02			2.85		
4	24.3	44	10.5	2.90	3.03	2.86			2.62		
5	24.1	44	10	2.80	2.90	2.74			2.57		
6	23.9	54	9	2.70	2.74	2.59			3.03		
7	23.8	33	8	2.70	2.68	2.53			1.78		
8	23.7	43	7	2.70	2.62	2.48			2.21		

Test 18

Holes: 3 Tanks: 3
mass of propane used (kg) 2.07

Time (min)	Gas Temp. (°C)	Accumulato (L/min)	Pressure (psig)	Rotameter Reading (cfm)	Flow Rate (scfm)	Flow Rate (g/s)	Total Flow (scf)	Total Mass (kg)	Accumulato Flow Rate (scfm)	Total Flow (scf)	Total Mass (kg)
1	25.2	51	23	3.60	4.59	4.34	42.18	2.39	4.54	37.95	2.15
2	24.7	44	22	3.50	4.41	4.17			3.82		
3	24.3	47	20.5	3.50	4.32	4.08			3.92		
4	23.8	47	19	3.40	4.11	3.89			3.76		
5	23.2	46	18	3.35	3.99	3.78			3.57		
6	22.9	45	16.5	3.30	3.84	3.63			3.34		
7	22.6	47	15	3.20	3.64	3.44			3.32		
8	22.3	45	14	3.10	3.47	3.28			3.08		
9	22.1	45	13	3.10	3.41	3.22			2.97		
10	21.9	45	12	3.10	3.34	3.16			2.87		
11	21.7	45	11	2.90	3.07	2.90			2.76		

Test 19

Holes: 1 Tanks: 2
mass of propane used (kg) 0.77

Time (min)	Gas Temp. (°C)	Accumulato (L/min)	Pressure (psig)	Rotameter Reading (cfm)	Flow Rate (scfm)	Flow Rate (g/s)	Total Flow (scf)	Total Mass (kg)	Accumulato Flow Rate (scfm)	Total Flow (scf)	Total Mass (kg)
1	23.6	19	21	1.20	1.49	1.41	14.95	0.85	1.61	14.24	0.81
2	23.5	16	19	1.20	1.45	1.37			1.28		
3	23.5	17	20	1.20	1.47	1.39			1.40		
4	23.6	17	20	1.20	1.47	1.39			1.40		
5:30	23.7	29	22	1.20	1.51	1.43			2.52		
6:30	23.7	15	21	1.20	1.49	1.41			1.27		
7	23.6	7	21	1.20	1.49	1.41			0.59		
8	23.6	18	20	1.20	1.47	1.39			1.48		
9	23.6	18	21	1.30	1.62	1.53			1.52		
10	23.6	14	20	1.20	1.47	1.39			1.15		

Test 20

Hoels: 4 Tanks: 3
mass of propane used (kg) 1.76

Time (min)	Gas Temp. (°C)	Accumulato (L/min)	Pressure (psig)	Rotameter Reading (cfm)	Flow Rate (scfm)	Flow Rate (g/s)	Total Flow (scf)	Total Mass (kg)	Accumulato Flow Rate (scfm)	Total Flow (scf)	Total Mass (kg)
1	25.7	64	19	4.20	5.06	4.78	33.82	1.92	5.08	31.20	1.77
2	25	57	18	4.10	4.87	4.61			4.40		
3	24.4	58	16	4.00	4.61	4.36			4.21		
4	23.9	60	14	3.80	4.24	4.01			4.08		
5	23.5	54	13	3.80	4.17	3.94			3.55		
6	23.3	57	11	3.60	3.80	3.60			3.48		
7	23	56	10	3.50	3.63	3.43			3.29		
8	22.8	55	9	3.40	3.45	3.26			3.10		

Test 21

Holes: 3 Tanks: 3
mass of propane used (kg) 1.97

Time (min)	Gas Temp. (°C)	Accumulato (L/min)	Pressure (psig)	Rotameter Reading (cfm)	Flow Rate (scfm)	Flow Rate (g/s)	Total Flow (scf)	Total Mass (kg)	Accumulato Flow Rate (scfm)	Total Flow (scf)	Total Mass (kg)
1	25.2	48	31	4.20	5.90	5.58	37.92	2.15	5.18	33.56	1.90
2	25	43	27	3.60	4.83	4.57			4.23		
3	24.7	44	26	3.70	4.91	4.64			4.23		
4	24.3	44	23	3.60	4.60	4.35			3.93		
5	24	43	20.5	3.20	3.95	3.74			3.59		
6:15	23.7	49	18	3.15	3.75	3.55			3.80		
7	23.6	39	15.5	3.00	3.43	3.25			2.79		
8	23.5	43	14.5	3.00	3.38	3.19			2.98		
9	23.4	43	13	2.90	3.18	3.01			2.83		

Test 22

Holes: 5 Tanks: 4
mass of propane used (kg) 3.08

Time (min)	Gas Temp. (°C)	Accumulato (L/min)	Pressure (psig)	Rotameter Reading (cfm)	Flow Rate (scfm)	Flow Rate (g/s)	Total Flow (scf)	Total Mass (kg)	Accumulato Flow Rate (scfm)	Total Flow (scf)	Total Mass (kg)
1	22.1	72	19.5	5.00	6.10	5.77	41.32	2.34	5.87	38.22	2.17
2	21.4	68	18	4.80	5.74	5.43			5.32		
3	20.8	68	16	4.70	5.45	5.15			5.00		
4	20.3	67	15	4.60	5.25	4.96			4.78		
5	19.8	67	13.5	4.40	4.90	4.63			4.54		
6	19.5	67	12.5	4.40	4.81	4.55			4.39		
7	19.2	66	12	4.30	4.66	4.41			4.24		
8	19	66	11	4.15	4.42	4.18			4.09		

Test 23

Holes: 5 Tanks: 4
Flame Height (cm): 90-100
Flame Width (cm): 90
Flame Length along tank (c 100
mass of propane used (kg) 0.69

Time (min)	Gas Temp. (°C)	Accumulato (L/min)	Pressure (psig)	Rotameter Reading (cfm)	Flow Rate (scfm)	(g/s)	Total Flow (scf)	Total Mass (kg)	Accumulato Flow Rate (scfm)	Total Flow (scf)	Total Mass (kg)
1	21.3	69	18.5	4.90	5.90	5.58	11.56	0.66	5.48	10.64	0.60
2	20.8	68	17	4.80	5.65	5.35			5.16		

Test 24

Holes: 4 Tanks: 4 square
Flame Height (cm): 85
Flame Width (cm): 90
Flame Length along tank (c 100
mass of propane used (kg) 0.63

Time (min)	Gas Temp. (°C)	Accumulato (L/min)	Pressure (psig)	Rotameter Reading (cfm)	Flow Rate (scfm)	(g/s)	Total Flow (scf)	Total Mass (kg)	Accumulato Flow Rate (scfm)	Total Flow (scf)	Total Mass (kg)
1	21	57	21.5	4.30	5.41	5.12	10.55	0.60	4.94	9.53	0.54
2	20.7	56	19.5	4.20	5.14	4.86			4.59		

Test 25

**stopwatch battery died

Holes: 3 Tanks: 4 triangle
Flame Height (cm): 100
Flame Width (cm): 90
Flame Length along tank (c 65
mass of propane used (kg) 0.54

Time (min)	Gas Temp. (°C)	Accumulato (L/min)	Pressure (psig)	Rotameter Reading (cfm)	Flow Rate (scfm)	(g/s)	Total Flow (scf)	Total Mass (kg)	Accumulato Flow Rate (scfm)	Total Flow (scf)	Total Mass (kg)
final	19.9	96			0.00	0.00	0.00	0.00	3.39	3.39	0.19

Test 26

Holes: 1 Tanks: 2
Flame Height (cm): 100
Flame Width (cm): 50
Flame Length along tank (c 50
mass of propane used (kg) 0.24

Time (min)	Gas Temp. (°C)	Accumulato (L/min)	Pressure (psig)	Rotameter Reading (cfm)	Flow Rate (scfm)	(g/s)	Total Flow (scf)	Total Mass (kg)	Accumulato Flow Rate (scfm)	Total Flow (scf)	Total Mass (kg)
1	21.4	19	36	1.40	2.08	1.97	4.13	0.23	2.30	4.17	0.24
2	21.4	16	34	1.40	2.04	1.93			1.86		

Test 27

Note: a lot of gas burned after last rotameter reading

Holes: 2 Tanks: 3
Flame Height (cm): 100
Flame Width (cm): 55
Flame Length along tank (c 65
mass of propane used (kg) 0.41

Time (min)	Gas Temp. (°C)	Accumulato (L/min)	Pressure (psig)	Rotameter Reading (cfm)	Flow Rate (scfm)	(g/s)	Total Flow (scf)	Total Mass (kg)	Accumulato Flow Rate (scfm)	Total Flow (scf)	Total Mass (kg)
1	21.6	33	24.5	2.40	3.14	2.97	6.18	0.35	3.09	5.81	0.33
2	21.4	31	22	2.40	3.04	2.87			2.72		

Test 28

Holes: 3 Tanks: 4 straight line
Flame Height (cm): 85
Flame Width (cm): 45
Flame Length along tank (c 110
mass of propane used (kg) 0.49

Time (min)	Gas Temp. (°C)	Accumulato (L/min)	Pressure (psig)	Rotameter Reading (cfm)	Flow Rate (scfm)	Flow Rate (g/s)	Total Flow (scf)	Total Mass (kg)	Accumulato Flow Rate (scfm)	Total Flow (scf)	Total Mass (kg)
1	21.6	47	22	3.50	4.43	4.19	8.62	0.49	4.12	7.86	0.45
2	21.3	45	20	3.40	4.19	3.96			3.73		

Appendix 2

Flow Analysis for Underwater Bubbler

Analysis of Propane Flow for Underwater Bubbler

Basis: 2 g/s propane flow from a hole 45 cm below the water surface

Given:
- i) holes on 40 cm centres produce a continuous flame area;
- ii) each arm of a bubbler unit consists of 4 m of ¾" ID hose capped at one end with 11 holes facing down, spaced 40 cm apart;
- iii) each unit consists of three parallel arms spaced 35 cm apart connected to a 1" ID header approximately 70 cm long, including two tees and one ell;
- iv) each unit is fed by approximately 25 m of 1" hose from the manifold on the evaporator;
- v) two units are required to produce a flame area of 8 m long x 1.2 m wide;
- vi) manifold from evaporators supplies propane at 20 psig.
- vii) density of propane is 1979 g/m^3 @ 1 atm & 10°C; = 4318 g/m^3 @ 20 psig & 10°C
- viii) viscosity of propane gas is 0.007 mPas

Total propane flow is

11 x 3 x 2 x 2 g/s = 132 g/s; (475 kg/hr = 22,500,000 BTU/hr = 6.6 MW)

Therefore, flow per unit = 66 g/s

Flow velocity in the 1" hose feeding one unit:

$V = m/\rho A = 66[g/s] \,/\, ((4318\ g/m^3)\cdot \pi \cdot (1\cdot 0.0254/2)^2[m^2]) = 30\ m/s.$

Reynolds number in a 1" hose:

$N_{re} = DV\rho/\mu = (1\cdot 0.0254)[m]\cdot 30[m/s]\ 4.318[kg/m^3]) \,/\, 7x10^{-6}\ [Pas] = 470{,}000.$

Pressure drop down 25 m of 1" hose:

$$
\begin{aligned}
\Delta P_{1"} &= F\rho \\
&= (4fL/D)\rho V^2/2 \\
&= (4 \cdot 0.0033 \cdot 25[m]/0.0254[m])\cdot(4.318\ [kg/m^3] \cdot 30^2\ [m^2/s^2])/2 \\
&= 2.5 \times 10^4 \text{ Pa or } 3.6 \text{ psi.}
\end{aligned}
$$

Pressure drop in two tees and one ell of 1" ID header:

$$
\begin{aligned}
\Delta P_h &= \Delta F\rho \\
&= \rho\, kV^2/2 \\
&= 4.318\ [kg/m^3] \cdot ((1 \cdot 30^2) + (1 \cdot 20^2) + (0.75 \cdot 10^2)[m^2/s^2])\ /\ 2 \\
&= 1943 \text{ Pa or } 0.3 \text{ psi;}
\end{aligned}
$$

Pressure drop in 1 m of 1" ID pipe

$\Delta P_p = 1 \times 10^3$ Pa or 0.1 psi;

Therefore, total pressure drop in header ~ 0.4 psi

Therefore, the inlet pressure to an arm of the bubbler = 20 - 3.6 - 0.4 = 16 psig.

Inlet velocity of propane in a ¾" ID hose:

$V = m/\rho A$

$= 22[g/s] / ((4318\ g/m^3) \cdot ((16 + 14.7)/(20 + 14.7)) \cdot \pi \cdot (0.75 \cdot 0.0254/2)^2\ [m^2])$

$= 20.2$ m/s.

Reynolds number in a ¾" ID hose:

$N_{re} = Dv\rho/\mu$

$= (0.75 \cdot 0.0254)[m] \cdot 20[m/s] \cdot 4.318[kg/m^3] \cdot ((16 + 14.7)/(20 + 14.7))/ 7x10^6\ [Pas]$

$= 210{,}000$

Kinetic energy head of inlet stream to an arm of ¾" ID hose:

$KE = \rho\alpha V_i^2/2$

$= 4.318[kg/m^3] \cdot ((16 + 14.7)/(20 + 14.7)) \cdot 1.1 \cdot 20^2\ [m^2/s^2] / 2$

$= 840$ Pa or 0.12 psi

Pressure drop due to friction and momentum recovery down 4 m of ¾" hose with holes every 40 cm:

$\Delta h_p = ((4fL/3d) - 2))V_i^2/2$

$= ((4 \cdot 0.0038 \cdot 4[m] / 3 \cdot (0.75 \cdot 0.0254[m]) - 2) \cdot 20^2\ [m^2/s^2] / 2$

$= -187$ Pa or 0.03 psi.

Percent maldistribution of flow between the first and last hole along the 4 m length of one arm:

% maldistribution $= 100(1 - ((\Delta h_{oi} - \Delta h_p)/\Delta h_{oi})^{1/2})$

$= 100(1 - ((16 - 0.03)/16)^{1/2})$

$= 0.16\%$

Exit velocity of propane from a 3 mm ∅ hole at 2 g/s:

$V = m/\rho A$

$= 2[g/s] / ((4318\ g/m^3) \cdot ((16 + 14.7)/(20 + 14.7)) \cdot \pi \cdot (0.003/2)^2\ [m^2])$

$= 74$ m/s (sub-sonic).

Hole Reynolds number :

$N_{re} = Dv\rho/\mu$

$= 0.003[m] \cdot 74[m/s] \cdot 4.318[kg/m^3] \cdot ((16 + 14.7)/(20 + 14.7)) / 7x10^6\ [Pas]$

$= 120{,}000$ therefore the coefficient of discharge, $C_d = 0.62$.

For a 3 mm ∅ hole in a ¾" ID hose filled with propane, the expansion factor:

$Y = (r^{2/k}(k/(k-1))((1-r^{((k-1)/k)})/1-r)((1-\beta^4)/(1-\beta^4 r^{2/k}))^{1/2}$

for

$r = p_2/p_1 = (14.7 + 0.5)/(14.7 + 16) = 0.495;$

$\beta = 0.003/(0.75 \cdot 0.0254) = 0.16$ and

$k = c_p/c_v = 1.14$

$Y = 0.62$

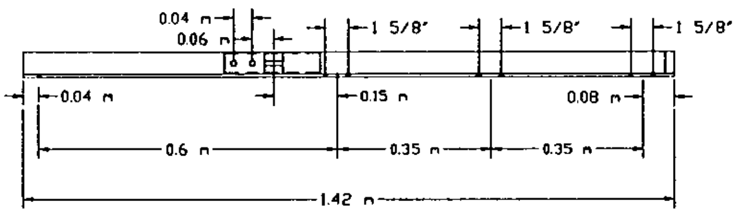
Flow of propane from a 3 mm ∅ hole in a ¾" ID hose located 45 cm under water with a 15.5 psi pressure drop:

$$m = C_d Y A_o (2(p_1-p_2)\rho_1/(1-\beta^4))^{½}$$
$$= 0.62 \cdot 0.62 \cdot \pi \cdot (0.003/2)^2[m^2]\ (2 \cdot (101325 \cdot 15.5/14.7) \cdot 4.318[kg/m^3] \cdot ((16 + 14.7)/(20 + 14.7))/(1 - 0.16^4))^{½}$$
$$= 2.5\ g/s,\ \text{close enough to the target flow of 2 g/s.}$$

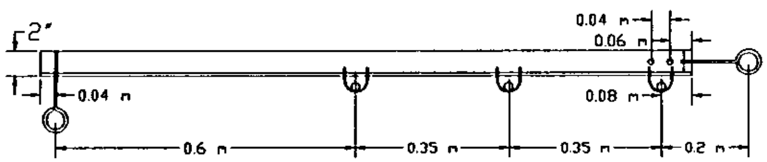
Experiments in the indoor tank at S.L. Ross showed that the flow of propane from a hole drilled with a ⅛" bit in ¾" ID flexible hose was 2.04 g/s at a back pressure of ~16 psig with the hose submerged 18" under water.

Appendix 3

Design of Underwater Bubbler Frames



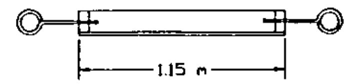
Two piece bubbler frame



Single piece bubbler frame

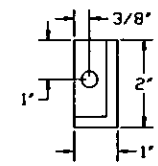
- Approx. 2" x 1" x 1/4" aluminum angle
- 1" thick welded end piece with 3/8" hole for boom attachment on all frames
- Three pairs of 3/8" holes on every frame for u-bolts
- Four of the frames made in two pieces to attach to the other four frames
- 1" thick welded end pieces with 3/8" hole on both sides of the joint of the break down frames
- 8" x 2" x 1/4" aluminum plate welded to one side of the break-down joint with two bolt holes at other side of joint (as indicated). Matching holes near boom end of single-piece frames

- All edges smoothed and all holes deburred
- Hardware (nuts, bolts, eye-bolts & u-bolts) not to be included in price



Brace

- Approx 2" x 1" x 1/4" aluminum angle
- 1" thick welded end piece at each end with 3/8" holes



Welded end detail

Gas Bubbler Framing

Fabrication Detailing
4 pc - Single piece frame by 1.42 m length
4 pc - Two piece frame by 1.42 m length
6 pc - Brace by 1.15 m length

SL Ross Environmental Research Ltd.

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Sept 30, 1996	Drawn by: Jake Morrison

Appendix 4

Draft Test Protocol

1. Summary

This protocol relates to implementing a system for the testing of fire-resistant containment booms in waves while the boom is being exposed to realistic heat loads from flames. The testing will be conducted primarily in the Outdoor Ship Maneuvering Basin (120 m x 60 m x 3 m deep) at the Montreal Rd. Campus of the National Research Council of Canada in Ottawa; its wave generator will produce 0.3 and 0.6 m waves for the tests. Heat loads on the boom will be produced by burning propane released from a series of underwater hoses located in the apex of the boom. The propane gas will feed a fire at the water surface that will produce a realistic heat flux to the boom while generating no smoke. The burn tests will involve a cycle of exposure to flames for a period of one hour, followed by a period of no flame for one hour. The wave generator will run continuously. Prior to exposing the boom to flames, the test section will be stressed in large (> 1 m) waves in the Canadian Hydraulic Center's Wave Research Flume. The boom will be returned to the Wave Research Flume after the fire tests and stressed again. Finally, if the boom still retains its structural integrity,it will be tested for its ability to contain thick oil slicks in a small, circular tank using a low-viscosity vegetable oil.

1.1 Background

Since the late 1970s when fire-resistant booms were first proposed and developed in North America [1,2,3] there has been an urgent need to conduct burn tests with fire-resistant booms in waves. Fire testing of these booms in quiescent conditions has been carried out, and much has been learned from these tests; [2,3,4,5,6,7] however, this type of testing has its limitations. The combined effect of exposure to water, wave action and high temperature flames is known to cause much more rapid boom failure in both metallic [2] and refractory fabric booms [8] than would be predicted from quiescent-condition tests.

In the early 1980s, some early fire proof boom designs were tested at OHMSETT; [2,9] however, the exposure time to fire was limited to the time it took to tow the boom the length of the tank (a few minutes).

Three burn tests with fire boom have been conducted offshore: one at Spitsbergen; one in Alaska; and one at NOBE. All involved booms constructed with refractory textile material. In the first two of these tests wave conditions were calm and a single burn was carried out in each instance with no damage to the booms reported. [10,11] The offshore test, at NOBE, involved two individual burns; during the second of these burns, in 0.5 m waves, the boom suffered severe damage.[8] This was not too surprising because it has been theorized for some time[12,13] that the combination of water, intense heat and mechanical flexure (from wave action) will cause mineral, ceramic or synthetic-based refractory textiles to rapidly self-abrade. It remains to be seen whether this problem has been solved with recent design changes, such as protective coatings on the individual fibres of the fabric and mechanical strengthening of the overall boom structure through the incorporation of stainless steel wire mesh and load-bearing members.[14,15] Realistic, inexpensive testing is needed in both waves and high-temperature flames and for extended time periods to evaluate any fire boom system's capabilities and limitations before expensive testing at sea.

Another problem recently discovered [7] is that one design of high temperature textile fire boom becomes significantly permeable to oil when exposed to a fire with a large slick thickness (i.e., 17 cm). This leakage was also observed during recent fire boom tests in the Pacific Northwest. The oil thicknesses at which leakage has been observed during these tests is on the lower end of what might be expected in a boom under tow. This phenomenon may be one reason that substantial amounts of burning was observed on the downstream side of the fire boom during the NOBE trials.[8] It is recognized that all containment booms leak some oil; however, fire boom tests should incorporate containment testing (after exposure to flames) using thick layers of low viscosity oils to confirm their ability to retain hot, burning oil under realistic conditions.

Finally, fire booms may be exposed to prolonged mechanical flexing caused by waves, both before and/or after exposure to flame, which could contribute to failure. The proposed tests will subject both virgin fire boom and boom exposed to flames to realistic wave conditions under typical tensional loads in order to evaluate boom durability.

1.2 Objective

The objective of this program is to develop a near full-scale screening test for the effectiveness and durability of fire-resistant oil containment boom that incorporates simultaneous testing in waves and flames. The ability of boom exposed to fire to contain thick, hot oil and survive extended exposure to wave action will also be determined. The flame test will be relatively simple and inexpensive to carry out in a wave tank, and possibly at sea. The test will not produce any visible air or water pollution, even while approximating full-scale *in situ* burning heat loads.

1.3 Goals

The specific goals of the tests are to:

- fit out and instrument the wave flume, wave basin and static tank for the wave endurance tests, simultaneous wave and flame tests, and thick oil containment tests, respectively;
- conduct tests in a large wave basin with mid-scale gas fires on water fed by an underwater bubbler; and,
- subject one fabric-based fire-resistant boom to the entire test series;

1.4 Targets

The following are the target dates for the proposed tests:

- finish test system design and shakedown tests - October 25, 1996
- finish preparation of test tanks - November 1, 1996
- initial stress tests in Wave Research Flume - November 5, 1996
- flame tests in Outdoor Maneuvering Basin - November 6, 1996
- final stress tests in Wave Research Flume - November 7, 1996
- thick oil containment tests - November 8, 1996

2. General Information

2.1 Test Locations

The tests will be conducted at two locations on the Montreal Rd. Campus of NRC in Ottawa. The Wave Research Flume is located in Building M-32, the Canadian Hydraulics Center. The static tank for low-viscosity oil containment testing will also be located here. The Outdoor Manuevering Basin (Building M-42), site of the wave/flame tests, is located on the northern edge of the campus.

2.2 Weather Conditions

The average weather conditions for October and November in Ottawa are given in Table 1.

Table 1: Climatic Normals for Ottawa (at the airport)

	October	November
Mean Max. T (°C)	13	5
Mean T (°C)	8	1
Mean Min. T (°C)	3	-2
Days with Rain	11	10
Days with Snow	1	7
Days with Freezing Rain	<1	2
Avg. Wind Speed (km/h)	14	15
Prevailing Wind	E	WNW

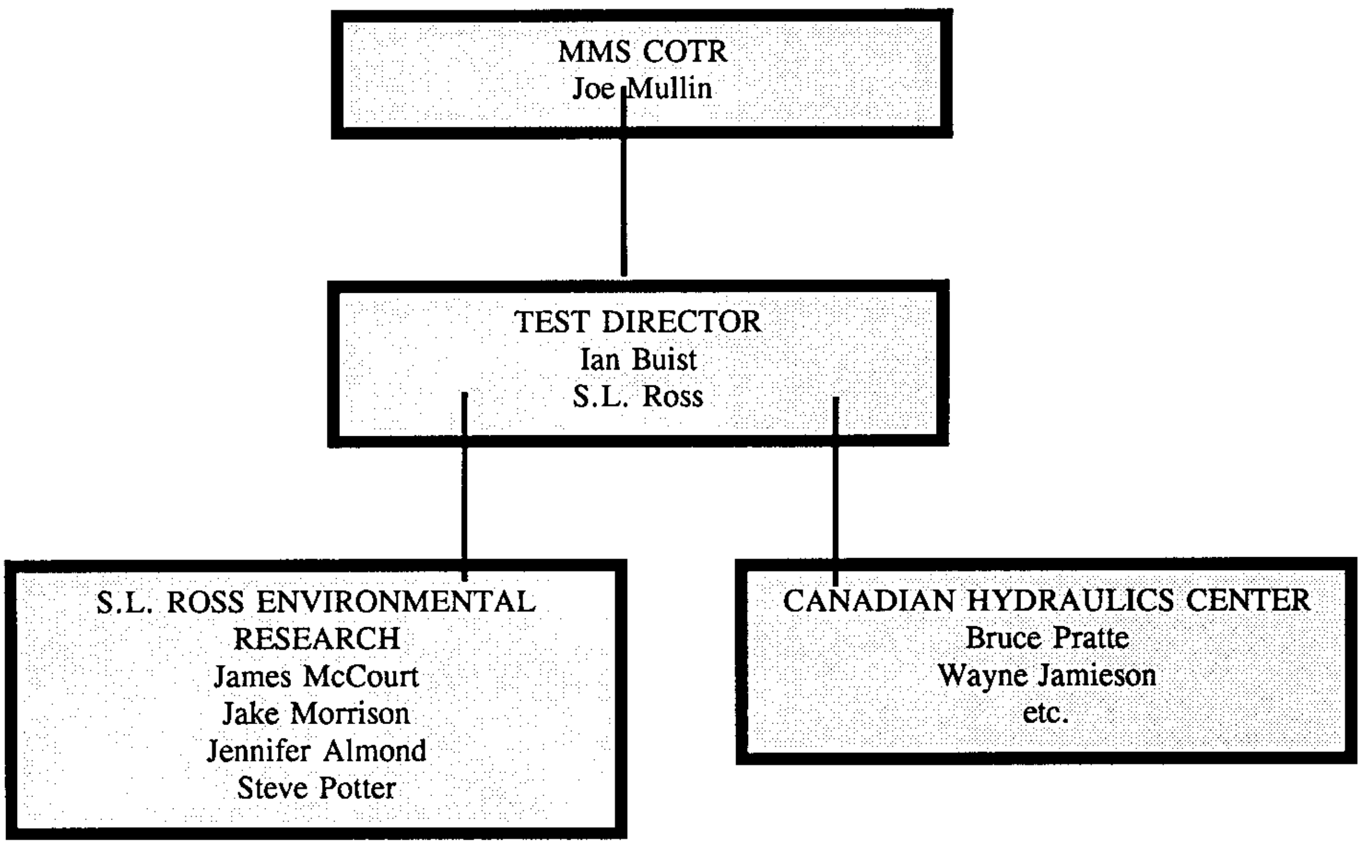
2.3 Project Team

The project team is shown in Figure 2. Mr. Ian Buist is overall project manager and Test Director responsible to the MMS COTR, Mr. Joe Mullin. Dr. Bruce Pratte is in charge of the team from the Canadian Hydraulics Center.

2.4 Operating Constraints

Work that generates appreciable noise is permitted at the Outdoor Manuevering Basin between the hours of 8:00 am and 5:00 pm Monday to Friday only. Winds from the north, east or southeast; flat calm conditions; or, sustained winds in excess of 30 km/hr will result in the tests being delayed until conditions improve. Precipitation in the form of rain or snow should not affect the tests; however freezing rain that results in working surfaces becoming slippery will necessitate a postponement. A decision will be made by the Test Director, in consultation with CHC staff and the MMS COTR on the suitability of the day's weather for testing.

Figure 2 - Project Team Organization



3. Test Plan

3.1 Initial Wave Stress Test

This test will involve stressing the fire-resistant boom in large waves in CHC's indoor Wave Research Flume (WRF) for a period of two hours. The boom will be installed longitudinally in the WRF and tensioned by a winch. The tension load imposed will simulate that expected for a 500 foot length of the boom deployed at sea in 1 m waves in a 0.5 knot current (or sweeping speed) and measured by a 5000 lb. load cell mounted to specially designed frames. The longitudinal stresses in the boom and the wave characteristics will be monitored using the lab's computer data aquistion system. Waves 1 m high will generated in the WRF and used to accelerate axial bending and flexing of the test boom and its refractory fabric, as would happen to a real boom over a much longer time period.

After the test, the boom section will be extracted from the WRF and its sacrificial plastic covering carefully removed so that the internal, fire-resistant components can be examined non-destructively. Removal of this covering will not affect the subsequent performance of the boom, since the cover is intended to burn up on exposure to flames. Particular attention will be paid to the appearance of the refractory material and structural members, and the presence of any loose fibres inside the plastic covering.

3.2 Test in Waves and Flames

Two 7 m (25 ft) sections of Fire Boom (previously used at the NOBE tests) will be placed in the middle of two 15 m (50 ft) sections of conventional containment boom to form an overall boom length of 45 m (150 ft). Flames will be generated along the middle 8 m (25 ft) of the Fire Boom. The width of the flames will be approximately 1 m (3 ft). Details on specific equipment may be found in Appendix A. In general, the plan is to subject the test section of boom to cycles of flame of one hour duration, followed by one hour of wave action with no flame.

<u>Flame Parameters</u> The underwater propane bubbler system will be fed gaseous propane from three 8 x 10^6 BTU/hr vaporizers located at the side of the basin. These are fed liquid propane from a 6000 L propane storage tank. The design maximum propane flow is 475 kg/hr (or 22.5 x 10^6 BTU/hr or 6.6 MW). The planned fire area is 8 m^2 giving an overall heat release rate per unit water surface area of 0.8 MW/m^2 or 2.6 x 10^5 BTU/hr ft^2. By comparison, the recent propane fire boom tests at Mobile, AL involved heat release rates on the order of 5 x 10^5 BTU/hr ft^2; this is also approximately the heat release rate of an oil slick burning at 3.5 mm/min. Radiant heat flux to the boom will be monitored using two MedTherm radiometers mounted on the steel connector joining the two sections of fire boom, in the middle of the flame test length. If the heat flux to the boom from the 1 m wide fire is not sufficient, the two sections of propane bubbler are designed so that they can be mated together to form a 4 m long by 2 m wide flame area. The heat release rate can also be doubled to 1.6 MW/m^2 (5 x 10^5 BTU/hr ft^2) by attaching both bubblers to one frame to form a 4 m x 1 m flame area. The surface temperature of the boom will be monitored using four Type K thermocouples mounted in the side facing the fire.

Other Test Parameters The wave characteristics will be measured using a single wave probe mounted updrift of the boom. Induced surface current will be measured by timing the movement of surface drifters near the mouth of the boom. Boom tension will be monitored using load cells fixed to the open ends of the "U" of boom. All data signals will be brought into Building M-42 and recorded on computers. A weather station will be mounted on the tower and used to monitor temperature, wind speed and direction during the tests. Video cameras will be mounted in the control tower and tankside to record the tests. Photographs (35 mm) will also be taken to document the tests.

Test Procedure At the beginning of the test day, the weather forecast will be obtained, and a decision to proceed made by the COTR, Test Director and CHC Director. At this point the safety checks will be run, notifications made, the data acquisition systems will be started, the video cameras started and the boat readied for ignition of the pilot flames. Once a verbal check has been made with all participants, the wave generator fans will be started, but not engaged. Then the Test Director will manually ignite the pilot flames and return to the side of the tank. If desired, the current will then be started to place the boom in its desired shape. Then the propane gas will be started first on the far bubblers. Once the far bubbler has ignited and established a stable flame, the near bubbler will be started. Once this bubbler has established a stable flame, the wave generator will be engaged. The flames will be left on for a period of one hour (timed from the first wave reaching the test boom), or until obvious structural degradation of the boom occurs. At the end of the hour, the flames will be shut off (near side first); the pilot lights will remain on. The boom will be inspected visually during the tests, using binoculars. If there is evidence of structural degradation during a period of wave exposure only, the boom will be assessed from the boat.

For the next hour, the boom will be exposed to wave action alone. At the end of that hour, the process above would be repeated. Three, or possibly four, 2-hour cycles of exposure will be fit into the first test day. If possible, it is planned to complete 6 cycles, which would necessitate a second day of testing. On completion of the tests, or at the end of the first test day, the wave generator will be secured, the pilot flames will be extinguished, and then the current generator shut down. On completion of the test, the boom will be carefully removed from the tank using the indoor crane, inspected and photographed carefully, then transported to the Wave Research Flume for the next stage of testing.

3.3 Post-Burn Wave Stress Test

This test will involve stressing the fire-resistant boom again in large waves in CHC's indoor Wave Research Flume (WRF) for a period of two hours. The boom will be installed longitudinally in the WRF and tensioned by a winch as described in 3.1 above. The longitudinal stresses in the boom and the wave characteristics will be monitored using the lab's computer data aquistion system. Waves 1 m high will generated in the WRF and used to accelerate axial bending and flexing of the test boom and its refractory fabric.

After the test, the boom section will be extracted from the WRF and examined carefully. Particular attention will be paid to the appearance of any visible refractory material and structural components.

3.4 Static Thick Oil Containment Tests

This final test will involve assessing the capability of the boom to contain thick slicks of low viscosity oil, simulating a layer of burning oil in the pocket of a boom under tow. A 15' diameter (50' circumference) 1 m (36") deep tank has been selected for this portion of the testing. It will be set up inside the CHC. A section of the boom, consisting of three float lengths, that were exposed to the propane flames will be clamped in a triangle. A thick layer of low viscosity, dyed vegetable oil will be poured onto the water surface contained by the three sections and the leak rate of oil through the boom measured by monitoring the decrease in contained slick thickness (as measured with a "cookie cutter" sample) over time.

4. Safety and Environmental Protection

4.1 Safety

Safety will be of paramount importance during all phases of the test program. If a safety problem is noticed, personnel are encouraged to either fix it immediately, or bring it to the attention of the Test Director or CHC representative. The following safety rules apply:

- when working with overhead hazards (i.e. the crane) wear a hard hat;
- all personnel in the small boat must wear a PFD, safety glasses and Nomex coveralls;
- when handling boom, wear work gloves;
- during burn tests periods, one person must attend the valves on the propane vaporizer manifold at all times, and be in radio contact (walkie-talkie on, radio check every 10 minutes);
- prior to each test the propane detectors around the tank must be activated and tested with a small bottle of propane;
- only CHC staff may operate the wave generator and controls;
- in the event of a propane leak or spill, evacuate the area on foot immediately, by proceeding uphill (propane gas is heavier than air);
- a first aid kit will be kept in Building M-42;
- several 20 lb ABC fire extinguishers will be located around the tank;
- the NRC Fire Chief and Security will be notified on days that burning is planned; and,
- all visitors must sign an NRC Guest Worker Agreement.

4.2 Environmental Protection

Although the Outdoor Maneuvering Basin is located in a secluded area of the NRC Montreal Road campus, it is situated near a residential area. In deference to the residents, operations that generate appreciable noise are only permitted between the hours of 8:00 am and 5:00 pm Monday to Friday. In addition, propane burning will not be conducted in conditions that would result in impacts on the surrounding areas (see 2.4 Operating Constraints above). S L Ross Environmental Research will remove the tested boom and the vegetable oil from the NRC premises at the end of the tests and arrange for their appropriate disposal.

5. References

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Appendix 5

Calibration of Wave Probes and Load Cells

Project: Fireboom | **Facility:** Wave Research Flume

Sensor: W PROBE | **Model:** RBR | **Serial Number:** 4244

Programmable Gain: 1 | **Plug-In Gain:** 1 | **Filter Frequency:** 10.0 Hz

Data Point No.	Input Signal (volts)	Physical Value (volts)	Fitted Curve Value (volts)	Error (volts)	
1	−0.186	1.9970	2.0011	0.0041201	
2	−1.158	1.6900	1.6877	−0.0023127	
3	−2.079	1.3990	1.3910	−0.0080069	⇐ Maximum Error
4	−2.995	1.0900	1.0962	0.0061996	
Maximum Error = −0.883 % of Calibration Range.					

Definition of Calibration Curve

Polynomial Degree = 1 (Linear Fit)

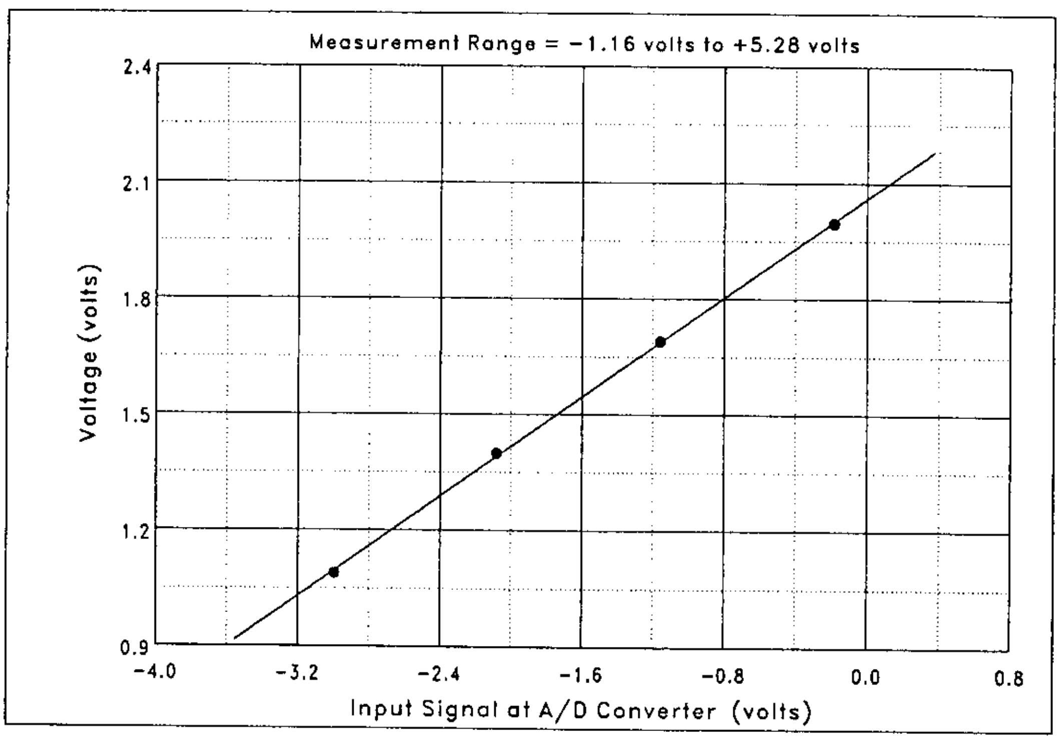
$$Y = C_0 + C_1 \cdot V$$

where $Y(t)$ = Voltage (volts),

$V(t)$ = input signal at A/D converter (volts),

C_0 = 2.06090 volts,

and C_1 = 0.322157 volts/volt.



Calibration of the wave probe used in the wave flume.

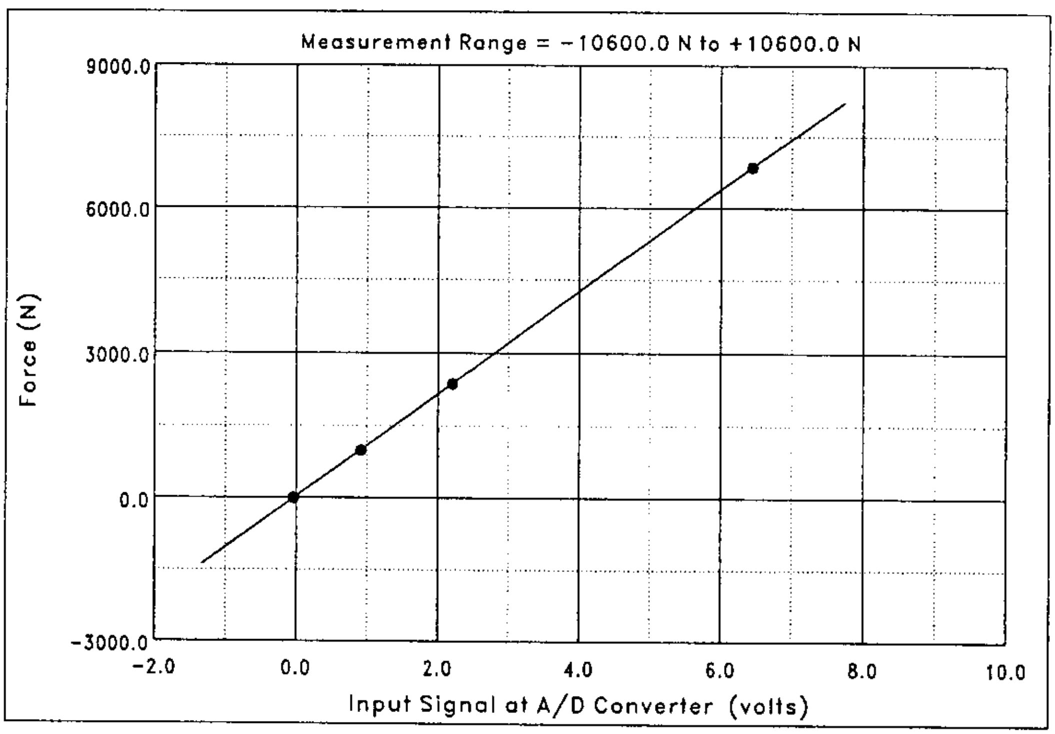
Project: Fireboom | **Facility:** Wave Research Flume
Sensor: Load Cell 1 | **Model:** Interface 2000lbs | **Serial Number:** 26943
Programmable Gain: 2 | **Plug-In Gain:** 1 | **Filter Frequency:** 1.0 Hz

Data Point No.	Input Signal (volts)	Physical Value (N)	Fitted Curve Value (N)	Error (N)	
1	−0.035	0.0	−5.8	−5.8096	⇐ Maximum Error
2	0.910	990.8	995.0	4.2028	
3	2.209	2369.1	2372.5	3.3958	
4	6.444	6862.1	6860.3	−1.7886	
Maximum Error = −0.0847 % of Calibration Range.					

Definition of Calibration Curve
Polynomial Degree = 1 (Linear Fit)

$$Y = C_0 + C_1 \cdot V$$

where $Y(t)$ = Force (N),
$V(t)$ = input signal at A/D converter (volts),
C_0 = 30.7887 N,
and C_1 = 1059.88 N/volt.



Calibration of the load cell used in the wave flume.

Calibration of Channel 1	10:44 7 November 1996

Wave Probe 1

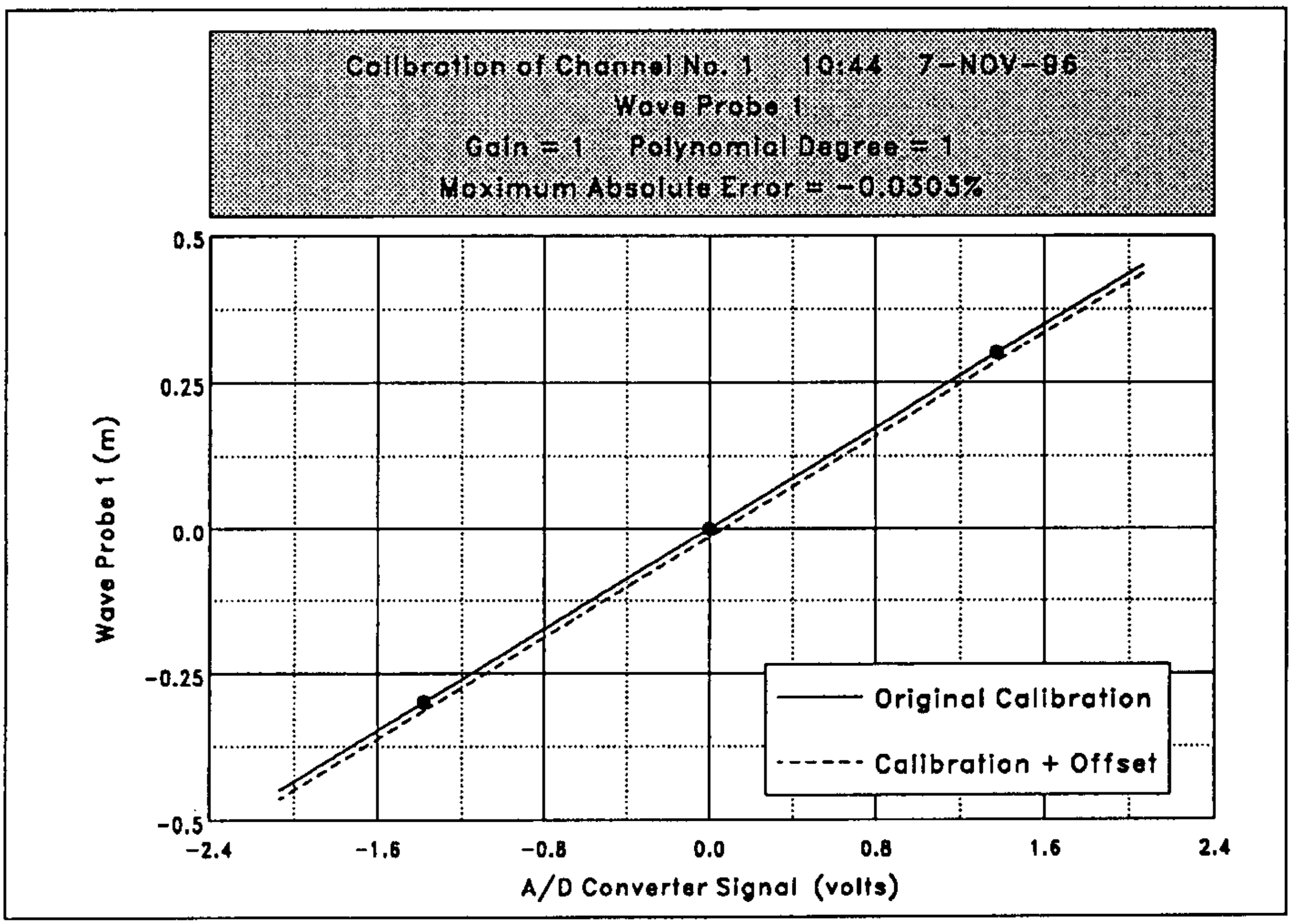
Point No.	Neff A/D Reading (volts)	Actual Value (m)	Cal Value (m)	Error (m)	
1	-0.003	0.00000	-0.00018	-0.00018197	⇐ Maximum Error
2	-1.381	-0.30000	-0.29991	0.00009108	
3	1.377	0.30000	0.30009	0.00009090	

Maximum Error = -0.0303% of Calibration Range.

Definition of Calibration Curve
Polynomial Degree = 1 (Linear Fit)

$$Y = C_0 + C_1 \cdot V$$

where $Y(t)$ = Wave Probe 1 (m),
$V(t)$ = sensor signal at Neff A/D converter (volts),
C_0 = 0.000526760 m (original calibration),
C_0 = -0.0140394 m (calibration + offset),
and C_1 = 0.217547 m/volt .



LC1 (48615)

Point No.	Neff A/D Reading (volts)	Actual Value (N)	Cal Value (N)	Error (N)	
1	-0.095	0.0	-3.4	-3.4008	
2	-3.129	8196.4	8192.3	-4.1289	
3	-2.640	6867.0	6871.3	4.3306	⇐ Maximum Error
4	-0.979	2383.9	2384.5	0.6313	
5	-0.464	990.8	993.4	2.5676	

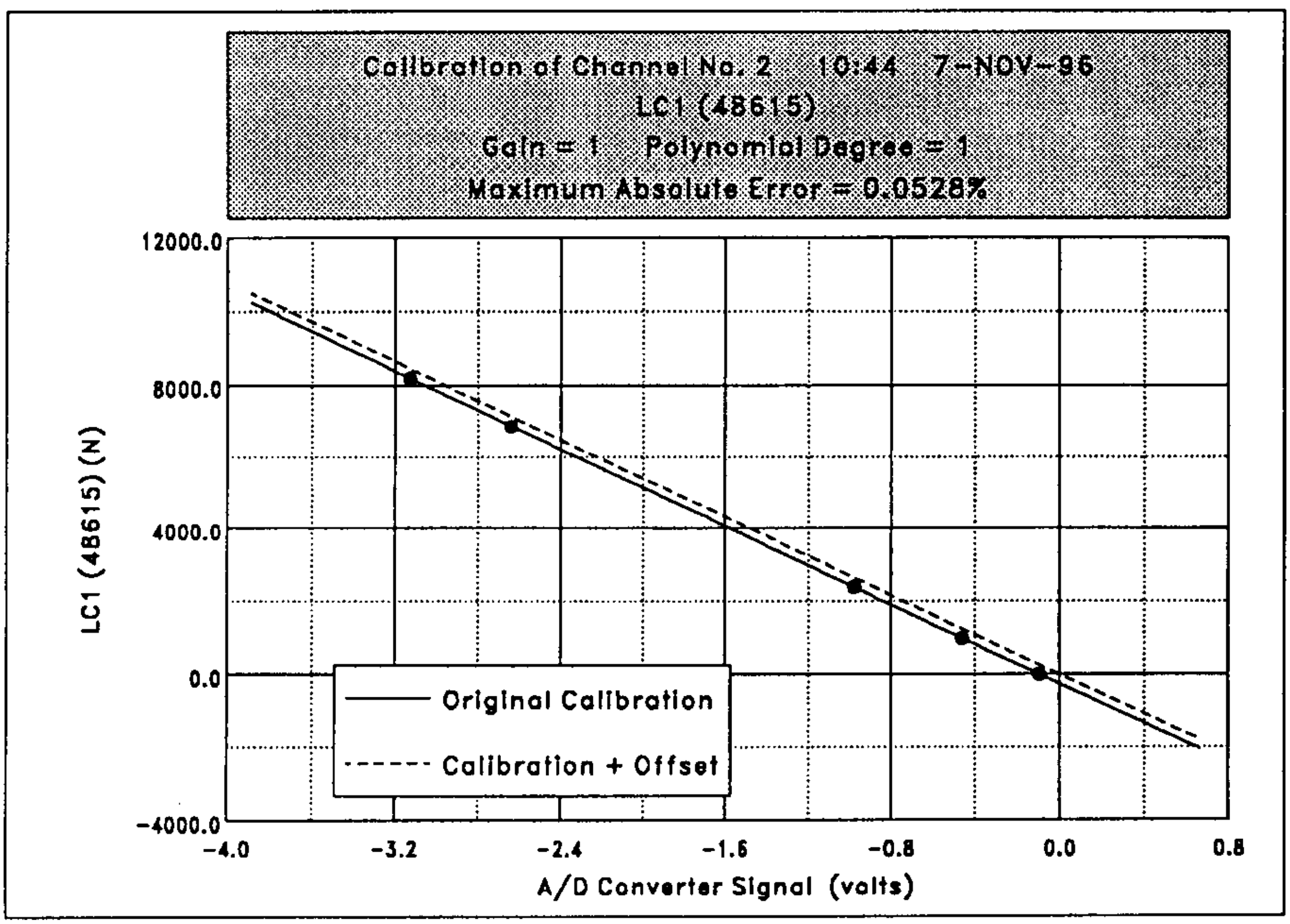
Maximum Error = 0.0528% of Calibration Range.

Definition of Calibration Curve

Polynomial Degree = 1 (Linear Fit)

$$Y = C_0 + C_1 \cdot V$$

where $Y(t)$ = LC1 (48615) (N),
$V(t)$ = sensor signal at Neff A/D converter (volts),
C_0 = -260.021 N (original calibration),
C_0 = -0.372833 N (calibration + offset),
and C_1 = -2701.27 N/volt .



LC2 (48635)

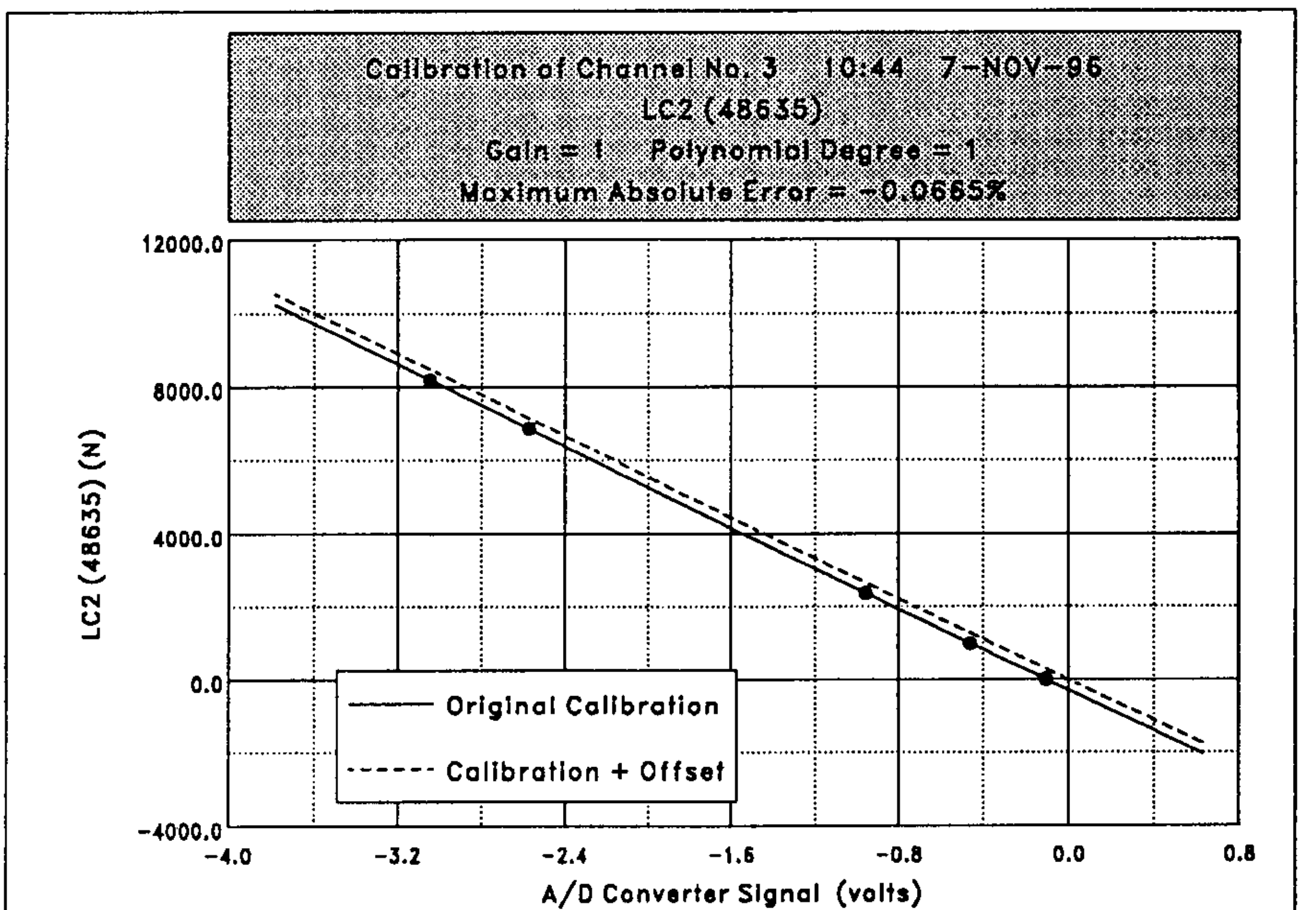
Point No.	Neff A/D Reading (volts)	Actual Value (N)	Cal Value (N)	Error (N)	
1	-0.105	0.0	-2.6	-2.5903	
2	-0.462	985.9	991.3	5.4341	
3	-0.958	2374.1	2372.2	-1.8416	
4	-2.574	6876.8	6871.4	-5.4429	⇐ Maximum Error
5	-3.048	8186.6	8191.0	4.4414	

Maximum Error = -0.0665% of Calibration Range.

Definition of Calibration Curve
Polynomial Degree = 1 (Linear Fit)

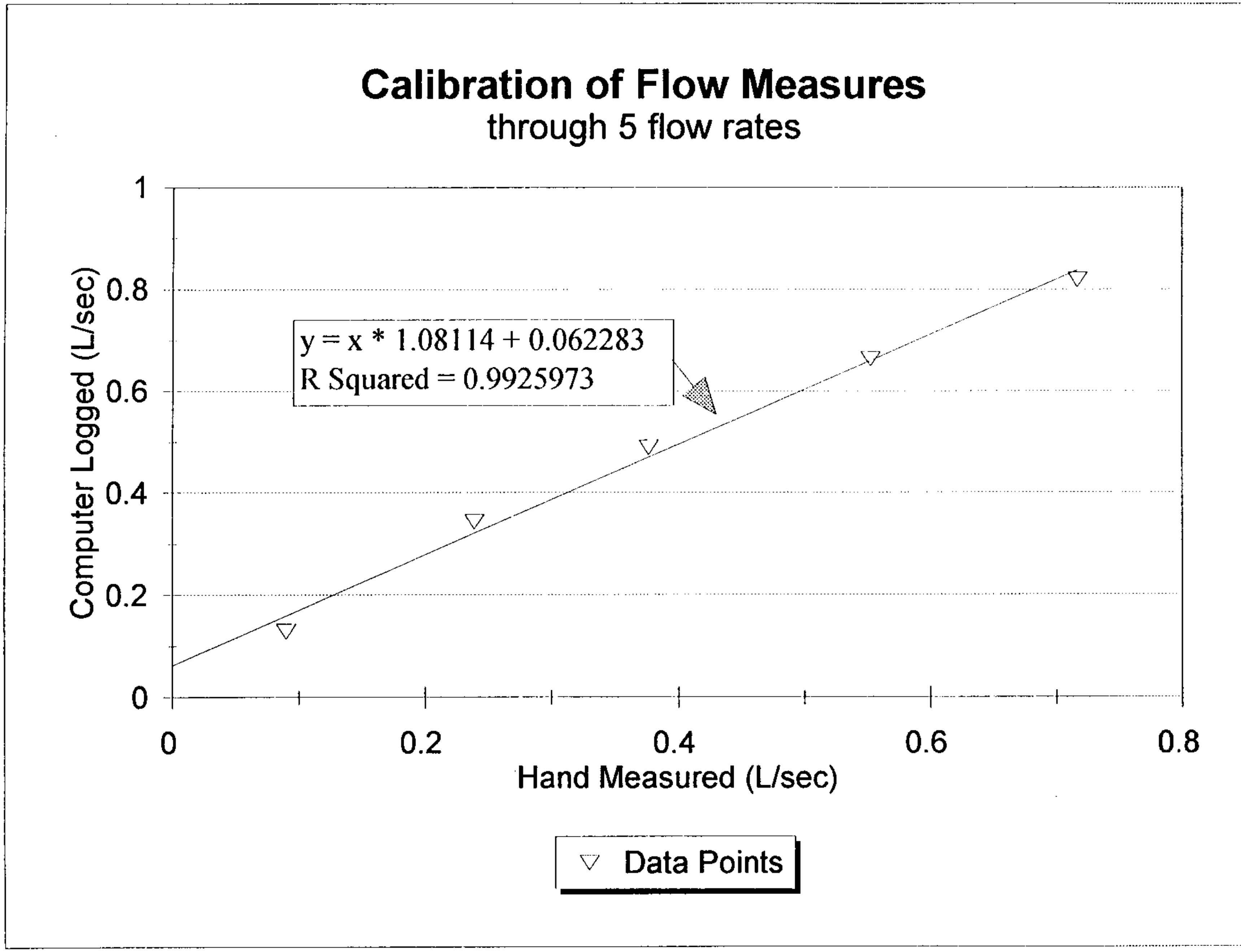
$$Y = C_0 + C_1 \cdot V$$

where $Y(t)$ = LC2 (48635) (N),
$V(t)$ = sensor signal at Neff A/D converter (volts),
C_0 = -294.921 N (original calibration),
C_0 = -9.50510 N (calibration + offset),
and C_1 = -2784.10 N/volt .



Appendix 6

Calibration of Doppler Flow Meter


Calibration of Flow Measures
through 5 flow rates
y = x * 1.08114 + 0.062283
R Squared = 0.9925973
Computer Logged (L/sec)
Hand Measured (L/sec)
0
0.2
0.4
0.6
0.8
1
Data Points

using dirty water

About 5 fps	Computer start time	Time to fill (Sec)	Bucket (L)	Measured Flow Rate (L/sec)	Logged Flow Rate (fps)	Logged to L/Sec (L/sec)
1	12:37:42	31.43	22.26	0.70824	4.8242	0.81987
2	12:38:39	30.99	22.26	0.71830	4.7970	0.81525
3	12:39:34	30.77	22.26	0.72343	4.8420	0.82290
Average		31.06	22.26	0.71660	4.82103	0.81934

About 4 fps	Computer start time	Time to fill (Sec)	Bucket (L)	Measured Flow Rate (L/sec)	Logged Flow Rate (fps)	Logged to L/Sec (L/sec)
1	12:41:34	40.41	22.26	0.55085	3.8944	0.66186
2	12:42:34	40.34	22.26	0.55181	3.9097	0.66446
3	12:43:32	40.06	22.26	0.55567	3.9251	0.66707
Average		40.27	22.26	0.55277	3.90975	0.66446

About 3 fps	Computer start time	Time to fill (Sec)	Bucket (L)	Measured Flow Rate (L/sec)	Logged Flow Rate (fps)	Logged to L/Sec (L/sec)
1	12:44:51	59.54	22.26	0.37387	2.89	0.49132
2	12:46:36	58.86	22.26	0.37819	2.86	0.48621
3	12:47:52	58.91	22.26	0.37786	2.87	0.48776
Average		59.10	22.26	0.37663	2.87395	0.48843

About 2 fps	Computer start time	Time to fill (Sec)	Bucket (L)	Measured Flow Rate (L/sec)	Logged Flow Rate (fps)	Logged to L/Sec (L/sec)
1	12:49:31	93.76	22.26	0.23741	1.992364	0.33860
2	12:51:23	93.07	22.26	0.23917	2.041452	0.34695
3	12:53:12	92.40	22.26	0.24091	2.050637	0.34851
Average		93.08	22.26	0.23916	2.02815	0.34469

About 1 fps	Computer start time	Time to fill (Sec)	Bucket (L)	Measured Flow Rate (L/sec)	Logged Flow Rate (fps)	Logged to L/Sec (L/sec)
1	12:55:17	245.23	22.26	0.09077	0.804632	0.13675
2	12:59:40	246.73	22.26	0.09022	0.730602	0.12417
Average		245.98	22.26	0.09050	0.76762	0.13046

	Measured litre/sec	Logged litre/sec
5 fps	0.7166	0.81934
4 fps	0.55277	0.66446
3 fps	0.37663	0.48843
2 fps	0.23916	0.34469
1 fps	0.0905	0.13046

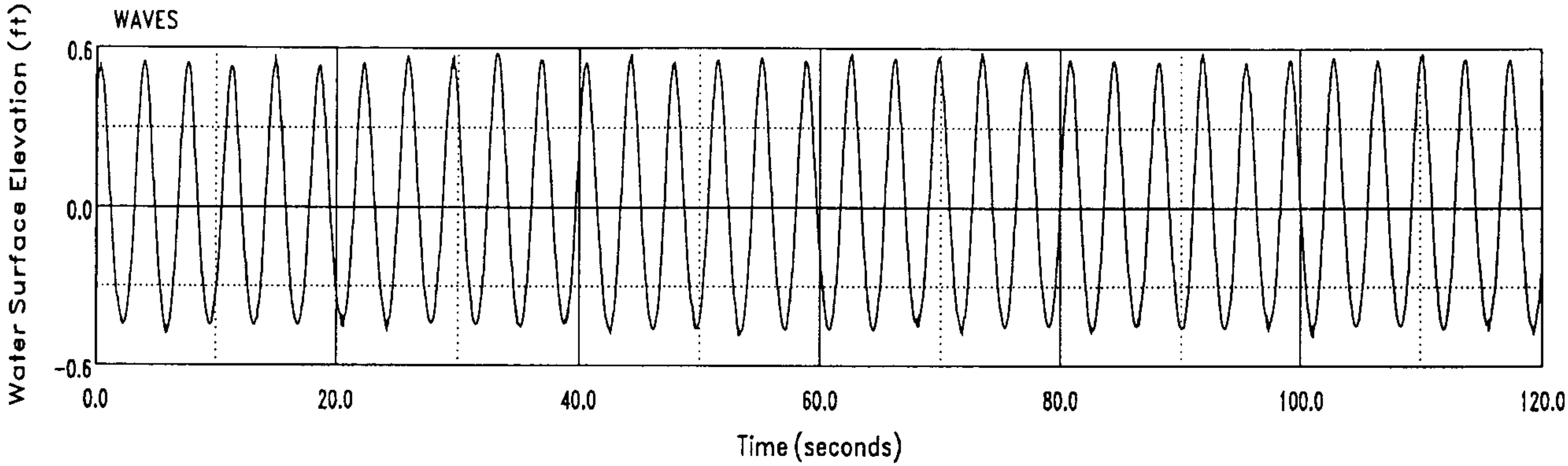
Appendix 7

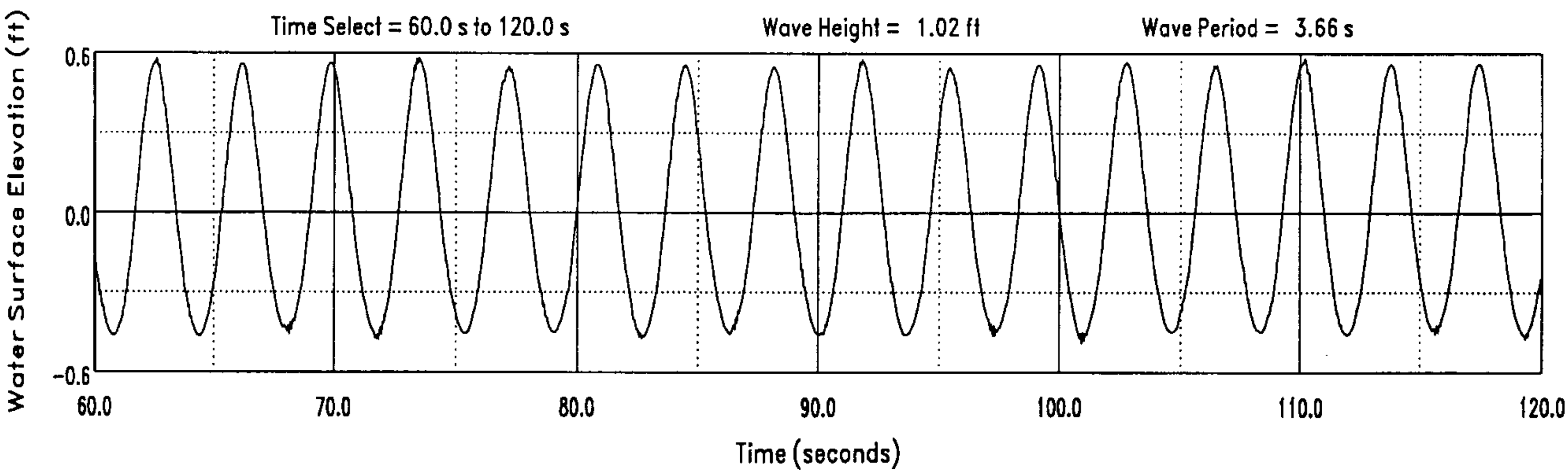
Records from Pre-burn Wave Stress Test

Test Number	Duration of Test (s)	Time Select (s)	Wave Height (ft)	Wave Period (s)	Tension Loads			
					Maximum (lbs)	Minimum (lbs)	Mean (lbs)	Standard Deviation (lbs)
nov5_testa_h0p30_t3p66_p_001	120	60-120	1.02	3.66	101.7	45.7	79.3	14.3
nov5_testa_h0p60_t3p66_p	120	60-120	2.04	3.66	190.3	37.8	128.5	35.4
nov5_testa_h0p80_t3p66_p	1200	1080-1200	2.69	3.66	228.8	73.6	167.7	37.9
nov5_testb_h0p80_t3p66_p	2500	2280-2400	2.66	3.66	279.4	93.7	200.7	48.1
nov5_testc_h0p80_t3p66_p	3600	3480-3600	2.63	3.66	250.5	83.5	187.9	43.5

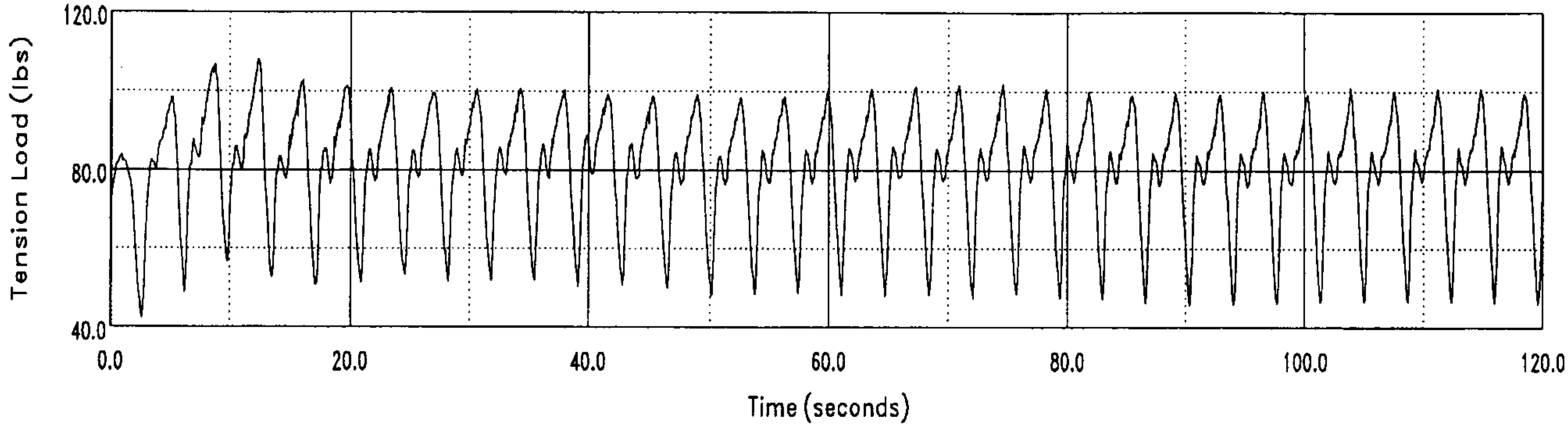
NOTE : For each test, a pre-tension of approximately 40 lbs was applied to the boom section.

Test Number : nov5_testa_h0p30_t3p66_p_001

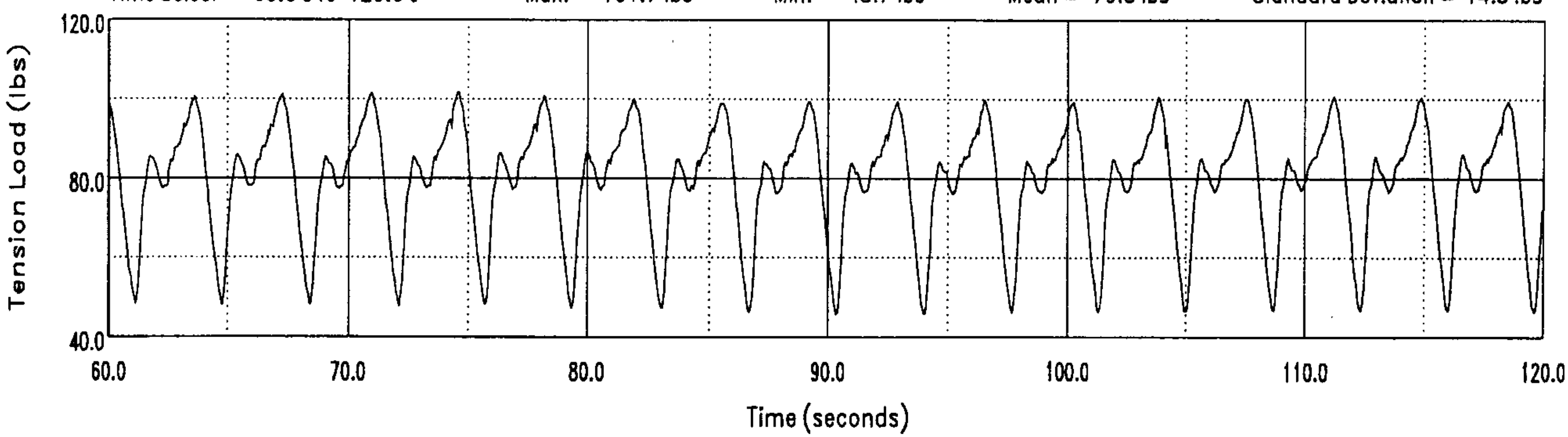




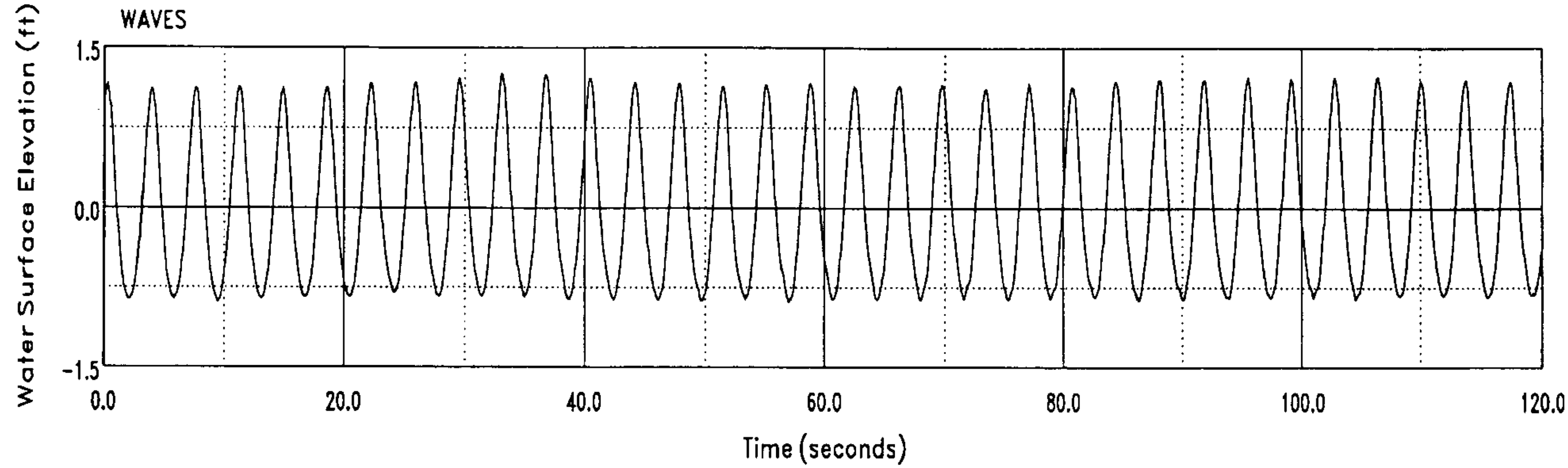
Test Number : nov5_testa_h0p30_t3p66_p_001
(Wave Height = 1.02 ft, Wave Period = 3.66 s)

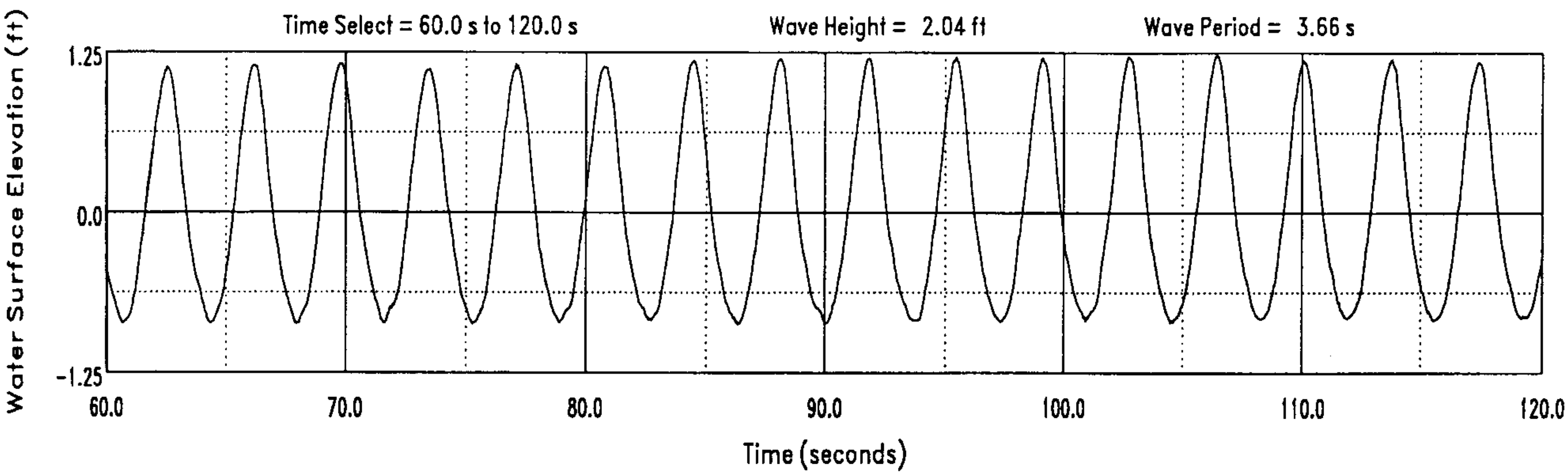


Time Select = 60.0 s to 120.0 s   Max. = 101.7 lbs   Min. = 45.7 lbs   Mean = 79.3 lbs   Standard Deviation = 14.3 lbs



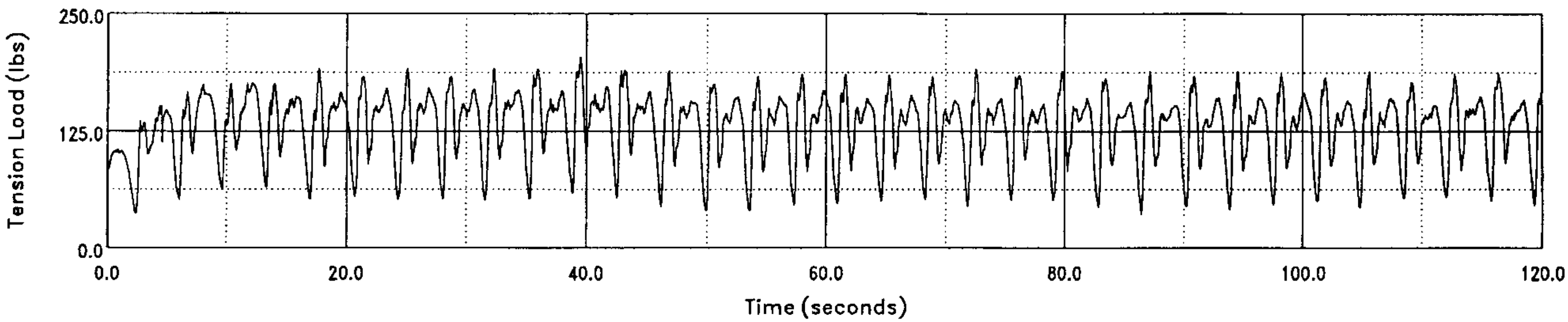
Test Number : nov5_testa_h0p60_t3p66_p

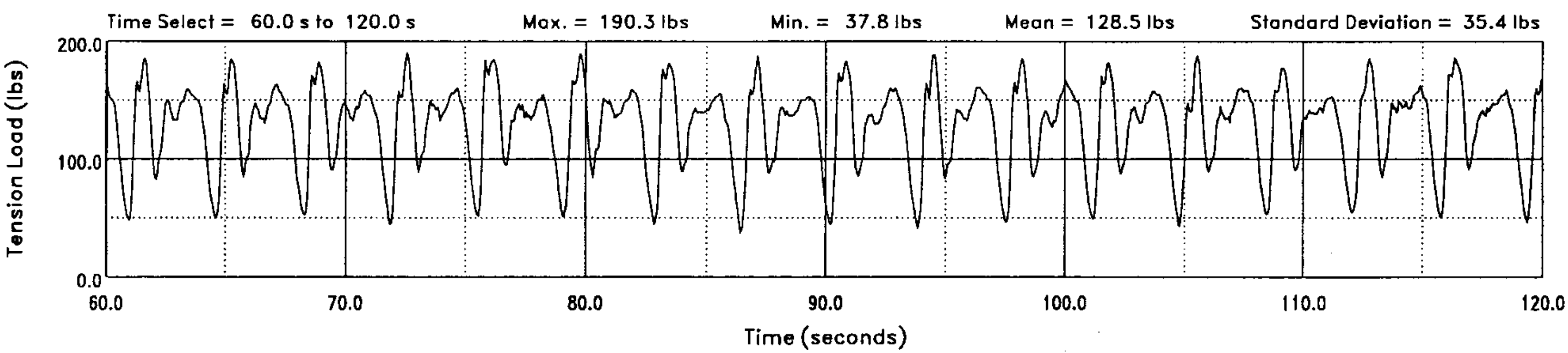




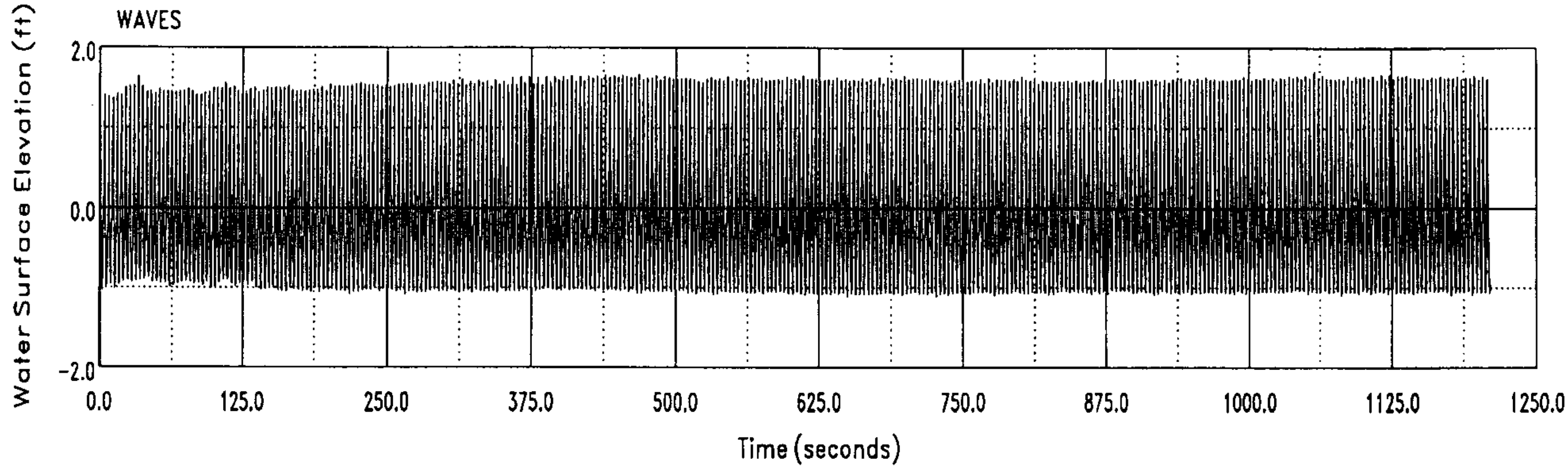
Test Number : nov5_testa_h0p60_t3p66_p

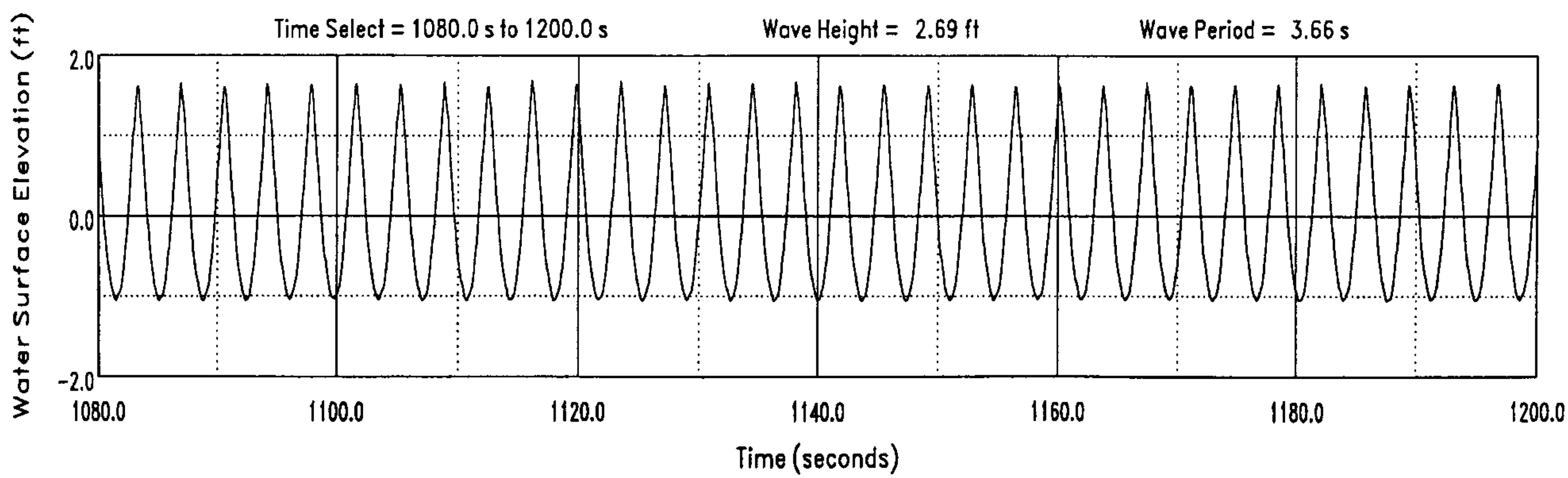
(Wave Height = 2.04 ft, Wave Period = 3.66 s)





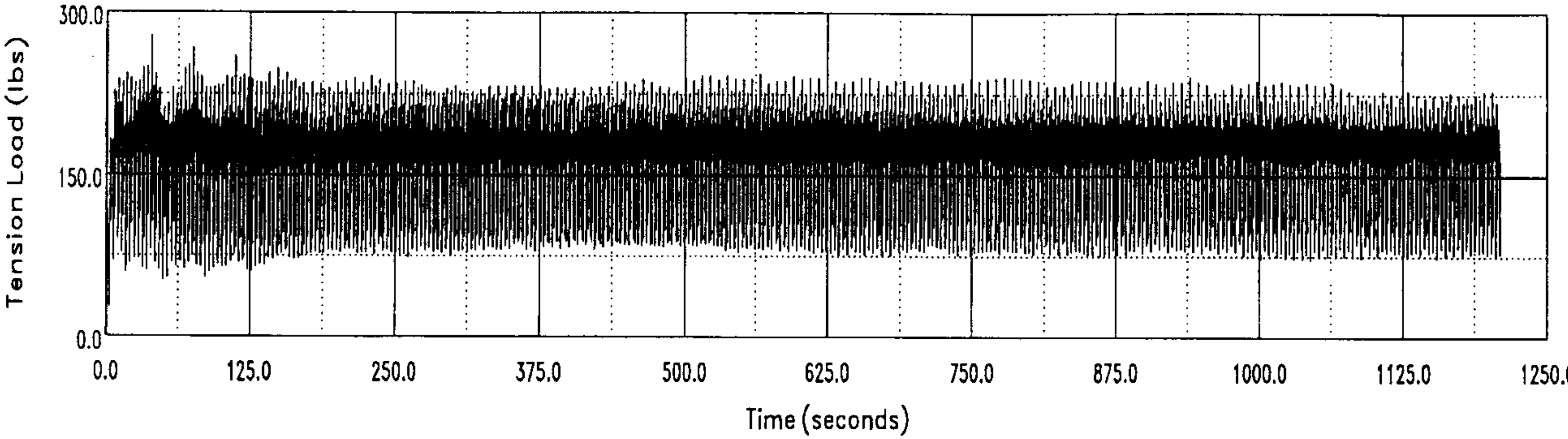
Test Number : nov5_testa_h0p80_t3p66_p





Test Number : nov5_testa_h0p80_t3p66_p

(Wave Height = 2.69 ft, Wave Period = 3.66 s)



Time Select = 1080.0 s to 1200.0 s Max. = 228.8 lbs Min. = 73.6 lbs Mean = 167.7 lbs Standard Deviation = 37.9 lbs