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A STUDY OF FIRE HAZARDS FROM COMBUSTIBLE AMMUNITION

EFFECTS OF SCALE AND CONFINEMENT (PHASE II)

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report presents the results of the second phase of a five-phase program sponsored by the Department of Defense Explosives Safety Board to improve safety distance standards for Hazard Divisions 1.3 and 1.4 munitions. This phase was directed toward study of effects of scale and confinement on hazards from a variety of munitions of these classes. The work was primarily experimental.

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Exploratory tests of smoke grenades indicated that hazards from this type of munition are minimal. In normal shipping container configurations, functioning of one grenade in a container does not normally cause sympathetic ignition of adjoining grenades.

Tests of munitions in the open showed marked differences in reactions of various types of munitions. Flares and solid-propellant rocket motors often react with ejection or propulsion of pieces from a stack or container, and hence very unpredictable behavior. Bulk materials such as gun propellants behave in a much more reproducible manner, but they do eject quantities of burning firebrands.

Tests were performed in two vented, intermediate-scale enclosures, an 8-foot cubicle made of fire-resistant material, and a tenth-scale geometric model of a standard storage igloo. All tests were instrumented with temperature and velocity probe sensors.

Tests were performed with smoke grenades, bulk propellants and flares in the cubicle. The smoke grenade tests were quite benign. The propellant tests showed that, beyond some critical loading density, much unburned propellant is carried out in an exhaust plume, and temperatures are higher in the external plume than within the cubicle. Tests with flares showed that reproducibility of ignition and function of these munitions is poor, but that simultaneous ignition of several flares produces large fireballs. The last test of the series (with flares) produced enough pressure rise within the cubicle to fail the weak refractory wall panels.

Tests conducted within the tenth-scale igloo were limited to gun propellants in scaled shipping containers, because of inability to scale the other munitions. The phenomenon of ejection of large quantities of unburned propellants as burning firebrands, observed earlier in the 8-foot cubicle tests, was again observed and quantified for three propellants. The cardboard model cannisters usually served as good protection for "acceptor" propellants within the igloo structure, and did not ignite, thus strongly reducing thermal effects compared to tests with bulk propellant. The principal hazard was found to be dependent on the type of propellant.

All detailed test data are included in the report, either in the body or in appendices.

Concurrent with the testing, methods of analysis of the thermal data were developed which allow prediction of internal and plume characteristics for vented munition burns, given knowledge of quantities and properties of the energetic materials in the munitions.

One of the analyses presented in the report is the development of conceptual mathematical models for the gas generation and venting from enclosures, followed by development of tentative scaling relations to govern scaling of results from these intermediate-scale tests to larger scales more typical of munitions storage conditions. The tentative scaling presented maintains geometric similarity and equal pressures and temperatures, but predicts equal times and velocities scaled by the geometric scale factor.

The report includes a discussion and preliminary plan for larger scale testing. Needed facilities and suggested instrumentation are included in this plan. Some recommendations and a brief reference list conclude the report.

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1.0 Introduction

The Department of Defense Explosives Safety Board (DDESB) established a five-phase program to improve safety distance standards and classification test procedures for munition items in storage and transport with particular emphasis on items that present mainly a fire hazard. These items are assigned in current safety standards and regulations[1,2] to Hazard Class 1 (Explosives) and more specifically to Hazards Divisions (HD) 1.3 and 1.4, defined as:

1.3 Mass-fire
1.4 Moderate fire, no blast

The five phases of the program are identified as:

I. Methodology Development
II. Effects of Scale and Confinement
III. Effects on Exposed Targets
IV. Safety Standards Preparation
V. Classification Test Design

The first phase, Methodology Development, was conducted and reported.[3] Some test methods were developed and used for preliminary testing of four sample materials consisting of:

- M1 propellant
- Western Cartridge 844 (WC844 ball propellant)
- 2.75-in. rocket motors
- ALA-17 flares

Characteristics for these test materials and also for IMR-5010 propellant which was used for heat release calibrations are given in Table 1. This program also included a review of scaling models for free-standing flame-fire sources, fireballs and firebrands. Information generated from this program was beneficial to the design of the experimental effort conducted during Phase II, Effects of Scale and Confinement (subject of this report).

The intended statement of work for Phase II work can be described as follows:

> "Effects of Scale and Confinement. In this second phase of the program, testing and analysis will be performed to evaluate the parameters which influence the radiated heat flux and firebrand dispersal as functions of size of the stack of material and confinement by a substantial storage structure. An objective will be to identify significant behavior transitions as the size of the stack is increased, so as to determine the minimum test size at which the behavior of typical stored quantities is reproduced, and to validate the applicable scaling laws."

TABLE 1. TEST MATERIAL CHARACTERISTICS

Test Material	Constituent	Base	Shape	Filler Ingredients
M1	Nitrocellulose Dinitrotoluene Dibutylphthalate Diphenylamine	Single	Tubular	NA
IMR-5010	Nitrocellulose Diphenylamine Dinitrotoluene Potassium Sulfate	Single	Tubular	NA
IMR-8208-M	Nitrocellulose Diphenylamine Potassium Sulfate Ethylene Dimethacrylate	Single	Tubular	NA
HC Smoke Grenade	NA	NA	NA	Hexachloroethane Zinc Oxide Aluminum
ALA 17 Flare	NA	NA	NA	Magnesium Polytetrafluoroethylene Nitrocellulose
MK 40 Rocket Propellant	Nitrocellulose Nitroglycerine Diethylphthalate	Double	8 point Star	NA

Five specific tasks were identified as follows:

"Task 1. Conduct exploratory tests on a smoke-producing material to identify thermal source behavior and output phenomena as in the previous phase of this program, so as to broaden the coverage of representative materials of HD 1.3."

"Task 2. Conduct tests in the open with small to intermediate quantities of materials studied in the preceding phase and in Task 1 above. Determine thermal output parameters as functions of effective unconfined stack size."

"Task 3. Conduct tests in substantial enclosures with an opening at one end, using small to intermediate quantities of the materials previously studied. Determine thermal output parameters external to the enclosure as functions of density of the charge in the enclosed volume. Make appropriate measurements of internal conditions and output external to the enclosure."

"Task 4. Estimate the confinement of an internal fire by a nominal unstrengthened storage structure and the probable effect on thermal outputs external to the structure."

"Task 5. Develop a plan for a large-scale test or tests as may be required to confirm that small- and intermediate-scale testing can be utilized to characterize thermal outputs and effects from quantities typically stored at military installations."

The first three tasks were designed to be experimental, and the last two were analytical or planning efforts. The efforts associated with these tasks are presented in Sections 2 through 6 of this report.

2.0 Exploratory Tests on Smoke Producing Material

A total of four tests (1 through 4) were conducted as exploratory tests on a smoke producing material (Task 1). The smoke producing material used in these tests was M8-HC smoke grenades. Descriptions of each of these four tests are provided in this section.

2.1 Test 1

A pool fire ignition source test was conducted on the HC smoke grenades to determine what kind of thermal gradient was necessary to initiate grenades in a shipping box. Each box contains 16 grenades and has an estimated gross weight of 45 lb. The box is constructed of 3/4-in. wood and is 14 in. x 14 in. x 8 in. high. The weight of combustibles, i.e., wood and cardboard, is approximately 11 lb. One of the boxes of grenades was modified to perform this test. All but three of the grenades were removed from the box and empty shipping tubes were intermixed with the grenades. Three of the shipping tubes were instrumented with Type K thermocouples to measure the temperature that the grenades would see. Two of the shipping tubes, each one containing a grenade, were instrumented with Type K thermocouples placed between the grenade skin and the shipping tube. Instrumenting actual grenades would allow for the measurement of the temperature at which the grenade would "function." Three other thermocouples were placed in the air spaces in between shipping tubes in order to measure the thermal environment inside the box. Figure 1 is a schematic illustrating the positioning of the grenades and the thermocouples inside the box. Figures 2 and 3 show the actual setup prior to testing. One additional thermocouple was positioned in the fire to record actual flame temperature.

The instrumented box was positioned inside of a protective arena as shown in Figure 4. The box was supported on a metal grill, and four 9-1/2 in. x 14 in. x 4 in. fuel pans each containing 1.25 gal of JP5 fuel were positioned underneath the box as shown in Figure 5. A radiometer was positioned approximately 1 ft from the grenade side of the box as shown in Figures 5 and 6. The purpose of the radiometer was to measure the thermal output of the fire and to measure the contribution made to the fire by the grenades and combustible materials, i.e., the wood and cardboard packing. The JP5 pool fire was ignited using electric matches and the grenade containment box was quickly involved. The thermocouple readings indicated a significant temperature rise within 3 min of ignition. The thermocouples mounted inside the full canisters, i.e., the shipping tubes containing grenades, continued to rise steadily. At approximately 6 min, the pool fire was so severe that the thermocouple insulation burned off resulting in erroneous readings. At approximately 19 min 10 sec after ignition, the first grenade "functioned." Since the insulation of the thermocouple wires had been damaged, the temperature of this event was not accurately known. Twenty seconds later, the second grenade "functioned" followed by the third grenade approximately 10 sec later. Each of the grenades emitted smoke/heat for a 2-min duration. At the time that the grenades "functioned," the

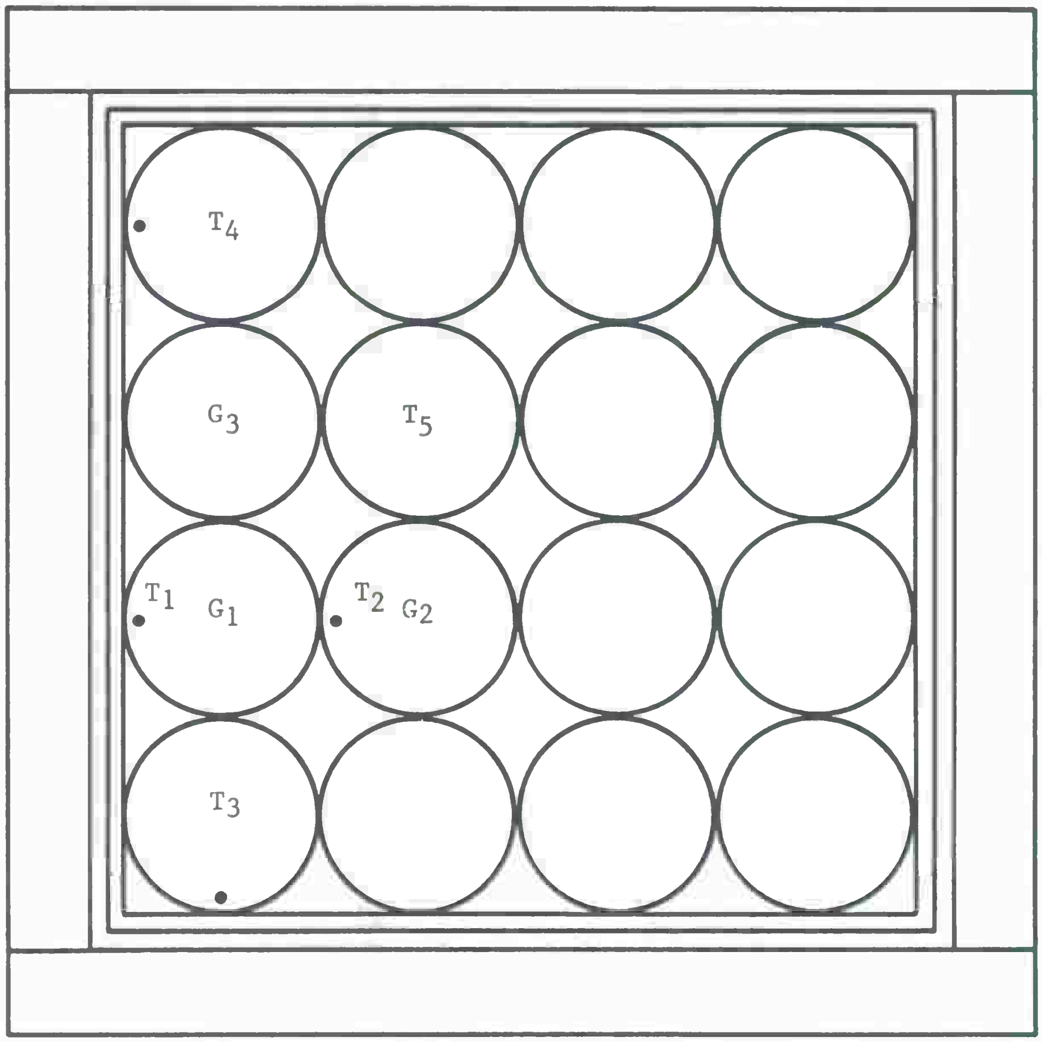


Figure 1. Grenade and Thermocouple Positions for Closed Box Test

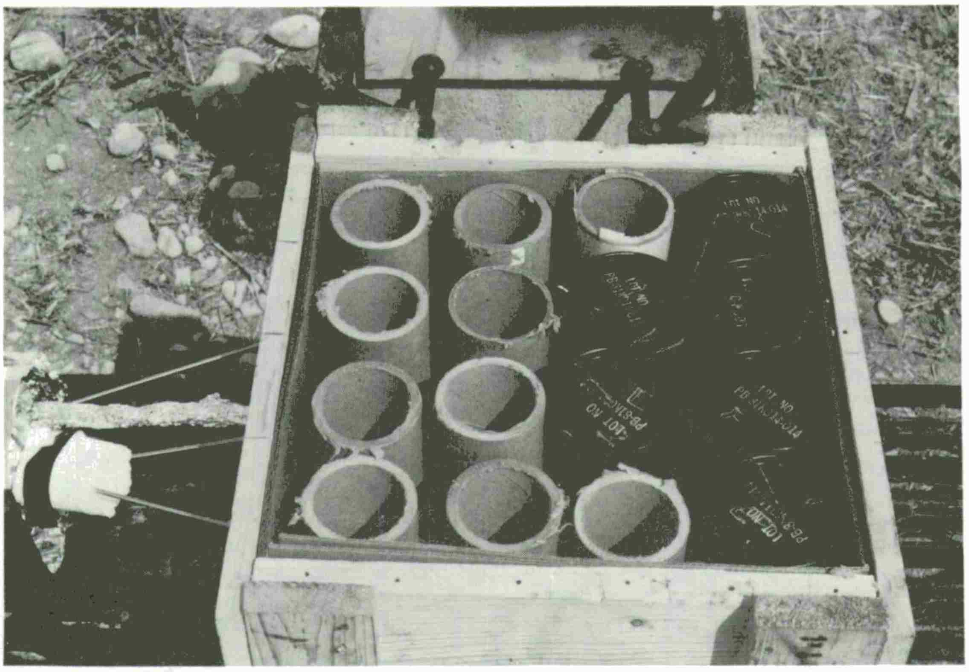


Figure 2. Grenade Box Test

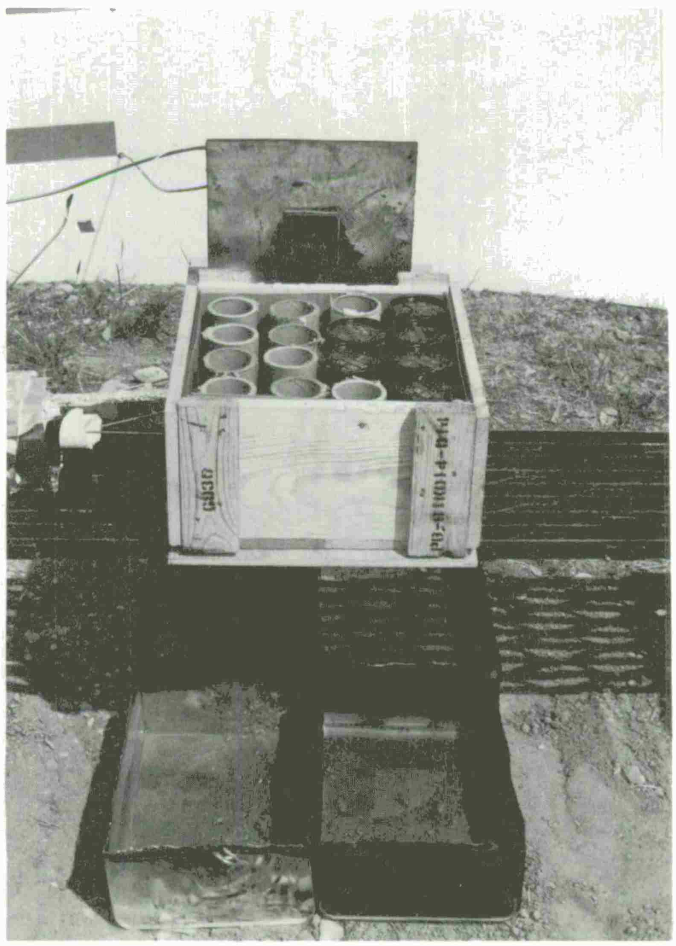


Figure 3. Grenade Box Positioned Over Fuel Pans

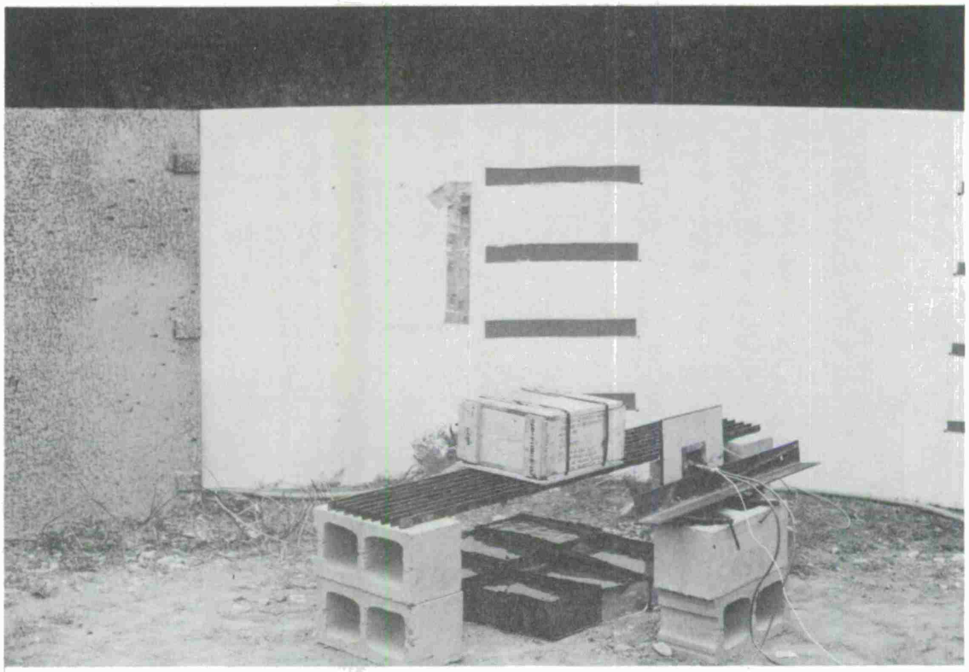


Figure 4. Sealed Grenade Box in Test Arena

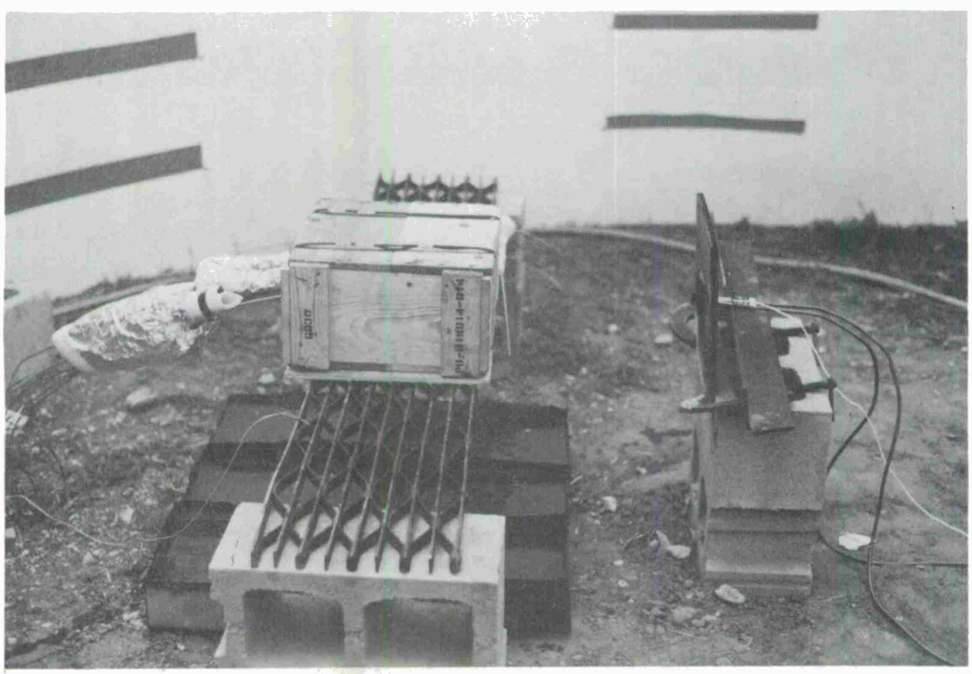


Figure 5. Side View of Grenade Box Positioned Over Fuel Pans

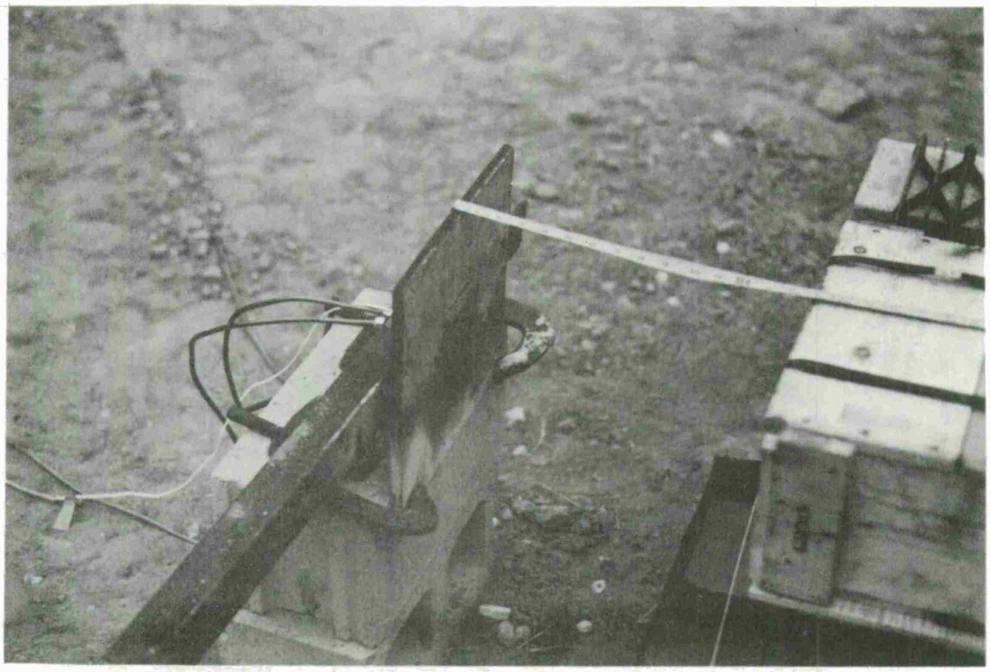


Figure 6. Radiometer Positioned 1 Foot Away from Grenade Box

wooden box was burned considerably; however, the remains of the box continued to burn for at least 10 min after the last grenade had "functioned."

Posttest inspection showed that one of the three spent grenades was still upright as shown in Figures 7 and 8. Closer inspection revealed that one of the remaining two spent grenades had fallen into one of the fuel pans. The remaining spent grenade was found on its side still on top of the grill. All three grenade bodies were severely burned (see Figures 9 and 10), and it was observed that two of the grenade bodies were significantly bulged and that one of the grenades had a failure in the seam. This seam failure appeared to be a pressure-type failure. The degree of bulging in the grenade bodies can be seen in Figure 9.

2.2 Test 2

A wooden crib fire ignition source test involving two smoke grenades was conducted. One grenade was in the black shipping canister and the second was a bare grenade. The two grenades were instrumented with Type K thermocouples and were placed upright on a grill similar to that used in the first test. An 11-lb wood crib consisting of 1/2 in. x 1/2 in. x 12 in. Douglas Fir wood elements was assembled surrounding the grenades as shown in Figure 11. The weight of the crib, 11 lb, was selected on the basis of the nominal weight of combustibles associated with the shipping box. The crib was ignited by touching a match to 50 ml of acetone contained in a 3.75-in. diameter by 3/4-in. deep canister. The crib fire surrounded the two grenades and the temperature of the bare grenade started rising rapidly. Approximately 4 min after ignition, the bare grenade "functioned" at a temperature in excess of 464°F. At the same time, the other grenade, i.e., the grenade in the shipping canister, was registering a temperature of 103°F. The temperature of this second grenade started rising shortly thereafter and continued to rise to an observed temperature of 447°F at which time it also "functioned." The second grenade "functioned" at approximately 8 min 20 sec after ignition.

Posttest examinations of both grenades showed considerable bulging of the grenade bodies and longitudinal failures in the seams (see Figure 12). Once again, the deformation of the grenade bodies and the seam failure indicate a pressure failure.

2.3 Test 3

A wooden crib fire ignition source test was conducted on a full box of grenades. The purpose of this test was to determine whether a fire involving only the wooden shipping box would generate sufficient heat to function any of the grenades. Wood pieces, 14 in.-long x 3/4-in. thick, were stacked to provide 5.5 lb of crib on either side of the full box of grenades, as shown in Figures 13 and 14, to simulate one-half of the fuel load that would be offered by two adjacent boxes being on fire and impinging on the center box (containing the test grenades). To minimize

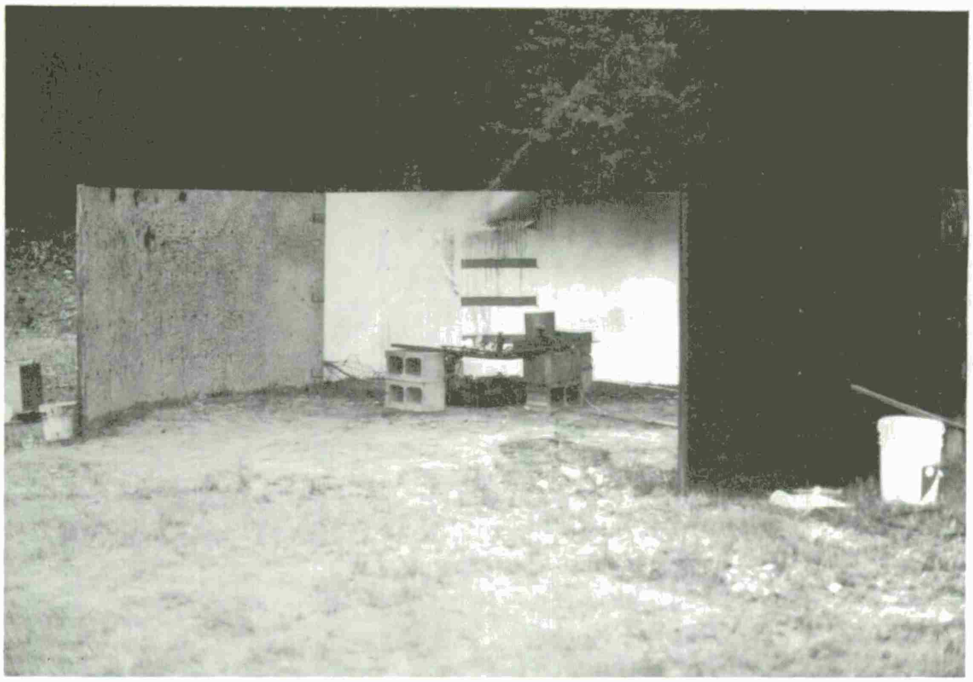


Figure 7. Test Setup After Functioning of Grenades

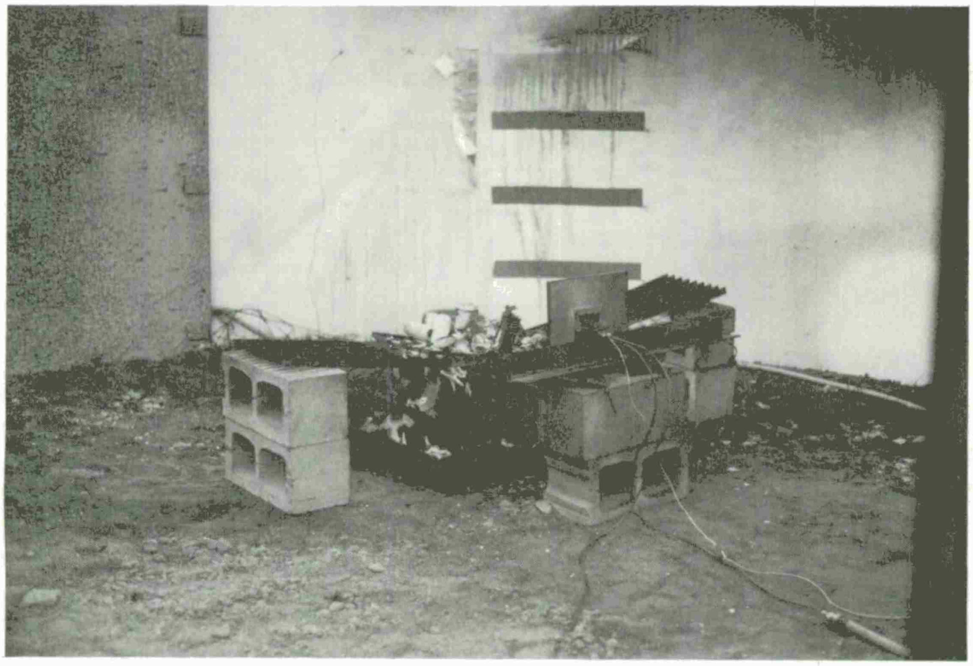


Figure 8. Single Grenade Still Upright After Test

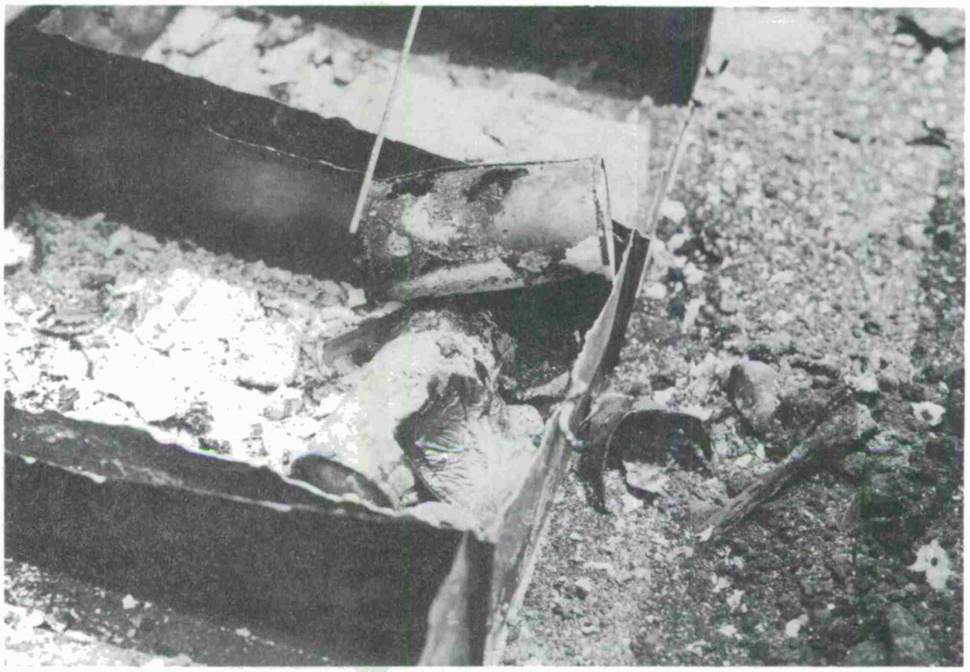


Figure 9. Two Grenade Bodies in Fuel Pan

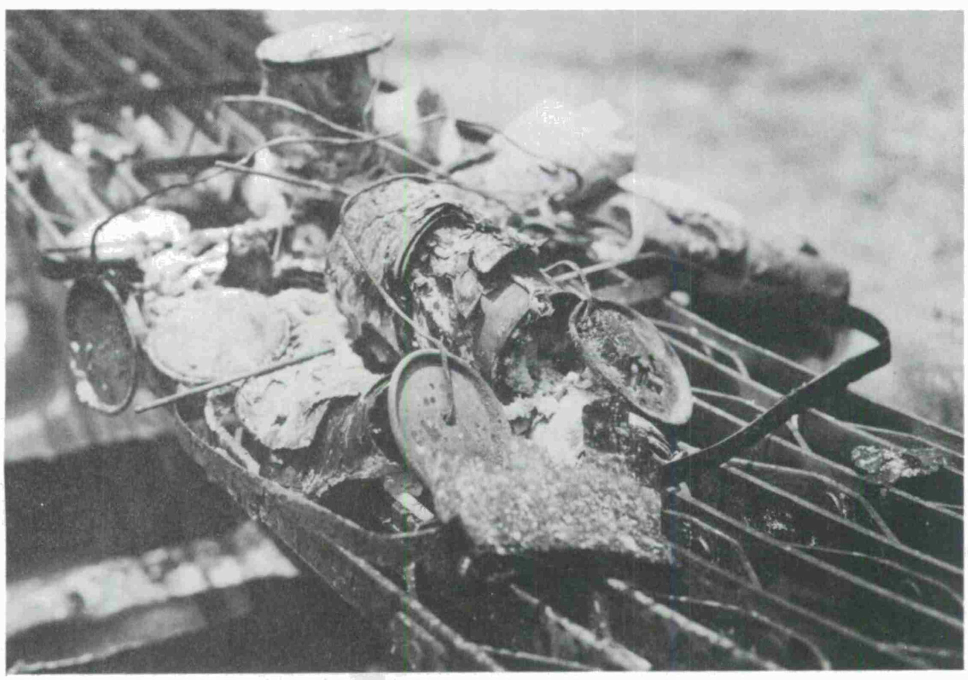


Figure 10. Third Grenade in Center of Picture

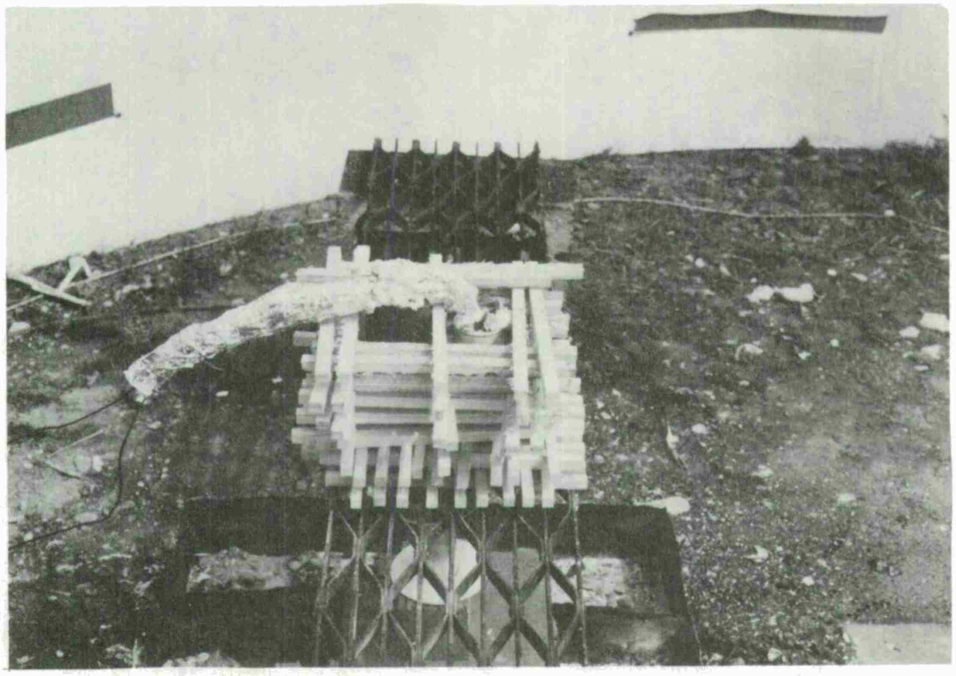


Figure 11. Setup for Dual Grenade Crib Fire Test

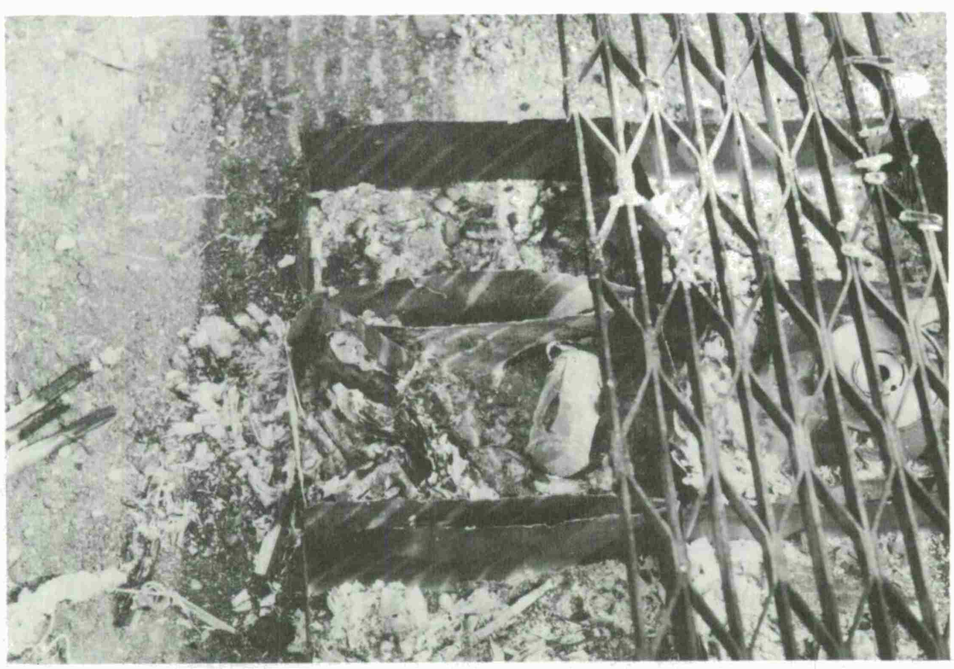


Figure 12. Bulged Grenade Body with Split at the Seam

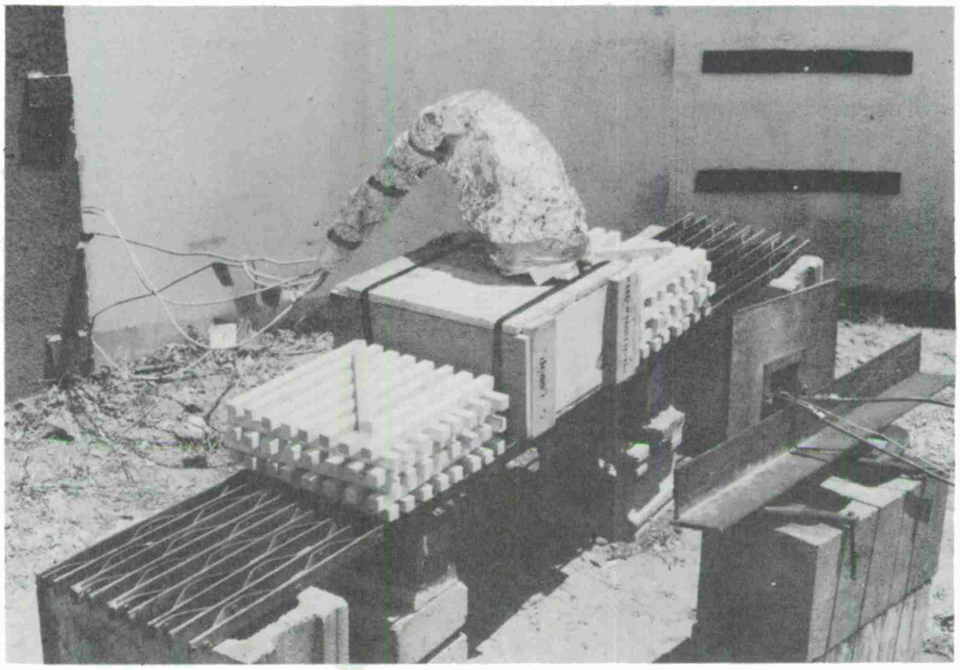


Figure 13. Full Grenade Box Crib Fire Test Setup

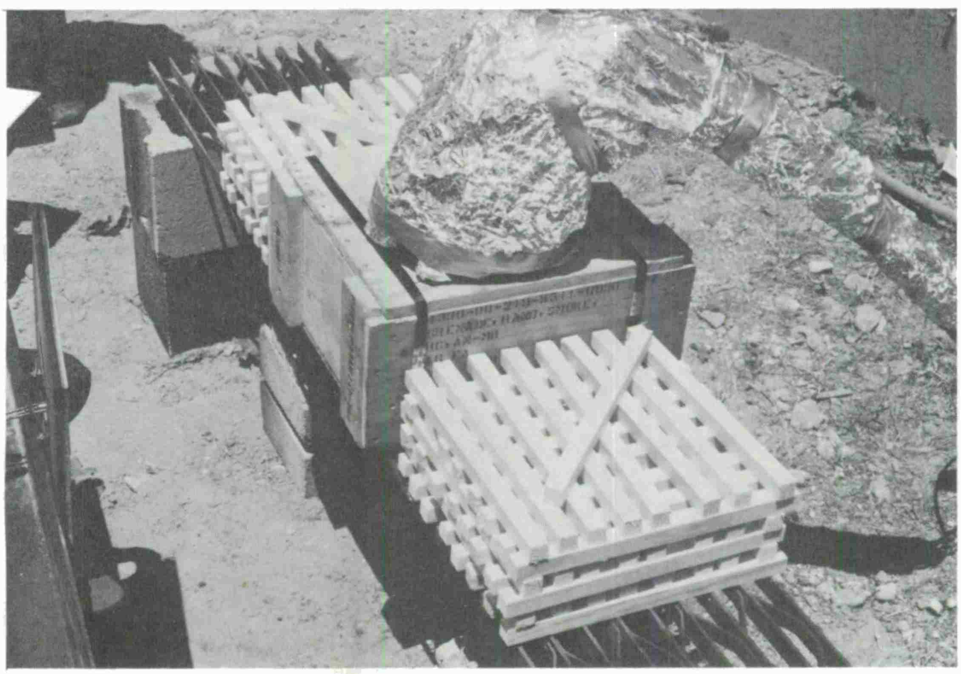


Figure 14. Grenade Box Thermocouples Wrapped in Insulation

problems with the thermocouple wire insulation failures encountered in Test 1, type K thermocouples with Refrasil/asbestos insulation were used to instrument five of the grenades. Figure 15 is a schematic illustrating the positioning of the thermocouples. Two canisters, each containing 50 ml of acetone, were used to ignite the two wooden cribs. Following ignition, the crib fires built up slowly. Uniform and sustained involvement of the crib elements was observed approximately 3 min after ignition of the acetone. The box containing the instrumented grenades eventually became involved. The temperatures inside the full box of grenades increased slowly during the first 30 min with the highest recorded temperature being 167°F recorded on Thermcouple 3 (see Figure 15). At this time, most of the crib fire ignition source had been dissipated; however, the box of grenades was still smoldering. The temperatures inside the box continued to rise at a faster rate, and approximately 9 min later (39 min after ignition), one of the grenades in the box "functioned." At this time, the five instrumented grenades were reading the following temperatures: T1--287°F, T2--182°F, T3--198°F, T4--104°F, and T5--109°F. The grenade identified in Figure 15 as T1 appears to have "functioned" 50 sec later (39 min 50 sec after ignition). Grenade T2 appears to have "functioned" 40 min 10 sec after ignition. Grenades T3 and T4 appear to have "functioned" 41 min 10 sec after ignition. [The grenades were considered to have "functioned" once the temperature exceeded 450°F. This criterion was based on our findings in the bare grenade crib tests (Test 2) where the two grenades each "functioned" at a temperature of approximately 464°F.] Grenades continued to "function" periodically inside the box for the next 40 min until all had "functioned." The cumulative time for all the events was 80 min after ignition of the acetone.

Posttest inspection showed a number of bulged grenade bodies and a number of grenades with seam failures (see Figures 16 and 17).

2.4 Test 4

This test was performed to determine whether the "accidental" actuation of one grenade in an enclosed box would provide sufficient heat to ignite adjacent acceptor grenades, i.e., sympathetic ignitions. A wooden box was built dimensionally like the wood boxes used to ship the grenades. Four grenades were positioned as shown in Figure 18. The cardboard packing normally used in packing the grenades was also included in the model. Grenade G1 was actuated remotely by removing the safey pin attached to a "lanyard" pull wire passing through a 1/8-in. hole in one of the sides of the box. The grenade was allowed to burn freely in the enclosed box (see Figure 19). The smoke was emitted through the seams of the box and the box itself started smoldering. The box continued to smolder for approximately 30 min. Allowing several hours for cooldown and to ensure that none of the remaining grenades would "function," the box was opened to inspect the damage.

Posttest inspection showed that the one grenade that was remotely actuated ignited the cardboard and burned the lid of the box significantly

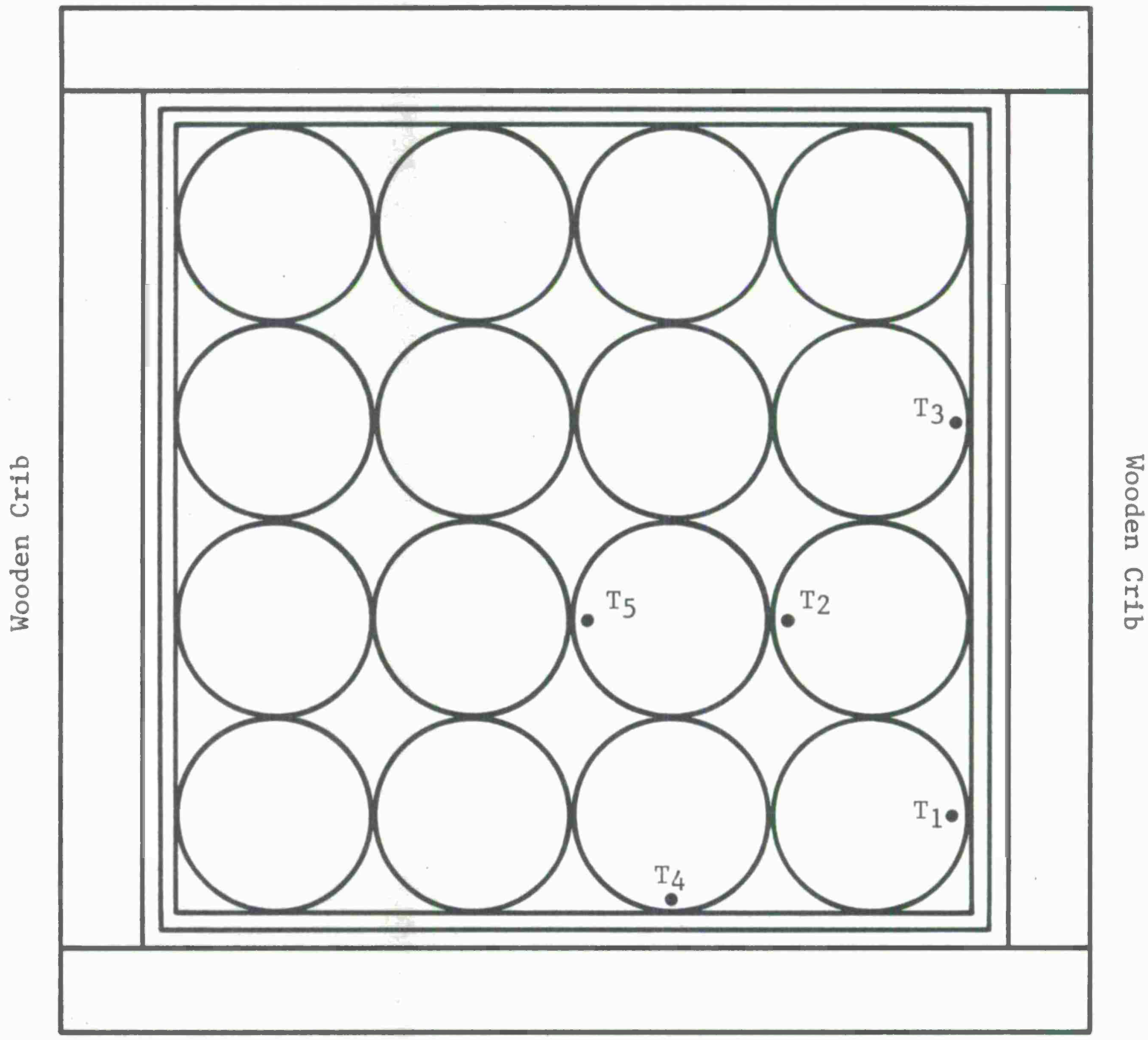


Figure 15. Test 3

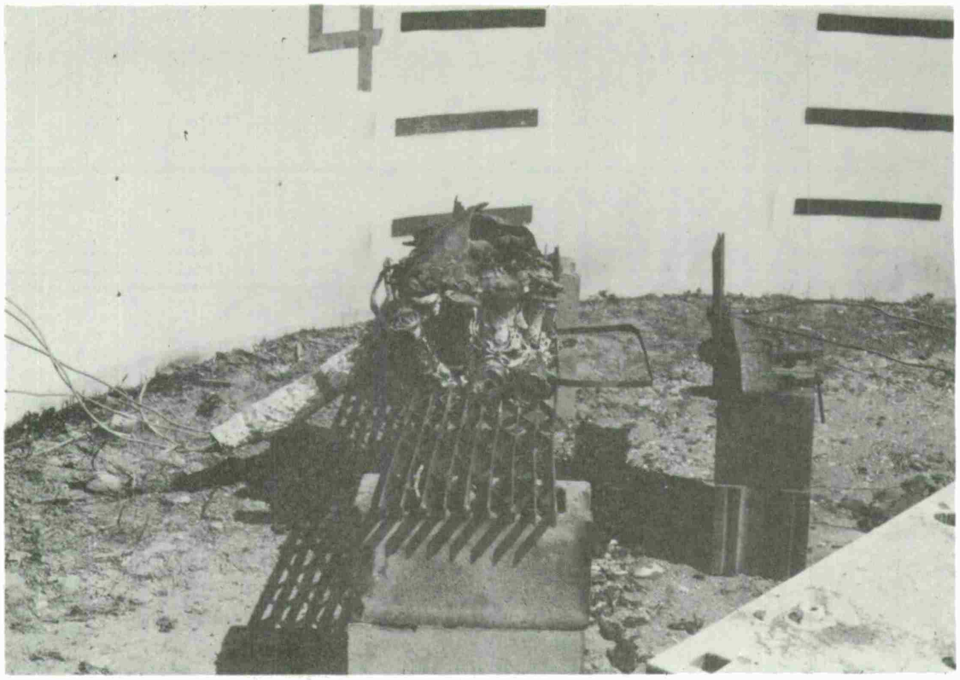


Figure 16. Grenade Box Posttest

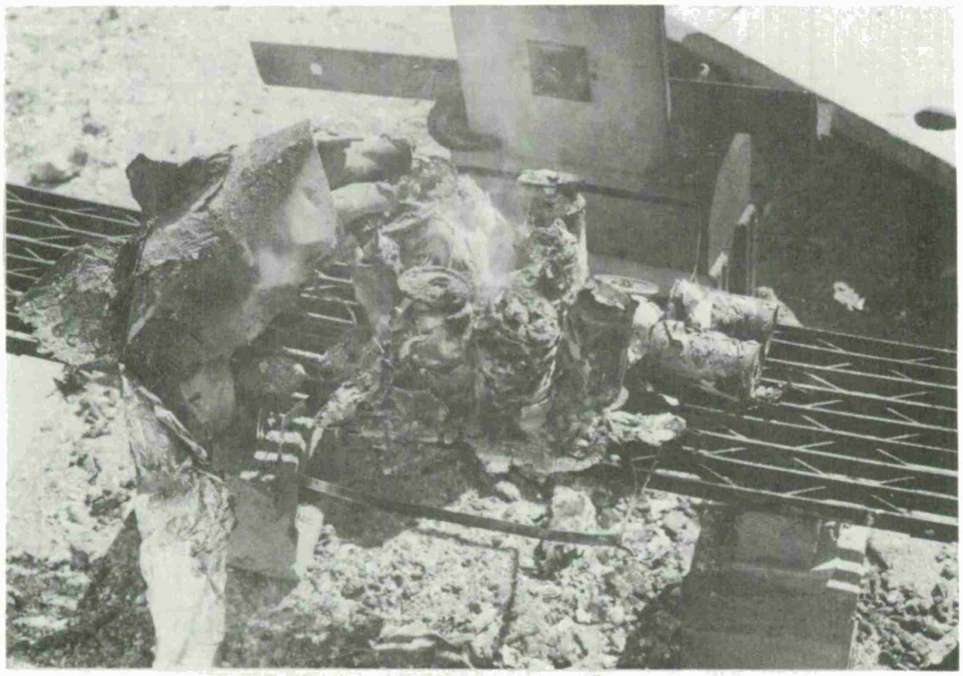


Figure 17. Grenade Bodies Upright Posttest

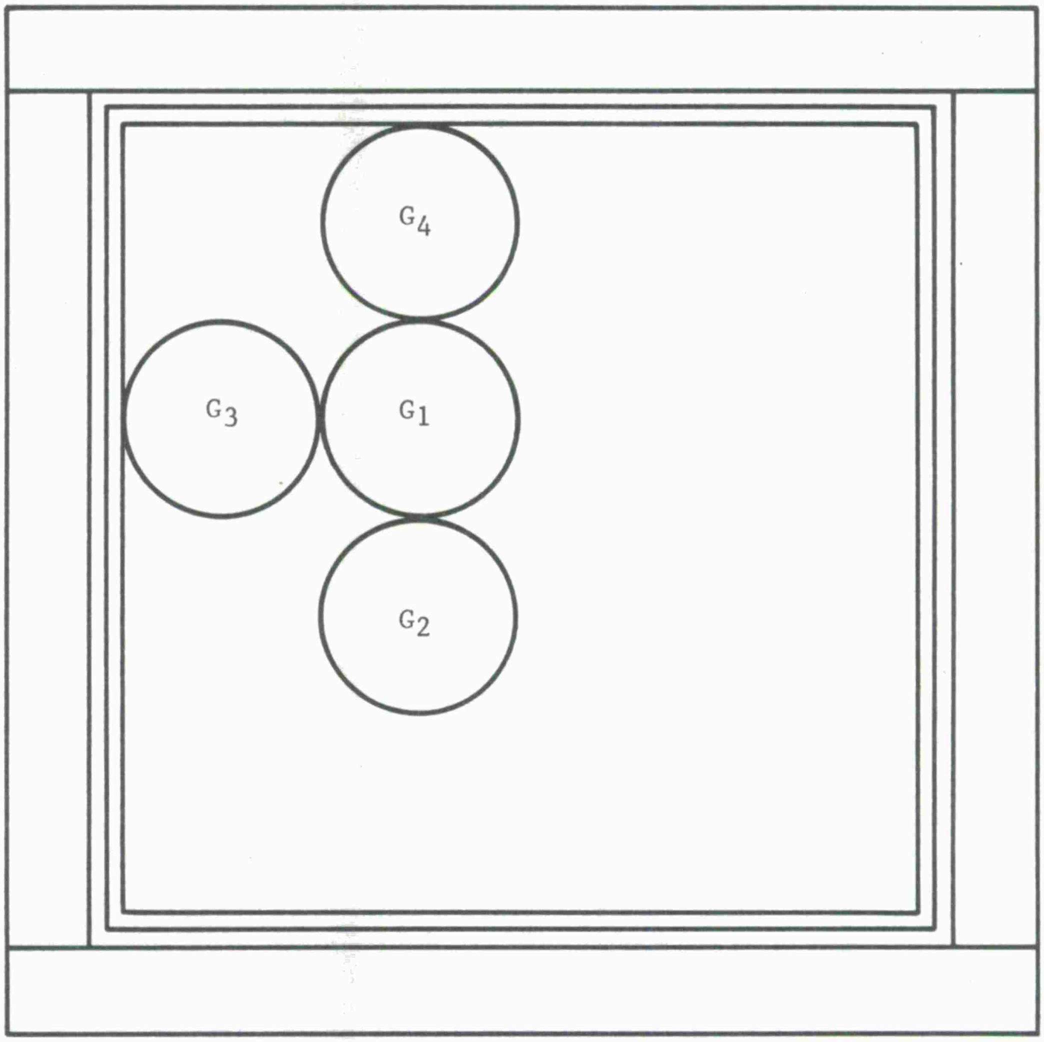


Figure 18. Positioning of Grenades Prior to Test

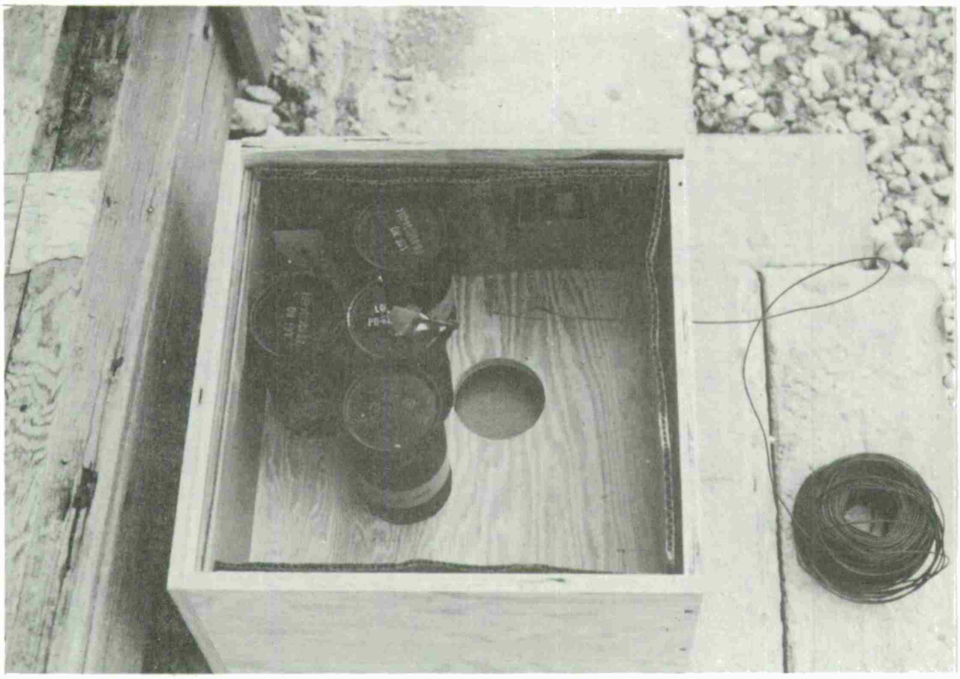


Figure 19. Center Grenade Wired for Remote Actuation

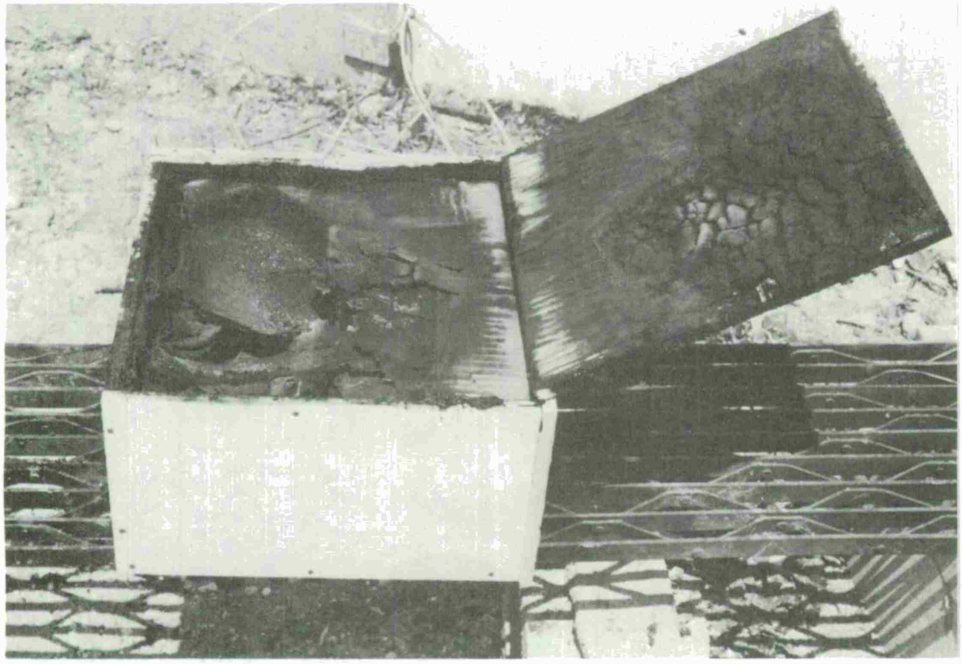


Figure 20. Lid and Shipping Cardboard Severely Burned

(the lid was charred to a depth of 3/16 in.). The black cardboard shipping canisters of the acceptor grenades were also severely burned as shown in Figure 20; however, on opening the canister, the grenades showed only slight discoloration and bulging at the seams (see Figures 21 and 22). The three surviving grenades were actuated remotely and each grenade operated normally. The results of the test indicated that the "accidental" actuation of a single grenade did not provide sufficient heat buildup to reach temperatures (>450°F) necessary to cause sympathetic ignition of adjacent acceptor grenades.

Figure 21. Surviving Acceptor Grenade Canisters

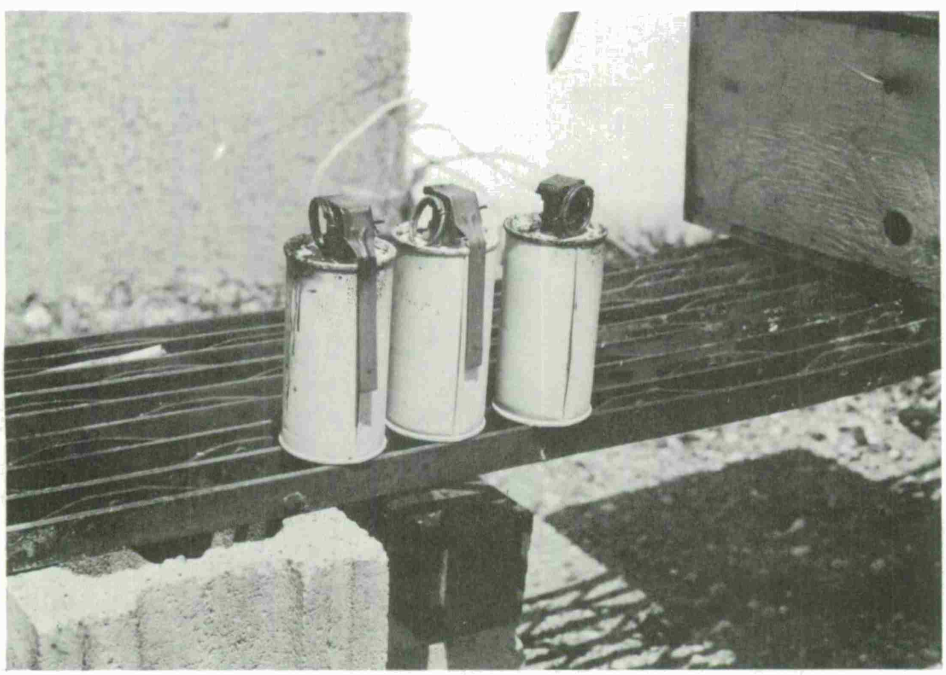


Figure 22. Surviving Acceptor Grenade Bodies Bulged at Seams

3.0 Tests in Open with Small and Intermediate Quantities

Eight preliminary open-air tests were conducted. The first of these (Test 1A) used the ALA-17 flares. The seven remaining open-air tests were conducted on the MK 45 rocket motors. The primary purpose of the intermediate scale tests was to determine the effect of different ignition scenarios on the development of the fire. The open-air tests were instrumented with thermocouples and radiometers. In addition, photographic coverage consisting of 35-mm color slides and closed circuit color TV video-tape recording were provided.

3.1 Test 1A

Test 1A was a crib fire test conducted on the ALA-17 flares. Two flares were positioned on the metal grill as was done for the smoke grenade tests. A 5.5-lb wooden crib consisting of 3/4 in. x 3/4 in. x 12 in. elements was assembled surrounding the flares. Acetone (50 ml) contained in a 3-3/4-in. diameter x 3/4-in. canister was used to ignite the crib. The metal grill holding the flares was once again set up inside the containment structure. The first flare "functioned" 5 min 7 sec after ignition of the acetone. The cover over the top half of the flare that ignited was against the containment shield and the ignited section traveled approximately 10 ft, striking against the opposite containment shield where the top half of the flare continued to burn for 9 sec. Approximately 15 sec after the first flare ignited, the top half of the second flare ignited, and it too was launched against the containment shield. The top halves of both flares burned to completion in approximately 8 to 9 sec. The second half of the first flare ignited approximately 1 min 7 sec after the first event and also burned to completion in about 9 sec. The bottom half of the second flare, however, never ignited and was remotely ignited at a later time.

3.2 Tests 1 and 2

The tests conducted on the MK 45 rocket motors were performed in order to estimate the size, severity and duration of the fireball produced by the rocket motor grain functioning. In addition, the tests provided for experimenting with ignition techniques. The first two tests were performed on the motor outside of the shipping container and without the cover on the warhead end of the rocket motor. Attempts to function the motor using the firing leads attached to the rocket motor resulted in ignition of the igniter charge, but no ignition of the grain. These two rockets were then functioned using a smokeless powder booster and electric match placed directly in contact with the grain. The rocket motors were restrained during their burn.

3.3 Test 3

On Test 3, the rocket motor was disassembled to remove the fins and nozzle assembly as well as the igniter cap. The prescored rupture disk, which is normally located between the igniter cup and the warhead, was left in place. The rupture disk did not blow out on ignition, and the burning grain jetted out of the rocket motor tube and burned on the ground.

3.4 Test 4

This test utilized a stripped rocket motor, i.e., the fins, rocket nozzle, igniter cap and prescored rupture disk were removed. The grain was inserted back into the tube, and a smokeless powder igniter was placed in contact with the grain. The grain was ignited and burned, thrusting out of both ends simultaneously. The grain burned for approximately 36 sec and remained stationary due to the thrusting out of both ends. During the burn, the grain was observed to pulse continuously and the plumes were estimated to be 4 to 6 ft long.

3.5 Tests 5 and 6

These tests were of the grain by itself placed in a metal ammunition container. The grains were again ignited using smokeless powder igniters. A very concentrated fireball resulted in each of the two tests, and the grain was consumed in about 25 sec.

3.6 Test 7

This test used a stripped rocket grain in the tube with masonry bricks located 2 ft away from each end serving as flame deflectors. The grain was ignited and burned for 36 sec. The bricks successfully deflected the fireball.

4.0 Tests in an Intermediate Enclosure

Task 3 of this program required that tests on the smoke grenades, flares, rockets and propellants be conducted in a substantial enclosure. Two intermediate scale enclosures were developed for this program, an 8-ft cubicle and a $1/10^{th}$ scale model igloo. The $1/10^{th}$ scale model igloo was designed and constructed to be capable of withstanding estimated maximum internal pressures associated with a maximum w/v of 21.6 lb/ft^3 loading density. The 8-ft cubicle was made necessary by the fact that some of the end items, e.g., finished munitions, could not be tested in the $1/10^{th}$ scale igloo in their standard storage configuration which is end on. The 8-ft cubicle was not a substantial enclosure but it was selected and used as an inexpensive expedient facility to evaluate the applicability of calorimetry for data gathering and interpretation. Complete descriptions of the 8-ft cubicle and igloo are presented in this section. A summary of the tests performed in the two enclosures is also presented in this section.

4.1 Marinite Cubicle Enclosure

An 8-ft cubicle was designed and fabricated for use in testing the 2.75-in. rockets, the ALA-17 flares and the M8-HC grenades (the propellants were tested in the $1/10^{th}$ scale igloo). The 8-ft cubicle consisted of a steel frame covered with Marinite 36 which is a fire-proof structural insulation made by Johns Mansville and can withstand heats up to approximately 900°F. An appropriate vent area, i.e., the door, was also included and is shown in Figure 23. The cubicle was instrumented with a total of 27 Type K thermocouples positioned as indicated in Figure 24. The thermocouple data which was recorded for each test was used to perform the thermal energy balance calculations which were used to determine the mass burning rate of the materials tested. The procedure for calculating the heat output generated by the materials is described by Fitzgerald.[4] The cubicle door or vent area was instrumented with a total of four Keil probes for measuring plume velocity. Thermocouples were mounted on the Keil probes in order to measure the plume temperature.

As previously mentioned, the cubicle walls were instrumented with 27 Type K thermocouples having exposed junctions. Each thermocouple wire was mounted in the walls such that the junction was flush with the inside surface of the Marinite walls. Specific thermocouples were connected in parallel to give average temperatures for selected "zones." Figure 24 shows the locations of each of the 27 thermocouples. Thermocouples T1, T15, T16, T17 and T18 were connected in parallel comprising Zone 1 (Data Channel 1). Thermocouples T2, T14 and T19 were connected in parallel comprising Zone 2 (Data Channel 2). Thermocouples T3, T4, T12, T13, T20 and T21 comprised Zone 3 (Data Channel 3). Thermocouples T23, T24, T25 and T26 comprised Zone 4 (Data Channel 4) and the roof thermocouples, T5, T6, T7, T8, T9, T10 and T11, comprised Zone 5 (Data Channel 5). Keil air velocity probes were installed in the door to measure plume velocity. Four probes were installed 2.5 in. outside the door. Keil Probe 1 was located approximately 5 in. from the top of the door, while Keil Probe 2 was

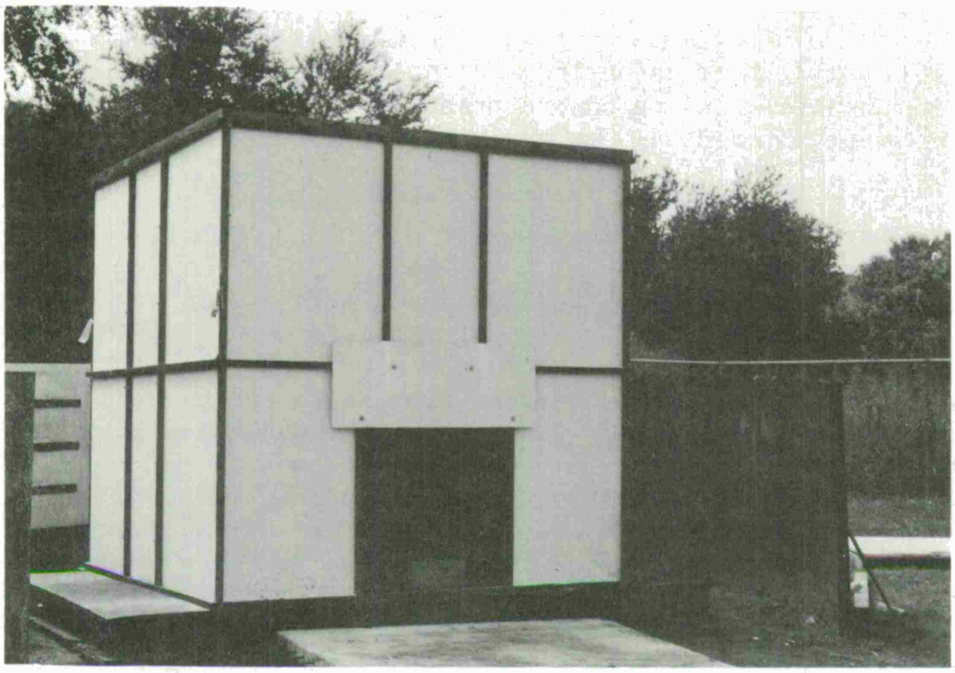


Figure 23. 8-Foot Marinite Cubicle

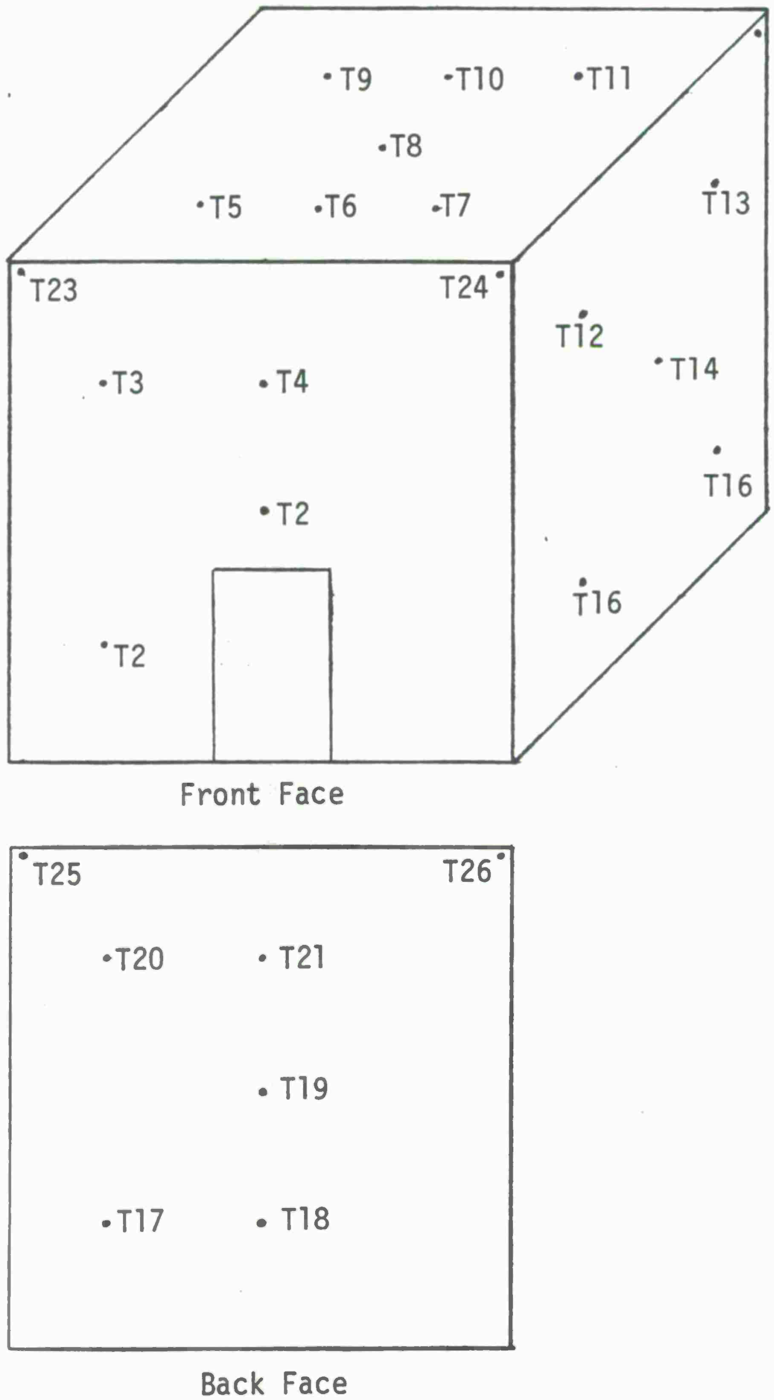


Figure 24. Thermocouple Locations

located 12 in. from the top of the door. Keil Probe 3 was located 24 in. from the top of the door and Keil Probe 5 was positioned 30 in. from the top of the door. Probes 1 and 2 were positioned facing towards the cube thereby measuring the plume velocity, while Probes 3 and 4 were positioned facing away from the cube thereby measuring the air intake velocity. If the plume size encompassed the entire doorway, then Probes 3 and 4 (which were facing away from the plume) would read a negative pressure. Each of the four probes was connected to a magnehelic gauge which was monitored throughout the test via a video camera. Type K thermocouples were mounted to each of the Keil probes to measure the plume temperature and air intake temperatures at the door (Data Channels 6, 7, 8 and 10, respectively). Two additional thermocouples were located approximately 17 in. and 21 in. from the top of the door in order to better define size and temperature (Data Channels 13 and 9, respectively). An additional array consisting of three Type K thermocouples was located 3 ft in front of the door to measure the plume temperature at a specific distance away from the door (Data Channels 11, 12 and 14). Figure 25 is a sketch showing the locations of the external thermocouples which were monitored on each test.

Several preliminary tests were performed in the cubicle using small quantities of a small caliber propellant (IMR-5010). The purpose of these tests was to calibrate the cube instrumentation, i.e., thermocouples and air velocity Keil probes, and also to verify the thermal energy balance equations with a material whose thermal output was already known. IMR-5010 has a heat of combustion of 2900 cal/g. Mass burning rates were measured for 5 lb of propellant in an aluminum tray as shown in Figure 26a. The propellant was 1-5/8 in. deep in this tray. The tray was placed on a load cell, ignited using an electric match and the mass burning rate recorded in terms of weight loss versus time. Mass burning rate for 10 lb of propellant was also measured with the propellant placed in a larger tray as shown in Figure 26b. The propellant for the 10-lb test was also at a depth of 1-5/8 in. The load cell output for the 5-lb test is shown in Figure 27a. The vertical scale corresponds to the propellant weight (1.67 lb/div) and the horizontal scale is the time scale (2.05 sec/div). The mass burning rate for the 5-lb test was calculated at 1.00 lb/sec. The load cell output for the 10-lb test is shown in Figure 27b. The vertical scale is the propellant weight (3.34 lb/div), and again the horizontal scale is the time scale (2.05 sec/div). The mass burning rate for the 10-lb test was calculated at 2.1 lb/sec. Three calibration tests were performed in the cubicle using 5 lb of IMR-5010 in each test. A fourth test was performed in the cubicle using 10 lb of propellant. In the 5-lb tests, the propellant was placed in an aluminum tray with dimensions as shown in Figure 26a. The propellant was ignited using two electric matches in series located in the bottom center of the tray. The 10-lb test was performed using the tray shown in Figure 26b.

4.2 Summary of Tests Performed in the Marinite Cubicle

As previously mentioned, a total of four preliminary tests (Tests 1 through 4) were performed using quantities of the IMR-5010 propellant to

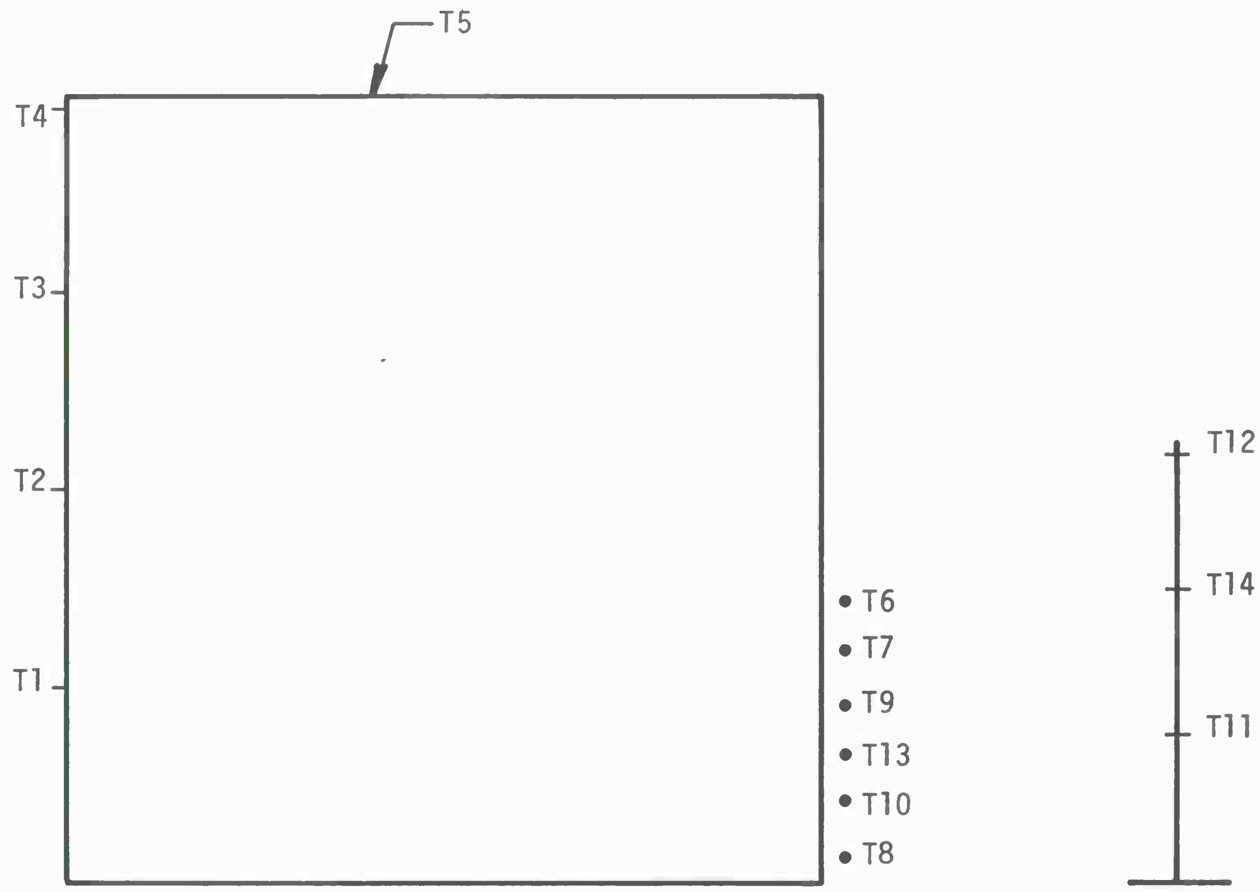


Figure 25. Locations of External Thermocouples

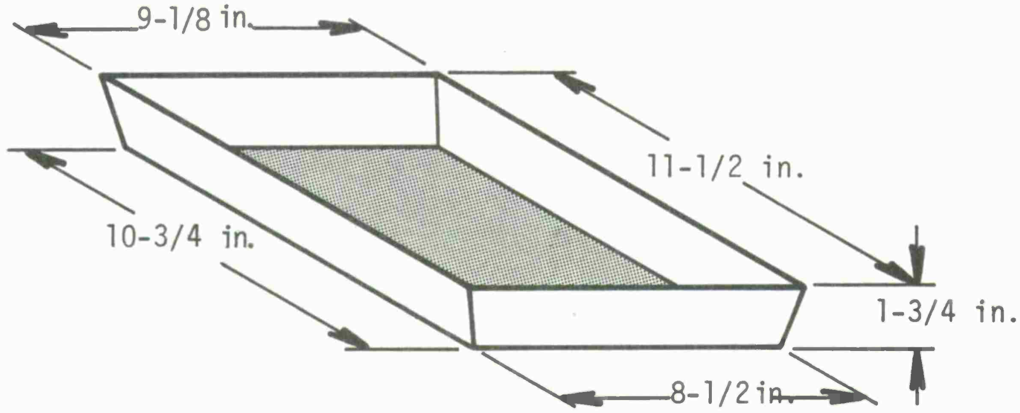


Figure 26a. Tray Used in 5-Pound Test

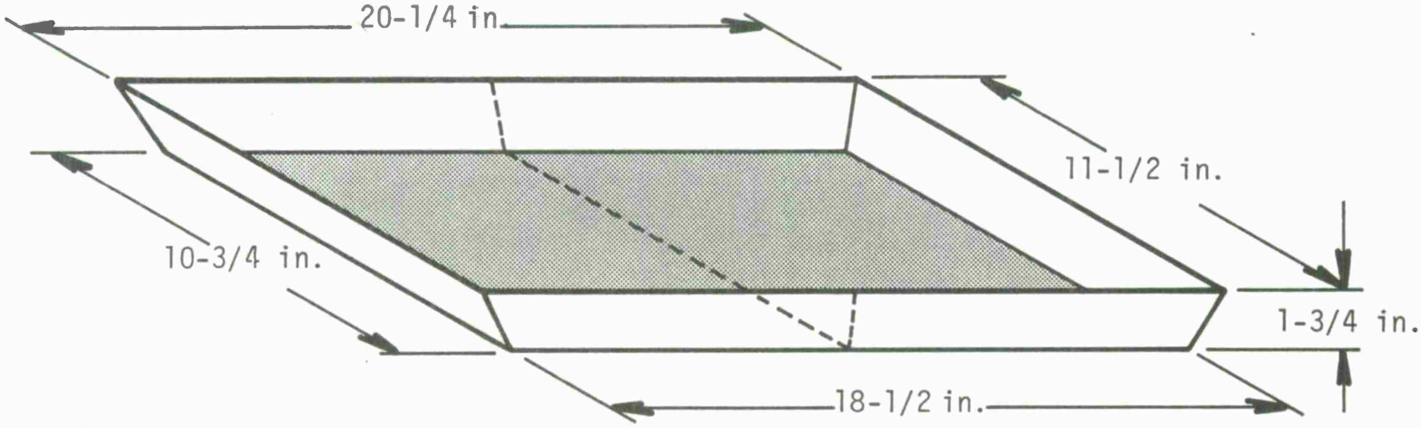


Figure 26b. Tray Used in 10-Pound Test

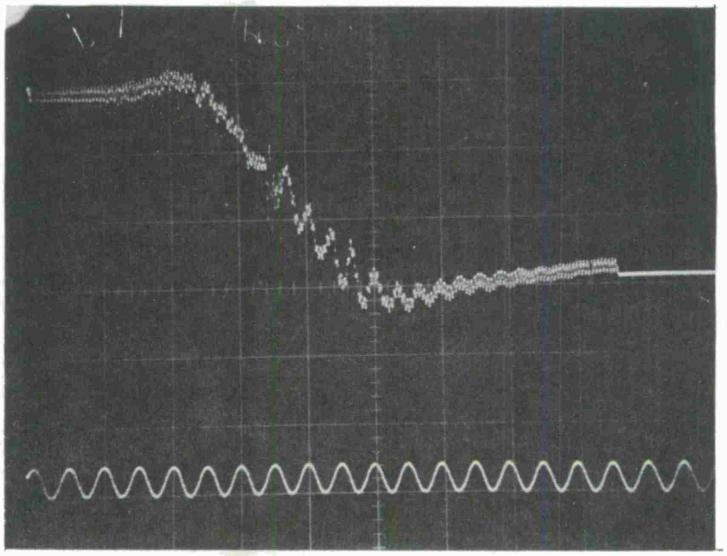


Figure 27a. Load Cell Response for 5-lb of IMR-5010 Propellant Test

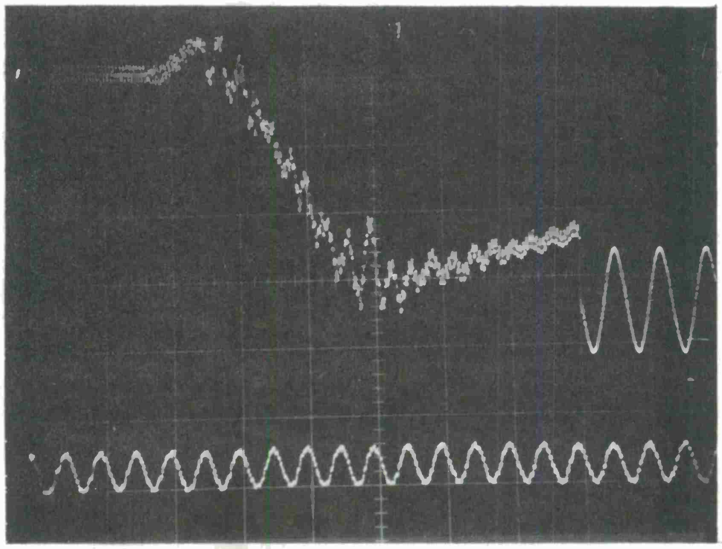


Figure 27b. Load Cell Response for 10-lb of IMR-5010 Propellant Test

check out instrumentation and test procedures. The full test program using the M8-HC smoke grenades, the IMR-5010 propellant, the IMR-8208 propellant, and the ALA-17 flares was then initiated.

4.2.1 Tests with the M8-HC Smoke Grenades

Two tests were performed with the smoke grenades. The first test involved half of a box of grenades (eight each) and the second test involved a full box. (Detailed descriptions of the two tests are provided in Appendix A.) In both tests, the smoke grenades were initiated simultaneously. The standard fuze, that ignites the starter-mix which in turn ignites the HC mix, was removed from each of the grenades and replaced with an Atlas electric match to affect simultaneous initiation. The combustion of the smoke grenades was a very mild event and smoke gently billowed out of the cube door. Table 2 summarizes the results of the two smoke grenade tests.

TABLE 2. SMOKE GRENADE TESTS

Test No.	Quantity (grenades)	Max Internal Temp (°F)	Max External Temp (°F) Rake 1	Max External Temp (°F) Rake 2	Plume Velocity (ft/sec)
6	8	185	360		negligible
10	16	284	743	153	6.8

4.2.2 Tests with the IMR-5010 Propellant

Seven tests were performed using various quantities of the IMR-5010 propellant. The quantities of propellant used varied between 5 lb and 12.5 lb. The purpose of these tests was to establish a baseline for use in predicting thermal output. Complete descriptions of each of the seven tests are presented in Appendix A of this report. Table 3 is a summary of the seven tests using the IMR-5010. Included in this table are the maximum internal temperature recorded, the maximum external temperature recorded at the first rake, the maximum external temperature recorded at the second rake, and the plume velocity.

TABLE 3. IMR-5010 CUBE TESTS

Test No.	Quantity (lb)	Max Internal Temp (°F)	Max External Temp (°F) Rake 1	Max External Temp (°F) Rake 2	Plume Velocity (ft/sec)
5	5	230	924	440	37.8
7	10	307	1028	1024	53.6
8	5*	268	891	626	34.3
12	7.5	Instrumentation problems			
13	12.5	Instrumentation problems			
14	12.5	243	1202	1293	45.1
15	7.5*	241	1067	650	38.2

* Propellant was spread out in the larger pan.

Figure 28 presents a curve of the internal and external temperatures as a function of propellant weight. As can be seen in Figure 28, once the propellant weight gets up above 10 lb, the two external temperatures become quite close, while the internal temperature remains quite low and fairly uniform.

4.2.3 Tests with the IMR-8208 Propellant

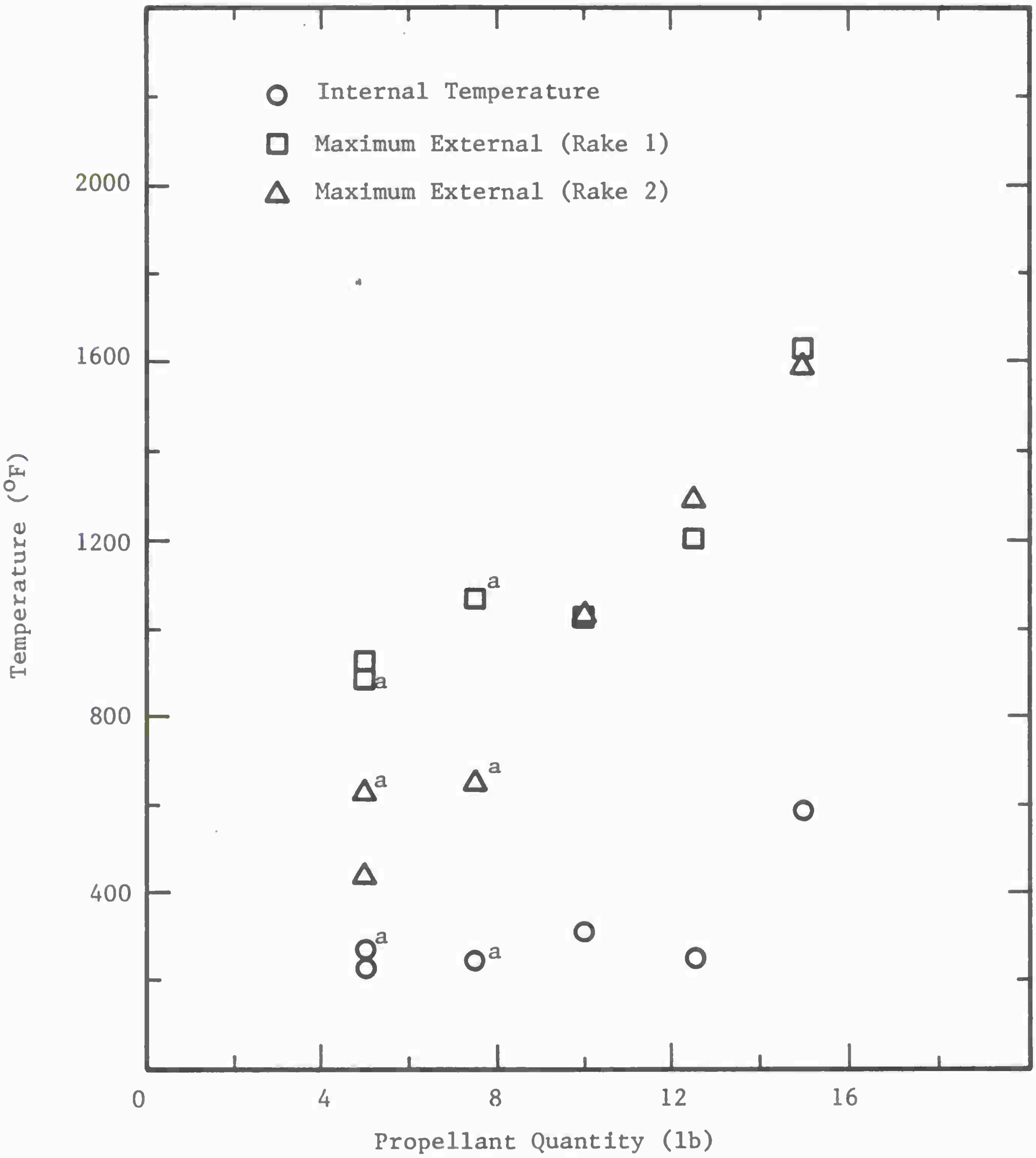
Three tests were conducted using the IMR-8208 propellant. Complete details on these three tests are contained in Appendix A. Table 4 summarizes the results of the three IMR-8208 propellant tests. The maximum internal and external (plume) temperatures at both rakes and the plume velocities are included in the table. The quantities of propellant tested varied from 10 lb to 15 lb. Test 20 was a repeat of Test 19 because of instrumentation problems in the cube roof.

TABLE 4. IMR-8208 CUBE TESTS

Test No.	Quantity (lb)	Max Internal Temp (°F)	Max External Temp (°F) Rake 1	Max External Temp (°F) Rake 2	Plume Velocity (ft/sec)
18	15	593	1626	1596	41.4
19	10	245	1427	644	61.7
20	10	352	1173	932	35.4

4.2.4 Tests with the ALA-17 Flares

Six tests were performed using the ALA-17 flares. Complete details on the six flare tests are included in Appendix A. Table 5 summarizes the results of the tests and includes the maximum internal and external (plume) temperatures as well as the plume velocities.



a. Propellant in large tray.

Figure 28. Curve of Temperature vs. Propellant Wt for IMR-5010

TABLE 5. ALA-17 FLARE CUBE TESTS

Test No.	Number of Flares	Max Internal Temp (°F)	Max External Temp (°F) Rake 1	Max External Temp (°F) Rake 2	Plume Velocity (ft/sec)
9	2	710	787	354	47.4
11[a]	2	1127	712	359	43.4
16[b]	2	313	746	280	23.1
17[b]	4	1803	1751	1015	77.3
21[b]	4	569	1344	381	45.4
22[b]	4	Cube failed--no data available			

a. Flares were placed in an ammo box which had a top vent.
b. Flares were placed in an ammo box which had uniform vents on all sides.

As shown in Table 5, the first test (Test 9) was performed with the flares in the open inside the cube. However, to prevent damage to the cube from the jettisoned flare casings, the next test was performed with the flares in an ammunition box which had a top vent cut out of it. This top vent resulted in directionalizing the plume to the roof as verified by the high internal temperature (1127°F). Therefore, the subsequent tests were all performed with the flares placed in an ammunition box which had symmetric vents on all sides.

If a comparison is made between Test 16 which involved two flares and Test 21 which involved four flares, it can be seen that the maximum internal temperature and the maximum external temperature at the first rake for Test 21 are almost double those of Test 16, and the maximum external temperature at the second rake for Test 21 is almost 50% higher than that of Test 16. Test 17 also involved four flares; however, the temperatures recorded for Test 17 were much higher than those measured in both Test 16 and Test 21.

4.3 1/10th Scale Model Igloo Enclosure

A 1/10th scale model igloo was fabricated out of steel for use in testing of the propellants. A sketch of the model igloo is included as Figure 29. The igloo was provided with a water cooling jacket for a dual purpose. The thermal output of the burning material was expected to be exceedingly high so as to compromise the steel test fixture thus requiring some protection through water cooling. The cooling water itself would in turn serve as a flowing heat sink that could be used in computing the thermal output from the test materials. At the start of the testing, it became apparent that at a fuel loading density in excess of 2 lb. unburned propellant is carried out of the igloo in the plume and is consumed external to the igloo. This burning behavior led to moderate temperatures inside the test fixtures, which were tolerable, and eliminated the need for the protection that would have been available through the use of the water

ID Radius	16.25"
Length	96"
Vent	12" x 12"

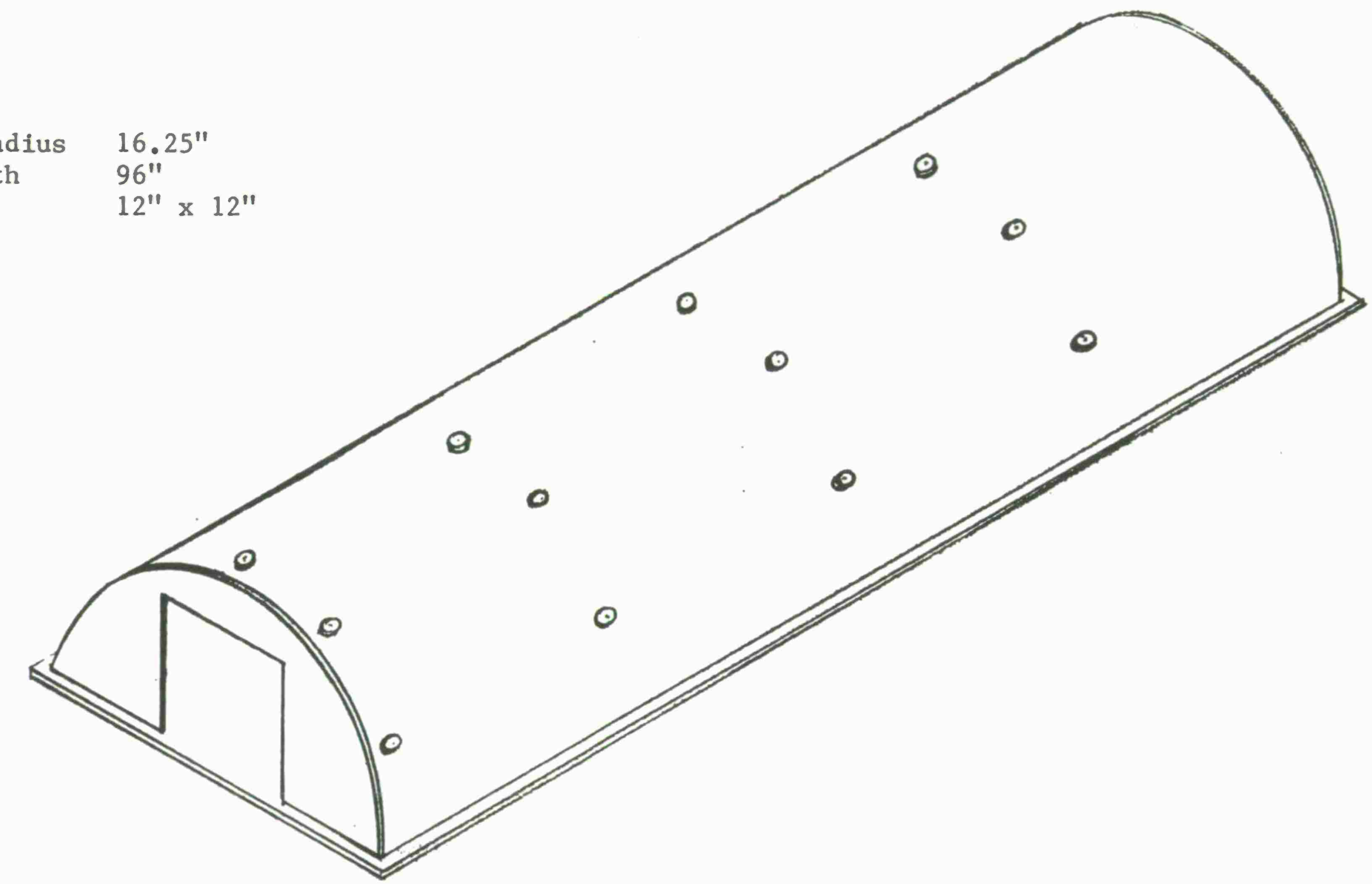


Figure 29. Sketch of 1/10th Scale Model Igloo

cooling jacket. The igloo propellant holding tray was supported on four load cells, one at each corner, to allow for dynamic measurements of propellant mass loss during testing. The igloo was fabricated with a number of penetrations to allow for instrumenting with thermocouples. Four Type K thermocouples were located in the roof of the igloo equally spaced from front to back (Thermocouples 1 through 4, respectively). Four Type K thermocouples were located in the wall of the igloo, 45° down from the roof, and were also equally spaced (Thermocouples 5 through 8, respectively). Two rakes each containing three thermocouple probes and two Keil probes were located outside of the igloo door. The thermocouple probes and Keil probes were used to measure plume temperatures and pressures which were then converted to velocities. The first rake was located 7 in. from the door and contained Thermocouple Probes 9 through 11 and Keil Probes 1 and 2. The second rake was positioned 3 ft from the igloo door and contained Thermocouple Probes 12 through 14 and Keil Probes 3 and 4. Video camera coverage was provided for each of the tests.

As part of the test procedure, SwRI obtained scale model cardboard canisters to hold the test quantities of propellant. In full scale, the IMR-8208 propellant is shipped in cardboard canisters that are 14 in. in diameter, 22 in. high and 0.2 in. thick. This canister is used to ship 100 lb of propellant. SwRI used a canister that was 3.5 in. in diameter, 6 in. high and 0.060 in. thick which corresponded to approximately a $1/50^{th}$ volumetric scale model of the large canister. This particular canister held 2 lb of IMR-8208 propellant. The IMR-5010 propellant is also shipped in similar large canisters so the $1/50^{th}$ scale model was used for those tests also. The M1 propellant is shipped full scale in canisters 15.5 in. in diameter, 26.5 in. high and 0.2 in. thick. The aforementioned small scale canisters represented a $1/65^{th}$ volumetric scale model of the M1 canisters and were loaded with a maximum of 1.5 lb. Cardboard lids were used on all tests.

On each of the propellant tests, the propellant was ignited remotely with an electric match placed in contact with the top of the propellant.

4.4 Summary of Tests Performed in the $1/10^{th}$ Scale Model Igloo

The igloo test program consisted of 16 tests using M1 propellant, IMR-5010 propellant, and IMR-8208 propellant. A brief description of each test is provided in this section.

4.4.1 Tests with the M1 Propellant

A total of six tests were performed using the M1 propellant in the igloo. The quantities of propellant varied from 0.5 lb to 6 lb. Detailed descriptions of all M1 tests are included in Appendix B. Table 6 presents a summary of each test and includes maximum internal and external (plume) temperatures as well as plume velocities.

TABLE 6. M1 IGLOO TESTS

Test No.	Quantity (lb)	Max Internal Temp (°F)	Max External Temp (°F)		Plume Velocity (ft/sec)	
			Rake 1	Rake 2	Rake 1	Rake 2
1	1.5	799	845	719	Not available	
2	3.0	777	983	1069	45.0	42.0
3	4.5	1148	1127	570	37.5	29.0
4	6.0	1014	1099	1194	73.0	73.0
13	0.5	242*	451	170	18.0	10.5
14	1.0	291*	584	299	30.4	19.7

* Only two channels (1 and 5) of internal temperatures were recorded on this test.

As can be seen in Table 6 and Figure 30 for propellant test quantities of 3 lb and above, the temperatures of the two external rakes exceeded the internal igloo temperature. This phenomena would imply that quantities of unburned propellant were carried out in the plume and were igniting outside. A review of the video tape of these tests showed that a considerable amount of firebranding did occur.

4.4.2 Tests with the IMR-5010 Propellant

Five tests were performed using the IMR-5010 propellant in amounts varying from 0.5 lb to 6 lb in the igloo. Appendix B contains detailed descriptions of these tests, and a summary of each test is included in Table 7. Maximum internal and external (plume) temperatures and plume velocities are reported.

TABLE 7. IMR-5010 IGLOO TESTS

Test No.	Quantity (lb)	Max Internal Temp (°F)	Max External Temp (°F)		Plume Velocity (ft/sec)	
			Rake 1	Rake 2	Rake 1	Rake 2
5	2.0	984	1100	1181	54.0	52.0
6	4.0	1070	1284	1704	78.0	78.0
7	6.0	1299	1877	1672	97.0	61.0
15	0.5	225*	492	268	34.0	25.0
16	1.0	284*	501	136	19.6	11.0

* Only two channels (1 and 5) of internal temperatures were recorded on this test.

As shown in Table 7 and Figure 31, the temperatures recorded at the two external rakes exceeded the igloo internal temperatures for tests with 2.0

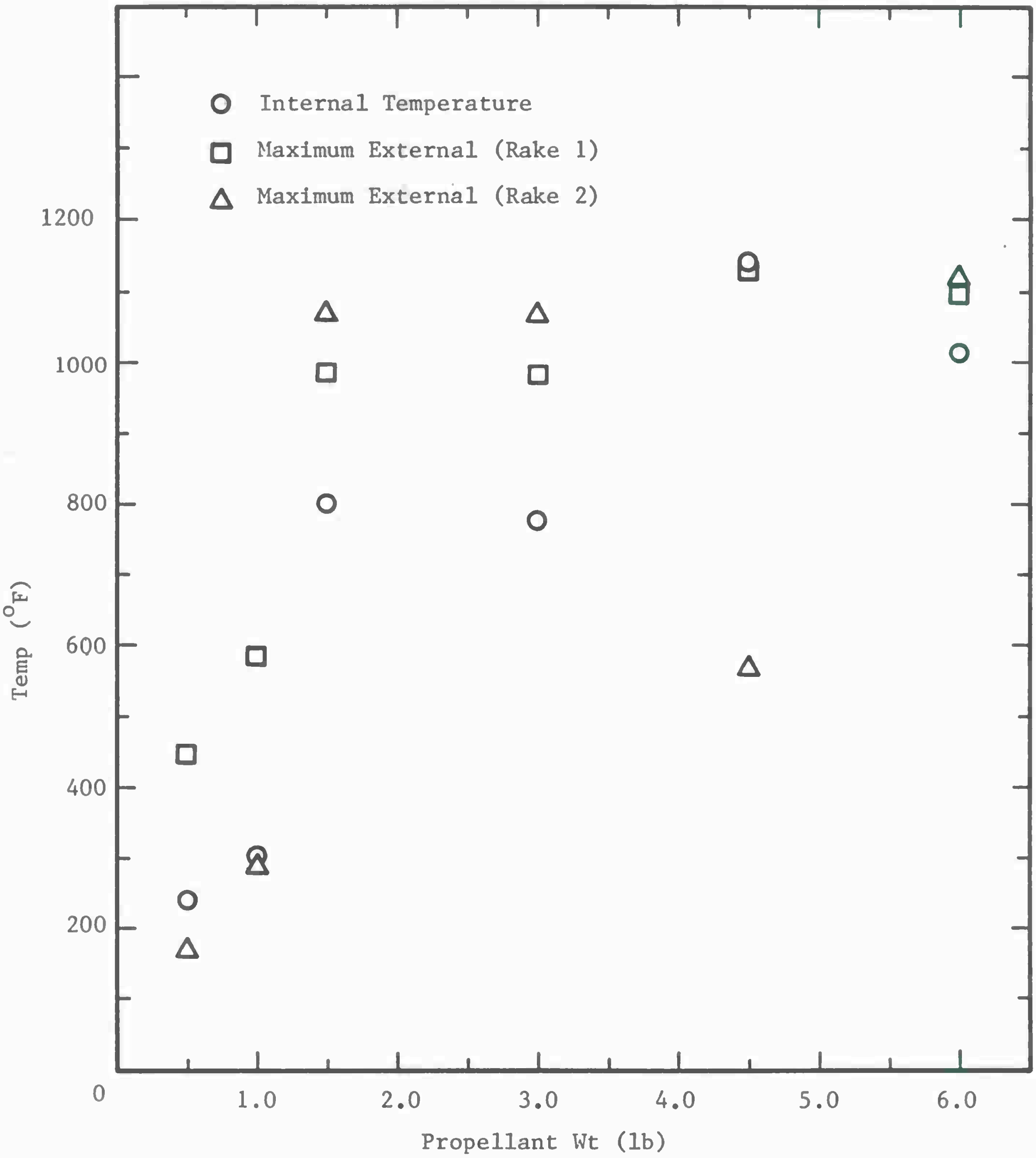


Figure 30. M1 Propellant Temperature Profiles

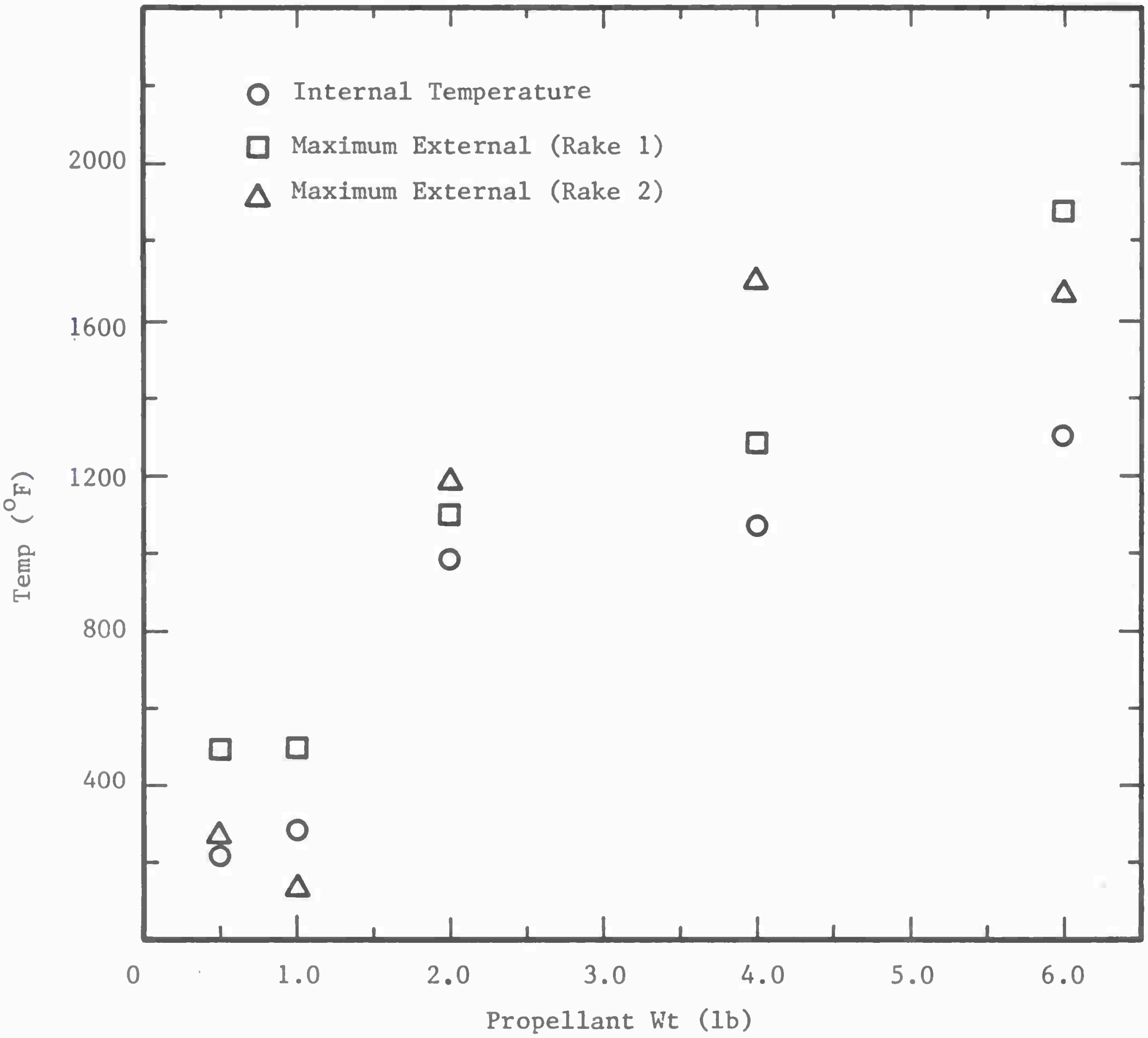


Figure 31. IMR-5010 Propellant Temperature Profiles

lb and higher. As was the case in the tests with the M1 propellant, it appears that a thermal saturation stage occurs at 2.0 lb and above and unburned propellant is jettisoned out of the igloo in the plume and burns outside.

4.4.3 Tests with the IMR-8208 Propellant

Five tests using the IMR-8208 propellant were performed in the igloo. Quantity was varied from 0.5 lb to 6 lb of propellant. Detailed descriptions of these tests are presented in Appendix B. Table 8 presents a summary of each IMR-8208 test, including maximum internal and external (plume) temperatures recorded and plume velocities.

TABLE 8. IMR-8208 IGLOO TESTS

Test No.	Quantity (lb)	Max Internal Temp (°F)	Max External Temp (°F)		Plume Velocity (ft/sec)	
			Rake 1	Rake 2	Rake 1	Rake 2
8	2.0	1102	1014	1474	58.3	62.4
9	4.0	675	1439	1469	85.0	81.0
10	6.0	1231	1315	1633	85.0	83.6
11	0.5	244*	445	176	20.3	12.3
12	1.0	228*	414	196	25.0	16.0

* Only two channels (1 and 5) of internal temperatures were recorded for this test.

Table 8 and Figure 32 shows that for the tests using 2.0 lb, 4.0 lb and 6.0 lb the external rake temperatures are much higher than the internal temperatures. This same phenomena was noted in the tests performed using the M1 propellant and the IMR-5010 propellant and it appears that burning of propellant is occurring in the plume outside of the igloo.

4.5 Thermal Output Analysis

An analysis for determining the thermal output of the smoke grenades, flares and rockets as well as the scalability of this thermal output was performed. Fitzgerald[4] reports that fires have been quantified through the use of calorimeters that utilize some element within the fire environment as a heat sink. Two methods based on heat sink are described: static heat sink and flowing heat sink.

In the case of a static heat sink, the total heat released, Q, is proportional to the temperature rise, T, of the heat sink. The rate of heat release, $\dot{Q}$, is proportional to the rate of temperature change:

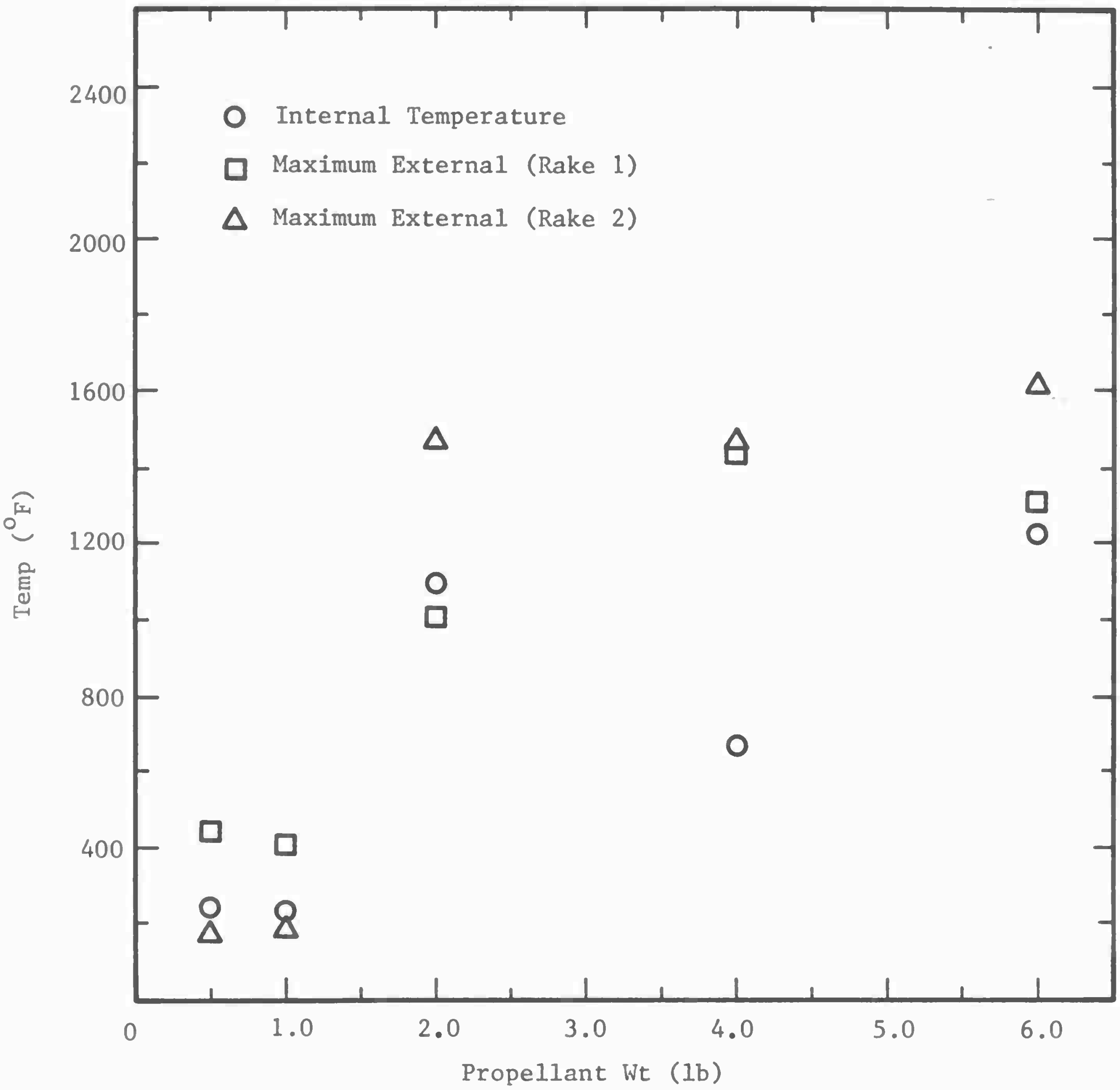


Figure 32. IMR-8208 Propellant Temperature Profiles

$$\mathring{Q} = dQ/dt = k_s dT/dt = k_s \mathring{T} \quad (1)$$

The proportionality constant, k_s, contains the heat capacity, Cp, (assumed to be a constant) and the mass of the heat sink. In practice, materials of known heating value are burned in the calorimeter to determine an effective k_s which compensates for systematic heat losses of the system.

For flowing heat sinks, the rate of heat release $\mathring{Q}$ is proportional to the temperature rise of the heat sink.

$$\mathring{Q} = k_f \Delta T \quad (2)$$

The proportionality constant, k_f, contains the heat capacity and mass flow rate of the heat sink material and systematic heat loss of the system. The total heat released by the fire can be obtained by integrating the heat release rate over the time of the experiment.

The flow rate of the heat sink should preferably be high enough to maintain a moderate air temperature rise and minimize the temperature rise of the walls of the burn chamber. These systems are considered dynamic, but the response time to fast thermal changes is limited by the thermal inertia of the system (primarily the walls of the burn chamber). The more massive the walls, the slower the response time. This limitation is partially compensated for by more massive air flows to reduce the temperature of the walls. The dynamics of the fires resulting from the energetic materials evaluated favor the use of a flowing heat sink calorimeter.

Heat from the munition(s) fire in the test cubicle will either be absorbed by the air around the fire or by the walls, ceiling and floor. The exact mode of heat transfer does not have to be specified. The walls may be heated by convective transfer or by direct radiation from the fire. This heat is contained in the room until it is carried out as heated air or transferred through the walls. It is assumed that the heat capacity of any material (wall or air) can be described by a two-term polynomial in temperature. The rate of heat absorption, $\mathring{Q}_a$, is approximated by:

$$\mathring{Q}_a = a\mathring{T} + bT\mathring{T} \quad (3)$$

where T is the temperature above ambient and $\mathring{T}$ is the rate of temperature rise with time.

It was assumed that with an approximately constant external air temperature, the temperature gradient through the wall and the heat loss through the wall is a function of the internal surface temperature. The rate of heat loss, $\mathring{Q}_1$, through the wall was assumed proportional to the first two terms of a polynomial in T (temperature above ambient).

$$\mathring{Q}_{1_w} = a_2 T_w + b_2 T_w^2 \tag{4}$$

The rate of heat loss from the calorimeter Q_{1_g} via flowing heat sink of temperature T_g is:

$$\mathring{Q}_{1_g} = a_3 T_g + b_3 T_g^2 \tag{5}$$

The rate of heat release of a fire burning in the calorimeter is the sum of all the contributions:

$$\mathring{Q} = \mathring{Q}_a \text{ (walls)} + \mathring{Q}_1 \text{ (walls)} + \mathring{Q}_a \text{ (floor)} + \mathring{Q}_a \text{ (air)} + \mathring{Q}_1 \text{ (air)} \tag{6}$$

Assuming that the thermally thick floor would not lose any heat and that the heat is contained in the room until it is transferred through the walls or carried out as heated air by the plume, a mathematical expression can be derived to describe this rate of heat release for the materials being tested as given in the following equation:

$$\mathring{Q} = A + BT_w + C\mathring{T}_w + D(T_{D1}) + E(T_{D2}) \tag{7}$$

where A,B,C,D,E – appropriate constants

T_w – temperature of the walls and roof

$\mathring{T}_w$ – rate of temperature rise with time

T_{D1} – air temperature at the top of the door, i.e., Probes 6, 7, 9 and 13

T_{D2} – air temperature at the bottom of the door, i.e., Probes 8 and 10

By performing a regression analysis on the appropriate temperature and pressure data for a material whose rate of heat release $\mathring{Q}$ is known such as the IMR-5010, the constants A, B, C, D and E can be calculated. Then for a material whose rate of heat release is not known (such as the ALA-17 flare) but whose burn duration and peak temperatures are similar to that of the IMR-5010 propellant, one can use the coefficients calculated for the IMR-5010 and the corresponding temperatures and pressures for the flare and rerun the regression analysis to solve for the rate of heat release $\mathring{Q}$. By doubling the number of flares that are tested inside the cubicle, recording the temperatures and pressures and performing the regression analysis for $\mathring{Q}$, one can determine how the rate of heat release will scale up with the addition of more flares.

4.5.1 Regression Analysis--Marinite Cubicle Tests

A multiple regression analysis was performed using the temperature data recorded from the calibration tests using the IMR-5010 propellant in the marinite cubicle. The charge weight in these tests ranged from 5 lb to 12.5 lb. This regression analysis was used to derive a model for predicting the heat release rate, $\mathring{Q}$, for the ALA-17 flares and for the IMR-8208 and M1 propellants. The temperature data for each test were recorded at 14 locations both inside and outside the marinite cubicle. (Thermocouples were mounted in the inner walls, the ceiling, the doorway and outside the cube 3 ft away from the door.) A review of the temperature profiles and peak temperatures measured inside the cubicle for each of the tests showed that there was little difference in temperatures between the different wall locations and that these temperatures were relatively low. The only high temperatures recorded in all of the tests occurred at the ceiling. Since the wall temperatures other than at the ceiling were low, it was decided not to include them in the analysis. The temperature data recorded by the thermocouples located 3 ft away from the door were also not included in the analysis because the doorway thermocouples more than adequately profiled the plume. However, the data from the thermocouples mounted 3 ft from the door were used to determine the size and shape of the plume.

Thus, the parameters considered important for the regression analysis included the temperatures in the ceiling and at the door opening, the rate of heat absorption in the ceiling, the rate of heat loss through the ceiling, and the temperature variation with time at several locations in the door opening. Different combinations of all pertinent parameters were used in the multiple regression analyses to create prediction models which were then tested for goodness of fit and validity of the individual terms. Two models which showed good correlation were selected for further study.

The first model has the following form:

$$\mathring{Q} = A + B_i \sum_{i=1}^{7} T_i + C_i \sum_{i=1}^{7} \mathring{T}_i + DT_5\mathring{T}_5 + ET_5^2 \qquad (8)$$

where i=1,7 represents temperatures at locations in the ceiling and in the door opening (Locations 5, 6, 7, 8, 9, 10 and 13).

The term $(C_5\mathring{T}_5 + DT_5\mathring{T}_5)$ is the rate of heat absorption in the ceiling. The rate of heat loss through the ceiling is $(B_5T_5 + ET_5^2)$. All

TABLE 9. HEAT FLOW CALCULATIONS IN CUBE USING MODEL 1 FOR IMR-5010 PROPELLANT

$$\mathring{Q} = 1101.0 - 15.191T_5 + 3.7196T_6 - 3.7294T_7 - 3.7713T_9 + 2.6236T_{13} - 0.31078\mathring{T}_5 + 1.8973\mathring{T}_6 + 1.9987\mathring{T}_7 + 0.35556\mathring{T}_9 + 3.5338\mathring{T}_{13} - 1.3565T_8 + 1.4742T_{10} + 1.6728\mathring{T}_8 - 4.4905\mathring{T}_{10} + 0.011182T_5\mathring{T}_5 + 0.055372T_5^2$$

Test No.	Charge (lb)	Average $\mathring{Q}$ (Btu/100 msec)*	Average Predicted $\mathring{Q}$ (Btu/100 msec)*	Percent Variation
8	5.0	334	371	+11
5	5.0	451	446	-1
15	7.5	576	563	-2
7	10.0	816	834	+2
14	12.5	926	879	-5

* The units for $\mathring{Q}$ are expressed in relation to 100 msec because this was the increment between data points (temperatures). The average $\mathring{Q}$ represents the heat flow over a particular time interval.

TABLE 10. HEAT FLOW CALCULATIONS IN CUBE USING MODEL 2 FOR IMR-5010 PROPELLANT

$$\mathring{Q} = 106.41 + 2.4251T_6 - 1.0527T_7 - 5.1833T_9 - 0.12963T_{13} + 1.4351\mathring{T}_6 + 2.5886\mathring{T}_7 - 1.3911\mathring{T}_9 + 6.5904\mathring{T}_{13} - 0.56511T_8 + 4.2097T_{10} - 0.076125\mathring{T}_8 - 0.1070\mathring{T}_{10}$$

Test No.	Charge (lb)	Average $\mathring{Q}$ (Btu/100 msec)*	Average Predicted $\mathring{Q}$ (Btu/100 msec)*	Percent Variation
8	5.0	334	393	+18
5	5.0	451	439	-3
15	7.5	576	570	-1
7	10.0	816	796	-1
14	12.5	926	892	-4

* The units for $\mathring{Q}$ are expressed in relation to 100 msec because this was the increment between data points (temperatures). The average $\mathring{Q}$ represents the heat flow over a particular time interval.

terms containing temperatures measured in the ceiling (Location 5) are removed in the second model, leaving the form:

$$\mathring{Q} = A + B_i \sum_{i=1}^{6} T_i + C_i \sum_{i=1}^{6} \mathring{T}_i \quad (9)$$

where i=1,6 represents temperatures at locations in the door opening (Locations 6, 7, 8, 9, 10 and 13).

Data from five tests using IMR-5010 propellant were used in a multiple regression analysis to determine the values of the constants in Equations (8) and (9). Tables 9 and 10 show these values and summarize the tests used for Equations (8) and (9), respectively, and to a certain degree indicate goodness of fit by comparing the actual average $\mathring{Q}$ for each test with the average predicted $\mathring{Q}$. For each of the tests with varying amounts of IMR-5010 propellant, a separate, open-air burn of the same amount of the propellant was performed on a load cell to obtain a measurement of the mass burning rate and the total time of the burn. The test results were plotted using a strip chart recorder. An example plot of the burn rate of 12.5-lb IMR-5010 is shown in Figure 33. There is an initial thrusting of the material upon ignition which causes the load cell to record a weight larger than the weight actually present on the tray, as indicated by the initial upswing of the curve in Figure 33. To account for this phenomenon, two different heat release rates were calculated--one to address the thrusting at ignition and the other to represent the burning of the major amount of propellant (the steep section of the trace in Figure 33). The burn time duration for each of these two events was used to determine the number of temperature data points which would be input into the regression analysis. For each test used in the regression analysis, two different heat release rates were used with the temperature data. The actual average $\mathring{Q}$ presented in Tables 9 and 10 was calculated by summing the heat release rates for each of the data points for a given test and then calculating a simple average. As shown in the tables, the model in Equation (8) predicts the average $\mathring{Q}$ within $\pm$11%, and the model in Equation (9) predicts the average $\mathring{Q}$ within $\pm$18% for data used in the regression. Figures 34 through 43 show the predicted change in heat release rate over time using both models. It should be noted that the overall amplitude of each curve increases as the amount of propellant (heat of combustion) increases. This trend can be seen in the average $\mathring{Q}$s in Tables 9 and 10 also, but the capability of each model to carry this trend throughout the event lends credibility to the prediction models beyond the statistical goodness of fit. The model predictions for the ALA-17 flares using both models are presented here as Figures 44 through 47.

Since both models indicated relatively good correlation, data from several tests involving the burning of two flares were used with each model to estimate the heat release rate $\mathring{Q}$ for flares. Tests 9, 11 and 16

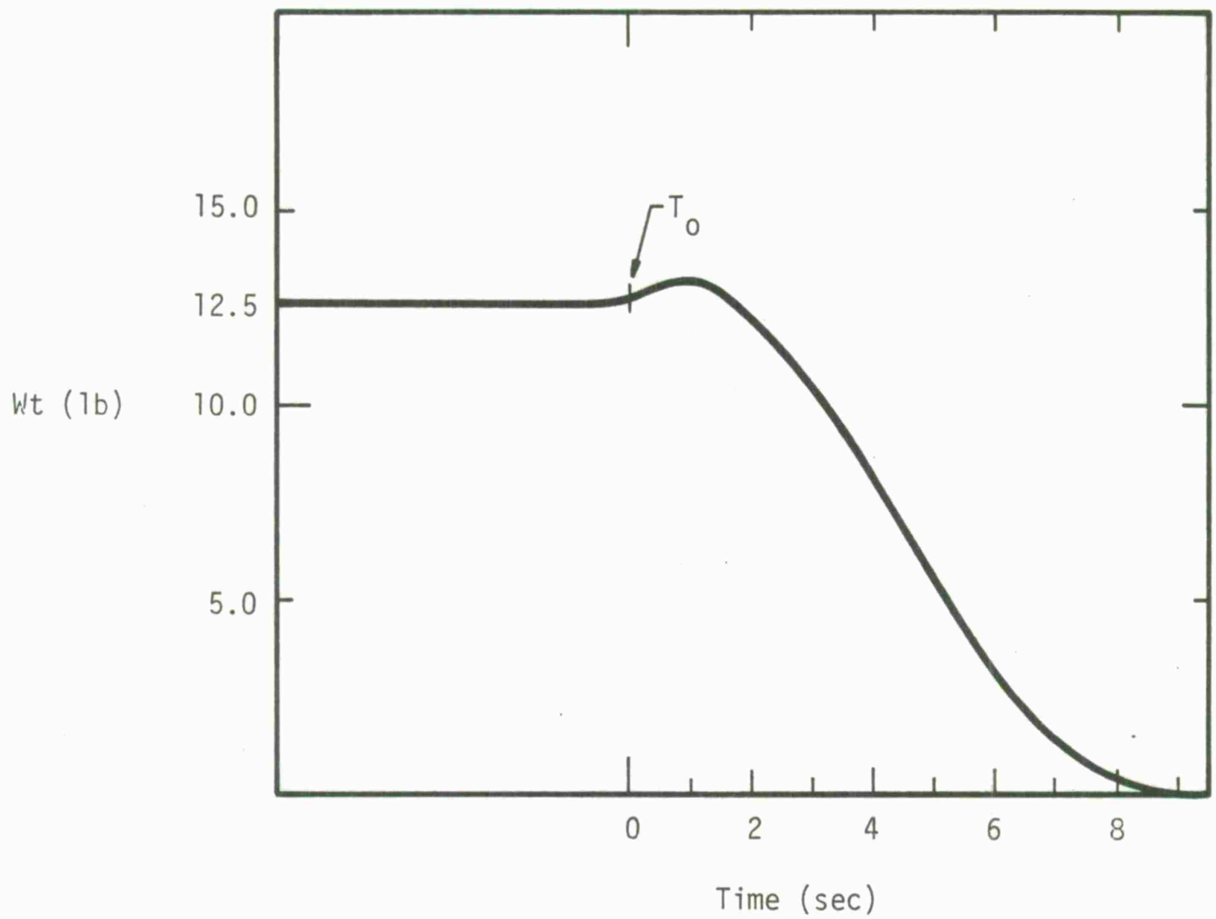


Figure 33. Burn Rate for 12.5 lb of IMR-5010 Propellant

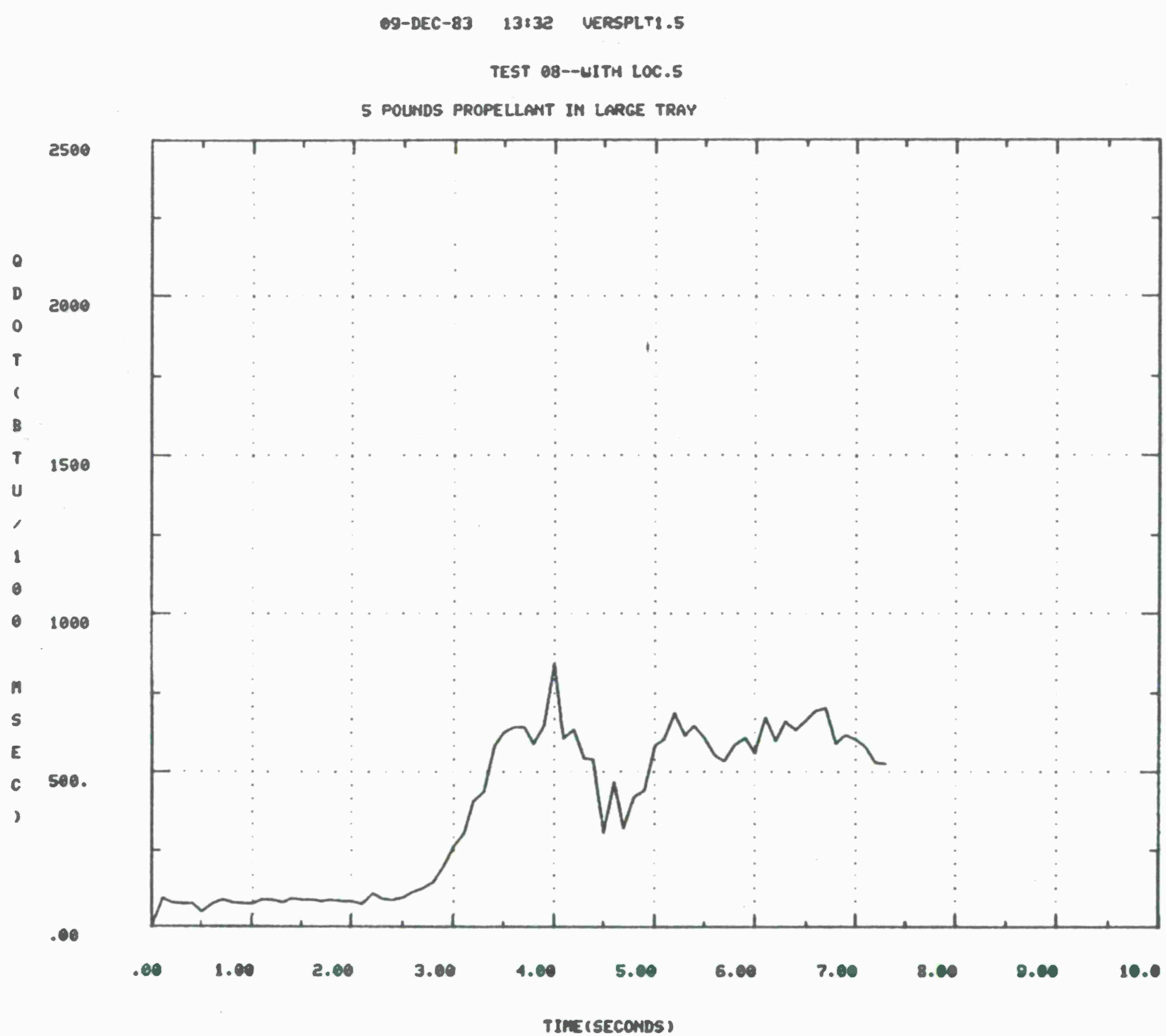


Figure 34. Model 1 Prediction with 5 lb IMR-5010 Propellant in Large Tray

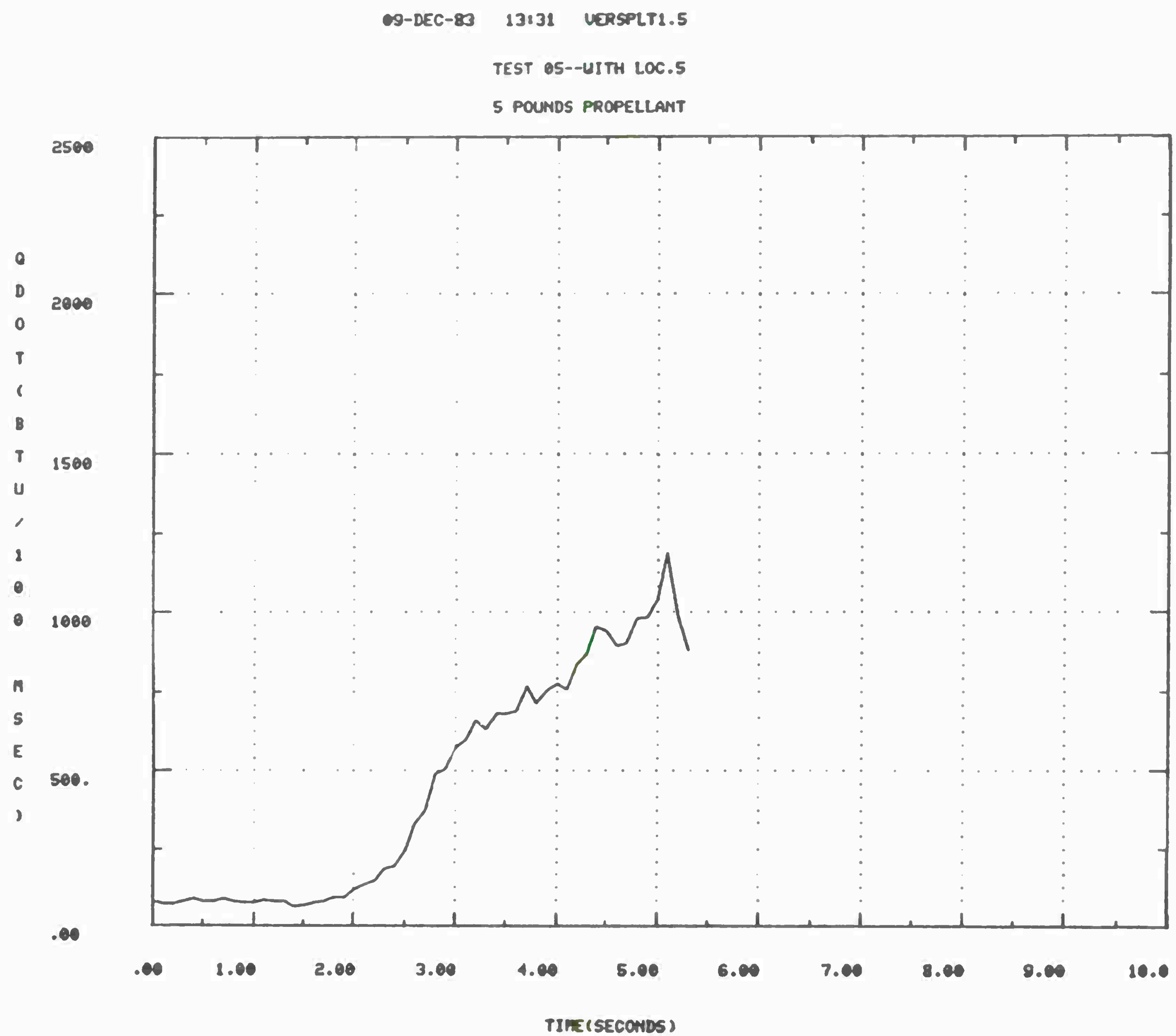


Figure 35. Model 1 Prediction with 5 lb IMR-5010 Propellant

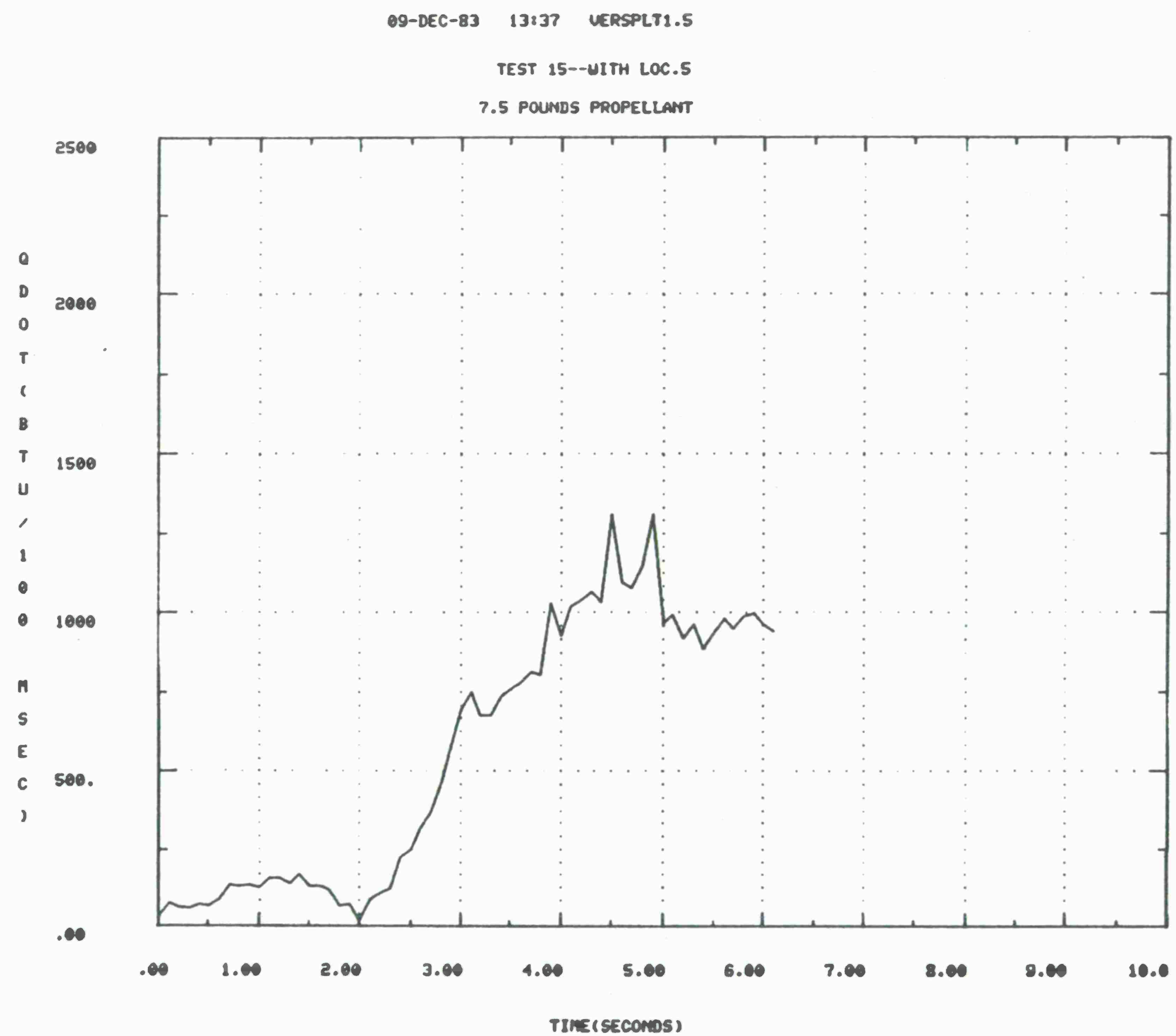


Figure 36. Model 1 Prediction with 7.5 lb IMR-5010 Propellant

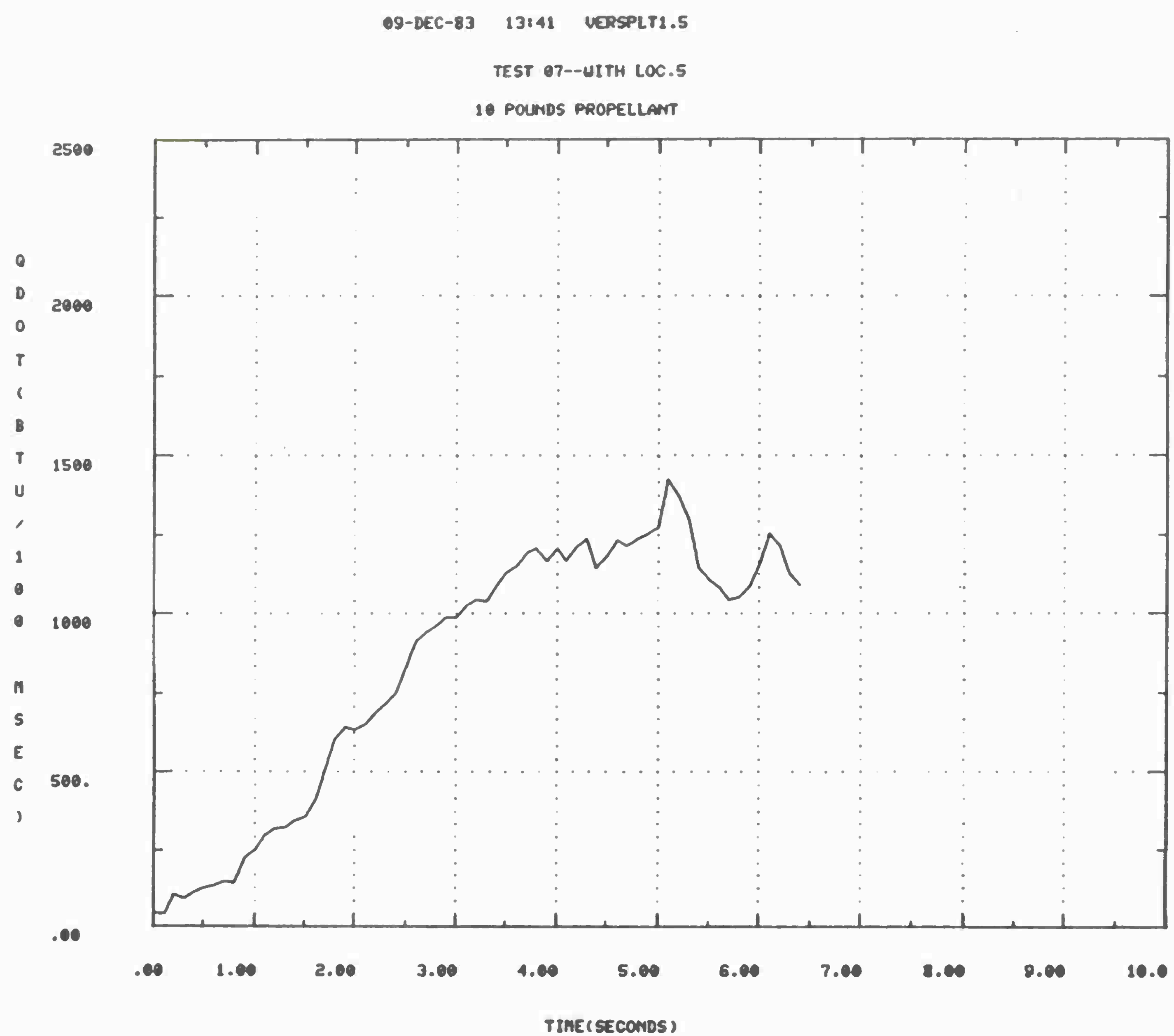


Figure 37. Model 1 Prediction with 10 lb IMR-5010 Propellant

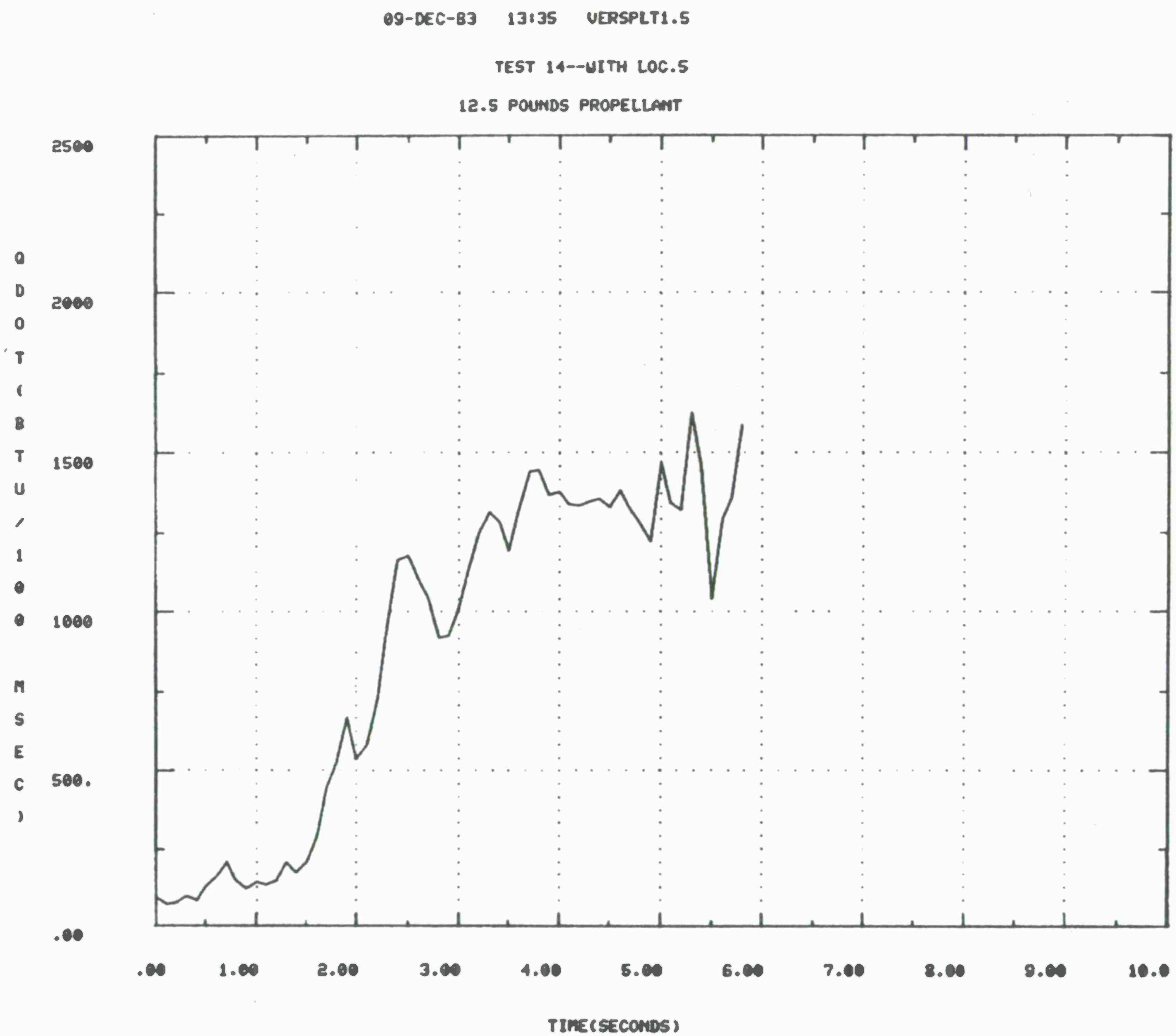


Figure 38. Model 1 Prediction with 12.5 lb IMR-5010 Propellant

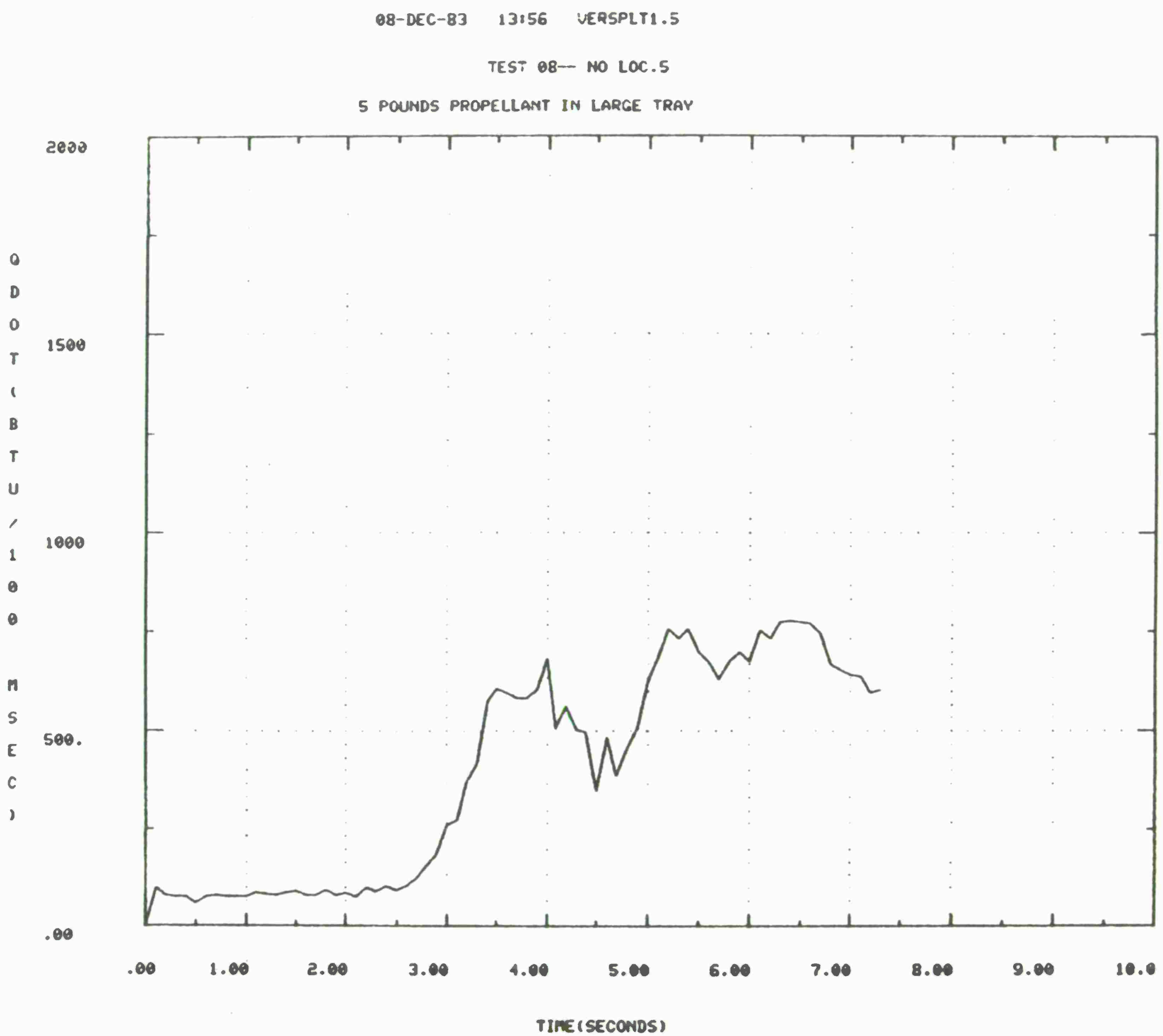


Figure 39. Model 2 Prediction with 5 lb IMR-5010 Propellant in Large Tray

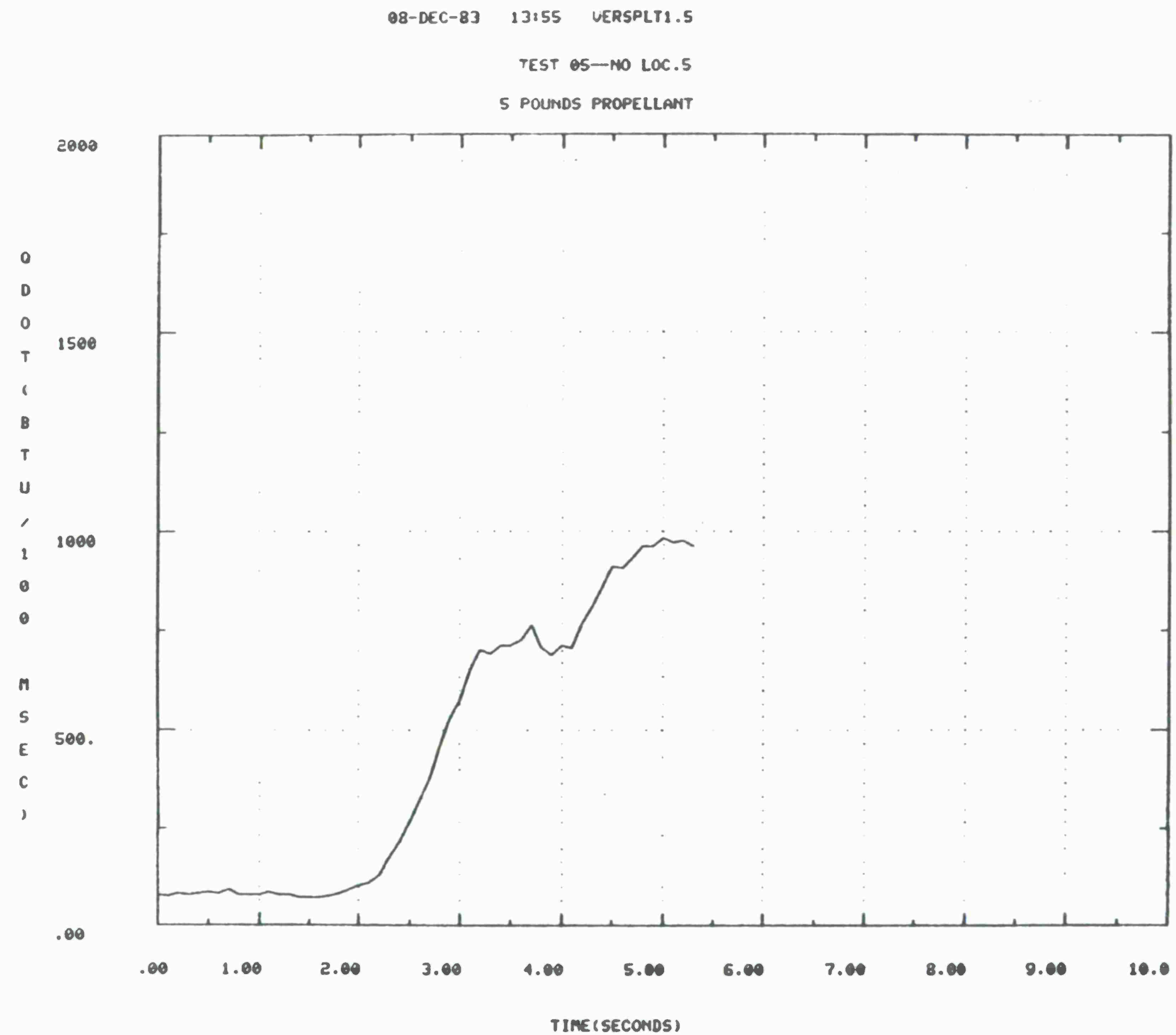


Figure 40. Model 2 Prediction with 5 lb IMR-5010 Propellant

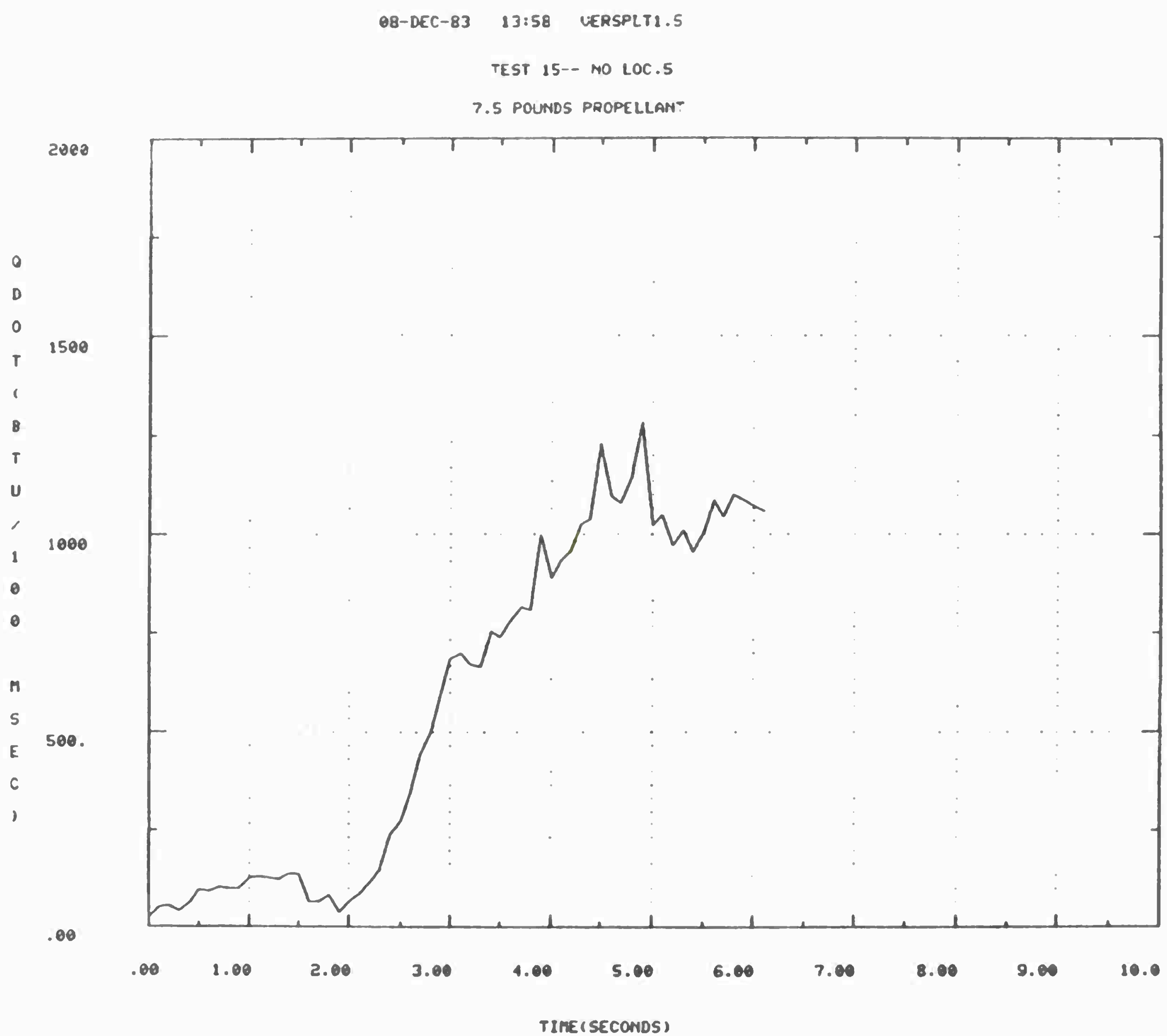


Figure 41. Model 2 Prediction with 7.5 lb IMR-5010 Propellant

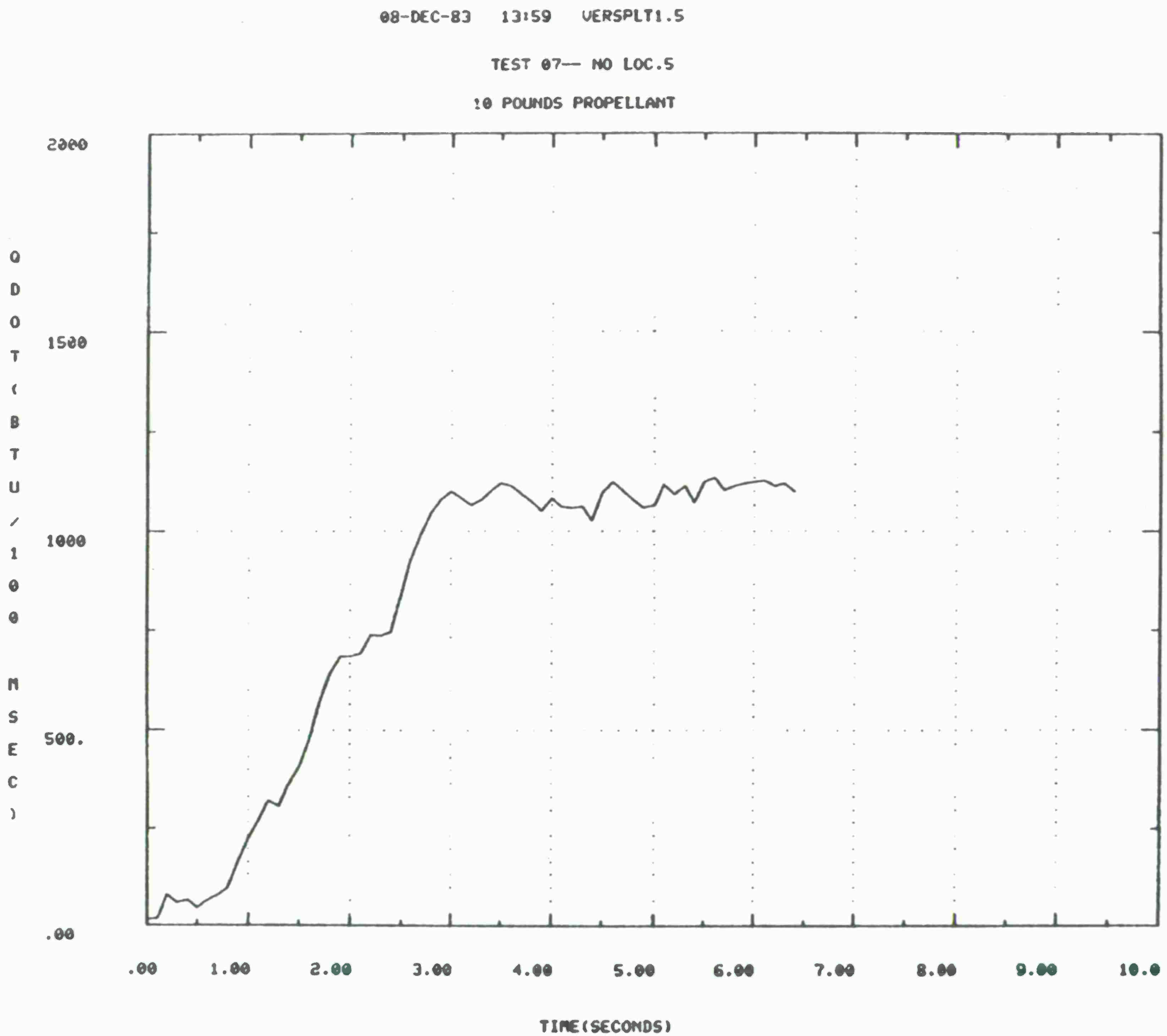


Figure 42. Model 2 Prediction with 10 lb IMR-5010 Propellant

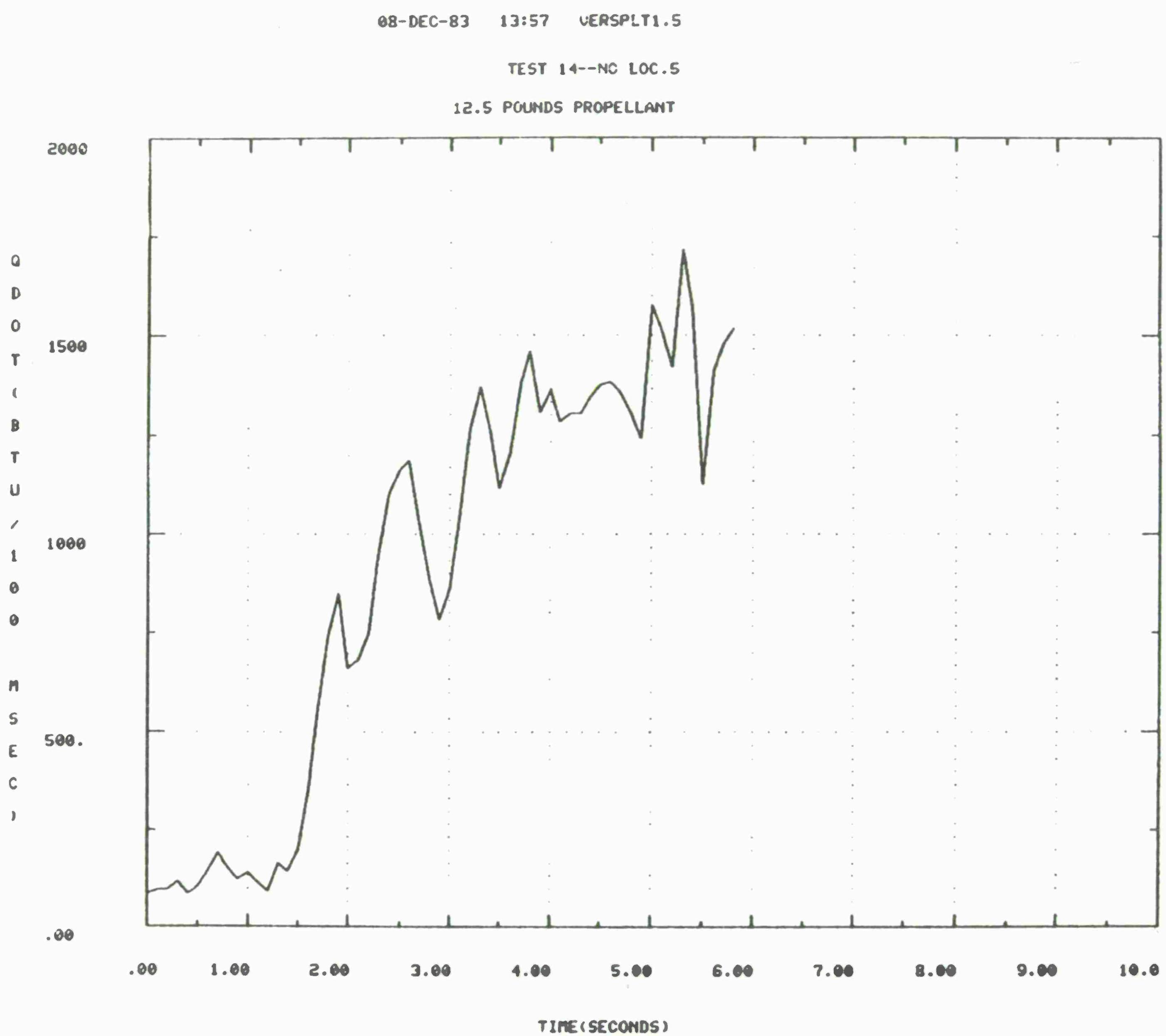


Figure 43. Model 2 Prediction with 12.5 lb IMR-5010 Propellant

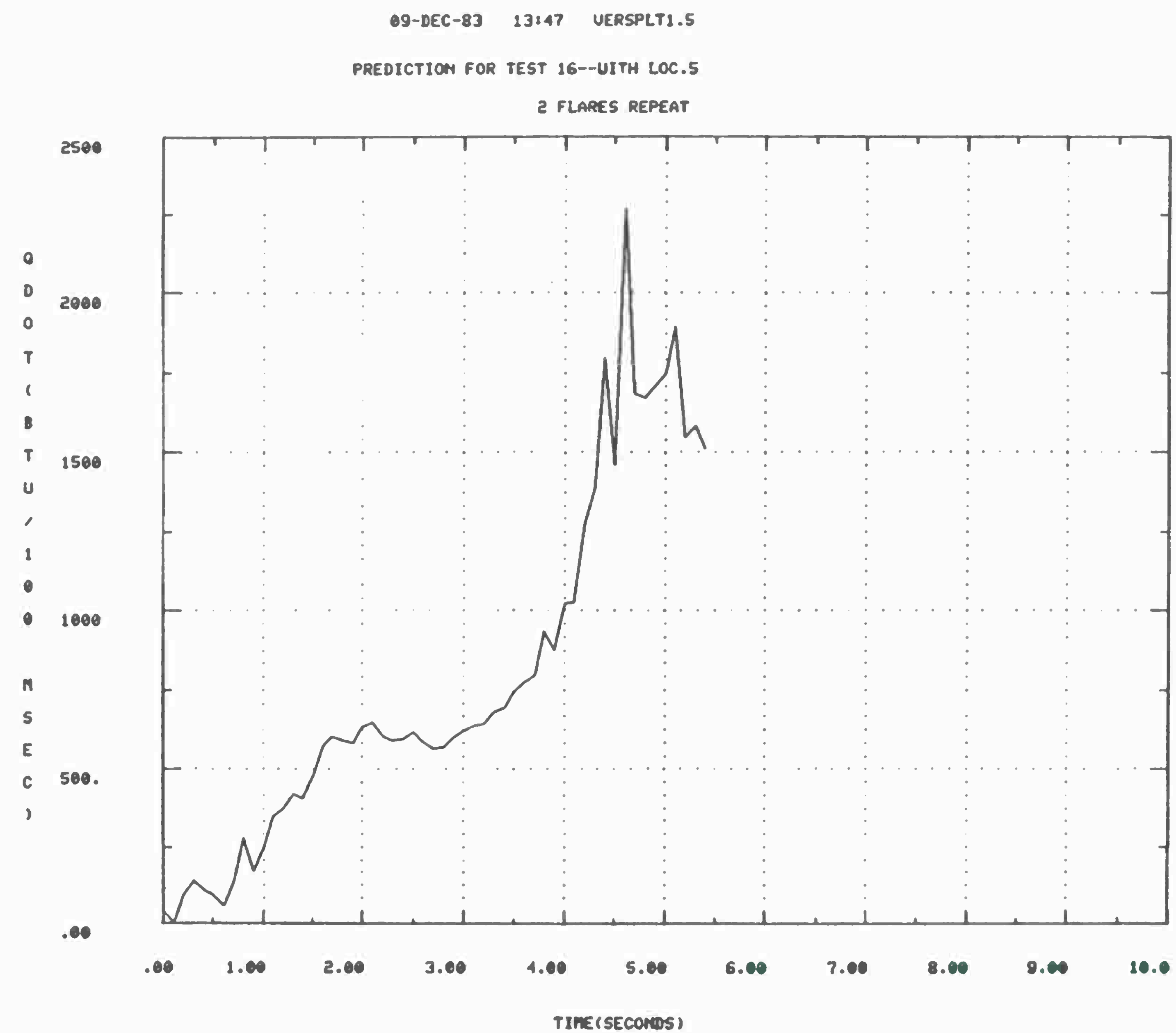


Figure 44. Model 1 Prediction of Test 16, Two ALA-17 Flares

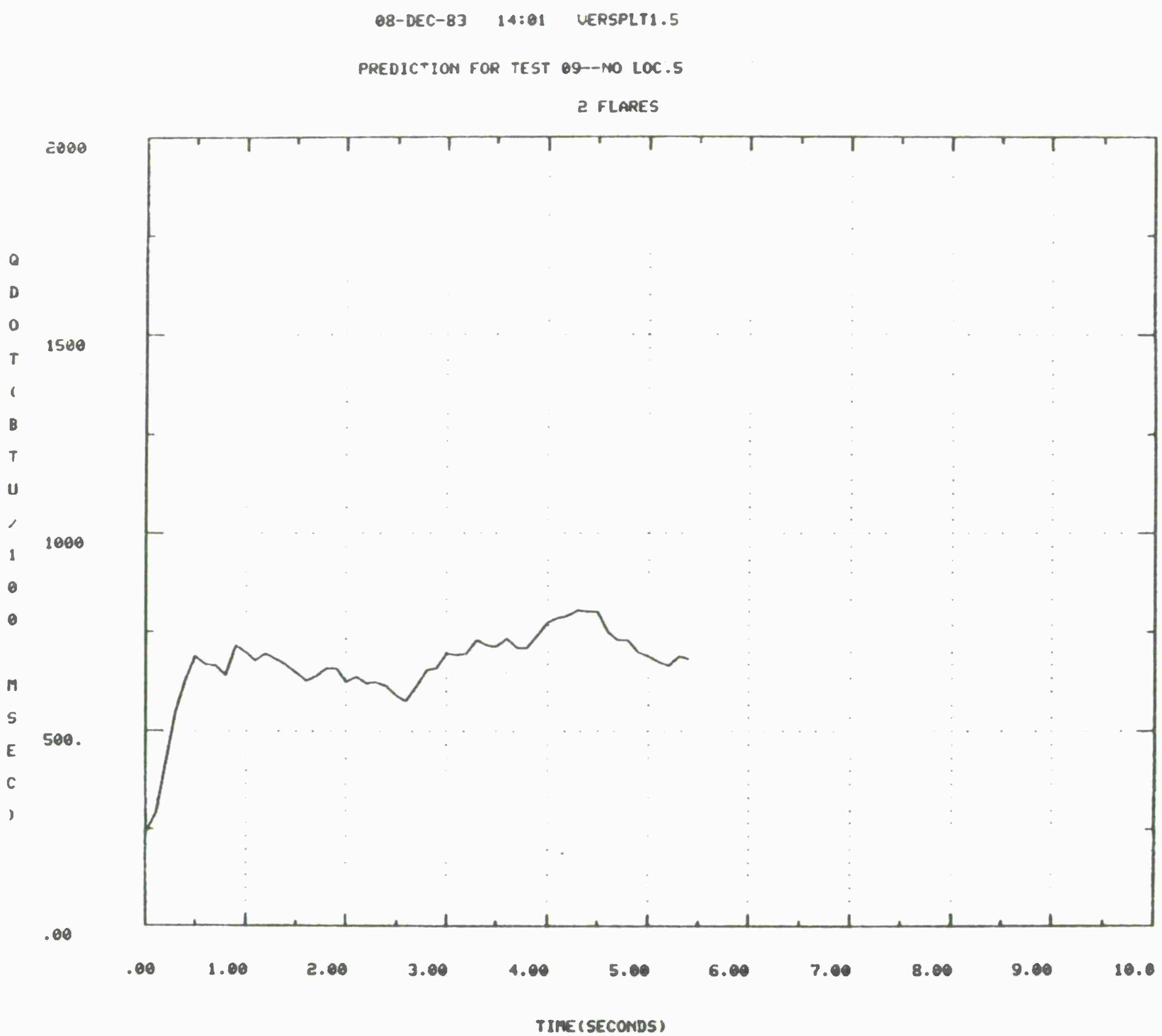


Figure 45. Model 2 Prediction for Test 9, Two ALA-17 Flares

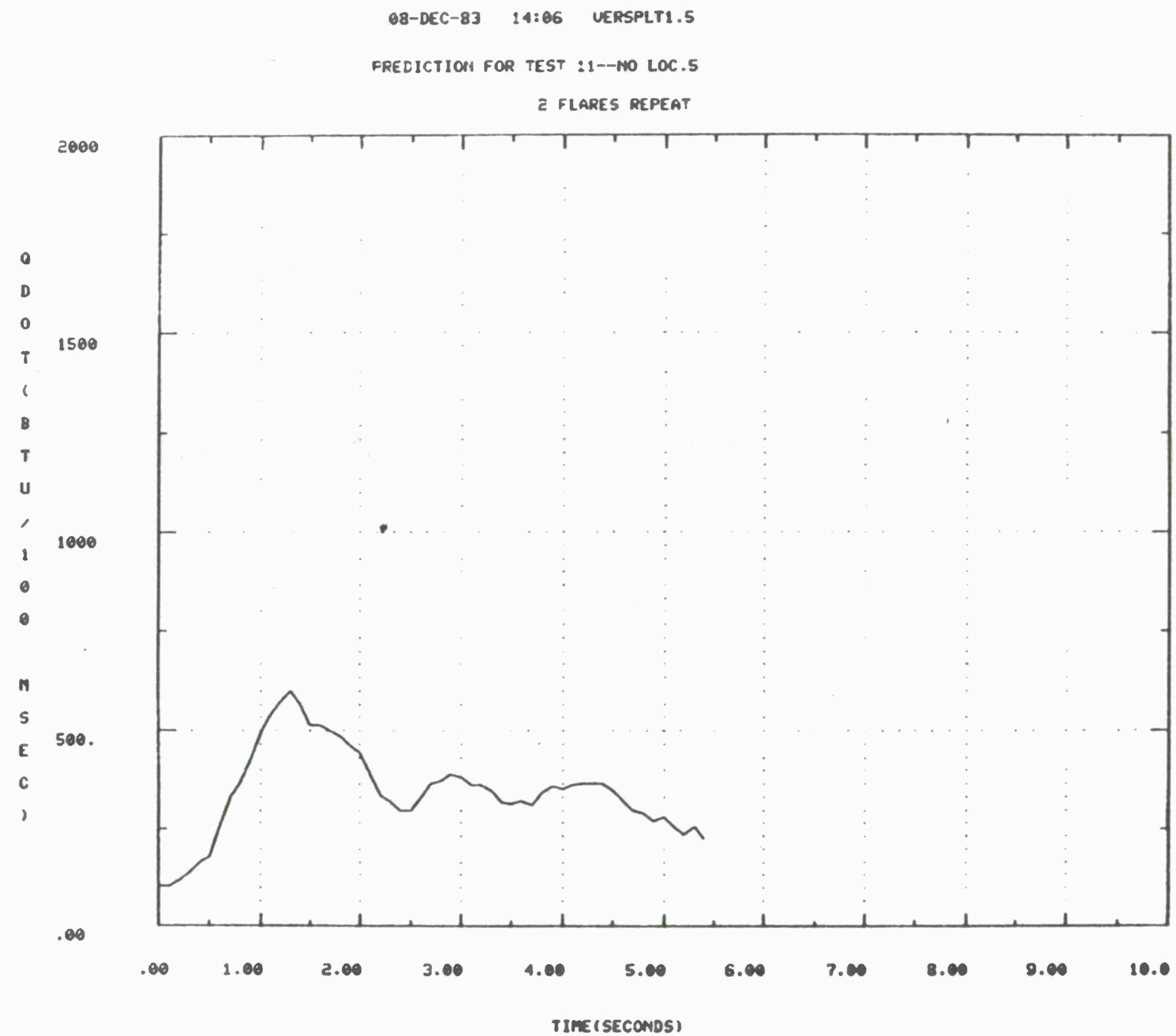


Figure 46. Model 2 Prediction for Test 11, Two ALA-17 Flares

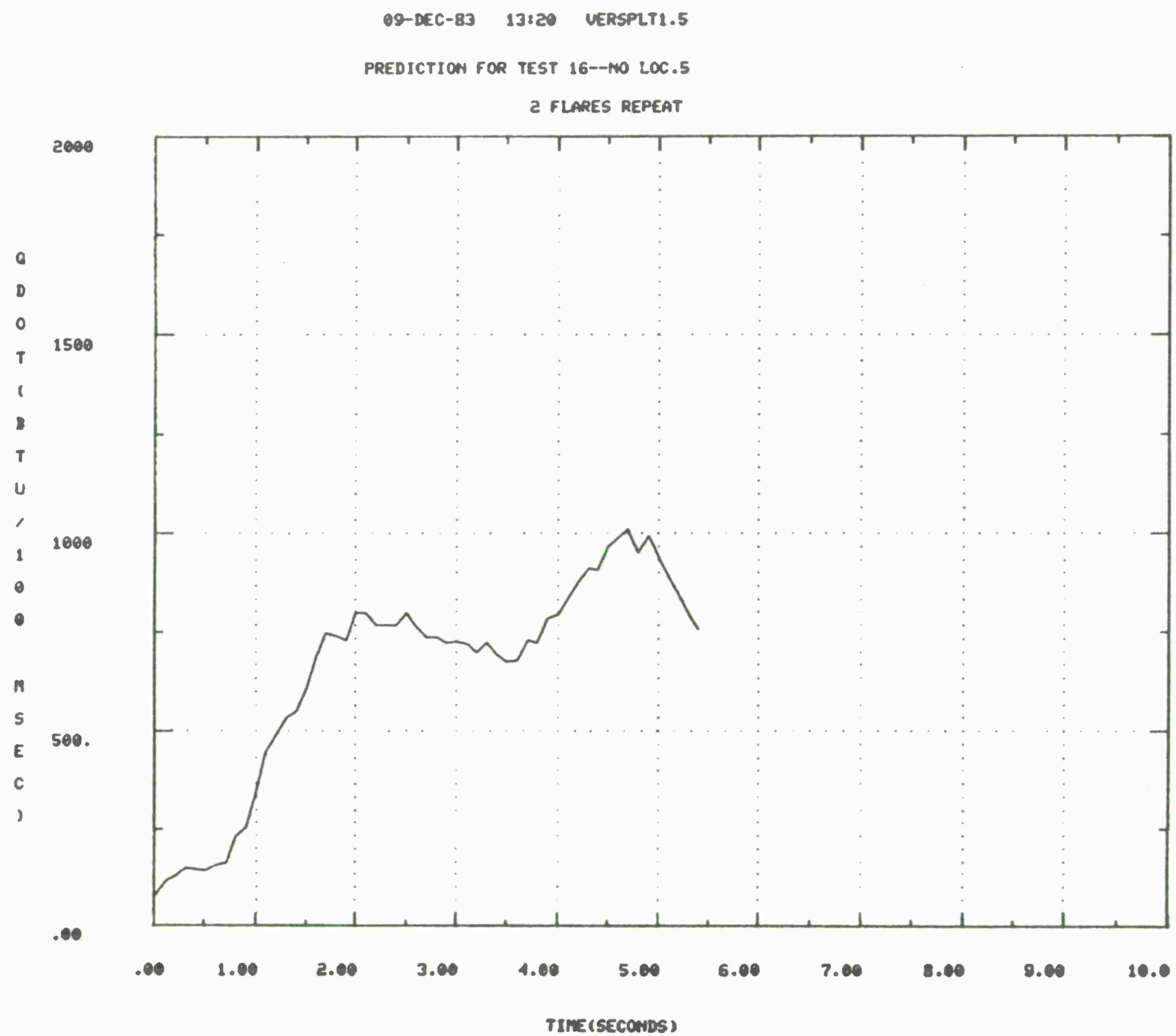


Figure 47. Model 2 Prediction for Test 16, Two ALA-17 Flares

were the tests with two flares each; however, the temperatures measured in the ceiling in Tests 9 and 11 were unusually high due to an apparent plume "torching" effect. In Tests 9 and 11, the two flares were placed in an ammunition box which had a single vent in the lid of the box. As a result, the heat generated by the flares was directed at the ceiling creating a torching effect. It was felt that the high temperatures seen at the ceiling were not realistic and should therefore not be included in the regression analysis. It was therefore decided that Tests 9 and 11 would be analyzed using regression analysis model 2 which does not require ceiling temperatures. Test 16 was performed using the modified ammunition box, i.e., equipped with side vents in addition to the top vent, and the ceiling temperatures were found to be acceptable. Test 16 was analyzed using both regression analysis models 1 and 2. Table 11 is a summary of the heat release rate $\mathring{Q}$ predicted for the two flare tests using each of the two models.

TABLE 11. HEAT FLOW PREDICTIONS FOR FLARES

Test No.	Model Used	Charge	Average Predicted $\mathring{Q}$ (Btu/100 msec)
16	1	2 flares	778.0
9	2	2 flares	665.0
11	2	2 flares	347.0
16	2	2 flares	649.0

Although all three tests were set up to ignite the two flares simultaneously, it is possible that they did not ignite together with Test 11. This would account for the lower temperatures and the predicted $\mathring{Q}$ being about half that predicted for Tests 9 and 16, which agreed very well. Figures 44 through 47 show the predicted change in heat release rate over time for each of the models.

The limited temperature data for Test 22 recorded prior to failure of the cube was used to calculate the rate of heat release up to the time of failure. Table 12 and Figures 48 and 49 provide a comparison of this data with values obtained for Test 17 which also involved four ALA-17 flares. This comparison indicates that the burning rate for Test 22 was three to four times higher than for Test 17 while a peak of 9500 Btu/100 msec and 2750 Btu/100 msec was obtained for Test 22 and Test 17, respectively. This gross variation in burning rate would have to be evaluated through tests in a substantial cubicle before any conclusions can be made on the burning behavior of multiple flares igniting and burning simultaneously.

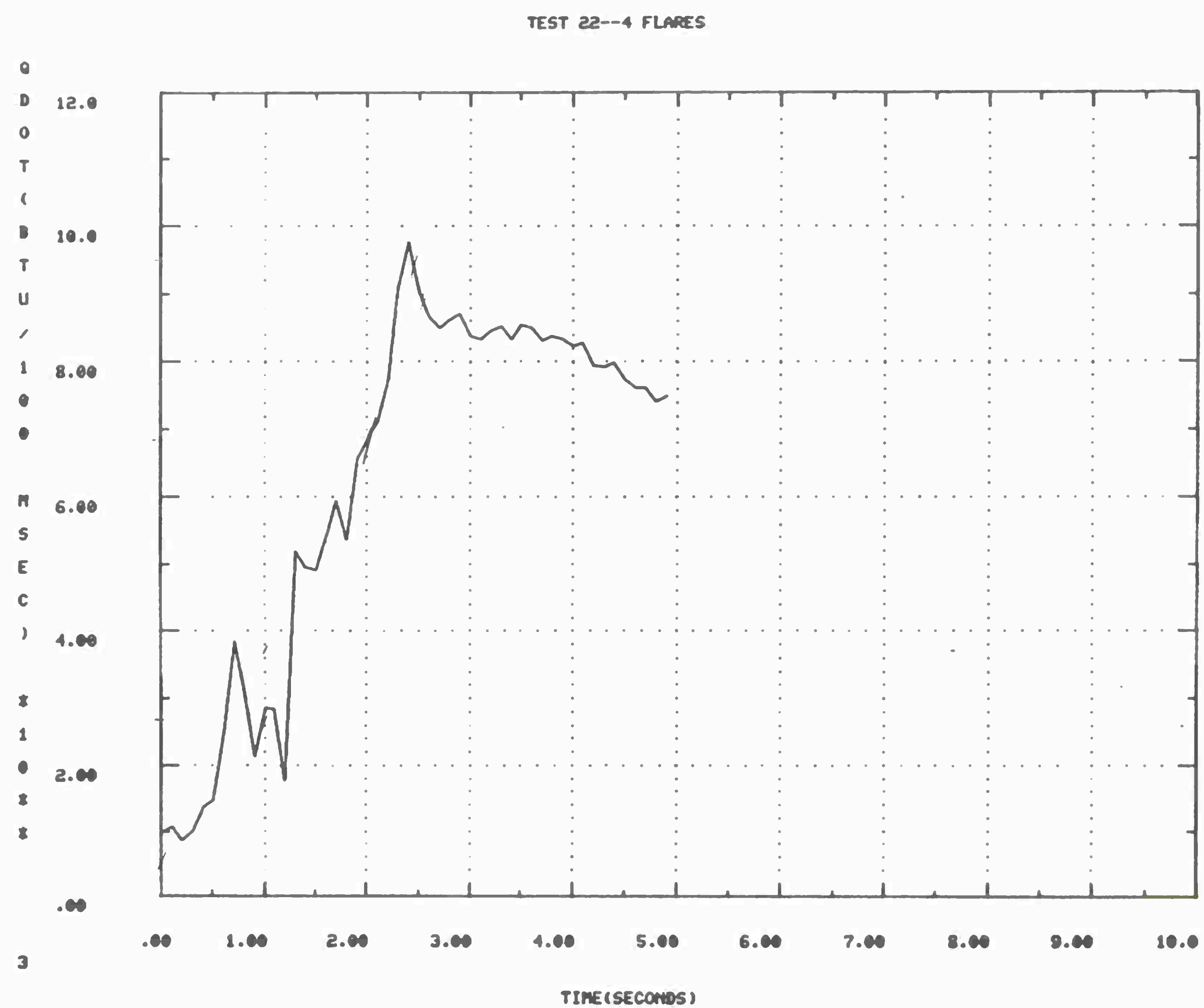


Figure 48. Plot of Heat Release, $\mathring{Q}$, vs. Time for Test 22--4 ALA-17 Flares

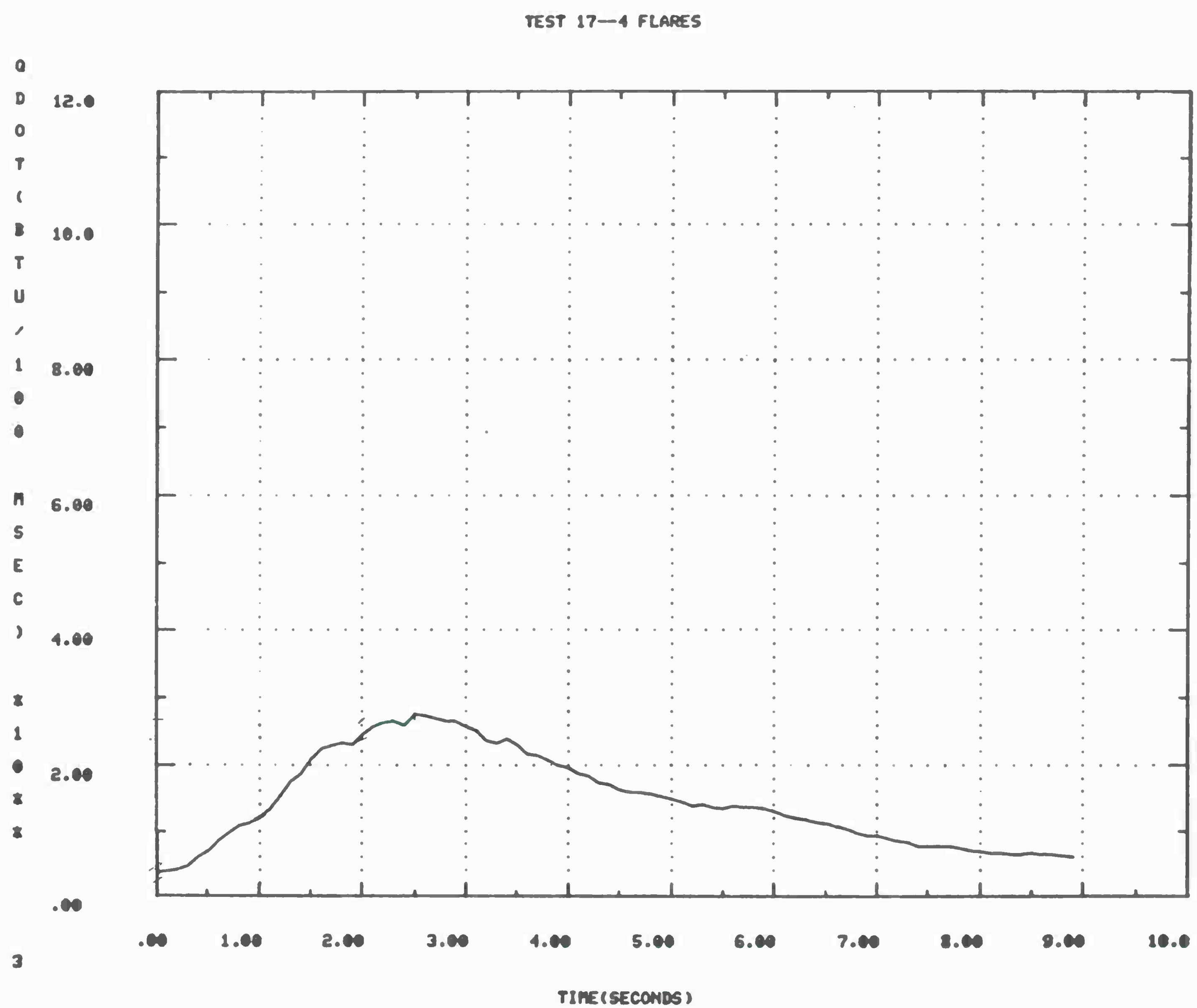


Figure 49. Plot of Heat Release, $\mathring{Q}$, vs. Time for Test 17--4 ALA-17 Flares

TABLE 12. COMPARISON OF RATE OF HEAT RELEASE FOR TESTS 17 AND 22--4 ALA 17 FLARES

Time seconds	Test 17 $\dot{Q}$ Btu/100 msec/sec	Test 22 $\dot{Q}$ Btu/100 msec/sec
0-1	1000	3300
1-2	1500	4100
2-2.5	700	(5000)*
0-2.5	900	3360

* Data becomes questionable after 2.4 sec.

Either model can be used to estimate heat release rate materials for which $\dot{Q}$ is not known, providing the unknown $\dot{Q}$ is within the range of the average heat flows for the calibration tests used in the multiple regression analysis. If the average $\dot{Q}$ is predicted with either model to be lower than 334 Btu/100 msec or higher than 926 Btu/100 msec, the accuracy of that $\dot{Q}$ would be questionable. If data from more tests of material with average heat flow lower than 334 Btu/100 msec or higher than 926 Btu/100 msec were collected and added to the regression, the range of prediction for each model could then be expanded.

4.5.2 Regression Analysis--1/10th Scale Model Igloo Tests

A similar multiple regression analysis was performed using temperature data recorded from the IMR-5010 propellant tests (and one IMR-8208 test) in the igloo. The propellant quantities varied from 1 lb to 6 lb. A model was derived for predicting the rate of heat release $\dot{Q}$ for the IMR-8208 and M1 propellants. The temperature data for each test were recorded at eight locations inside the igloo, in the doorway and outside the igloo. The parameters considered important for the regression analysis included the temperatures at two locations inside the igloo, in the doorway and outside the igloo, the rate of heat absorption at the two internal locations, the rate of heat loss through the internal surfaces, and the temperature variation with time at the doorway and external locations. Various combinations of these pertinent parameters were used in the regression analysis to create prediction models which were then tested for goodness of fit and examined for validity of the individual terms. The model selected for further study which shows the best correlation has the following form:

$$\mathring{Q} = A + B_i \sum_{i=1}^{6} T_i + C_i \sum_{i=1}^{6} \mathring{T}_i + D_j \sum_{j=1}^{2} T_j + E_j \sum_{j=1}^{2} \mathring{T}_j + \qquad (10)$$

$$G_j \sum_{j=1}^{6} T_j\mathring{T}_j + H_j \sum_{j=1}^{2} T_j^2$$

where i=1,6 represents temperatures at locations in the door opening (Locations 9, 10 and 11) and outside the igloo (Locations 12, 13 and 14) and j=1,2 represents temperatures at locations inside the igloo (Locations 1 and 5).

The terms ($E_1\mathring{T}_1 + G_1T_1\mathring{T}_1$) and ($E_2\mathring{T}_2 + G_2T_2\mathring{T}_2$) are rates of heat absorption in one wall and in the ceiling. The rates of heat loss through the wall and ceiling are represented by ($D_1T_1 + H_1T_1^2$) and ($D_2T_2 + H_2T_2^2$).

Data from three tests using the IMR-5010 propellant and one test using the IMR-8208 propellant were used in a multiple regression analysis to determine the values of the constants in Equation (10). Table 12 shows these values along with test summaries. A certain degree of goodness of fit is indicated by comparing the actual average $\mathring{Q}$ for each test with the average predicted $\mathring{Q}$. The mass burning rate and total burn time were measured in a separate open-air burn of equivalent amounts of propellant for each test. The burn times associated with each heat release rate were used to determine the number of temperature data points to use with each heat release rate in the regression. The "average $\mathring{Q}$" in Table 12 is an average determined from the load cell data. As shown in the table, the model predicts the average $\mathring{Q}$ within 8% for data used in the regression. Figures 50 through 53 show the predicted change in heat release rate over time using Equation (10). The overall amplitude of each curve increases with an increase in the amount of propellant. This trend can also be noted in the average $\mathring{Q}$s in Table 13, but seeing this trend through the event lends more credibility to the model than just the statistical goodness of fit being acceptable.

Since the model indicated fairly good correlation, data from tests involving the IMR-8208 and the M1 propellants were used with the model to estimate heat release rates for different propellants. Table 14 is a summary of the heat release rates predicted for the other propellants. Figures 54 through 58 show the predicted change in heat release rate over the total burn times.

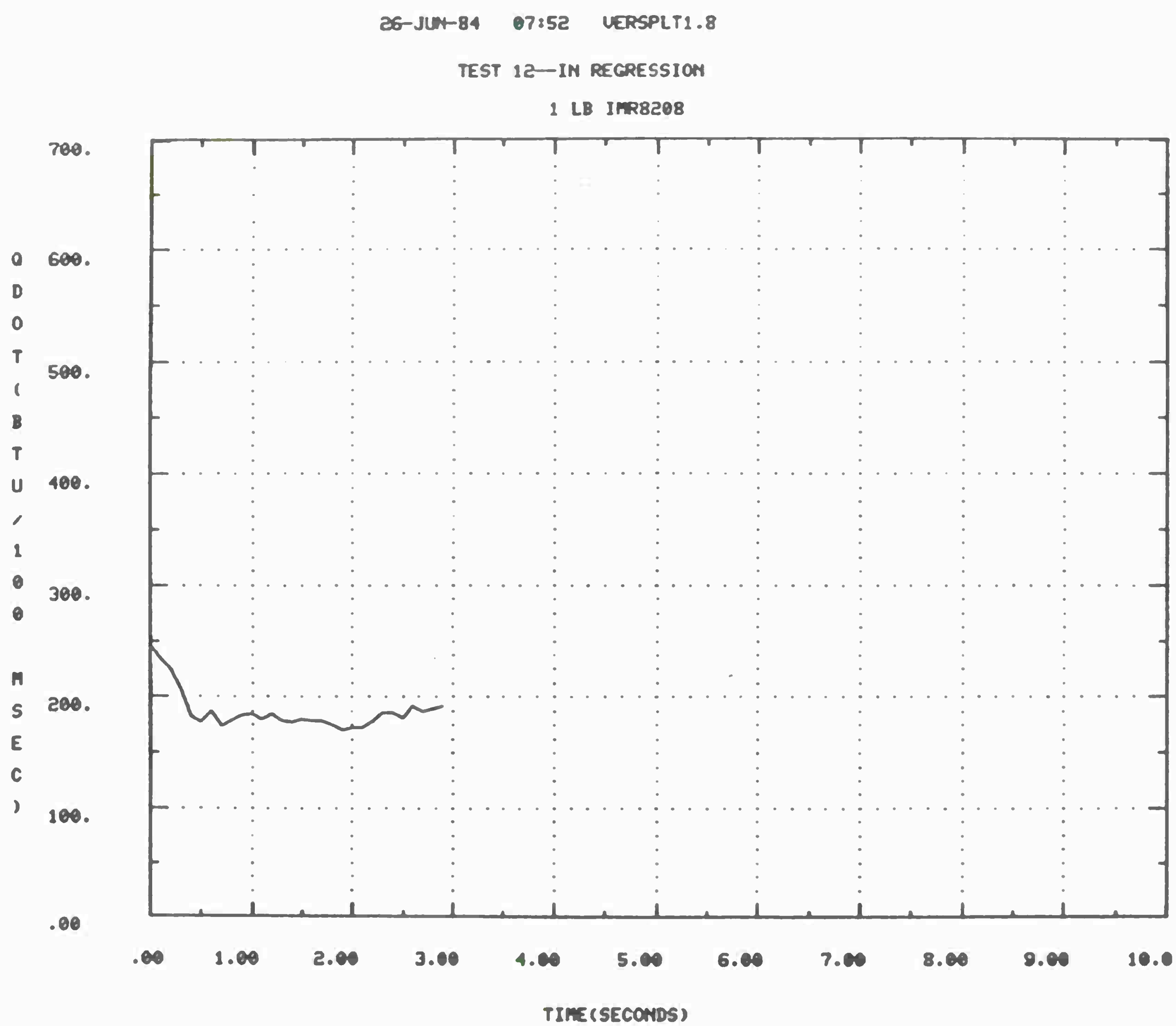


Figure 50. Plot of $\dot{Q}$ vs. Time for 1 lb IMR-8208

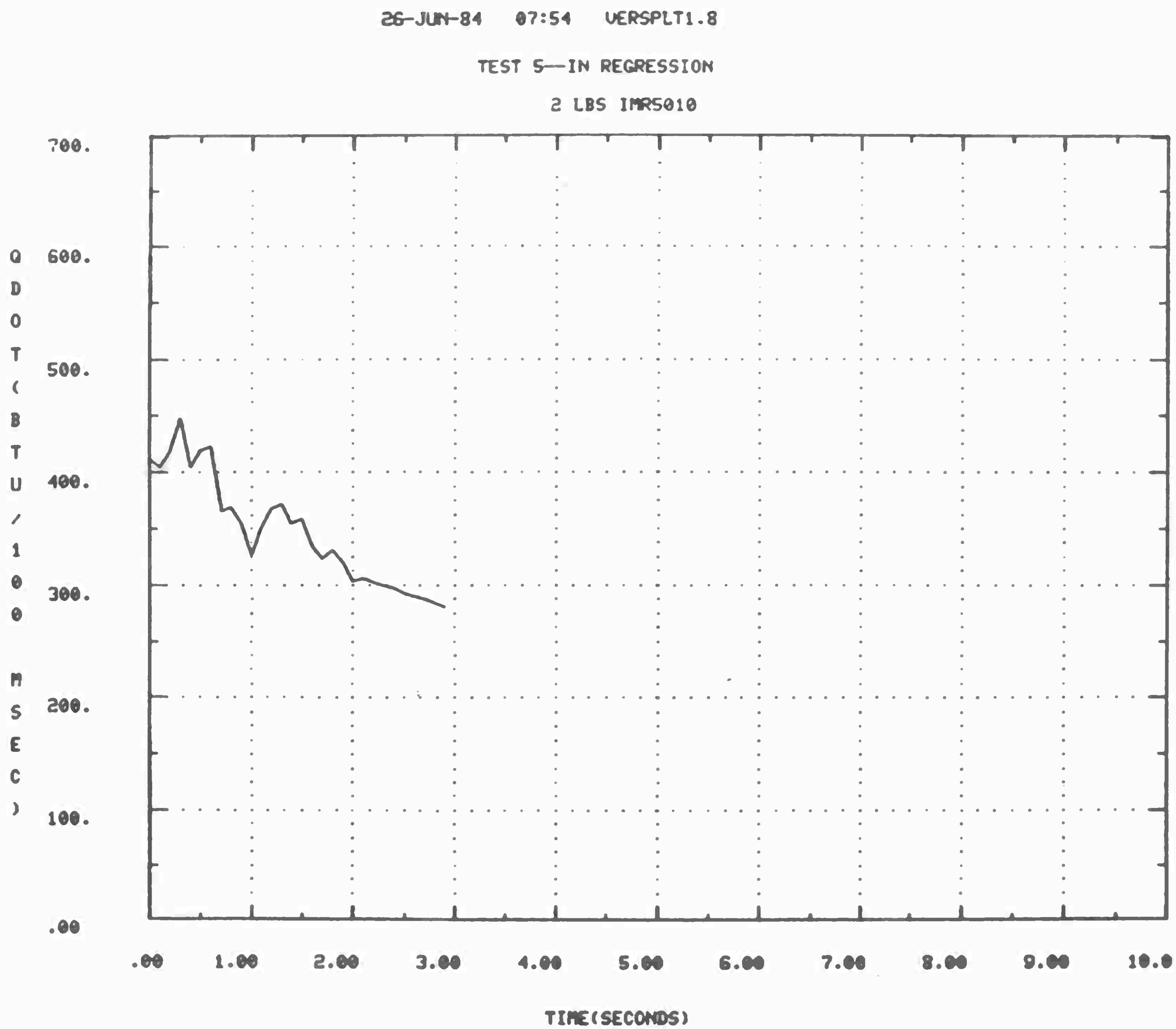


Figure 51. Plot of $\mathring{Q}$ vs. Time for 2 lb IMR-5010

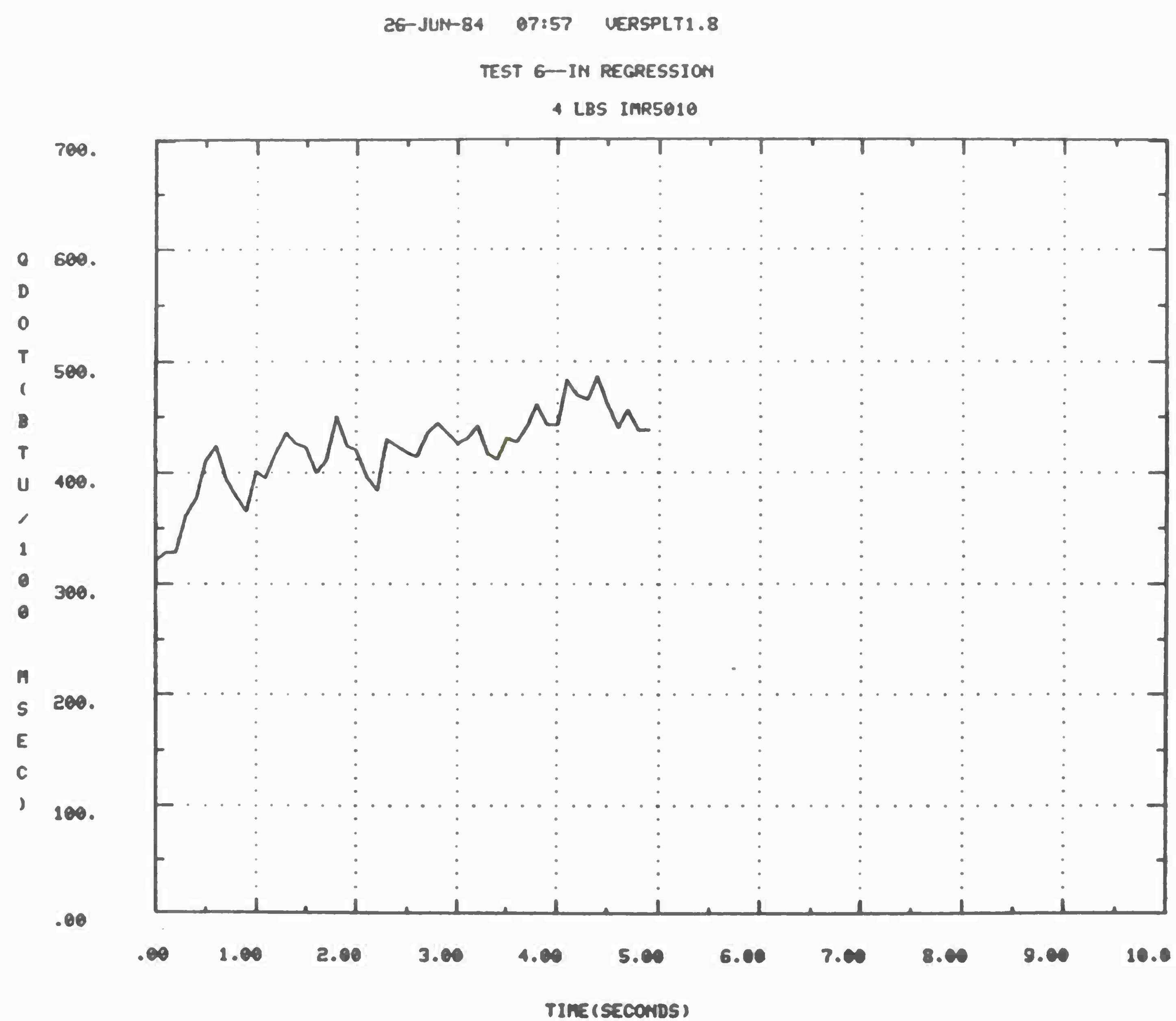


Figure 52. Plot of $\mathring{Q}$ vs. Time for 4 lb IMR-5010

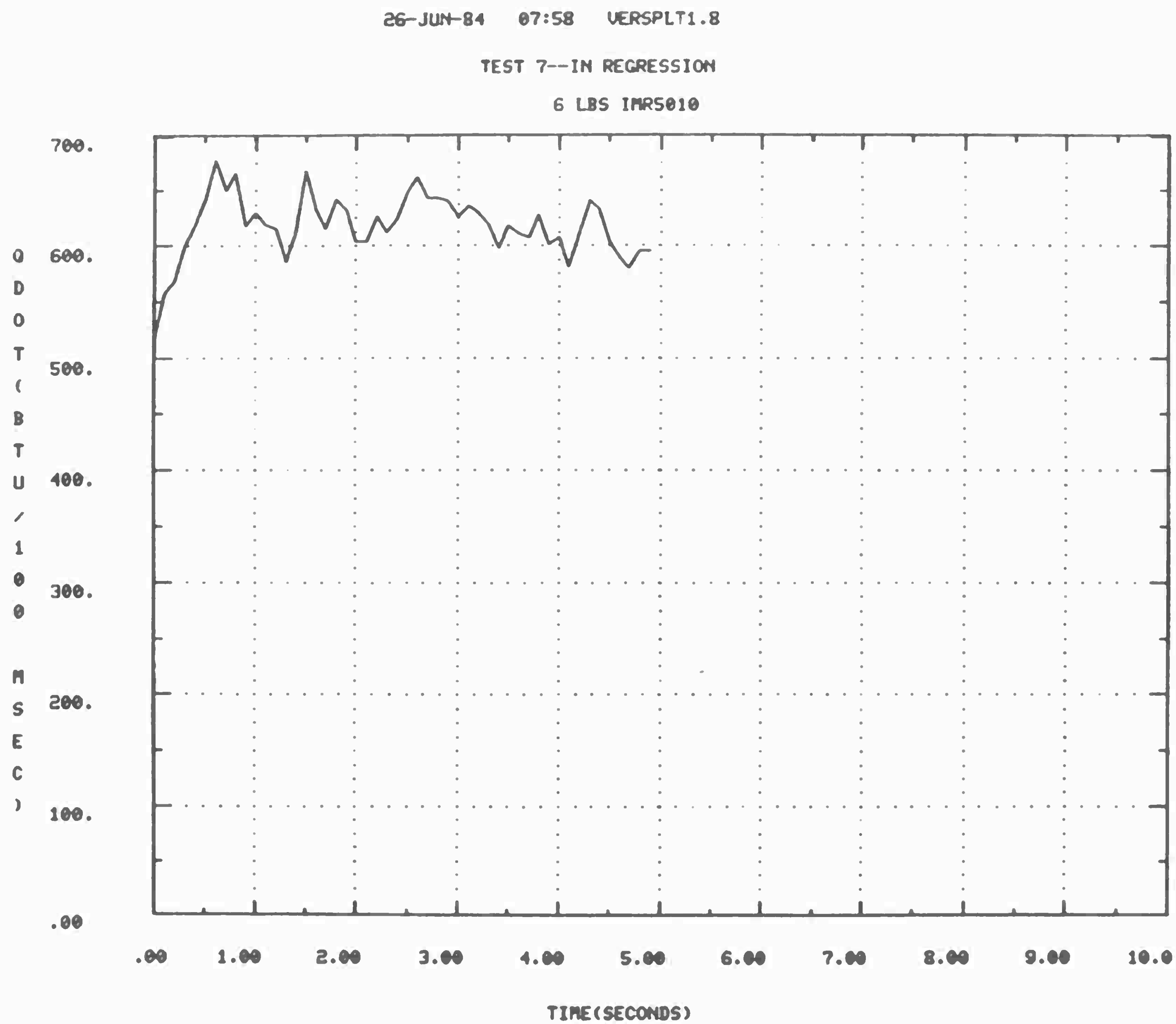


Figure 53. Plot of $\mathring{Q}$ vs. Time for 6 lb IMR-5010

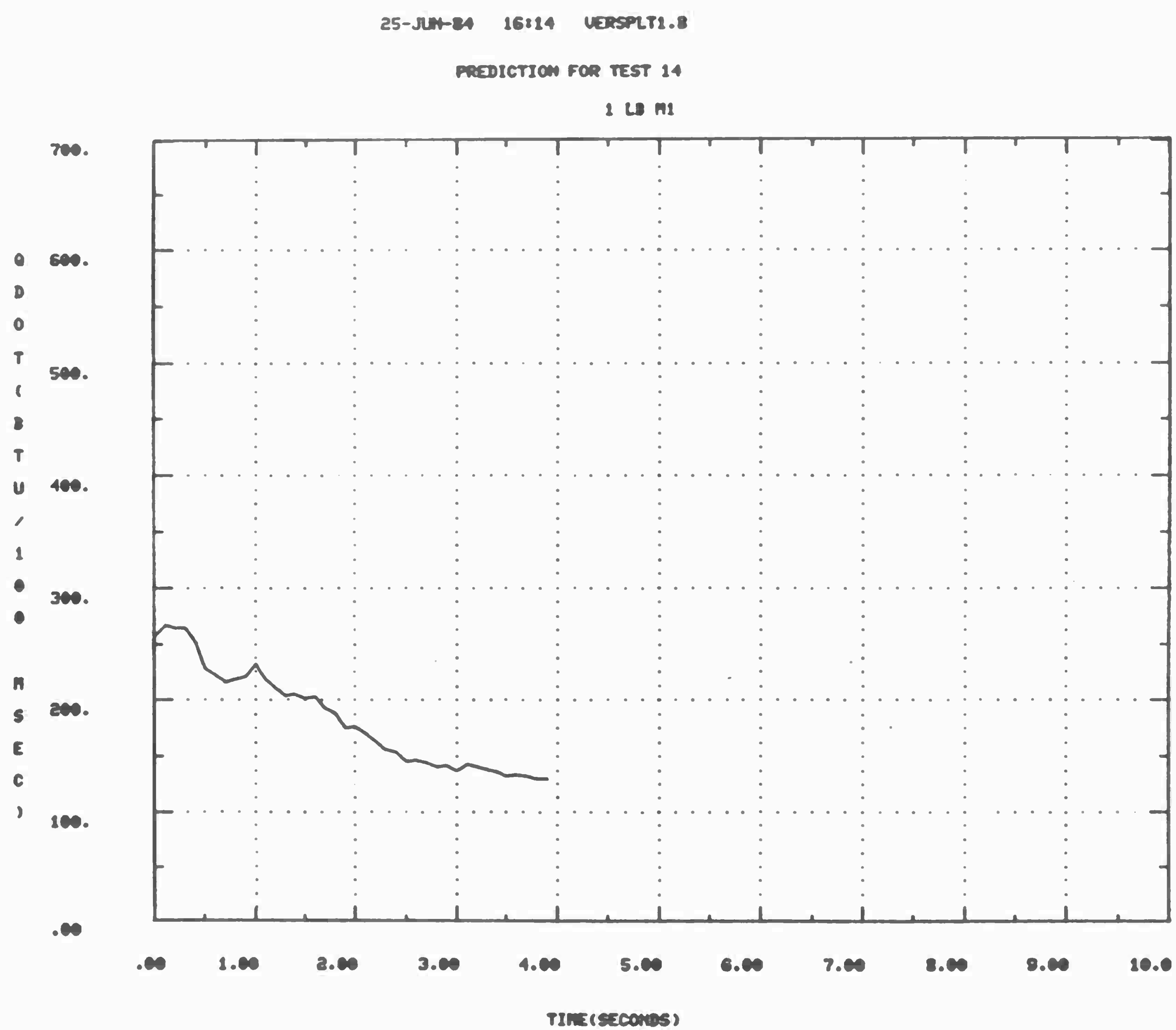


Figure 54. Plot of $\mathring{Q}$ vs. Time for 1 lb M1

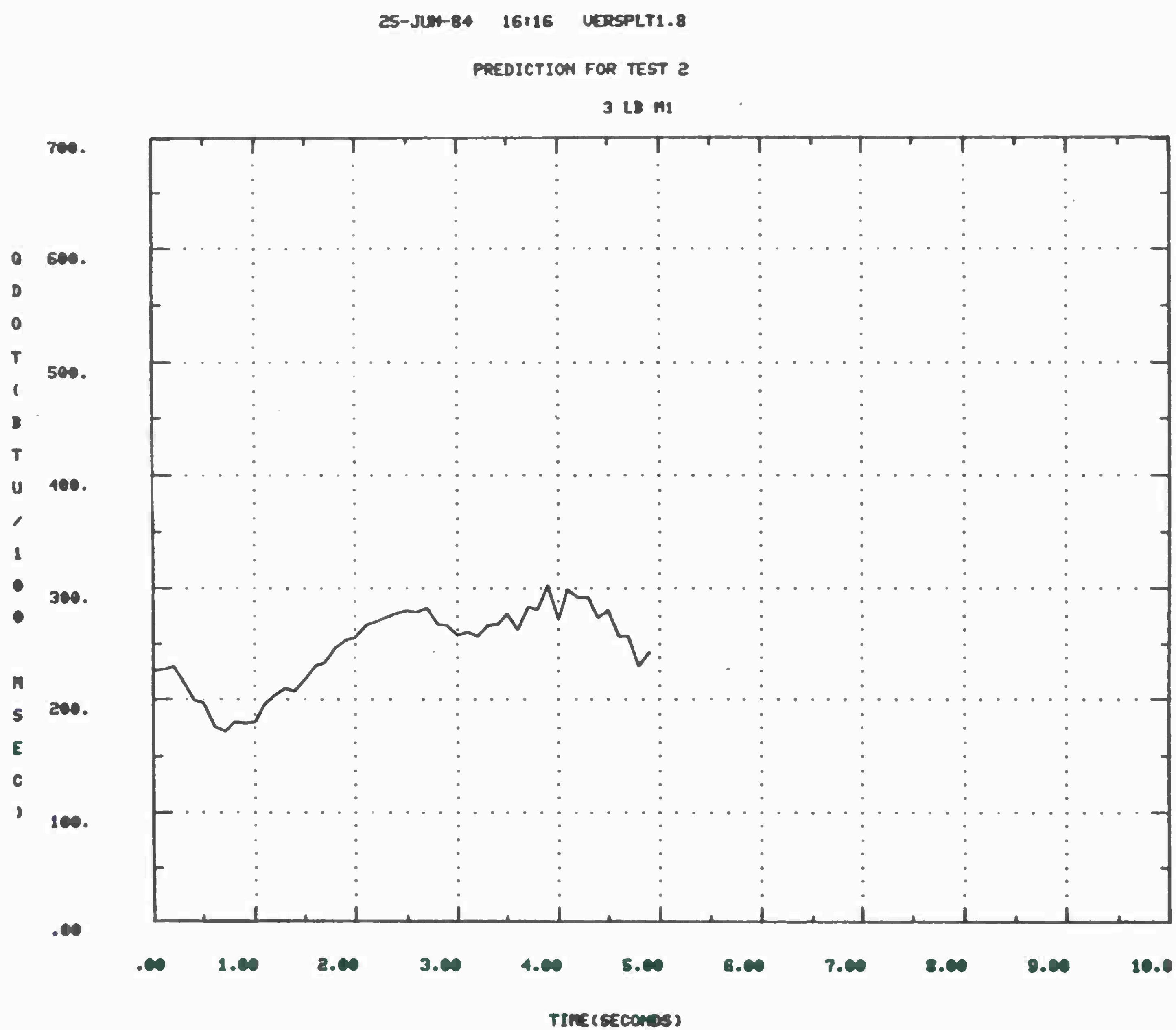


Figure 55. Plot of $\mathring{Q}$ vs. Time for 3 lb M1

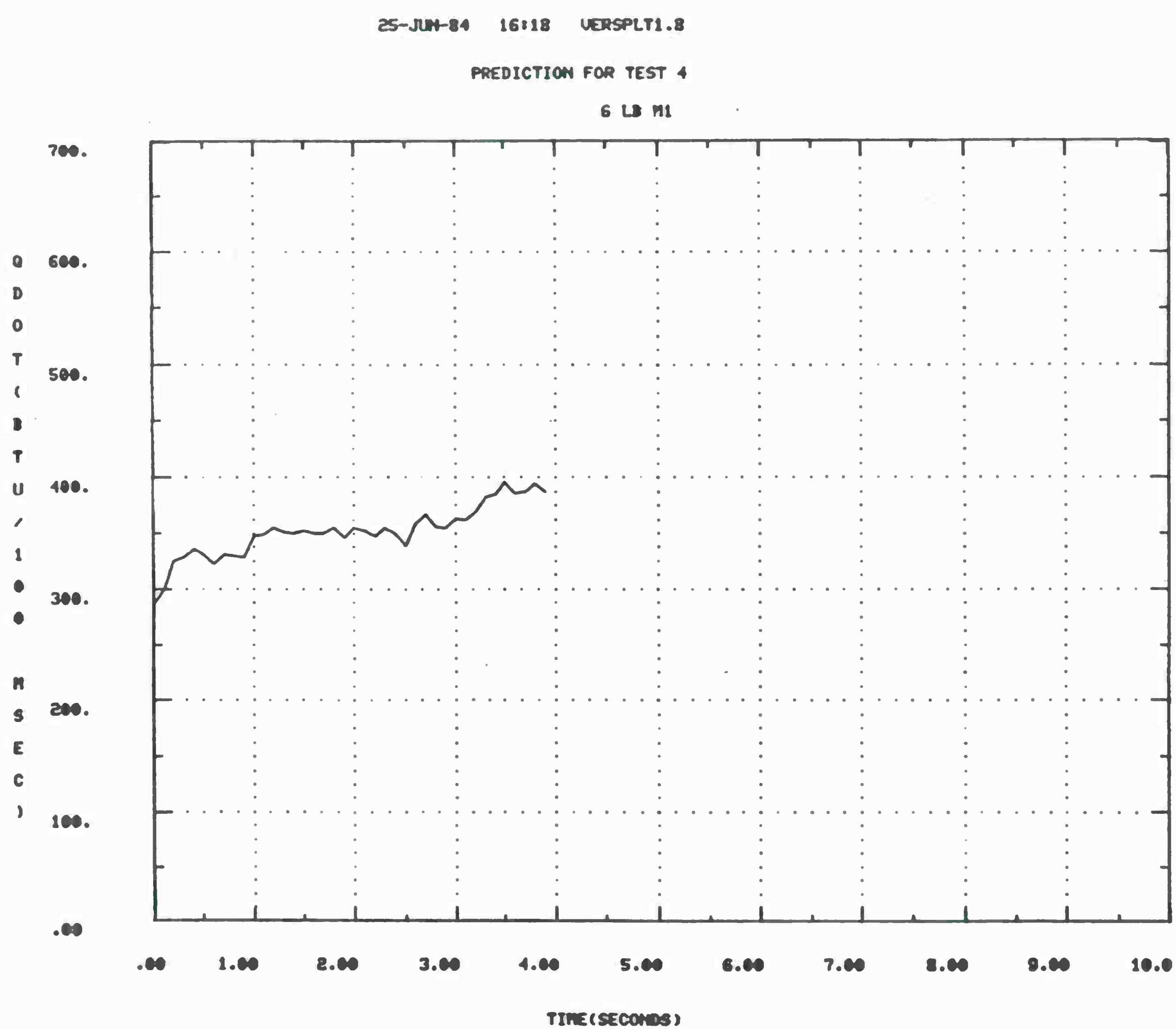


Figure 56. Plot of $\dot{Q}$ vs. Time for 6 lb M1

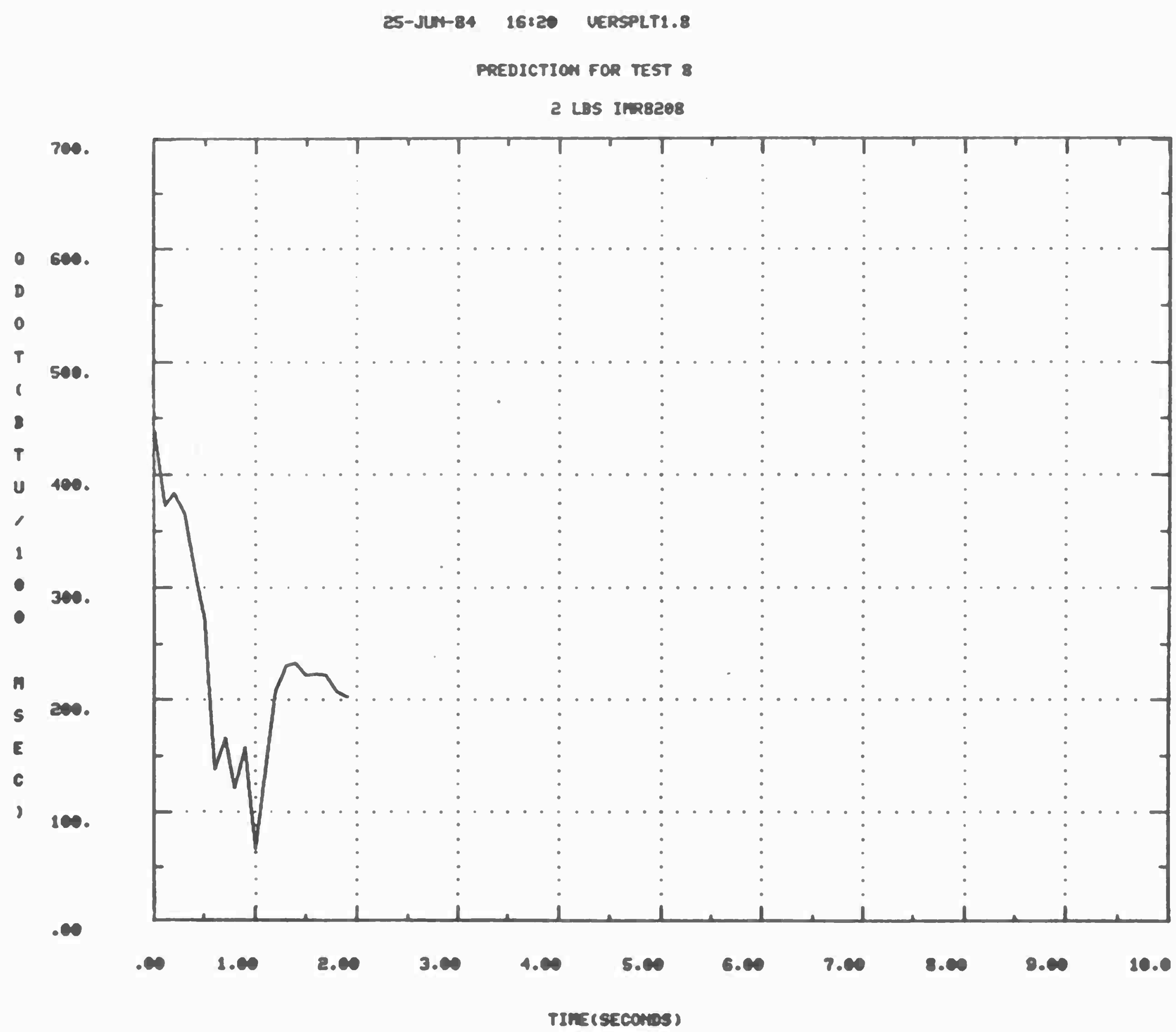


Figure 57. Plot of $\mathring{Q}$ vs. Time for 2 lb IMR-8208

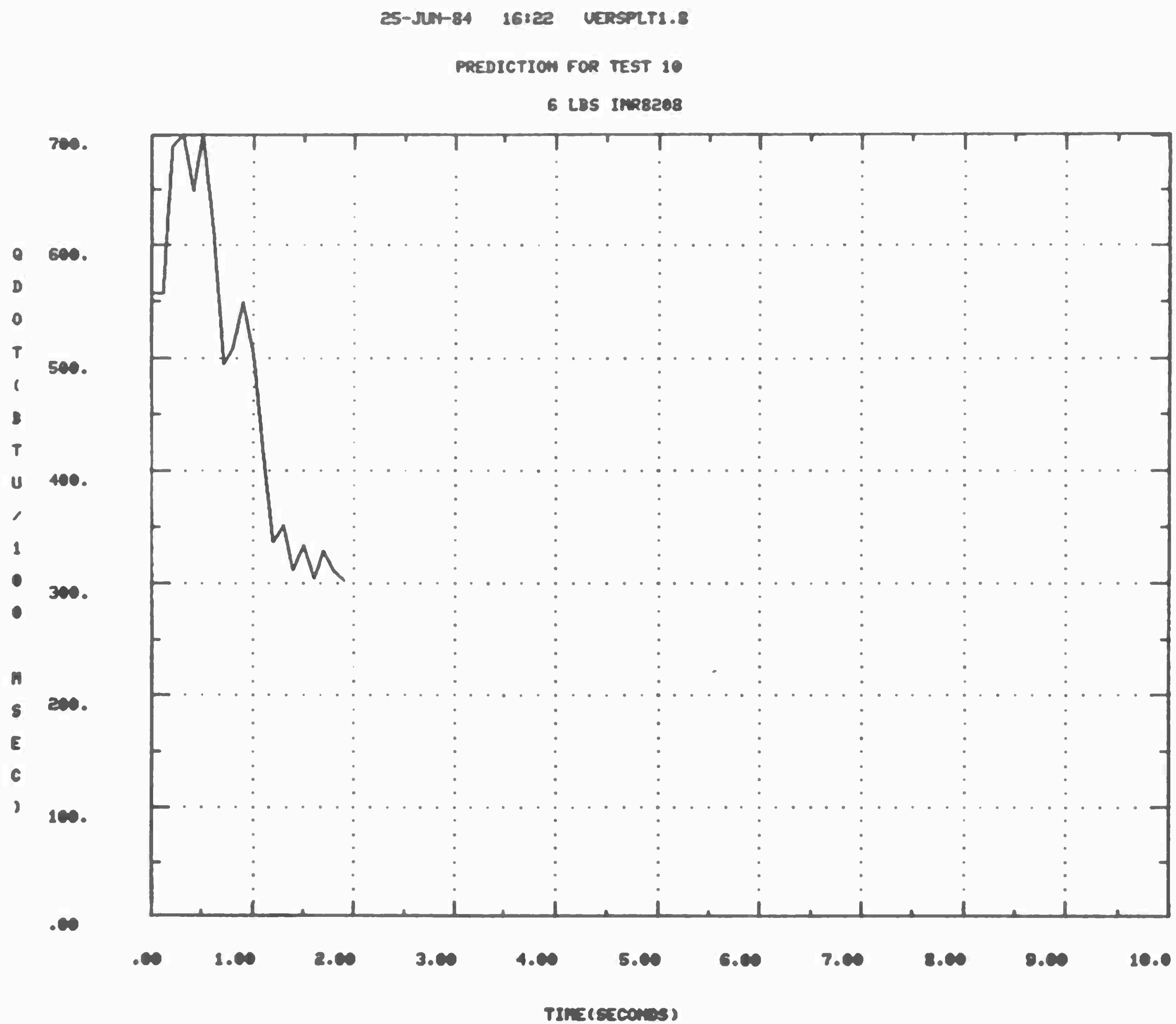


Figure 58. Plot of $\mathring{Q}$ vs. Time for 6 lb IMR-8208

TABLE 13. HEAT FLOW PREDICTIONS FOR IMR-8208 AND M1 PROPELLANTS

Test No.	Propellant	Charge (lb)	Average Predicted $\mathring{Q}$ (Btu/100 msec)
14	M1	1.0	183
2	M1	3.0	246
4	M1	6.0	352
8	IMR-8208	2.0	234
10	IMR-8208	6.0	479

The model presented here should provide good estimates of heat flow of propellants for which heat flow is unknown, providing the unknown quantity is within the range of average heat flows for the four tests used in the igloo regression analysis. The accuracy of the prediction would be questionable if it is expected to be or is predicted to be higher than 627 Btu/100 msec or lower than 174 Btu/100 msec.

TABLE 14. HEAT FLOW CALCULATIONS IN IGLOO (IMR-5010 and IMR-8208)

$$\mathring{Q} = 1600 + 0.0125T_9 + 0.00359T_{10} + 0.105T_{11} + 0.0931T_{12} - 0.0699T_{13} - 0.0538T_{14} + 0.214\mathring{T}_9 - 0.116\mathring{T}_{10} + 0.0965\mathring{T}_{11} + 0.0487\mathring{T}_{12} + 0.109\mathring{T}_{13} + 0.0131\mathring{T}_{14} - 31.1T_1 + 10.4T_5 - 35.1\mathring{T}_1 + 10.9\mathring{T}_5 + 0.243T_1\mathring{T}_1 + 0.0783T_1^2 - 0.0476T_5\mathring{T}_5 - 0.0159T_5^2$$

Test No.	Propellant IMR	Charge (lb)	Average $\mathring{Q}$ (Btu/100 msec)*	Average Predicted $\mathring{Q}$ (Btu/100 msec)*	Percent Variation
12	8208	1**	174	188	+8.0
5	5010	2	348	347	-0.3
6	5010	4	418	420	+0.5
7	5010	6	627	618	-1.4

* The units for $\mathring{Q}$ are expressed in relation to 100 msec because this was the increment between data points (temperatures). The average $\mathring{Q}$ represents the heat flow over a particular time interval.

** The 1.0-lb IMR-8208 propellant was used instead of the 1.0-lb IMR-5010 propellant.

5.0 Confinement of Fire by an Unstrengthened Enclosure

In this section, several conceptual mathematical models are developed which are then used to establish scaling relations for estimating the confinement of an internal fire by a nominal unstrengthened storage structure. Scaling laws for the fire plume temperature and velocity and the enclosure pressure will be given. More importantly, a scaling criterion will be developed that allows the conditions to be estimated for which firebrands and still-burning propellant are carried outside the enclosure by the plume.

5.1 Conceptual Mathematical Models

The mathematical models developed in this section are merely meant to represent the physics of a propellant fire in an enclosure so scaling relations can be established but are not meant to be accurate in all details to the point where quantitative predictions might be made from the models. Figure 59 shows a schematic of the physical arrangement.

It is assumed that as long as the geometrical configuration of the propellant remains similar and only the amount is changed, the rate of burning is proportional to the initial mass:

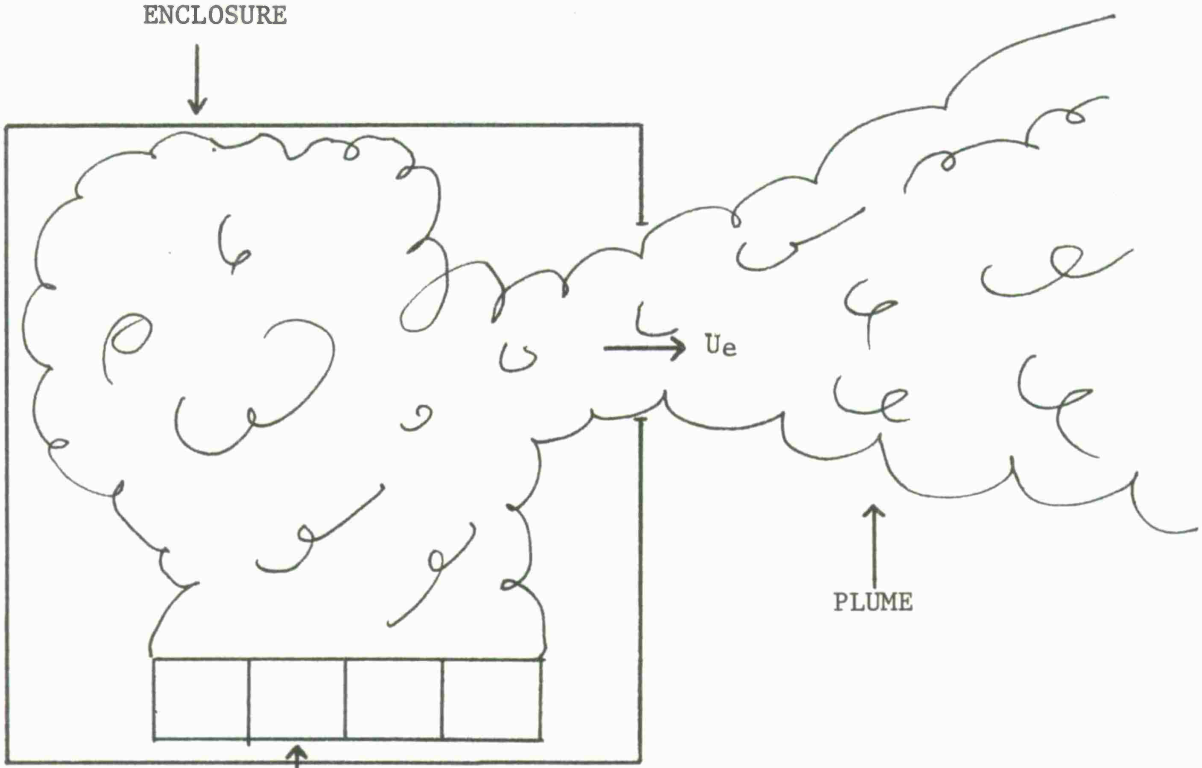
$$\mathring{M} = mM \qquad (11)$$

where $\mathring{M}$ is the mass rate of propellant consumption. Here, m is a proportionality constant, with dimensions of reciprocal time, that is, a function of only the chemical composition of the propellant and the geometrical configuration. Equation (11) is in agreement with the open-air tests reported in Section 3.0 as well as with the enclosure tests reported in Section 4.0 for those tests in which the geometrical shape of the propellant mass was similar. It also is in agreement with the tests reported in the previous IITRI work;[3] see, for example, Figure 18 of the referenced report. Deviations from Equation (11) might be expected when the enclosure overpressure is substantial, but this will not occur in an unstrengthened, vented enclosure.

The rate at which gas volume (products of combustion) is liberated is:

$$\mathring{V}_g = v\mathring{M} \qquad (12)$$

where v is a proportionality constant, with dimensions of molar volume per unit mass, that is, a function of the chemical composition of the propellant. Likewise, the rate at which energy is liberated is



V_o - enclosure volume

ΔP - enclosure overpressure

T - plume temperature

U_e - plume exit velocity

A_e - vent area

V_g - gas volume

Figure 59. Schematic of Propellant Fire in a Vented Enclosure

$$\mathring{Q} = q\mathring{M} \tag{13}$$

where q is a proportionality constant, with dimensions of energy per unit mass, that is, a function of the chemical composition of the propellant.

Although the enclosure cannot support a large overpressure, a small pressure drop across the vent is required to force the combustion gases through the opening. The overpressure, ΔP, is related to the average velocity of the plume at the vent:

$$U_e = C_d\sqrt{2\Delta P/\rho_g} \tag{14}$$

Here, C_d is a loss coefficient (which depends on the shape of the vent) and ρ_g is the average density of the plume gas.

From the equation of state for the gas in the enclosure, the rate of change of the overpressure is:

$$\frac{1}{P_g}\left(\frac{d\Delta P}{dt}\right) = \frac{1}{M_g}\left(\frac{dM_g}{dt}\right) + \frac{1}{T_g}\left(\frac{dT_g}{dt}\right) \tag{15}$$

where P_g, M_g and T_g are the pressure, mass and temperature of the gas in the enclosure. Likewise, the rate of change of the amount of gas in the enclosure is:

$$\frac{dM_g}{dt} = W_g\mathring{V}_g - \rho_g A_e U_e \tag{16}$$

Here, W_g is the molecular weight of the products of combustion; the last term on the right of Equation (16) is the rate of mass loss through the vent.

The rate at which the temperature of the enclosure and the gases change is, roughly,

$$\mathring{Q} = {}_{av}C_{av}V_o \frac{dT_{av}}{dt} + \rho_g C_p A_e U_e T_g \tag{17}$$

Here, ${}_{av}$, C_{av} and T_{av} are respectively mass-weighted average density, specific heat, and temperature of the enclosure and its contents. (Estimating numerical values for these quantities would be extremely difficult. However, such values are not needed in the scale modeling relations to be developed. If values are required, they can be assumed to be the corresponding numbers derived in the regression analysis presented in Section 4.0.)

Equations (14) and (15) can be combined to give:

$$\frac{1}{P_g}\left(\frac{d\Delta P}{dt}\right) = \frac{1}{M_g}\,[W_g\mathring{V}_g - \rho_g A_e U_e] + \frac{1}{T_g}\,\frac{dT_g}{dt} \qquad (18)$$

Although neither the pressure nor the temperature in the enclosure may ever reach a steady state, Equation (18) can be used to estimate the pressure rise and the plume velocity by neglecting the transient terms. Thus,

$$W_g\mathring{V}_g - \rho_g A_e U_e \approx 0 \qquad (19)$$

Therefore:

$$\Delta P \quad (W_g\mathring{V}_g/C_d A_e)^2/2\rho_g \qquad (20)$$

or

$$\Delta P \approx (\ mW_g M_i/C_d A_e)^2/2\rho_g \qquad (21)$$

and, therefore,

$$U_e \approx (\nu m W_g M_i/\rho_g A_e) \qquad (22)$$

In Equation (17), it is probably not valid to neglect the transient effects. Thus, the plume temperature is roughly:

$$T_g = [qmM_i - P_{av}C_{av}V_o\,\frac{dt_g}{dt}]/\rho_g C_p A_e U_e \qquad (23)$$

or

$$T_g = \left(\frac{q}{\nu C_p}\right) - \left[\frac{P_{av}C_{av}V_o}{\nu m W_g M_i C_p} \quad \frac{dT_{av}}{dt}\right] \qquad (24)$$

The first term on the right is just the adiabatic flame temperature of the propellant, while the second term represents the energy losses. This expression is helpful in understanding the trends observed in the test data.

One of the more important observations from the tests is that there is a certain critical propellant mass (for a given propellant and test setup) above which the plume carries firebrands and still-burning propellant outside the enclosure. To analyze this, it is assumed that there is a characteristic time, t_c, for the complete combustion of each propellant particle. Then, as the propellant is swept up into the plume, the particles will continue to burn as firebrands outside the enclosure if they do not remain within the enclosure for at least a time equal to t_c. Further, the volumetric rate at which gases exit the vent determines the time that representative propellant particles remain within the enclosure. Thus, the time available for combustion of the particles is:

$$t_a \approx KV_o/A_eU_e \tag{25}$$

Using Equation (22) gives

$$t_a = K\rho_g V_o/\nu m W_g M_i \tag{26}$$

Here K is an empirical factor relating the interior mixing to the geometrical shapes of the enclosure and vent. In the simplest case, K is just a function of V_o and A_e:

$$K = f\langle V_o^{2/3}/A_e\rangle \tag{27}$$

Firebrands will be created when $t_a < t_c$. Thus, a critical value of the ratio of propellant mass to enclosure volume can be defined:

$$\left(\frac{M_i}{V_o}\right)_c = K(\rho_g/t_c \nu m W_g) \tag{28}$$

When M_i/V_o is greater than the critical value, firebrands will occur. The critical values for the tested propellants and enclosures can be estimated from the test data. Note that the quantities within the parentheses on the right-hand side of Equation (28) only depend on propellant chemistry.

This completes the development of the conceptual mathematical models.

5.2 Scaling Relations

The preceding conceptual models can be used to establish scale modeling relations that permit the test data to be generalized and to design further tests at a scale that is large enough to ensure full-scale, prototypical behavior. The scaling relations will be presented in terms of a geometrical length scale factor; λ, which is the ratio of a length in the model to a corresponding length in full-scale. It is assumed that the propellants are the same or have similar energy release rates in both model and full-scale.

Geometrical similarity of the enclosure volume and vent areas are required in order to ensure similar mixing and similar plume velocities. Thus,

$$V_o \sim \lambda^3 \tag{29a}$$

$$A_e \sim \lambda^2 \tag{29b}$$

$$V_o^{2/3}/A_e \sim 1 \tag{29c}$$

Equation (29a) is the familiar "two-thirds" scaling law.

The quantity of propellant must scale as the enclosure volume to reproduce results. In effect, this law gives the relation that should be used to interpret the test results in terms of the prototype:

$$M_i \sim V_o \sim \lambda^3 \tag{30}$$

From Equation (21) the enclosure overpressure scales as

$$P \sim (M_i/A_e)^2 \sim \lambda^2 \tag{31}$$

Likewise from Equation (22) the plume velocity (from which firebrand trajectories are determined) scales as

$$U_e \sim (M_i/A_e) \sim \lambda \tag{32}$$

Note that Equation (32) implies that time durations have a scale factor of one (i.e., the same in model and full-scale). This is also a consequence of Equation (11), which assumes that the burning rate increases linearly as the propellant mass is increased. Such an assumption requires strict geometrical similarity between the propellant configuration; such similarity is not likely to be realized in practice and so the scaling of time implied by Equation (32) is only approximate.

Finally, Equation (28) states that the critical amount of propellant needed to create firebrands is proportional to the enclosure volume. Thus, the critical propellant in full-scale can be established from the tests by volume scaling:

$$(M_i)_{crit} \sim V_o \sim \lambda^3 \qquad (33)$$

The above scaling relations are based on the use of the same propellants in the tests as are expected in full-scale. The relations can be generalized to include dissimilar propellants, if needed, by including the characteristic properties v, m and q of the propellant; these characteristics are functions only of propellant chemistry but were not measured in the tests described here.

The sealing for time and velocity differ from those in conventional "cube-root", or Hopkinson-Cranz, blast more sealing. This is, of course, not at all surprising, because some quite different physical processes are being sealed. The difference is mentioned here because some readers may assume that because lengths, areas and volumes maintain geometric similarity as in Hopkinson-Cranz blast sealing, that the time sealing in that law must also apply.

6.0 Large-Scale Test Plan

The complexity and variability of fire growth in an enclosure has provided an enticement to fire researchers. The challenge of finding common observations in both controlled experimental fire and accidental fires has led to the development of scale model tests. These tests can generate data on different phases of general fire development such as flame spread rates, fuel consumption rates (i.e., mass burning rates), and ventilation-controlled burning rates that can be related to full-scale fire growth scenarios. In general, the complete development of an enclosure fire depends on the complex interaction of the fuel load characteristics, the enclosure geometry, and the ventilation parameters.

An acceptable approach to fire modeling is the establishment of relative correlations between reduced-scale and full-scale prototype or controlled fires. A technically valid approach to this is the development of relative heat release data for the controlled fires and then the use of reduced-scale tests to predict full-scale behavior. Published enclosure fire data[5] indicate that two fires having similar heat release and temperature characteristics could present entirely different hazards depending on whether the fire development is fuel or ventilation controlled. Since the combustible materials that are of interest to this program exhibit an inherent fuel/oxygen balance, ventilation control variables can be minimized and emphasis can be placed on the fuel. Ventilation can affect the burning characteristics of an external ignition source, i.e., "spilled" fuel pool, and flame spread/fire growth from incipient involvements by the nonenergetic packaging materials that are present. As discussed in Section 5, the geometric configuration of the enclosure volume and the vent area can affect the mixing and the effluent plume velocities, thereby influencing the combustion processes inside the enclosure. Consequently, the development of relative correlations between scaled fires will require the use of geometrically similar test enclosures.

Coulbert[6] presents a fire test concept based on relative energy release criteria (RERC). Five energy release constraints for fire development in an enclosure are defined. Three of these are based on the rate of energy release and two constraints on the total energy released. The five energy release constraints are identified as follows:

1) Flame Spread Rate. Initially the rate of energy release is controlled by the rate of fire spread or the flame spread velocity.

2) Fuel Surface Area Limit. A second constraint on energy release rate is reached when the flame has spread to involve the total fuel surface. If not constrained by available air, the fire would burn at a heat release rate proportional to the exposed fuel area. As burning proceeds, changes in fuel area and other fuel characteristics alter the heat release rate as the fuel supply diminishes.

3) Ventilation Limit. A third constraint on energy release rate is encountered when the combustion becomes ventilation controlled. While the fire is ventilation controlled, the rate of energy release in the enclosure is independent of the fuel surface limit.

4) Enclosure Volume. A constraint on total energy release in the enclosure is due to the depletion of the initial oxygen supply if ventilation is limited, as in a closed room or sealed compartment.

5) Fuel Load. The fifth constraint is the total fuel load.

These five fire development constraints are called RERC because numerical approximations of their values can be readily calculated, and they can be presented graphically as shown in Figure 60. Using the initial graphical representation of the RERC, one can assess the potential importance of each constraint and review the adequacy of the values calculated. The relative effect of changes in the fire constraints can be estimated. Questions can be answered, such as whether factor-of-two changes in flame spread rate, fuel surface area, room volume or ventilation openings would appreciably affect the fire development rate.

6.1 Experimental Program

The development of test methods that can be used to establish relative correlations between reduced-scale and full-scale prototype or controlled fires will require:

- suitable test apparatus and instrumentation,
- a procedure which can readily be replicated with a fair degree of accuracy,
- adequate calibration techniques,
- test materials of known basic characteristics for use in securing the desired performance information,
- a "standard" material for proof of the method in application.

6.1.1 Facilites and Instrumentation

6.1.1.1 Facilities

The results of this program indicated that heat release calorimetry can provide a valid method for assessing such hazards. Accordingly, two heat release calorimeters operating on the same basic principles but differing in physical scale will be utilized to establish relative heat release data from controlled experiments. The two units will be identified as:

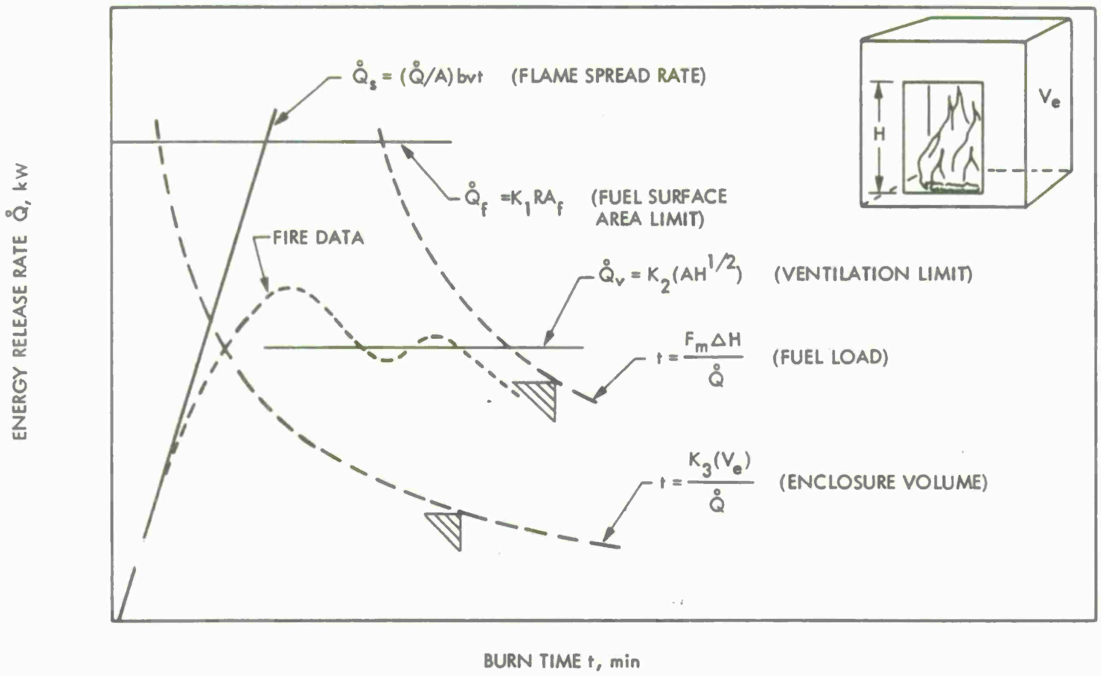


Figure 60. Relative Energy Release Criteria for Enclosure Fire Development

A	- ventilation opening area, m^2
A_f	- fuel surface area, m^2
b	- flame front length, m
F_m	- fuel mass, kg
H	- vertical dimension of ventilation opening, m
ΔH	- heat of combustion, kW-min/kg
K_1, K_2, K_3	- proportionality factors in consistent units
Q	- total heat released, kW/min
$\mathring{Q}$	- heat release rate, kW
$\mathring{Q}_f$	- fuel surface-controlled heat release rate, kW
$\mathring{Q}_s$	- heat release rate during flame spreading, kW
$\mathring{Q}_v$	- ventilation-controlled heat release rate, kW
R	- fuel burning rate, kg/min
t	- burning time, min
V_s	- enclosure volume, m^3
v	- flame spread velocity, m/min

1) Full-Scale Calorimeter. The internal volume of an approved munitions storage magazine is typically 23,120 ft^3 and there is a single main opening having an area of 100 ft^2. Figure 61 provides a sketch of such a magazine as described in Reference 7.

2) Reduced-Scale Calorimeter. A reduced-scale calorimeter representing a 1/3 volumetric scale model (7700 ft^3) of a full-scale munitions storage magazine would be used during the experimental program. This calorimeter will have a 45 ft^2 opening to provide the appropriate scaled vent area, i.e., $\underline{A}$ = 0.1232. This reduced-scale calorimeter will have to be hardened to sustain repetitive dynamic fire/pressure conditions.

6.1.1.2 Instrumentation

The two calorimeters will be instrumented to evaluate initiation, propagation and heat release rate. Measurements will include:

- ignition energy,
- flame spread,
- mass burning rate,
- temperature measurements for computing heat release rate,
- thermal characteristics of effluent plume,
- pressure-time history of the event(s).

Instrumentation will consist of arrays of thermocouples, load cells, pressure transducers, Keil probe anemometers, thermal flux transducers, thermopiles, radiometers and appropriate signal conditioning and recording instrumentation with fast response capabilities.

6.1.2 Experimental Design and Procedures

Experiments will be designed to quantify the initiation and propagation of fires involving combustible ammunition. Controlled experiments will be conducted in a 1/3 volumetric scale model and in a full-scale munitions storage compartment. Test methodologies obtained during the study reported herein and those reported previously[3] will be incorporated into the experimental design. The tests will assess the following:

1) Ignition Source
   - external, e.g., "spilled fuel" pool fire
   - internal, e.g., accidental ignition of a munition fuze

2) Flame Spread
   - involvement of nonenergetic packaging materials

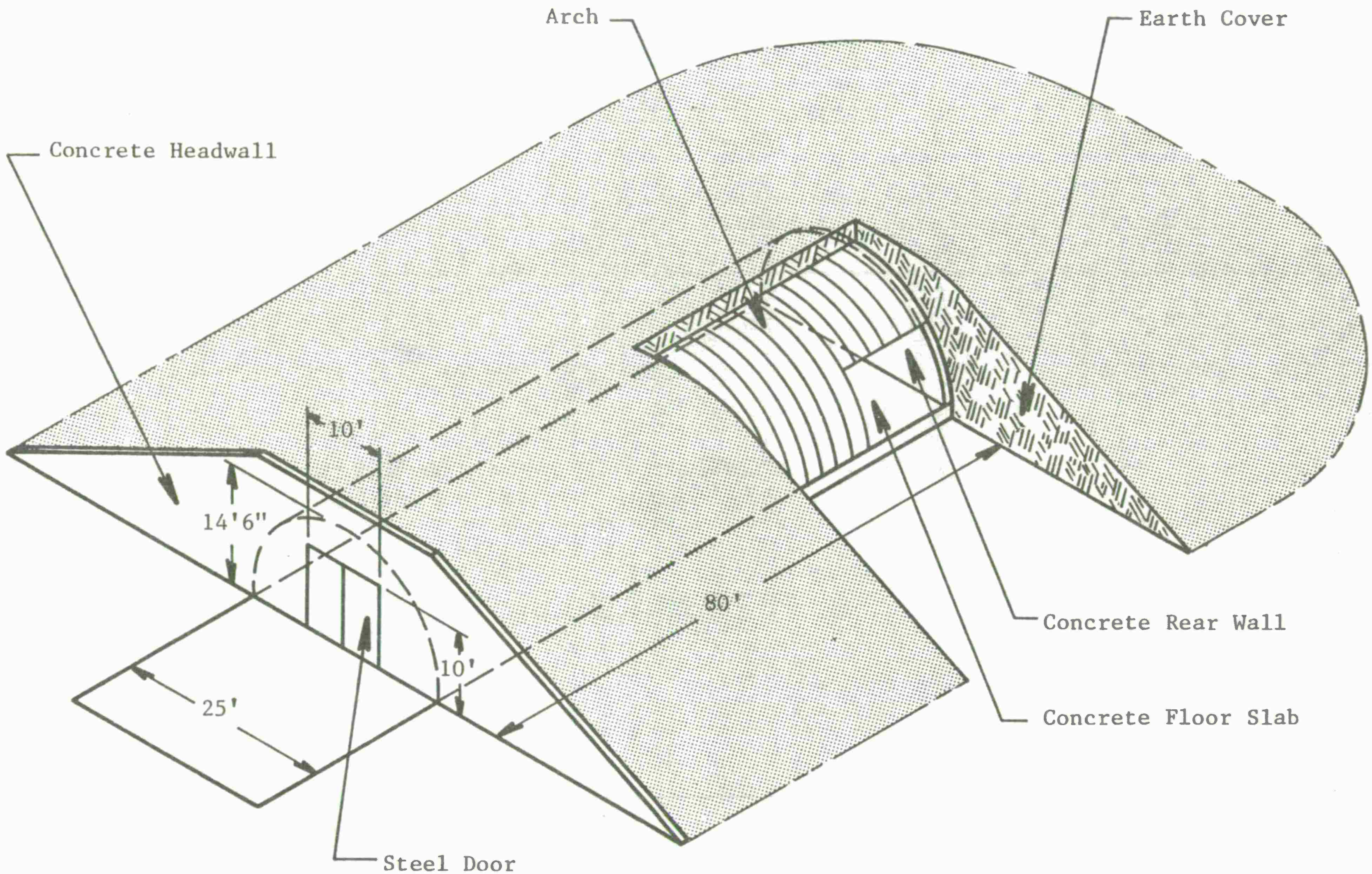


Figure 61. Features of Earth-Covered Steel Circular Arch Magazines (Full-Scale Calorimeter)

- growth within the packing unit
- interaction between adjacent units (horizontal and vertical growth rate)

• involvement of energetic materials
  - finished munitions, e.g., ALA-17 flares
  - bulk propellants

3) <u>Rate of Heat Release</u>

• availability of fuel load, i.e., packaging materials and energetic materials
• fuel consumption rate, i.e., mass burning rate
• fuel-to-volume ratio
• fuel-to-scaled vent area ratio

4) <u>Hazards</u>

• thermal output
• pressure failure
• firebrand
• toxic products

As stated earlier, the experiments will be designed to obtain answers to the following questions:

• What is the minimum amount of energy required to initiate a fire?

• Will the packaging materials provide any safeguards?

• Will packaging design hindrances that are inherent or can be incorporated into the packing units do their intended function and delay or eliminate propagation to the next item(s)?

• What is the factor-of-two effect?

• What is the effect of geometric spacing on the susceptibility of adjacent units?

• Can the initiation and involvement of the packaging materials be ventilation controlled?

• Does $\mathring{Q}$ reach/approach an "allowable" level before the onset of a catastrophic failure of the storage magazine?

• Does $\mathring{Q}$ reach/approach a "saturation" level which can lead to the enhancement of the fire development outside the magazine?

• What is the effect of $\mathring{Q}$ on the effluent plume's thermal signature and dynamics?

• What is the effect of $\mathring{Q}$ on the formation and propagation of firebrands?

• What is the effect of scaled vent area on the internal and external $\mathring{Q}$?

• Can the magazine be ventilated safely?

6.1.3 Replicate Tests and Calibration

Since each of the test calorimeters will have its own experimental limitations, all of the test variables will be selected so as to extend the limitations of the individual test unit. For example, donor/acceptor experiments conducted on packaging materials can be conducted with inert fillers to extend the usefulness of the reduced-scale calorimeter. The contributions by the energetic materials in the donor will be adjusted to evaluate the fire growth characteristics. Replicate tests will be conducted on these donor/acceptor (as well as for other tests) to assure confidence in the results and to establish criteria for the full-scale tests. The accuracy within the repeated tests will be noted and compared to anticipated values that can be calculated from handbook values tabulated for the test materials. These handbook values will also be used to obtain calibration data for heat release models that will be developed during the test program.

6.1.4 Test Materials

Test results reported previously[3] and those presented in this report indicate that the proposed test materials should consist of:

- bulk propellants: M1 and IMR-8208
- assembled munitions: ALA-17 flares, M8-HC smoke grenades

A version of Technical Manual TM9-1950[8] also provides observations on M-35 rockets. Chapter 5 of TM9-1950 also reports that demolition of complete rockets and rocket motors by burning is not practicable since the first rocket or rocket motor taking off will disrupt the pile and cause the remaining units to take off in all directions. Consequently, the proposed test program should not include rocket motors. At best, the propellant grain can be removed from the rocket motor for quantification in terms of heat release.

6.1.5 "Standard" Material

A "standard" material should be selected for the derivation of $\mathring{Q}$ and for periodic verification of the accuracy of the test results obtained from fires conducted with "stressed" instrumentation that has been subjected to repeated testing. It is anticipated that one of the bulk propellants can serve this purpose.

7.0 Conclusions

Based on the results of the experimental efforts of this program, a number of general conclusions have been formulated. The following sections provide details on the conclusions for:

- exploratory tests on smoke-producing materials,
- open-air tests,
- tests in an enclosure.

7.1 Exploratory Tests on Smoke-Producing Materials

Four tests were conducted using the M8-HC smoke grenades. Based on the results of these tests, the following conclusions have been developed.

- When exposed to an external fire, the skin temperature of the grenade must reach 450°F to cause "functioning."
- Grenades subjected to pool fires showed a considerable amount of bulging of the grenade body and longitudinal failures in the seams indicating a pressure failure.
- The accidental functioning of a single grenade in its shipping container, i.e., wooden box, does not provide sufficient heat buildup to reach temperatures necessary to cause sympathetic ignition of adjacent grenades.

7.2 Open-Air Tests

Eight open-air tests were conducted. Based on the results of these tests, the following conclusions have been developed.

- Functioning of the ALA-17 flare results in the separation of the flare body into two parts that are jettisoned distances in excess of 30 ft. Resulting thermal characteristics are difficult to quantify when these materials are tested in the open, thereby requiring "confinement" of the flares.
- Ignition of the MK45 rockets could result in the burning grain jetting out of the rocket motor casing or the propulsion of the entire assembly in an uncontrolled manner. Resulting thermal characteristics are difficult to quantify, thereby requiring "confinement" of the rockets.
- Ignition of a stripped rocket motor, i.e., without the fins, rocket nozzles, igniter cap and prescored rupture disk, results in simultaneous thrusting out of both ends of the casing.
- When in bulk, geometric changes, i.e., increase in depth, width and length, did not have a noticeable effect on the burning rate of the propellants.

- Extent of firebrand emissions was not affected by geometric changes, but the amount of firebrand emissions varied among the propellants tested. In similar size tests, the M1 propellant produced more firebrands and jettisoned more unburned material than did the 8208 and 5010.

7.3 Tests in an Intermediate Enclosure

A number of tests were performed using two intermediate scale enclosures, i.e., an 8-ft cubicle and a 1/10th scale model igloo. A total of 18 tests involving the smoke grenades, propellants and flares were performed in the 8-ft cubicle. A total of 16 tests involving propellants were performed in the 1/10th scale model igloo. Based on the results of these tests a number of conclusions have been developed and are presented in the following paragraphs.

7.3.1 Tests in the 8-ft Marinite Cubicle

7.3.1.1 Smoke Grenade Tests

- The combustion of a box of smoke grenades simultaneously initiated resulted in a very mild event with relatively low internal temperatures and the exiting smoke plume was very low velocity (6.8 ft/sec). One would expect that for the same grenade loading density in a full-scale igloo the resultant plume velocity would be similar.
- For the smoke grenade tests, temperature measurements at the vent and 3 ft external to the cube indicated that the plume rose very rapidly thus contributing to the reduction of the accumulation of smoke in the immediate area, thereby diminishing the inhalation related hazards to personnel at the site.

7.3.1.2 Propellants

- For each of the tests performed with the IMR-5010 propellant, the temperatures inside the cube were much lower than those measured external to the cube.

- As the loading density increased, the temperature of the plume 3 ft away from the cube approached that measured at the door and eventually surpassed it. This phenomena indicates that as the loading density increases, the mass burning rate inside the cube reaches a steady state condition and unburned propellant is carried out in the plume. Burning of the unburned propellant then takes place outside of the cube.
- The critical loading density for the IMR-8208 propellant was reached during the tests. This is evidenced by the fact that two external rake temperatures never converged during the tests.

7.3.1.3 ALA-17 Flares

- The predictability of multiple simultaneous ignition of two and four ALA-17 flares had a lot to be desired. Limited data obtained indicates that a "factor-of-two" relation exists from the burning of one and two flares. This assumes that the delayed ignition of one of the flares in Test 11 resulted in the attainment of a steady state $\mathring{Q}$ equivalent to one-half of the $\mathring{Q}$ obtained for two flares.
- Problems associated with simultaneous ignition were also encountered with four flares. The $\mathring{Q}$ (peak of 9500 Btu/100 msec) generated from the apparent simultaneous ignition of four ALA-17 flares created sufficient pressure to fail the cubicle.
- The principal hazards associated with the flares are: the large resultant fireball and associated pressures and the propagation of secondary fires by the jetting of unrestrained flare sections.

7.3.2 Tests in the $1/10^{th}$ Scale Model Igloo

- At the higher loading densities in excess of 2 lb, unburned propellant is carried out of the igloo in the plume and is consumed external to the igloo.
- The thermal characteristics of the fire inside the igloo were such that the ignition of a donor canister of propellant did not result in the ignition of adjacent acceptor canisters. The radiant energy associated with the plume inside the igloo was not sufficient to ignite the cardboard canisters of the acceptors. In many cases the donor canister itself survived without major damage.
- The principal hazard resulting from a propellant fire in a containment structure is the severe fireball, i.e., plume that exits the door. The potential exists for secondary ignition of materials in the immediate site of the containment structure.
- The hazards posed by firebrands was found to be propellant dependent, i.e., firebrands were observed with the M1 propellant but not with the IMR-8208 or IMR-5010.

8.0 Recommendations

The following recommendations are based on the results of this study.

The use of reduced-scale calorimeters can provide valuable information on the burning characteristics of combustible ammunition. It is recommended that the larger scale testing of these materials should include the use of calorimetry for data gathering and interpretation.

The shipping container will influence the burning rate of the propellant. Based on $\dot{Q}$ for IMR-5010, the burning rate of loose propellant in a tray appears to reach a steady rate of about 2.2 lb per second. Whereas, the burning rate of the propellant in scaled cannisters appears to reach a value of about 0.75 lb per second. It is recommended that effects of cannister design on burning rate, flame height and spread rate should be evaluated in a calorimeter.

The shipping container for the flares can influence the potential jetting of ignited flares. It is recommended that container designs be evaluated to eliminate the restrain the flares from jetting following accidental ignition.

Calculations indicate that the Marinite panels will fail in bending when exposed to pressures exceeding 0.02 psi. Since the simultaneous ignition of four ALA-17 flares very obviously exceeded this pressure, a more substantial test enclosure should be utilized to conduct tests at the higher loading densities.

The dimensional characteristics of some of the finished munitions preclude testing in their standard storage configuration in a small-scale enclosure. It is recommended that the size of the test calorimeter be selected as to allow for testing of these munitions.

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APPENDIX A

MARINITE CUBICLE TEST DESCRIPTIONS

A.1 SMOKE GRENADES

A.1.1 Test 6--One-Half Box of Smoke Grenades (Eight Grenades)

This test consisted of simultaneously igniting eight smoke grenades and recording the temperatures in the cube walls, temperature of the plume, plume velocity and temperatures of the plume 3 ft away from the cube door. Figure A-1 presents temperature profiles for 10 of the 14 thermocouples. Equipment problems resulted in the loss of Thermocouple Channels 2, 3, 11 and 12. The maximum temperature seen inside the cube was 185°F at Location 5 which is the cube roof. The maximum plume temperature recorded was 360°F as recorded by Thermocouple 6 which is at the top of the door. All of the temperatures recorded by the thermocouples were relatively low in comparison to those recorded in the propellant tests. The fact that the grenades burned for approximately 2 min as compared to approximately 5 sec for the propellant accounts for the slow rise in temperature in the grenade tests.

The four Keil probes mounted outside of the cube did not measure any considerable pressure during the burning of the grenades. However, a very slight pressure (0.05 in. of water) was measured simultaneously by all four probes at a time of 3 min 17 sec after ignition which is considerably past the burn time of the grenades. This same pressure was again recorded at 4 min 8 sec after ignition and it appears that this flow is being created by the cooling of the hot gases inside the cube.

A.1.2 Test 10--One Box of Smoke Grenades

This test consisted of simultaneously initiating an entire box of smoke grenades and then recording temperatures and plume velocities. Figure A-2 presents temperature profiles for the 14 thermocouple channels. The highest wall temperature recorded was that of Thermocouple Location 5 and is equal to 283.7°F. The highest plume temperature recorded was 742.5°F at Thermocouple 6 which is at the top of the door. Thermocouples 8, 10 and 11 recorded relatively high temperatures, i.e., approximately 345°F for Thermocouples 8 and 10 and 150°F for Thermocouple 11, shortly after ignition of the grenades. This initial temperature spike is believed to be caused by the first fire mix which spews out rather violently for several seconds after ignition of the grenades. Preliminary tests of grenades out in the open showed that the burning first fire mix is launched several feet away from the burning grenade. The fact that Thermocouples 8, 10 and 11 are all located in the lower 2 ft of the cube bears out this supposition. A review of the data for the thermocouples mounted at the door showed that the plume was affecting the top five thermocouples significantly. The plume, however, rises very rapidly as verified by the fact that the thermocouple array mounted 3 ft away from the cube registered a very small temperature rise.

TEST NUMBER 06

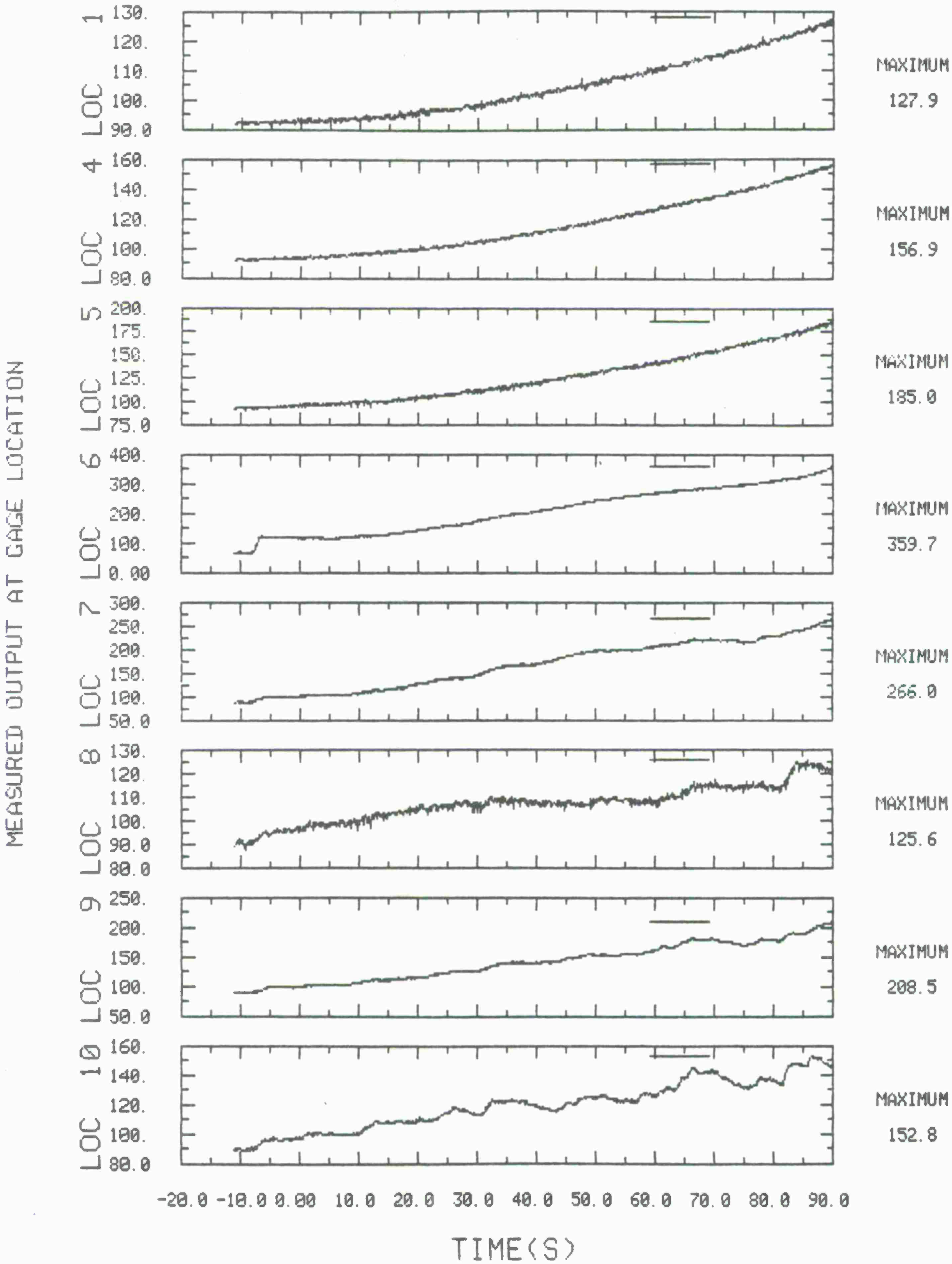
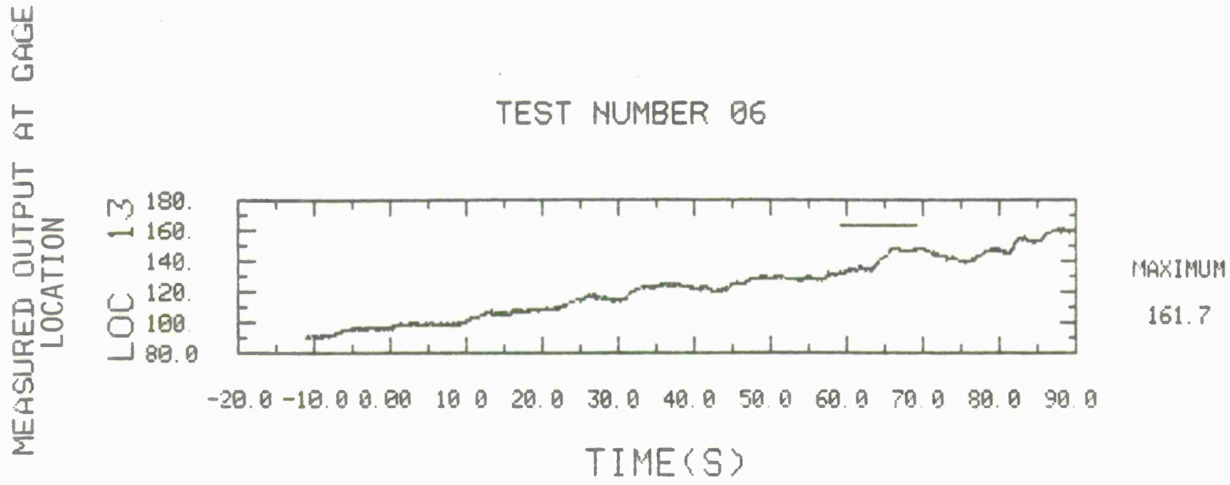


Figure A-1.



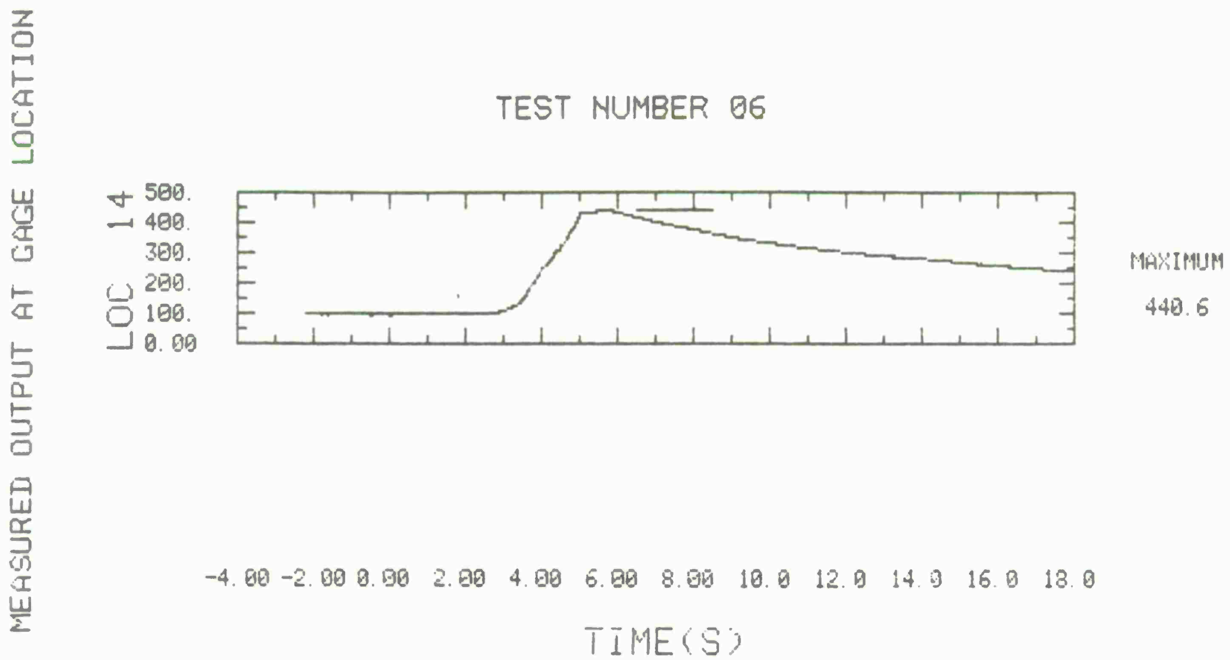


Figure A-1. (Continued)

TEST NUMBER 10

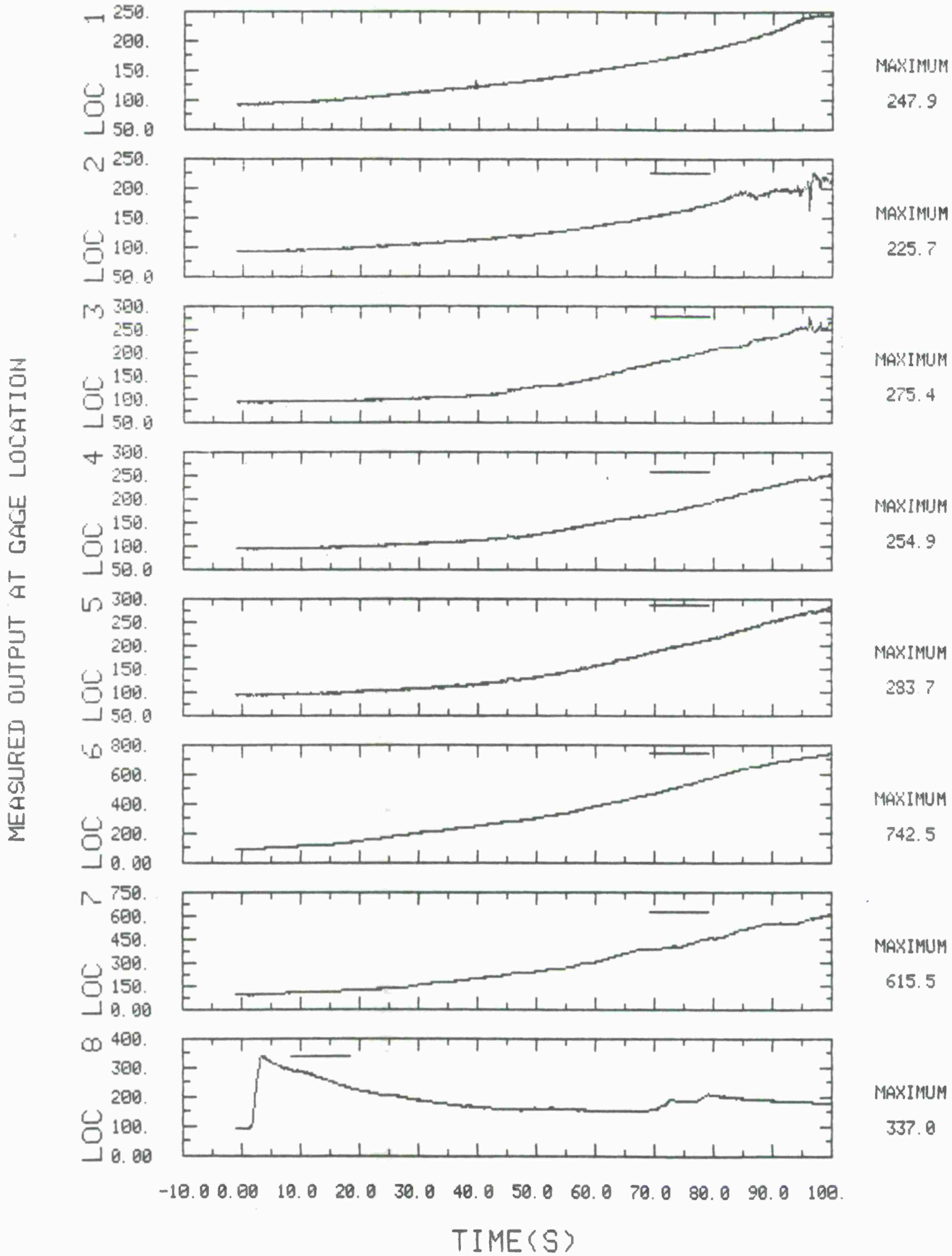


Figure A-2.

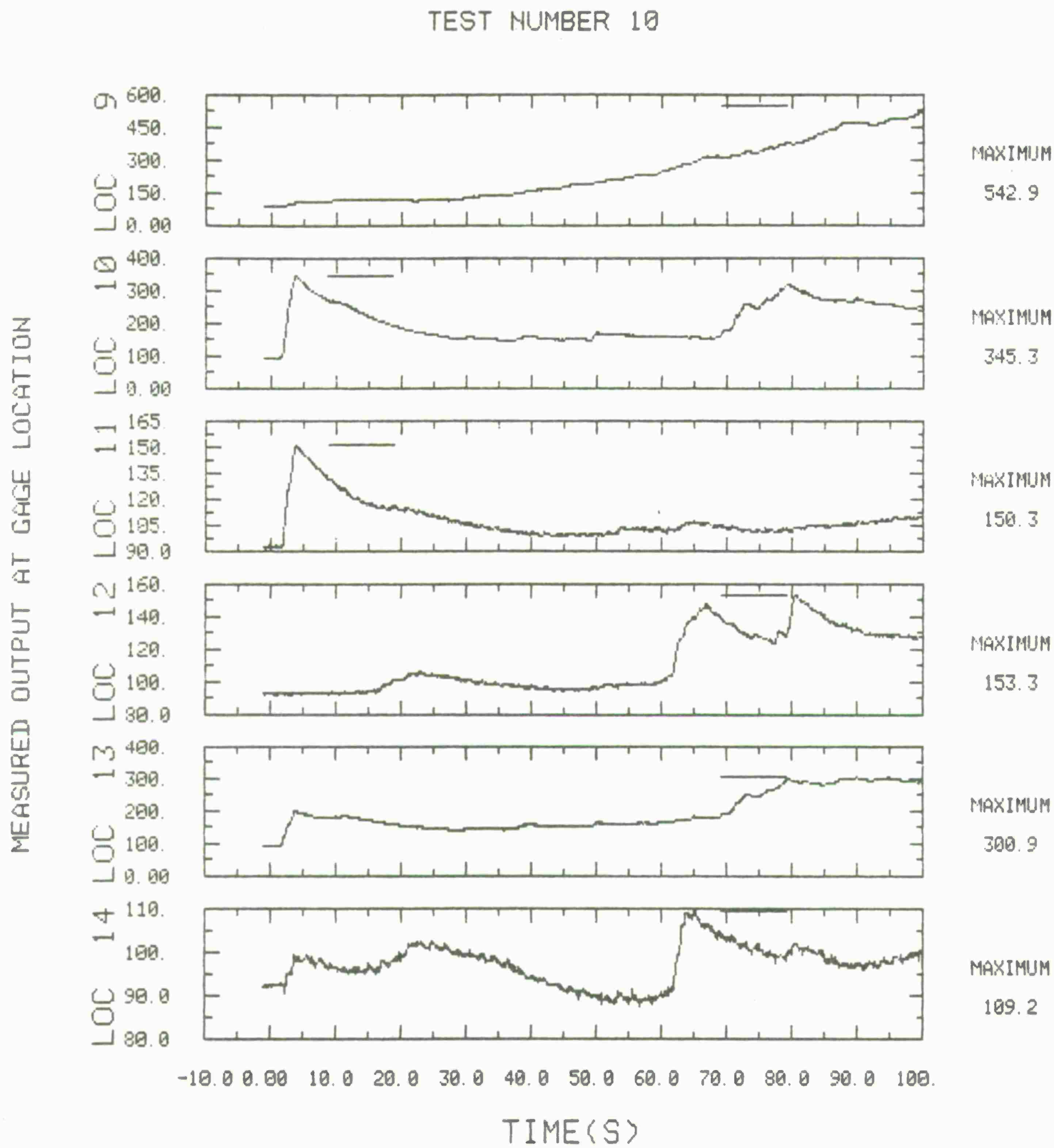


Figure A-2. (Continued)

A.2 PROPELLANTS

A.2.1 IMR-5010

A.2.1.1 Test 5--5 Pounds of IMR-5010

This test consisted of burning 5 lb of IMR-5010 propellant in a small tray and recording the wall temperatures, plume temperature and plume velocity. The propellant was ignited using electric matches and burned for approximately 6 sec. Figure A-3 presents the temperature profiles for the 14 thermocouple channels plotted as a function of time (Location 1 corresponds to Channel 1, etc.). The peak temperature has been identified on the right-hand side of each of the traces. The highest wall temperature recorded was 230.2°F and corresponded to the average temperature of the roof (Location 5). The maximum plume temperature recorded was 924.3°F by the thermocouple positioned just outside the door and the top (Location 6). By comparing the outside thermocouple reading, a profile of the width of the plume can be estimated. Figure A-3 shows that the thermocouples mounted outside of the door measured peak temperatures of 924.3°F (Location 6), 639.3°F (Location 7), 483.3°F (Location 9), 356.6°F (Location 13), 439.6°F (Location 10), and 166.3°F (Location 8). These temperature data indicate that the plume is directly affecting a zone 30 in. wide. The plume however turns upward within the first 2 ft indicated by the very low temperature recorded by the thermocouple array located 3 ft from the cube.

Plume velocities were calculated using the Keil probe data. The Keil probes measured a pressure in inches of water which can be converted to a velocity using the following equation:

$$V = 18.3 \frac{P(\text{inches of } H_2O)}{\rho}$$

where P - probe pressure in inches of water

ρ - gas density adjusted to the gas temperature at the probe ($\rho = 39.7/T° + 460°$). The density is calculated on the basis that the ambient pressure is standard and that the gas constant used is that for air.

Keil Probe 1 registered a maximum pressure of 0.22 in. of water at a time of 3.7 sec after ignition. The thermocouple at Keil Probe 1 (Thermocouple 6) registered a temperature of 310°F at this time. Solving the aforementioned equation, the plume velocity at Keil Probe 1 is 37.8 ft/sec. Keil Probe 2 (Thermocouple 7) registered a maximum presure of 0.19 in. of water at a temperature of 240°F which converts to a velocity of 33.5 ft/sec. Probe 3 was facing away from the cube and measured air intake. It registered a maximum pressure of 0.075 in. of water at 5.8 sec after ignition with a gas temperature of 440°F measured by Thermocouple 10. This

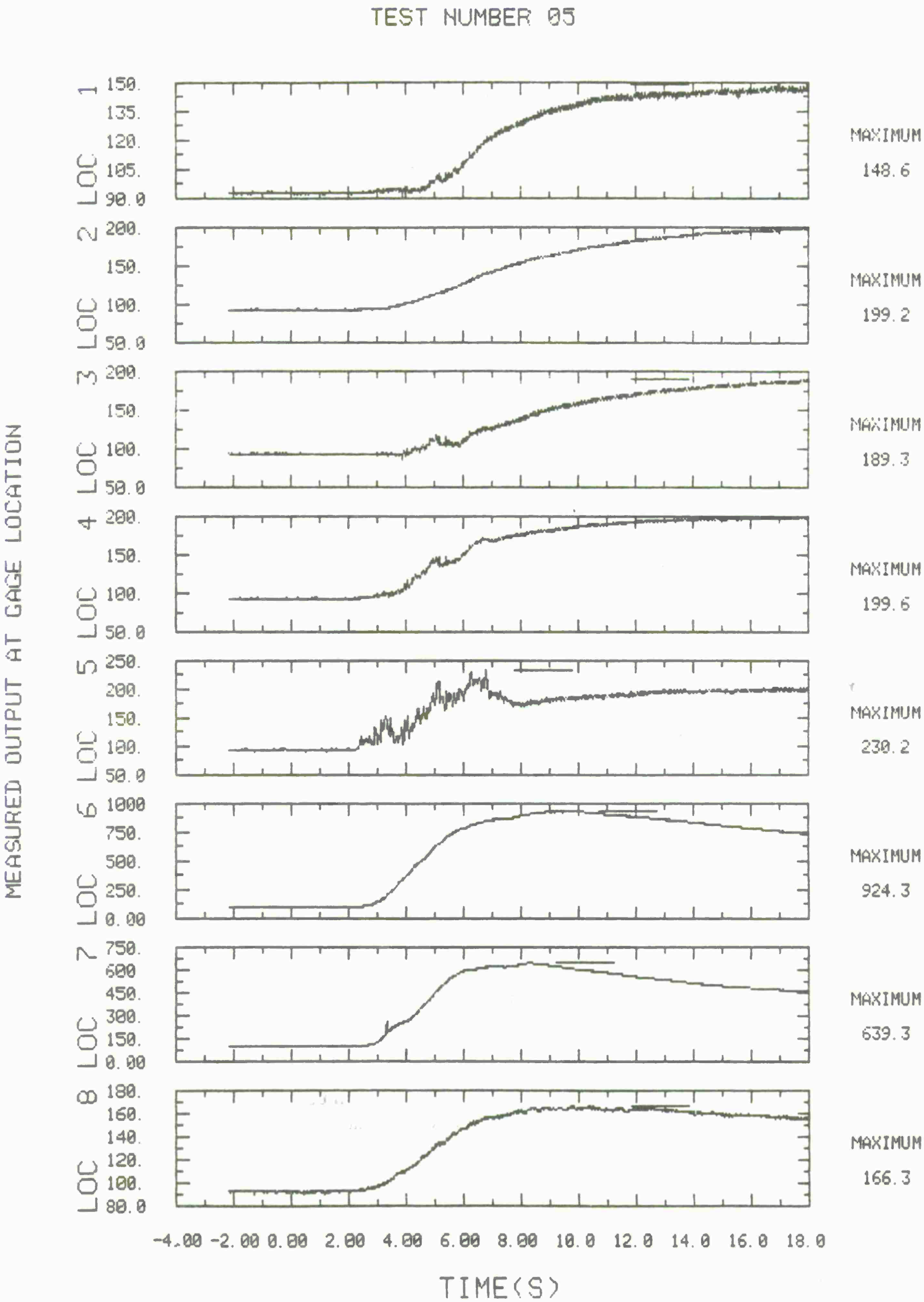

TEST NUMBER 05
MEASURED OUTPUT AT GAGE LOCATION
LOC 1
LOC 2
LOC 3
LOC 4
LOC 5
LOC 6
LOC 7
LOC 8
MAXIMUM 148.6
MAXIMUM 199.2
MAXIMUM 189.3
MAXIMUM 199.6
MAXIMUM 230.2
MAXIMUM 924.3
MAXIMUM 639.3
MAXIMUM 166.3
TIME(S)

Figure A-3.

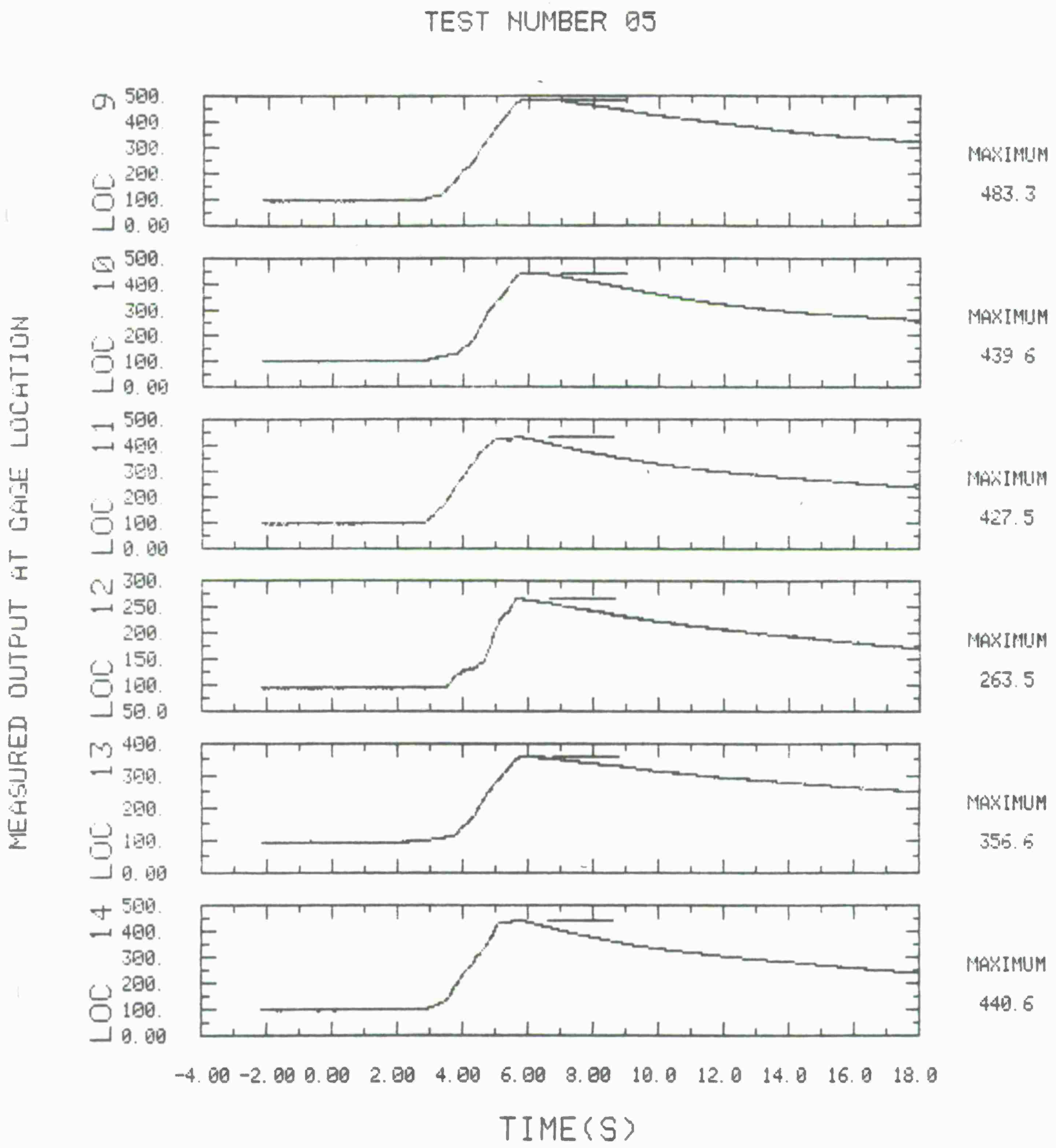


Figure A-3. (Continued)

pressure converts to an air intake velocity of 12.3 ft/sec. The bottom probe (Probe 4) measured a maximum of 143°F measured by Thermocouple 8. The resultant air velocity calculated was 16.7 ft/sec.

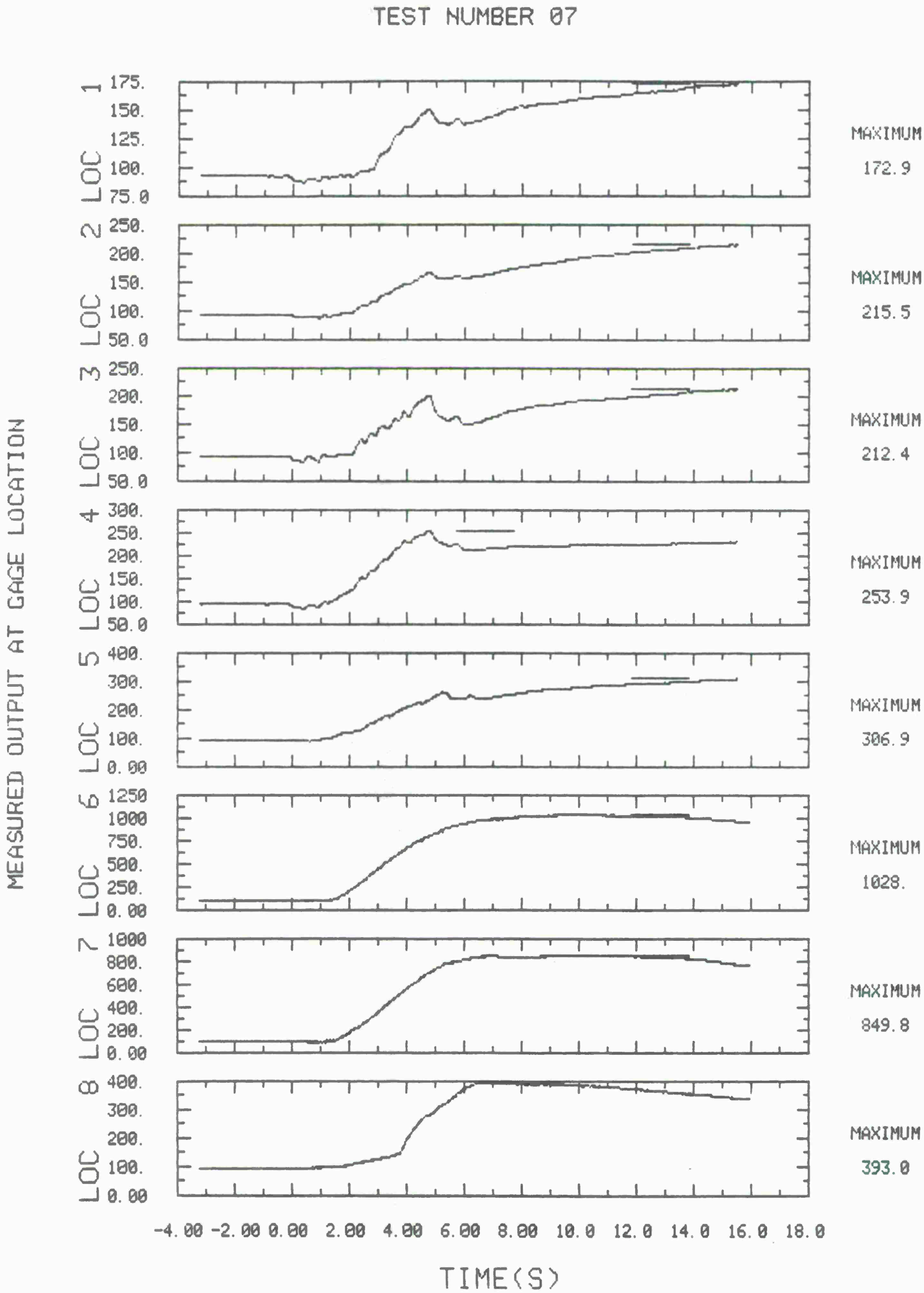
A.2.1.2 Test 7--10 Pounds of IMR-5010

Test 7 was a burn of 10 lb of IMR-5010 propellant placed in a large tray. The depth of the propellant in this test was 1-5/8 in. which was the same depth used in the 5-lb test. The propellant was ignited at the bottom center using two electric matches. Temperatures and plume velocity were recorded. Figure A-4 presents the temperature differential profiles for the 14 thermocouple locations. The highest wall temperature recorded (Locations 1 through 5) was 306.9°F above ambient at Location 5 which corresponds to the cubic roof. The maximum plume temperature recorded at any one of the six thermocouple locations (Locations 6, 7, 8, 9, 10 and 13) was 1028°F. As can be seen in Figure A-4, all of the thermocouples located at the door recorded high temperatures and the lowest temperature recorded was 393°F at Location 8 which is almost at the bottom of the door. In addition, the thermocouple array located 3 ft away from the door (Locations 11, 12 and 14) showed very high temperatures indicating that the plume was as wide as the doorway and was exiting the cube normal to the front wall at a relatively high velocity. Unlike the 5-lb test where the plume curves upward prior to reaching the thermocouple array located 3 ft away, the plume in this last test remains horizontal past the 3-ft mark as evidenced by the very high temperatures recorded by Thermocouples 11, 12 and 14.

The two Keil probes at the top of the doorway which were directly in the plume showed maximum pressures of 0.24 in. of water (Keil Probe 1) and 0.23 in. of water (Keil Probe 2). These pressures occurred 4.6 sec after ignition and the corresponding gas temperature for Probe 1 (Thermocouple 6) was 960°F and for Probe 2 (Thermocouple 7) 860°F. These two pressures convert to plume velocities of 53.6 ft/sec and 50.6 ft/sec for Keil Probes 1 and 2, respectively. Probe 3 showed a maximum air intake pressure of 0.05 in. of water at a time of 7.4 sec after ignition. The gas temperature measured at Thermocouple 10 was 760°F and the calculated air velocity is 22.6 ft/sec. Similarly for Keil Probe 4, the maximum pressure was 0.33 in. of water at 7.4 sec at a temperature of 380°F and the resultant velocity is 48.4 ft/sec. The high air intake velocity at Keil Probe 4 and also at Probe 3 indicates that a very substantial draw is being created once the propellant has finished burning and thereby creating gas. It appears from reviewing both the thermocouple and Keil probe data that while the propellant is actively burning, gases are being produced at a high enough rate that the combustion products are being vented out through the entire door. Once the propellant has been consumed, the quantity of gas is drastically reduced and the cube begins to draw in outside air.

A.2.1.3 Test 8--5 Pounds of IMR-5010

This test used 5 lb spread out in a pan twice as large as that used before. The purpose of the larger pan was to increase the propellant



TEST NUMBER 07
MEASURED OUTPUT AT GAGE LOCATION
LOC 1
175.
150.
125.
100.
75.0
MAXIMUM
172.9
LOC 2
250.
200.
150.
100.
50.0
MAXIMUM
215.5
LOC 3
250.
200.
150.
100.
50.0
MAXIMUM
212.4
LOC 4
300.
250.
200.
150.
100.
50.0
MAXIMUM
253.9
LOC 5
400.
300.
200.
100.
0.00
MAXIMUM
306.9
LOC 6
1250
1000
750.
500.
250.
0.00
MAXIMUM
1028.
LOC 7
1000
800.
600.
400.
200.
0.00
MAXIMUM
849.8
LOC 8
400.
300.
200.
100.
0.00
MAXIMUM
393.0
-4.00 -2.00 0.00 2.00 4.00 6.00 8.00 10.0 12.0 14.0 16.0 18.0
TIME(S)

Figure A-4.

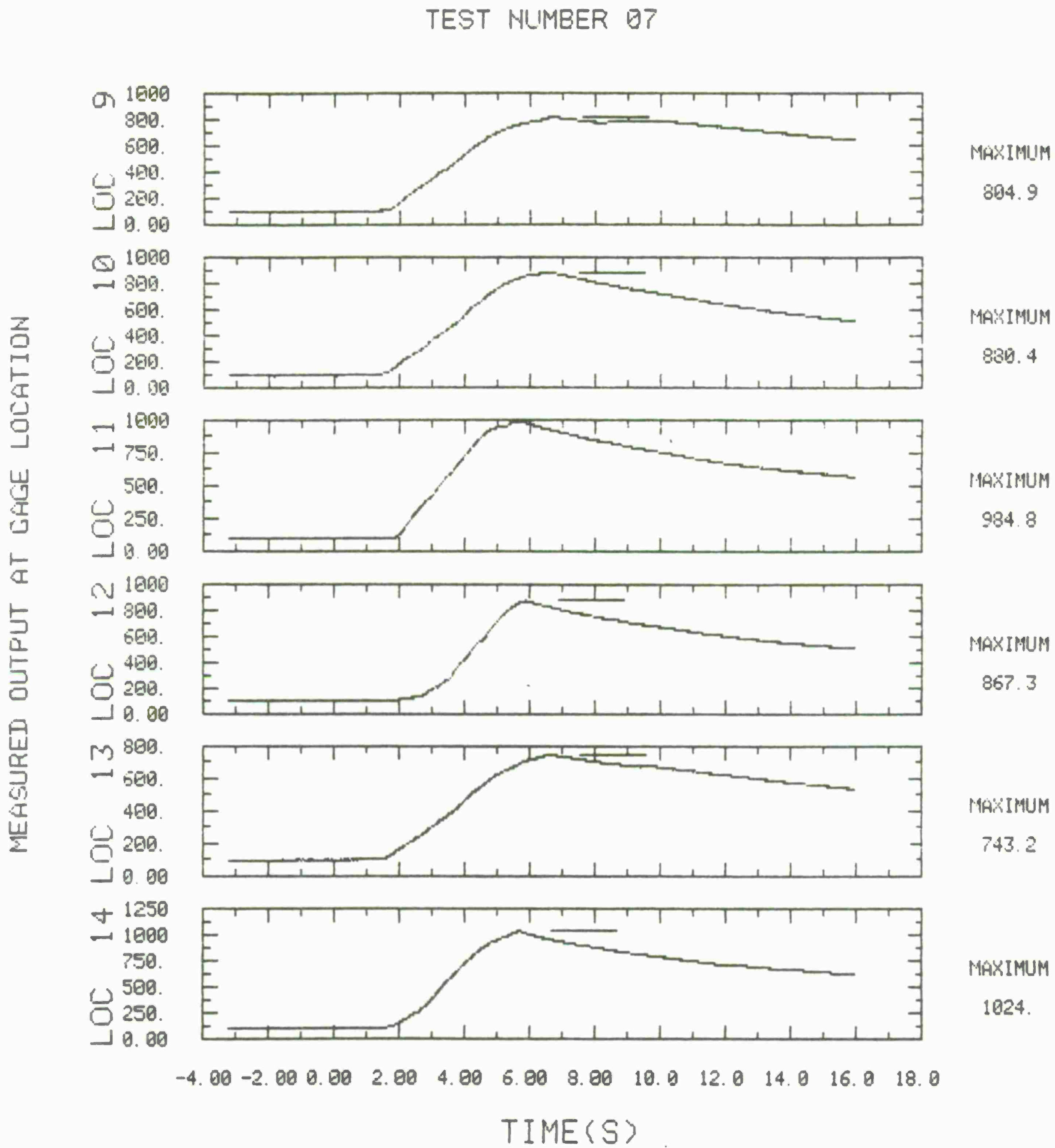


Figure A-4. (Continued)

burn duration time. The depth of the propellant was approximately 3/4 in. Figure A-5 presents the temperature profiles for the 14 thermocouple channels. The highest wall temperature recorded was 268.1°F at Location 5 which is the roof. The maximum plume temperature recorded by the six thermocouples located at the door was 890.6°F by Thermocouple 6. The lowest temperature recorded at the doorway was 195.3°F recorded by Thermocouple 8 located near the bottom of the door. Thermocouples 11 and 14 located outside of the cube approximately 3 ft away recorded maximum temperature differentials of 625.9°F and 611.2°F, respectively. The top thermocouple in that array, Thermocouple 12, saw a considerably lower temperature differential of 366.0°F. This would imply that as was the case in Test 7, the plume exited the door in a fairly flat trajectory and with enough velocity to easily reach the thermocouples 3 ft away. The fact that Thermocouple 12 which is at the top of the array registered a high temperature but not nearly as high as the bottom two thermocouples indicates that the plume was dispersing but had not curved upward yet.

The Keil probe at the top of the door, Probe 1, registered a maximum plume pressure of 0.17 in. of water approximately 4.8 sec after ignition. Temperature of the gas at the probe was measured at 360°F. The values correspond to a plume velocity of 34.3 ft/sec. Keil Probe 2 measured a maximum pressure of 0.15 in. of water at a time of 4.8 sec after ignition and at a corresponding temperature of 330°F. The plume velocity at Probe 2 was calculated to be 31.6 ft/sec. Keil Probe 3 measured a maximum plume pressure of 0.03 in. of water approximately 7.2 sec after ignition and at a gas temperature of 550°F. The calculated velocity of the air intake at Keil Probe 3 is 15.9 ft/sec. Probe 4 saw a maximum plume pressure of 0.01 in. of water at 7.2 sec after ignition and at a gas temperature of 185°F. This calculates to an air velocity of 7.4 ft/sec.

A.2.1.4 Tests 12 and 13--7.5 Pounds and 12.5 Pounds of IMR-5010

These two tests were performed using the IMR-5010 propellant. The purpose of these tests was to provide additional data for the regression analysis. Test 12 involved 7.5 lb of IMR-5010 propellant placed in the large tray. The highest plume temperature recorded was 905°F at Location 6 which is the top of the door. The highest plume temperature recorded on Test 13 which involved 12.5 lb of IMR-5010 was 1032°F also at Location 6. The roof temperatures for both tests were lost due to instrumentation problems; therefore, these tests could not be used in the regression analysis.

A.2.1.5 Test 14--12.5 Pounds of IMR-5010

Test 14 was a repeat of Test 13. The 12.5 lb of propellant was placed in a tray (18-1/2 in. x 10-3/4 in.) and initiated at the bottom center of the tray using two electric matches. Figure A-6 presents the temperature profiles for Thermocouple Locations 5 through 14. Since the temperatures recorded in the cube walls, i.e., Thermocouple Locations 1 through 4, were relatively low (150 to 200°F) in comparison to the roof

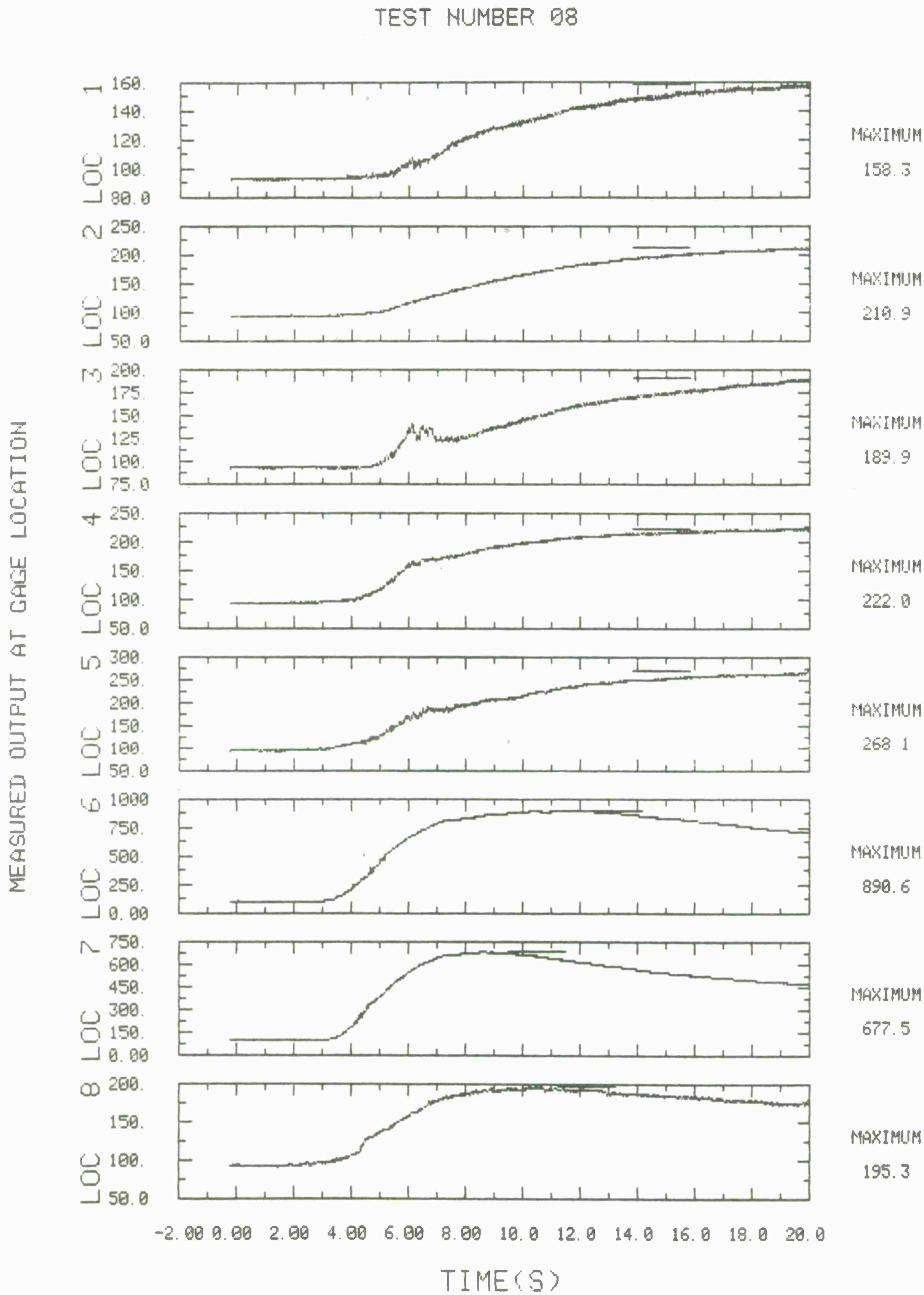

TEST NUMBER 08
MEASURED OUTPUT AT GAGE LOCATION
LOC 1
160.
140.
120.
100.
80.0
MAXIMUM
158.3
LOC 2
250.
200.
150.
100.
50.0
MAXIMUM
210.9
LOC 3
200.
175.
150.
125.
100.
75.0
MAXIMUM
189.9
LOC 4
250.
200.
150.
100.
50.0
MAXIMUM
222.0
LOC 5
300.
250.
200.
150.
100.
50.0
MAXIMUM
268.1
LOC 6
1000
750.
500.
250.
0.00
MAXIMUM
890.6
LOC 7
750.
600.
450.
300.
150.
0.00
MAXIMUM
677.5
LOC 8
200.
150.
100.
50.0
MAXIMUM
195.3
-2.00 0.00 2.00 4.00 6.00 8.00 10.0 12.0 14.0 16.0 18.0 20.0
TIME(S)

Figure A-5.

TEST NUMBER 08

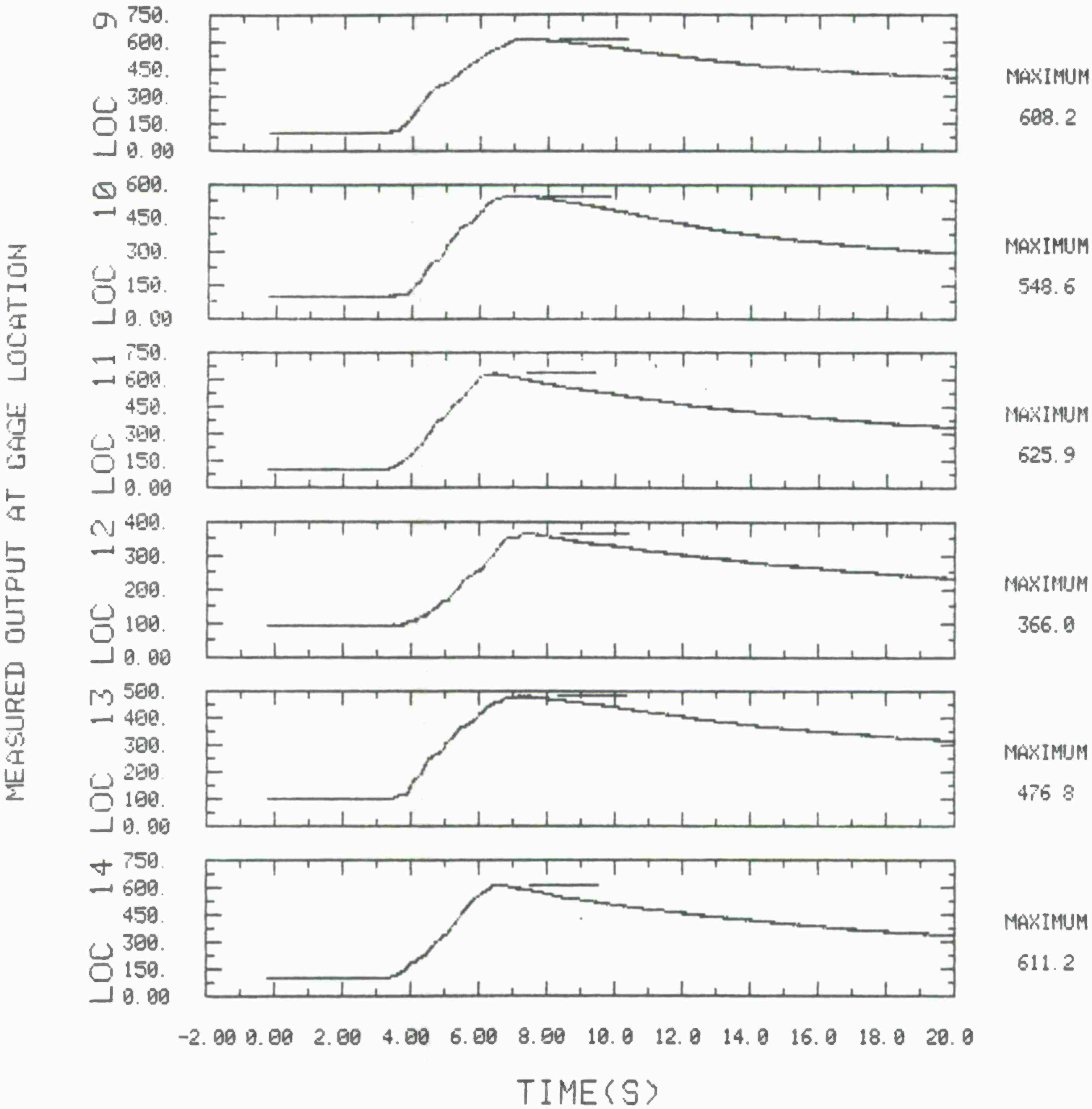
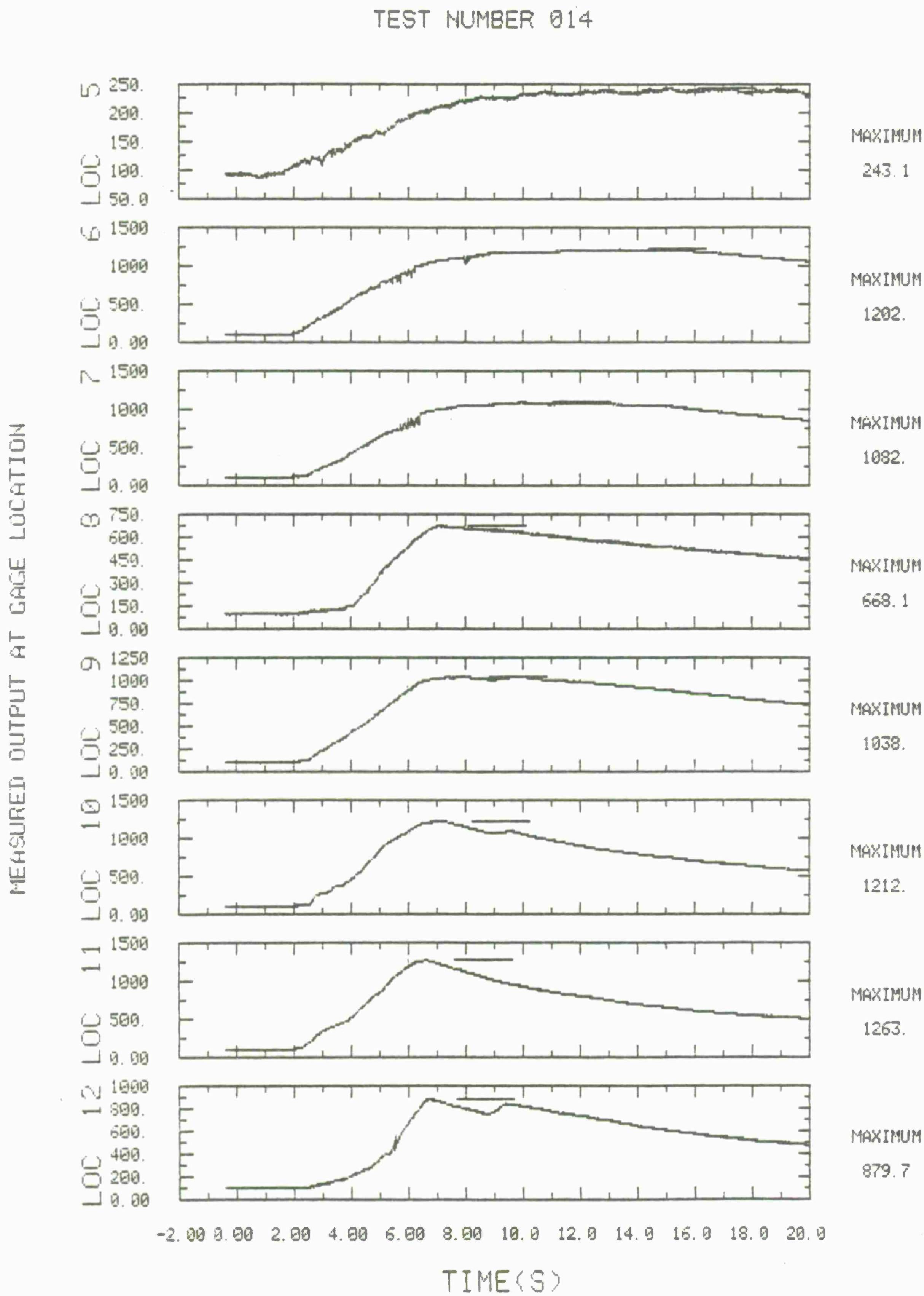


Figure A-5. (Continued)



TEST NUMBER 014
MEASURED OUTPUT AT GAGE LOCATION
LOC 5
250.
200.
150.
100.
50.0
MAXIMUM
243.1
LOC 6
1500
1000
500.
0.00
MAXIMUM
1202.
LOC 7
1500
1000
500.
0.00
MAXIMUM
1082.
LOC 8
750.
600.
450.
300.
150.
0.00
MAXIMUM
668.1
LOC 9
1250
1000
750.
500.
250.
0.00
MAXIMUM
1038.
LOC 10
1500
1000
500.
0.00
MAXIMUM
1212.
LOC 11
1500
1000
500.
0.00
MAXIMUM
1263.
LOC 12
1000
800.
600.
400.
200.
0.00
MAXIMUM
879.7
-2.00 0.00 2.00 4.00 6.00 8.00 10.0 12.0 14.0 16.0 18.0 20.0
TIME(S)

Figure A-6.

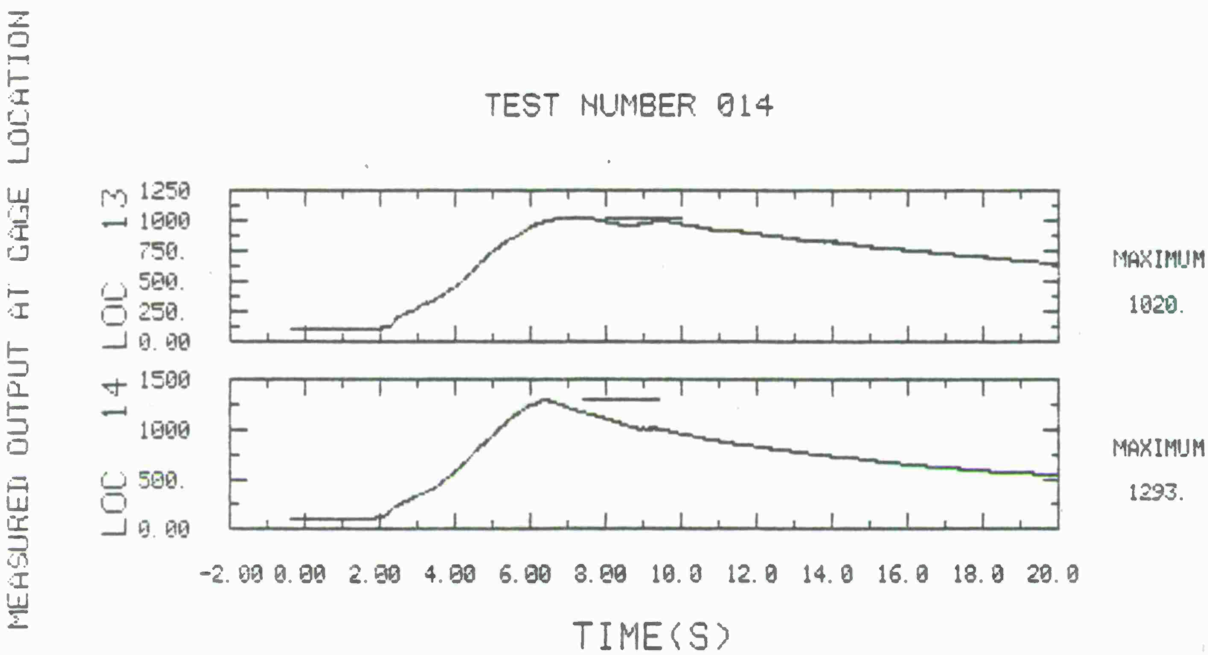


Figure A-6 (Continued)

temperature (243°F) and the plume temperatures (668 to 1202°F) and would have a negligible effect on the regression analysis, the outputs of Channels 1 through 4 were disregarded and are not included in Figure A-6. As previously mentioned, the plume temperatures at the doorway ranged from 1202°F at the top of the door down to 668°F at the bottom of the door. The plume temperatures at the thermocouple rake mounted 3 ft away were even hotter than at the top of the door. Thermocouple 11 which is at the bottom of the rake measured a temperature of 1263°F, while Thermocouple 14 midway up the rake measured a temperature of 1293°F. The fact that the plume temperatures are hotter 3 ft away from the cube implies that active combustion is taking place in the plume itself outside of the cube. This activity might prove useful for the understanding/prediction of firebrand emissions from the cube or from a storage facility.

The Keil probe at the top of the door, Location 1, measured a maximum plume pressure of 0.2 in. of water at a time approximately 5.0 sec after ignition and a gas temperature of 750°F. This plume pressure can be converted to a plume velocity of 45.1 ft/sec. Keil Probe 2 showed a maximum plume pressure of 0.18 in. of water also at approximately 5 sec and at a gas temperature of 600°F. This plume pressure converts to a plume velocity of 40.4 ft/sec. Probe 3 saw an air intake pressure of 0.055 in. of water at 6.6 sec after ignition and at an air temperature of approximately 1200°F. This air intake pressure converts to a velocity of approximately 27.7 ft/sec. Probe 4 measured a plume pressure of 0.04 in. of water, 7 sec after ignition and at a temperatue of 670°F. This pressure converts to a velocity of 19.6 ft/sec.

A.2.1.6 <u>Test 15--7.5 Pounds of IMR-5010</u>

This test was a repeat of Test 12 and involved 7.5 lb of propellant in a large tray (18-1/2 in. x 10-3/4 in.). The propellant was ignited at the bottom center of the tray using two electric matches. Cube wall temperatures and plume temperatures were recorded. Figure A-7 presents temperature-time histories for Thermocouple Channels 5 through 14. Channels 1 through 4 were again disregarded due to their relatively low temperatures and minimal effect on the regression analysis. The maximum temperature measured at the roof of the cube was 241°F (Thermocouple 5). The plume temperature ranged from 338°F at the bottom of the door at Thermocouple 8 to 1067°F at the top of the door, Thermocouple 6. The plume temperature 3 ft away from the door was also relatively high with the middle thermocouple on the rake, Thermocouple 14, registering a temperature of 650°F, while the two edge thermocouples, 11 and 12, registered temperatures of 577°F and 513°F, respectively. These high temperatures indicate that the plume had sufficient velocity to reach the rake 3 ft away in a fairly flat configuration. The plume did not start to rise until after it had passed the rake.

Plume velocity was calculated using the Keil probe data. The probe at the top of the door, Location 1, measured a maximum plume pressure of 0.17 in. of water at a time approximately 4.7 sec after ignition and

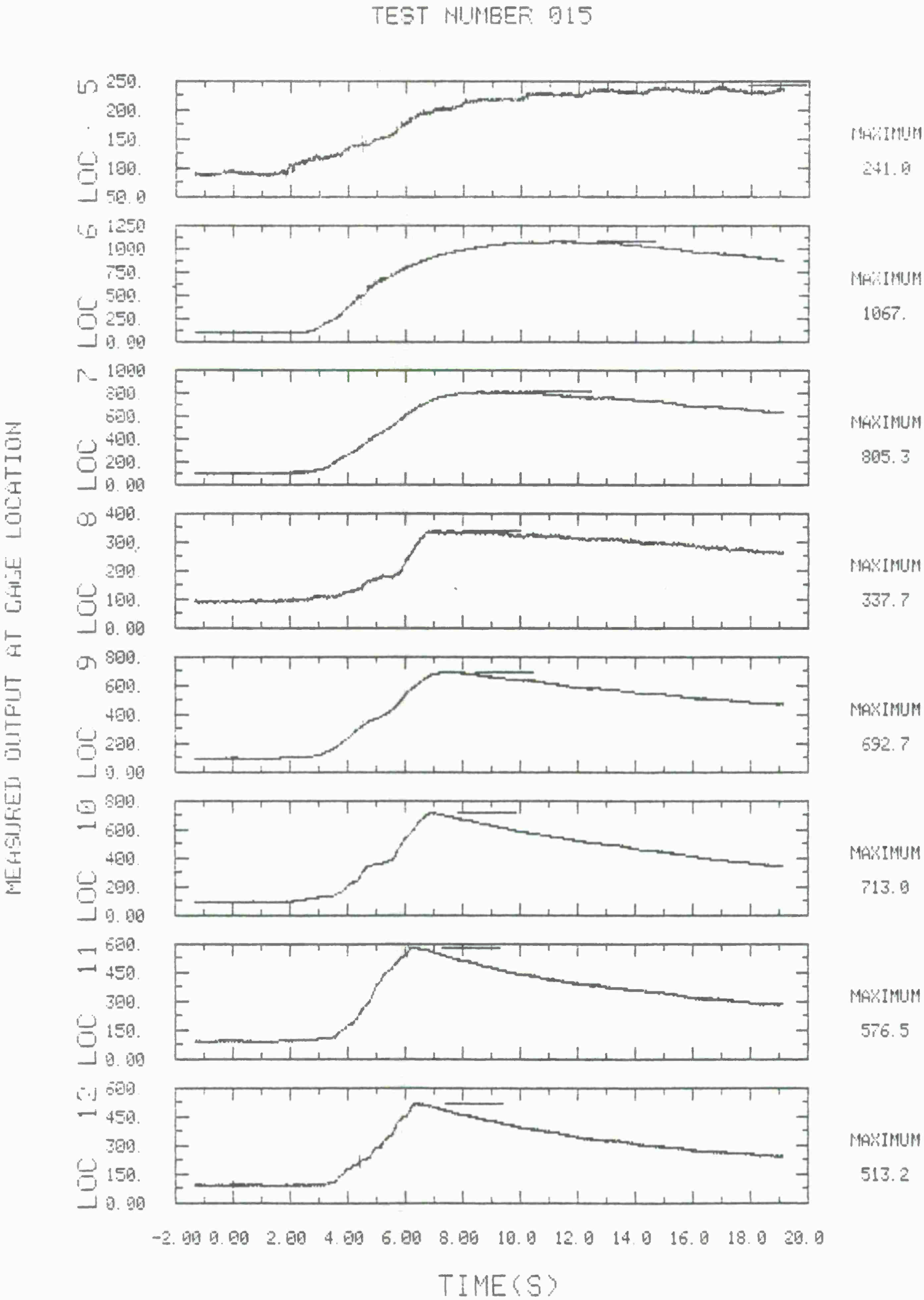

TEST NUMBER 015
MEASURED OUTPUT AT GAGE LOCATION
LOC 5
LOC 6
LOC 7
LOC 8
LOC 9
LOC 10
LOC 11
LOC 12
MAXIMUM
241.0
MAXIMUM
1067.
MAXIMUM
805.3
MAXIMUM
337.7
MAXIMUM
692.7
MAXIMUM
713.0
MAXIMUM
576.5
MAXIMUM
513.2
TIME(S)

Figure A-7.

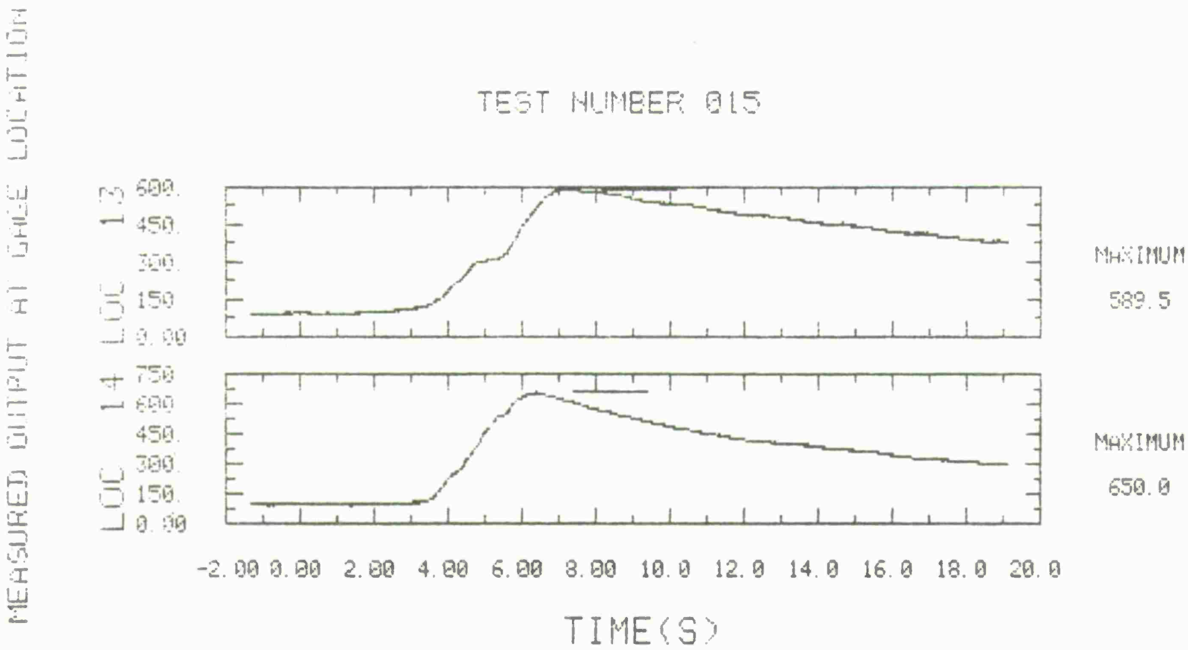


Figure A-7 (Continued)

with a gas temperature of 560°F. This pressure converts to a plume velocity of 38.2 ft/sec. Keil Probe 2 measured a maximum plume pressure of 0.16 in. of water at a time of 4.7 sec and with a gas temperature of 430°F. This pressure converts to a plume velocity equal to 34.5 ft/sec. Probe 3 measured a very low pressure which converts to a velocity of 10.6 ft/sec, and Probe 4 did not measure any appreciable pressure indicating that the cube did not ingest much outside air during the test. Thus, the plume was existing throughout the entire doorway, as shown by the high temperature recorded by the doorway thermocouples.

A.2.2 **IMR-8208**

A.2.2.1 Test 18--15 Pounds of IMR-8208

This test used 15 lb of the IMR-8208 propellant which was placed in the large (18-1/2 in. x 10-3/4 in.) tray and ignited at the bottom center using two electric matches. The tray of propellant was placed in the middle of the cube and ignited. Figure A-8 presents the temperature profiles for the 14 thermocouples. Once again, Channel 3 was lost; however, since it does not enter into the regression analysis its loss was minimal. The highest wall temperature measured occurred at the top of the cube (Thermocouple 5) and peaked at 593°F. The highest plume temperature as measured at the doorway occurred at the top of the door, Thermocouple 6, and was 1626°F. All of the other thermocouples mounted on the door registered high temperatures ranging from 1265°F at Thermocouple 7 down to 727°F at Thermocouple 8 which is at the bottom of the door. The thermocouple rake mounted outside of the cube also saw very high temperatures. Thermocouples 11 and 14, which are located at the bottom and at the center of the rake, saw temperatures of 1472°F and 1596°F, while Thermocouple 12, which is at the top of the rake, saw a temperature of only 988°F. These very high temperatures indicate that the plume had sufficient velocity to easily reach the rake in a flat position and indicated active burning within the plume after exiting the cube.

The plume velocity at the top of the door was calculated from the pressure measured by Keil Probe 1 which was 0.225 in. of water at 2.3 sec after ignition at a plume temperature of 450°F. These data convert to a plume velocity of 41.4 ft/sec. Probe 2 saw a pressure of 0.225 in. of water at 2.3 sec after ignition, but at a plume temperature of 350°F. These data convert to a velocity of 39.2 ft/sec. Probe 3 measured an air intake pressure of 0.06 in. of water at 5.7 sec after ignition (well into the burn) and at a temperature of 1450°F, which converts to an air intake velocity of 30.9 ft/sec. Keil Probe 4, however, did not measure any air intake. The fact that both Probes 1 and 2 measured basically the same velocity indicates the plume velocity itself is fairly uniform.

A review of the video tape showed that the plume does in fact exit the doorway in a very flat orientation and does pass the rake before rising. No firebrands were observed during this test.

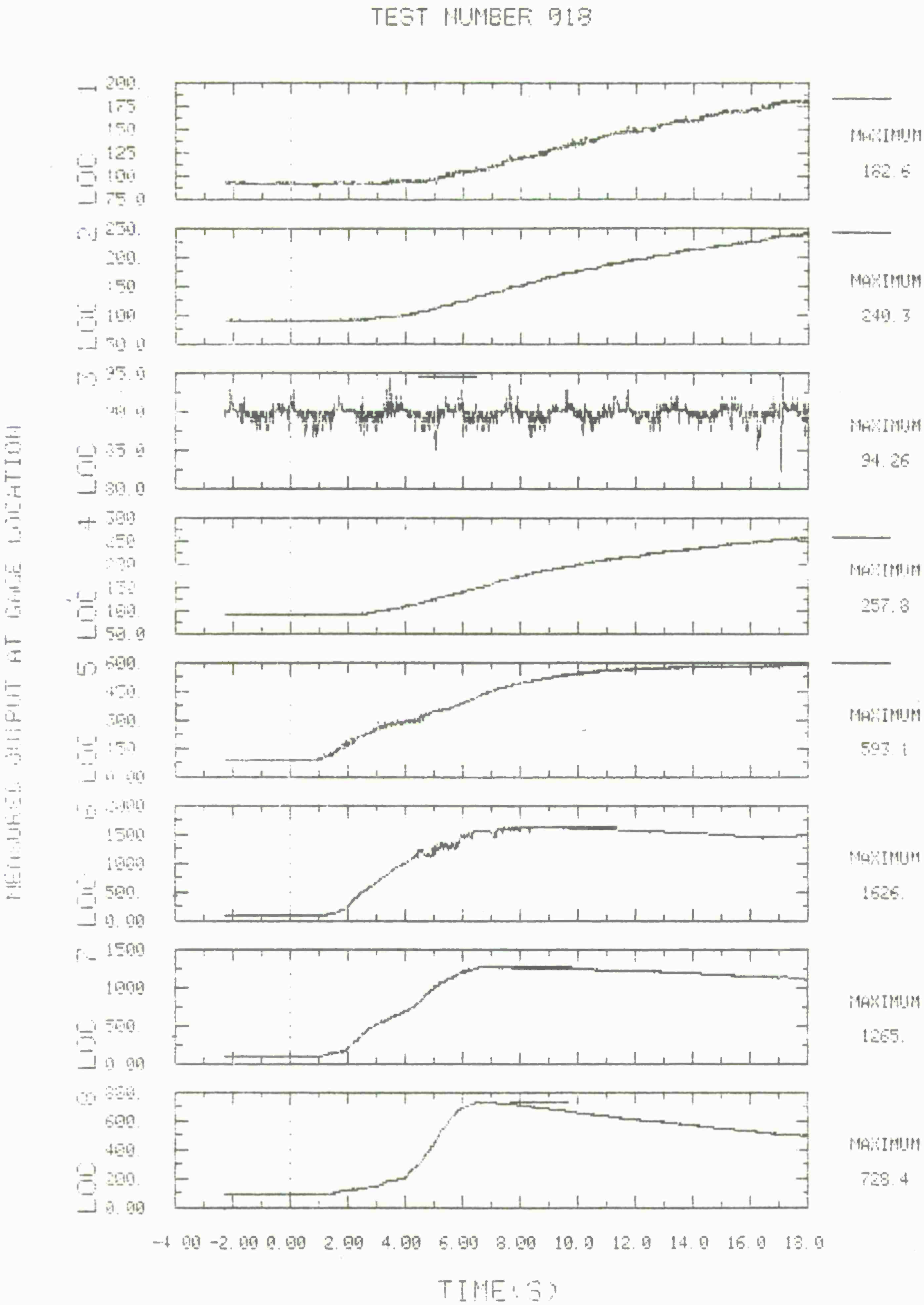

TEST NUMBER 018
MEASURED OUTPUT AT GAGE LOCATION
LOC 1
MAXIMUM
182.6
LOC 2
MAXIMUM
240.3
LOC 3
MAXIMUM
94.26
LOC 4
MAXIMUM
257.8
LOC 5
MAXIMUM
593.1
LOC 6
MAXIMUM
1626.
LOC 7
MAXIMUM
1265.
LOC 8
MAXIMUM
728.4
TIME(S)

Figure A-8.

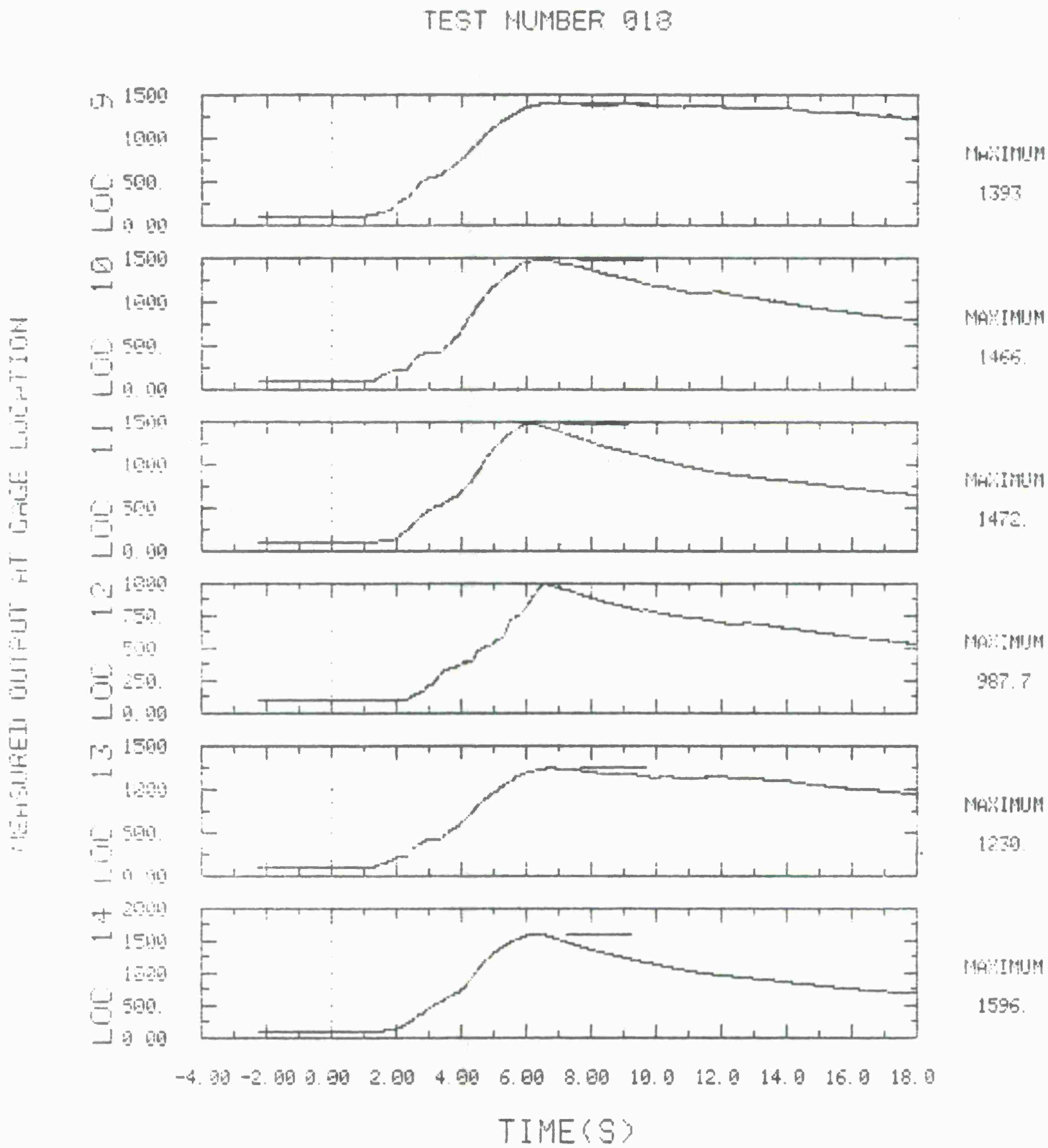


Figure A-8 (Continued)

A.2.2.2 Test 19--10 Pounds IMR-8208

Test 19 was performed using 10 lb of IMR-8208 in a large (18-1/2 in. x 10-3/4 in.) tray. The tray was placed in the cube and the propellant was ignited using two electric matches located at the bottom center of the tray. Figure A-9 presents temperature profiles for the thermocouples. As can be seen in Figure A-9, Thermocouples 3 and 5 developed problems and useful temperature profiles were not recorded. The maximum plume temperature recorded at the door was measured at Location 6 and was 1427°F. The temperature at the bottom of the door was 438°F. The temperatures at the thermocouple rake ranged from 644°F at the bottom of the rake to 448°F at the top of the rake (Thermocouples 11 and 12, respectively). The fact that the temperatures are higher at the bottom of the rake and at the center than at the top indicates that the plume had sufficient velocity to reach the rake in a fairly flat position and had not started to rise.

Velocities were calculated for the four Keil probes. Probe 1 measured a plume pressure of 0.25 in. of water, 7.3 sec after ignition and at a plume temperature of 1350°F. The resultant velocity was calculated to be 61.7 ft/sec. Probe 2 measured a pressure of 0.27 in. of water also at 7.3 sec after ignition and at a temperature of 1000°F. This velocity was calculated at 547.9 ft/sec. The two Keil probes used to measure air ingested into the cube, Probes 3 and 4, also saw significant air intake velocities. Probe 3 saw a pressure of 0.10 in. of water at 7.3 sec after ignition and at a temperature of 825°F. This pressure corresponds to a velocity of 32.9 ft/sec. Probe 4 saw a pressure of 0.065 in. of water also 7.3 sec after ignition and at a temperature of 380°F which converts to an air intake velocity of 21.5 ft/sec.

The video tape of this test showed that the plume did in fact reach the rake in a fairly flat position. As was the case in the previous test, no firebrands were observed.

A.2.2.3 Test 20--10 Pounds of IMR-8208

This test was a repeat of Test 19 since the data for Channel 5, i.e., the roof of the cube, was lost due to instrumentation problems and these data are necessary for the regression analysis. Once again, the 10 lb of propellant were placed in the large (18-1/2 in. x 10-3/4 in.) tray and ignited using two electric matches at the bottom center of the tray. Figure A-10 presents the temperature profiles for the thermocouples. The maximum roof temperature, 325°F, was recorded at Thermocouple 5. The maximum plume temperature as measured at the door was measured by Thermocouple 6 (top of door) and was 1173°F. All of the doorway temperatures were considerably high. On this particular test, Thermocouple 8, which is at the bottom of the door, measured a maximum temperature of 1093°F. The thermocouple rake mounted 3 ft away from the cube saw high temperatures especially in the middle and upper half. This would imply that the plumes reached the rake but had started to rise; therefore, the upper thermocouple saw higher temperatures than did the thermocouple at the bottom of the rake.

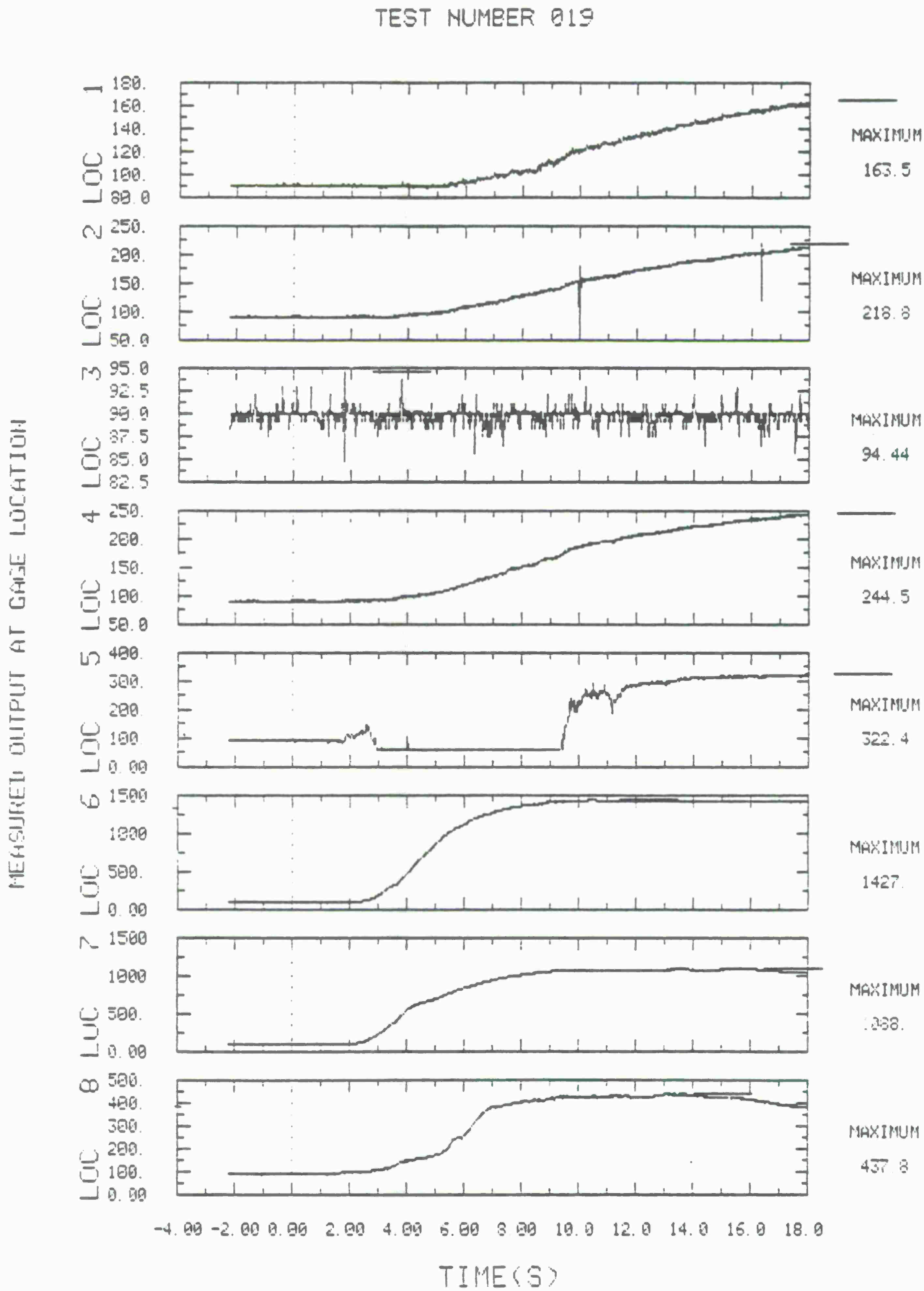

TEST NUMBER 019
MEASURED OUTPUT AT GAGE LOCATION
LOC 1
MAXIMUM
163.5
LOC 2
MAXIMUM
218.8
LOC 3
MAXIMUM
94.44
LOC 4
MAXIMUM
244.5
LOC 5
MAXIMUM
322.4
LOC 6
MAXIMUM
1427.
LOC 7
MAXIMUM
LOC 8
MAXIMUM
437.8
TIME(S)

Figure A-9.

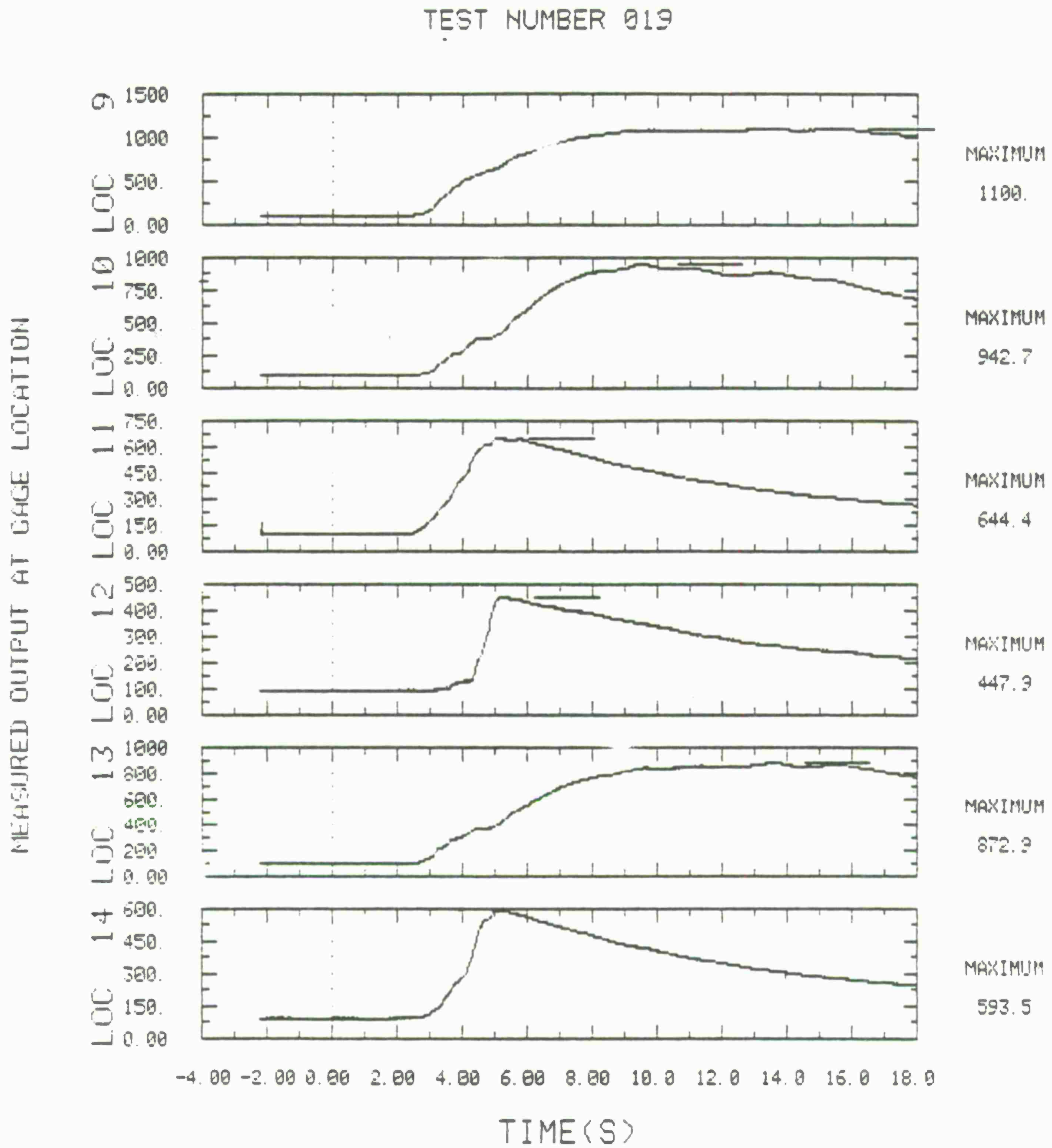
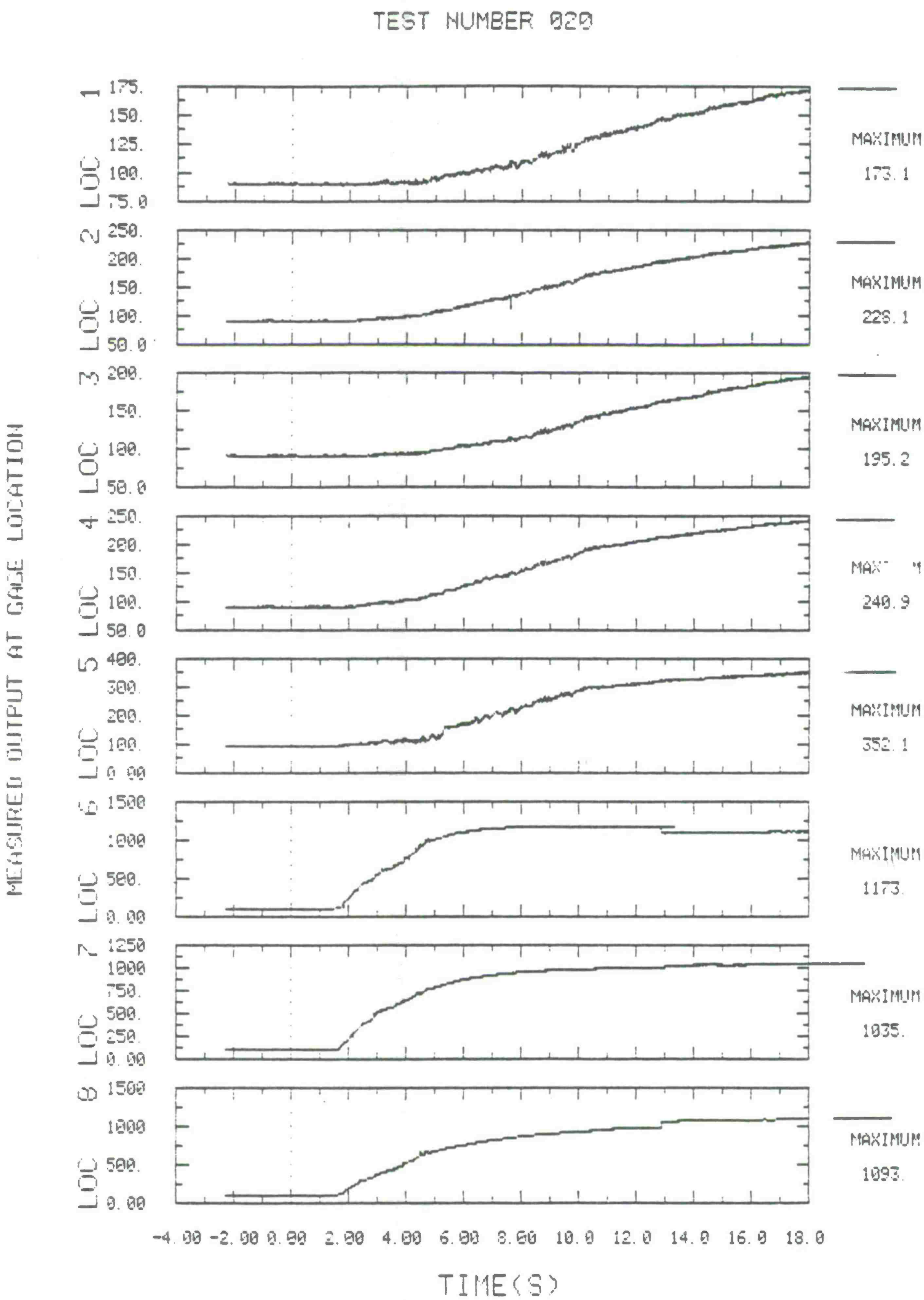


Figure A-9 (Continued)



TEST NUMBER 020
LOC 1
LOC 2
LOC 3
LOC 4
LOC 5
LOC 6
LOC 7
LOC 8
MAXIMUM 173.1
MAXIMUM 228.1
MAXIMUM 195.2
240.9
MAXIMUM 352.1
MAXIMUM 1173.
MAXIMUM 1035.
MAXIMUM 1093.
MEASURED OUTPUT AT GAGE LOCATION
TIME(S)
-4.00 -2.00 0.00 2.00 4.00 6.00 8.00 10.0 12.0 14.0 16.0 18.0

Figure A-10

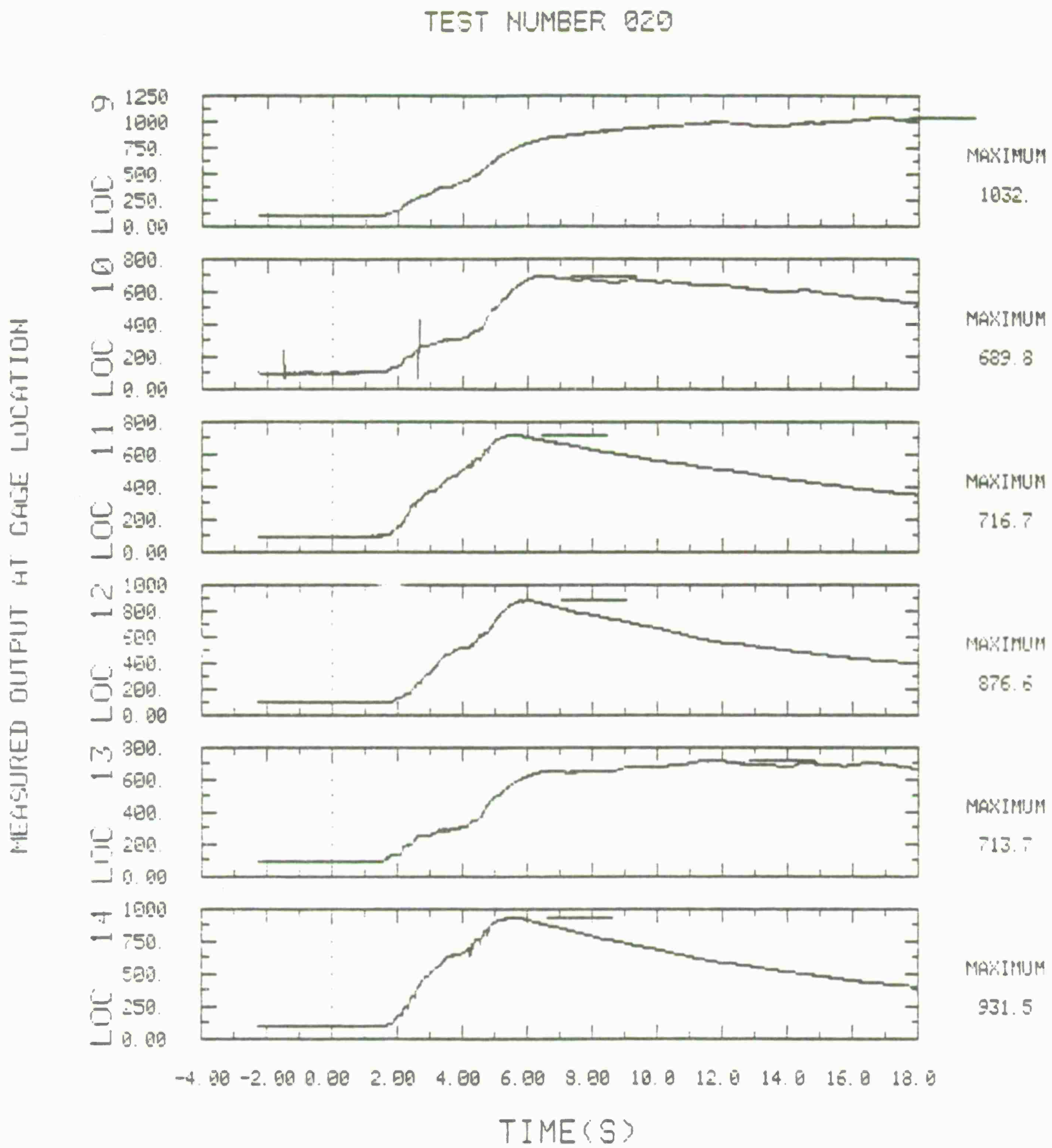


Figure A-10 (Continued)

Plume velocities were calculated for this test using data form Keil Probes 1 and 2. Probes 3 and 4 did not measure any pressure indicating that air ingestion into the cube did not occur. Probe 1 saw a maximum plume pressure of 0.165 in. of water at 2.4 sec after ignition and at a temperature of 450°F. The resultant velocity was calculated to be 35.4 ft/sec. Probe 2 saw a maximum plume pressure of 0.145 in. of water also at 2.4 sec after ignition and at a plume temperature of 375°F. This pressure converts to a velocity of 31.8 ft/sec. These lower plume velocities indicate that the plume did not have sufficient velocity to reach the rake in a flat orientation and had started slowing down and rising. The video tape of this test further verified the fact that the plume had started to rise by the time it reached the rake.

A.3 FLARES

A.3.1 Test 9--Two ALA-17 Flares

Two ALA-17 flares were placed in the test cube and simultaneously initiated. Figure A-11 presents the temperature profiles for the 14 thermocouple channels. As seen in Figure A-11, the highest wall temperature recorded was approximately 710°F above ambient at Location 5 which corresponds to the roof of the cube. The maximum plume temperature recorded by any of the six thermocouples located at the doorway was 787°F above ambient at Location 6 which is at the top of the door. All other thermocouples at the door showed lower temperatures ranging from 544°F to 383.6°F with the exception of Thermocouple Location 8 (at the bottom of the door) which recorded a maximum temperature of 219.8°F above ambient. These data indicate the hottest part of the plume is located at the top of the door; however, the plume is sufficiently large to affect the next four thermocouples. The thermocouple array mounted 3 ft away from the cube saw high temperatures at the top two thermocouple locations (Locations 12 and 14). This indicates that the plume exited the cube with significant velocity to reach the thermocouple rake mounted away from the box; however, the plume was starting to rise and affected only the two top thermocouples.

The Keil probe at the top of the door, at Location 1, measured a maximum plume pressure of 0.37 in. of water at approximately 0.9 sec after ignition and with a gas temperature of 260°F. This pressure calculates to a plume velocity of 47.4 ft/sec. Keil Probe 2 showed a maximum plume pressure of 0.36 in. of water also at approximately 9 sec and at a gas temperature of 210°F. This plume pressure converts to a plume velocity of 45 ft/sec. Keil Probe 3 did not measure any air intake velocity during the test. Probe 4 saw an air intake pressure of 0.005 in. of water at 4.8 sec after ignition and at an air temperature of approximately 210°F. This air intake pressure converts to a velocity of approximately 5.3 ft/sec.

A.3.2 Test 11--Two ALA-17 Flares

This test was basically a repeat of Test 9. The two flares were placed in a large metal ammunition box that served as a "bumper" to absorb the propulsive reaction of the ignited flare casings. The lid on the ammunition box had a section approximately 18 in. by 8 in. removed and replaced with a piece of expanded metal 0.125 in. grate to allow the fire and gases to vent out of the box into the cube. The two flares were simultaneously initiated. Figure A-12 presents the temperature profiles for the 14 thermocouple channels. The maximum temperature on the walls was 1127°F at Location 5 which consists of an array of seven thermocouples, connected in parallel, located symmetrically in the ceiling of the cube. However, this temperature trace appears erratic; this behavior may be attributed to the plume exiting the ammunition box and impinging on the roof as a torch. The highest plume temperature recorded by any of the six doorway thermocouples was 712°F at Thermocouple Location 6 which is at the top of the door. All other thermocouples at the door measured lower

TEST NUMBER 09

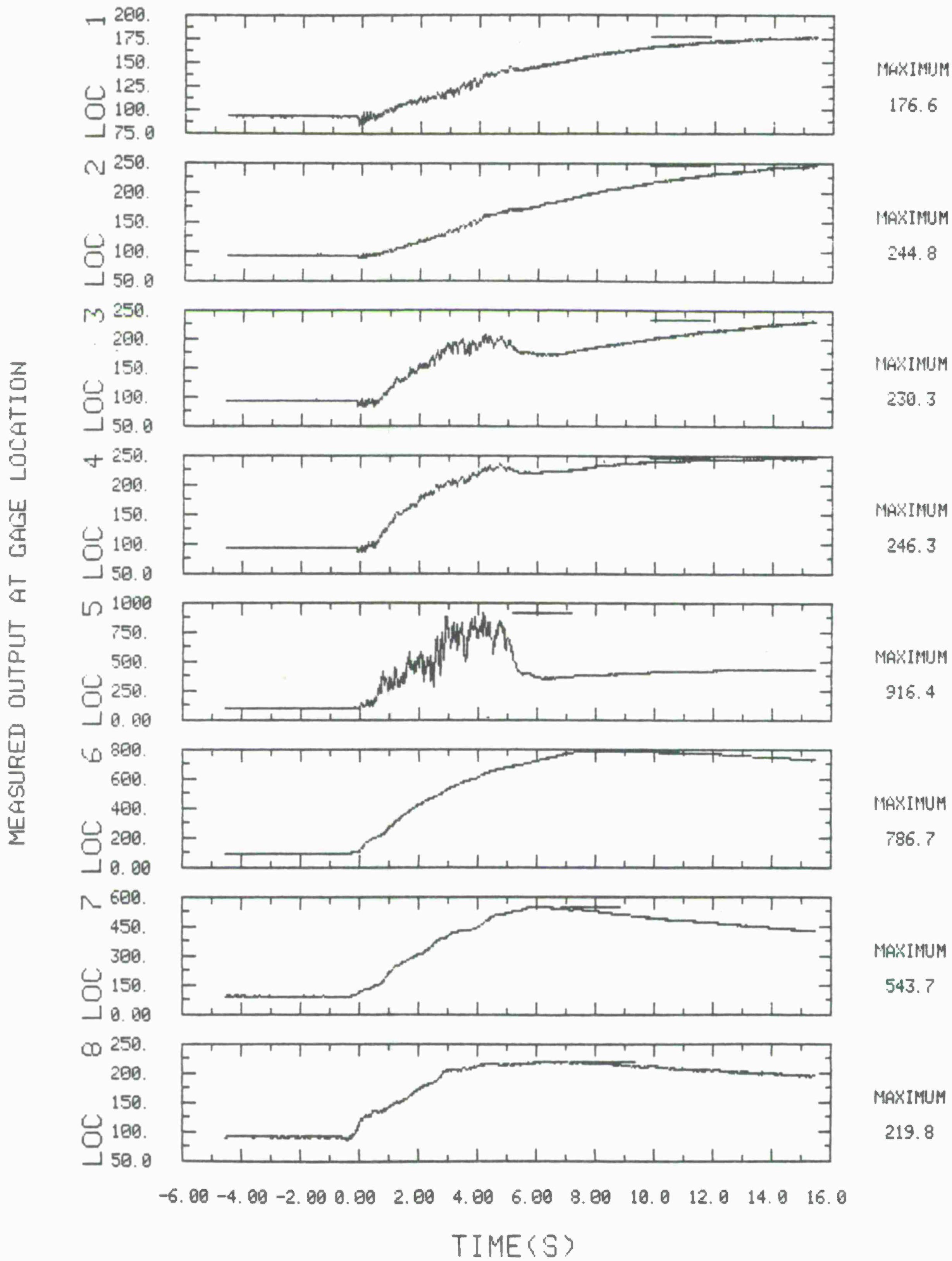


Figure A-11.

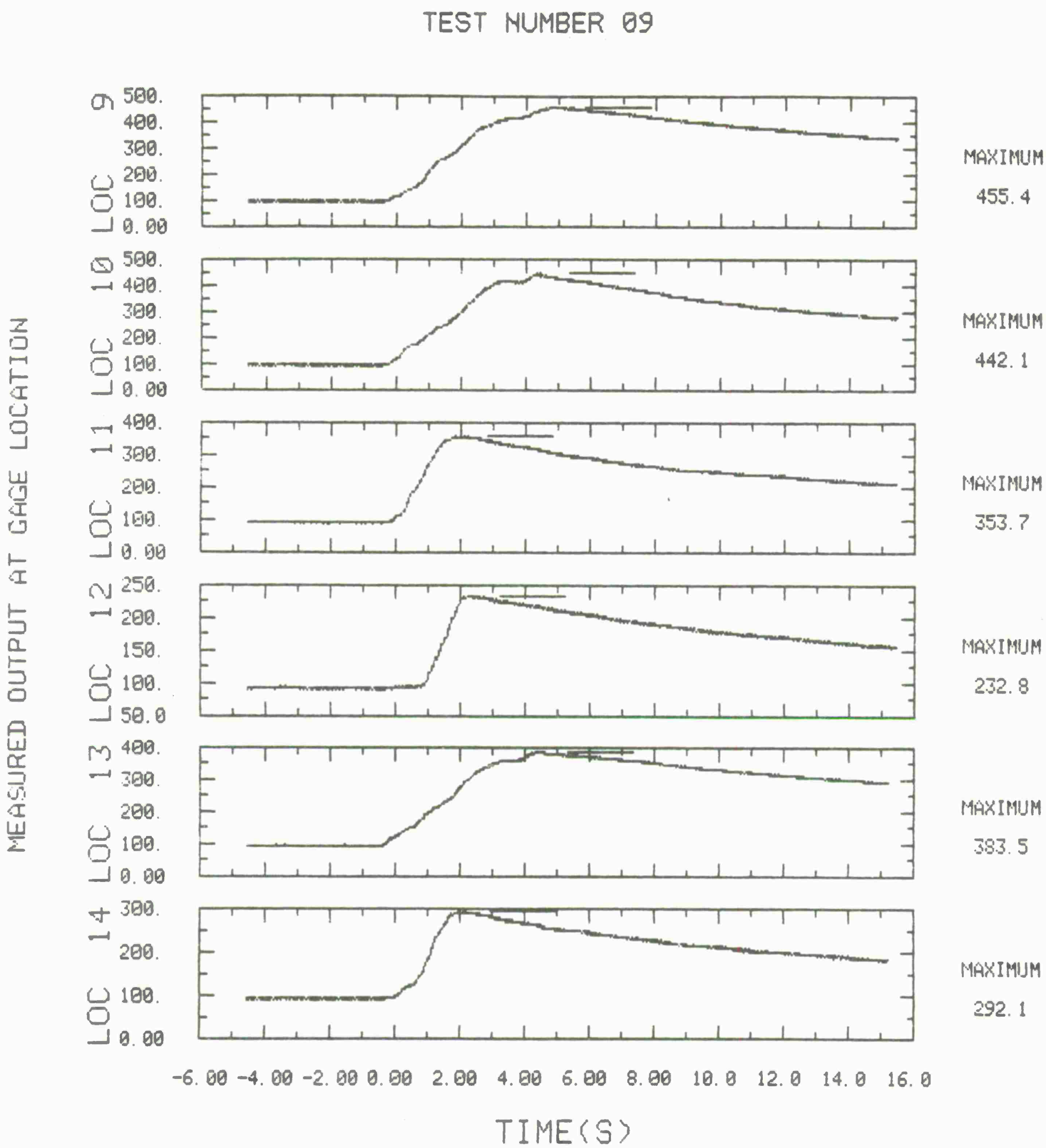


Figure A-11. (Continued)

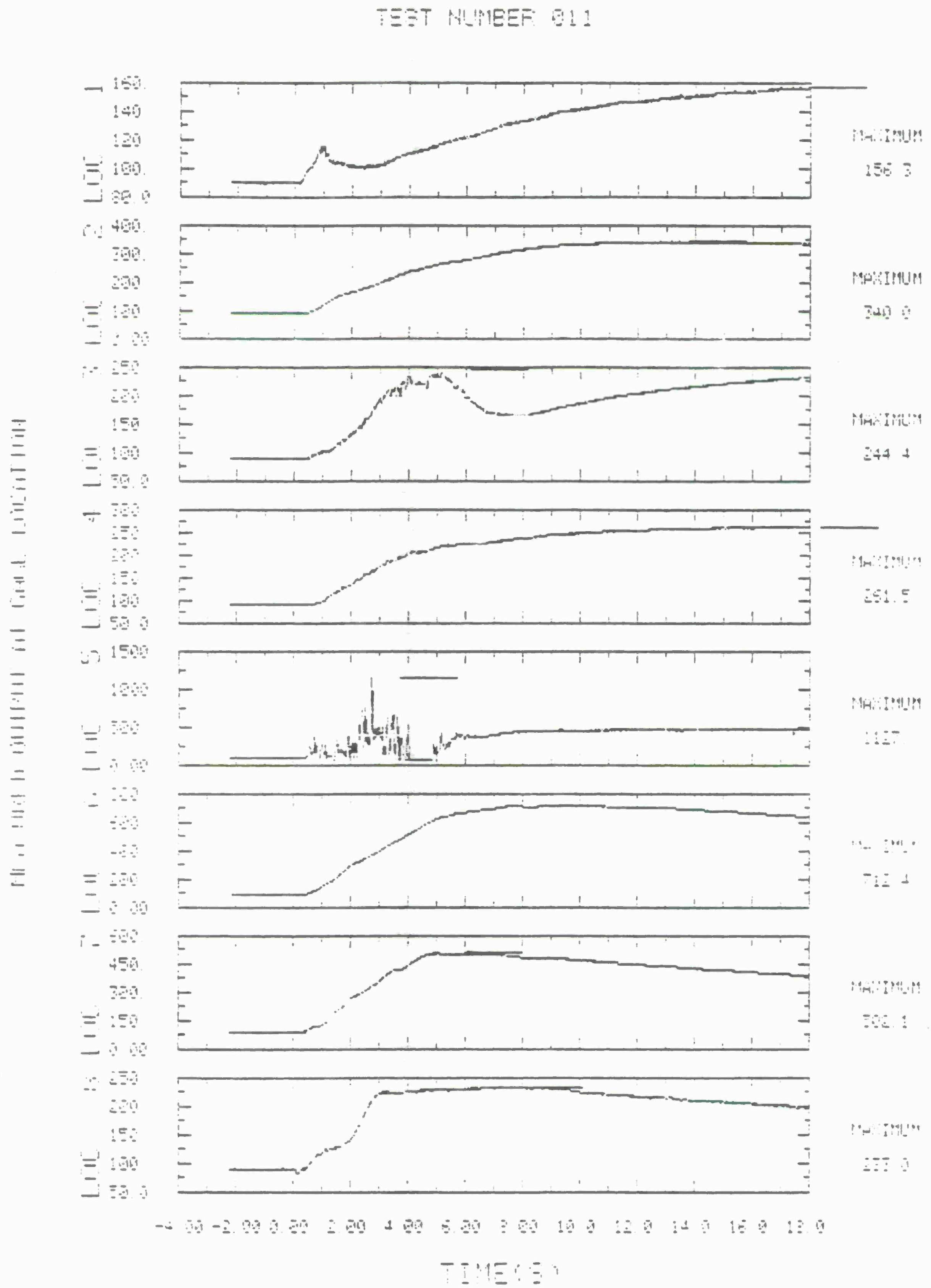

TEST NUMBER 011
MAXIMUM
156.3
MAXIMUM
340.0
MAXIMUM
244.4
MAXIMUM
251.5
MAXIMUM
MAXIMUM
MAXIMUM
-4.00 -2.00 0.00 2.00 4.00 6.00 8.00 10.0 12.0 14.0 16.0 18.0

Figure A-12.

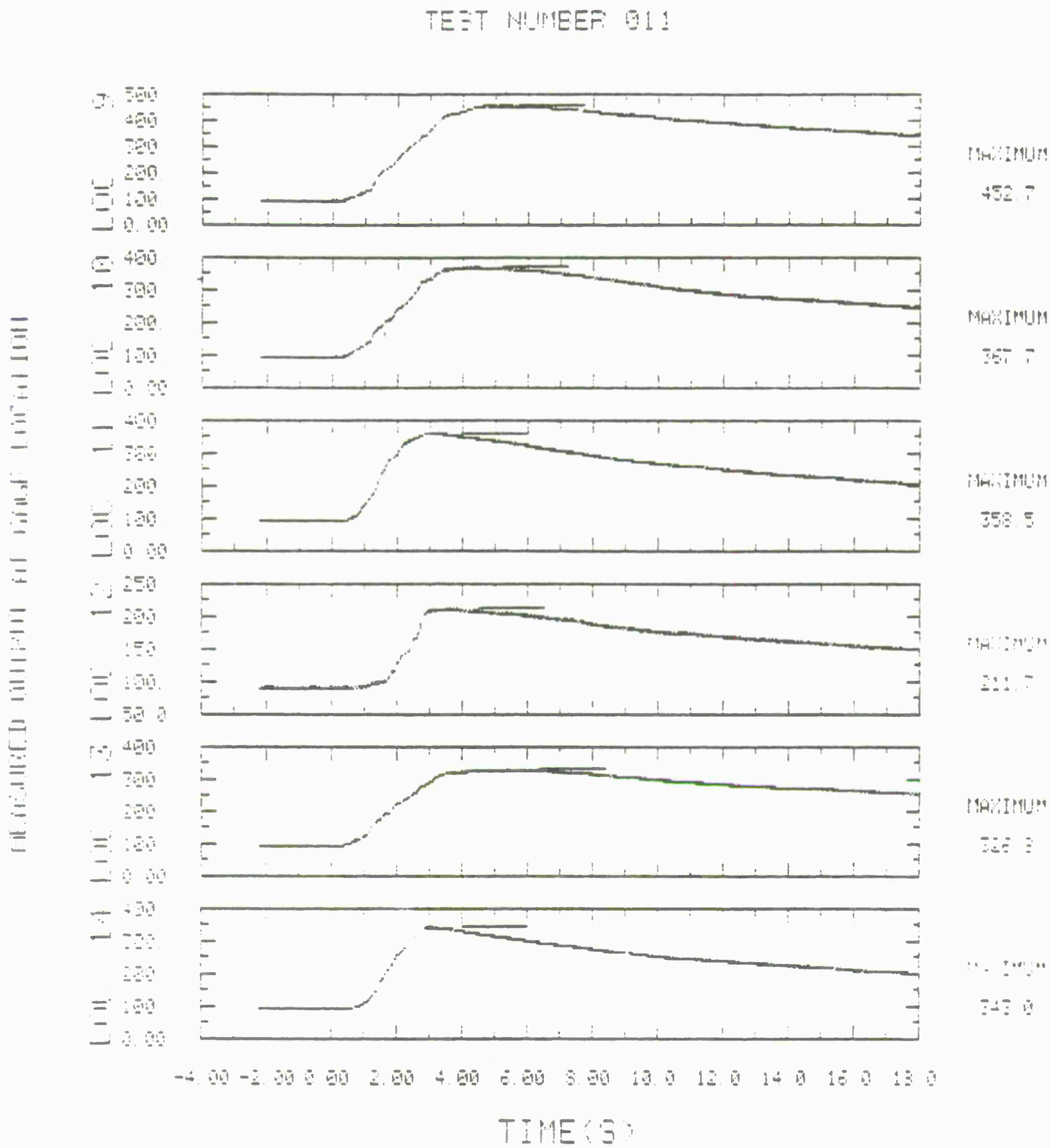


Figure A-12 (Continued)

temperatures ranging from 502°F at the second thermocouple from the top of the door to 233°F at the thermocouple at the bottom of the door. The thermocouple array mounted 3 ft away from the cube saw high temperature at the bottom two thermocouples (359°F and 343°F). The top thermocouple on the array saw a temperature of 212°F indicating that the plume exited the cube with a high enough velocity to reach the thermocouple rake and was significantly flat. The plume did not start to rise until after it had passed the rake.

The Keil probe at the top of the door (Location 1) measured a maximum plume pressure of 0.365 inches of water at approximately 1.0 sec after ignition and with a gas temperature of 150°F. This pressure calculates to a plume velocity of 43.4 ft/sec. Keil Probe 2 showed a maximum plume pressure of 0.365 in. of water also at approximately 1.0 sec and at a gas temperature of 130°F. This plume pressure converts to a plume velocity of 42.7 ft/sec. Probe 3 saw an air intake pressure of 0.05 in. of water at 2.8 sec after ignition and at an air temperature of approximately 330°F. This air intake pressure converts to a velocity of approximately 10.0 ft/sec. Probe 4 measured an air intake pressure of 0.035 in. of water at a time of 8.8 sec and at an air temperature of 230°F. This corresponds to an air velocity of 14.3 ft/sec.

A.3.3 Test 16--Two ALA-17 Flares

This test was basically a repeat of Test 11 with the exception that the metal ammunition box in which the flares were placed was modified to allow for side venting. Three holes approximately 2 in. in diameter were cut into the two long sides of the ammunition box. It was felt that using the ammunition box configuration used in Tests 9 and 11 with venting only through the top of the box would direct all of the fire plume through the top opening and would, in effect, create a torch impinging on the cube roof. By providing side vents it was felt that the torch effect would be minimized and a more "real life" burning behavior would be provided. The two flares were placed in the "new" ammunition box and simultaneously initiated. Figure A-13 presents the temperature profiles for the 14 thermocouple channels. As can be seen in Figure A-13, the highest wall temperature recorded was 313°F at Thermocouple 5 which corresponds to the roof of the cube. This temperature is significantly lower than the 1127°F mentioned previously at the roof in Test 11 using only the top vented ammunition box. The maximum plume temperature recorded by any of the six thermocouples located in the doorway was 746°F at Thermocouple 6 which is at the top of the door. All other thermocouples showed lower temperatures ranging from 348°F to 539°F with the exception of Thermocouple Location 8 (at the bottom of the door) which recorded a maximum temperature of 248°F. These data indicate the hottest part of the plume is located at the top of the door; however, the plume is sufficiently large to affect the next four thermocouples. The thermocouple array mounted 3 ft away from the cube saw a maximum temperature of 280°F at Thermocouple 14, while Thermocouples 11 and 12 measured a maximum of 255°F. These temperatures would indicate that the plume did not have sufficient velocity to reach the external rake and was rising between the cube and the external thermocouple rake.

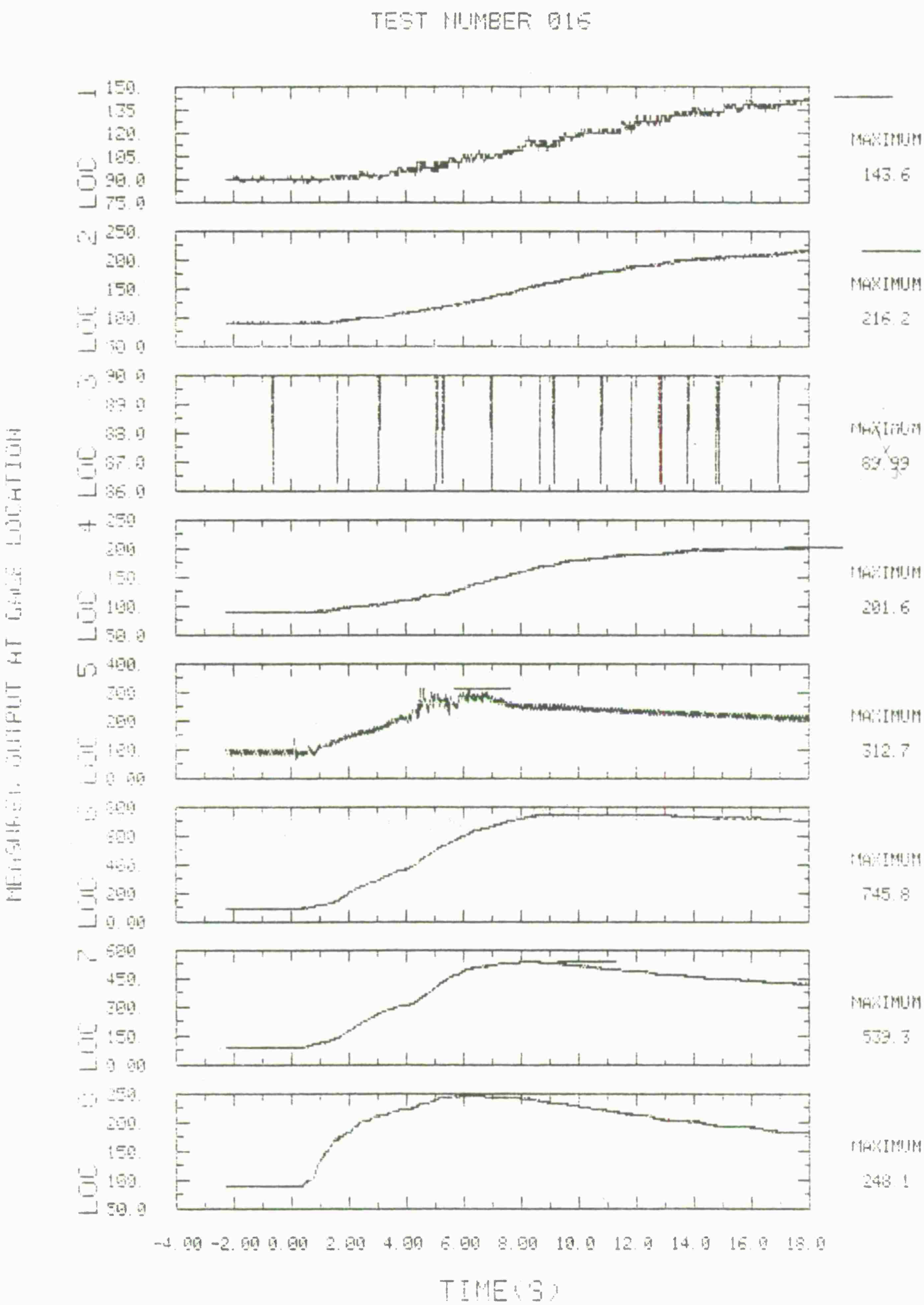

TEST NUMBER 016
MEASURED OUTPUT AT GAGE LOCATION
LOC 1
LOC 2
LOC 3
LOC 4
LOC 5
LOC 6
LOC 7
LOC 8
MAXIMUM
143.6
MAXIMUM
216.2
MAXIMUM
89.99
MAXIMUM
201.6
MAXIMUM
312.7
MAXIMUM
745.8
MAXIMUM
539.3
MAXIMUM
248.1
-4.00 -2.00 0.00 2.00 4.00 6.00 8.00 10.0 12.0 14.0 16.0 18.0
TIME(S)

Figure A-13.

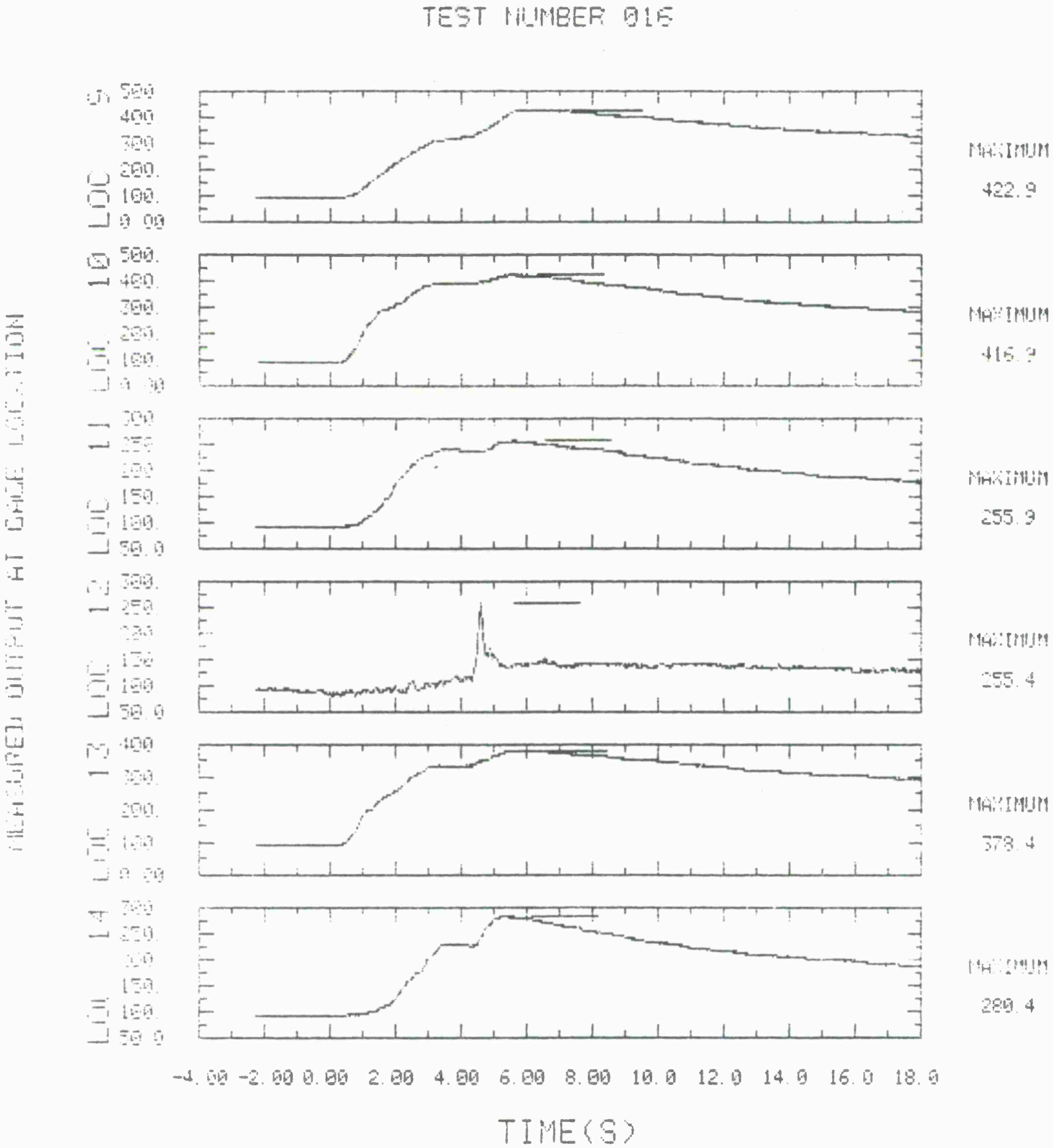
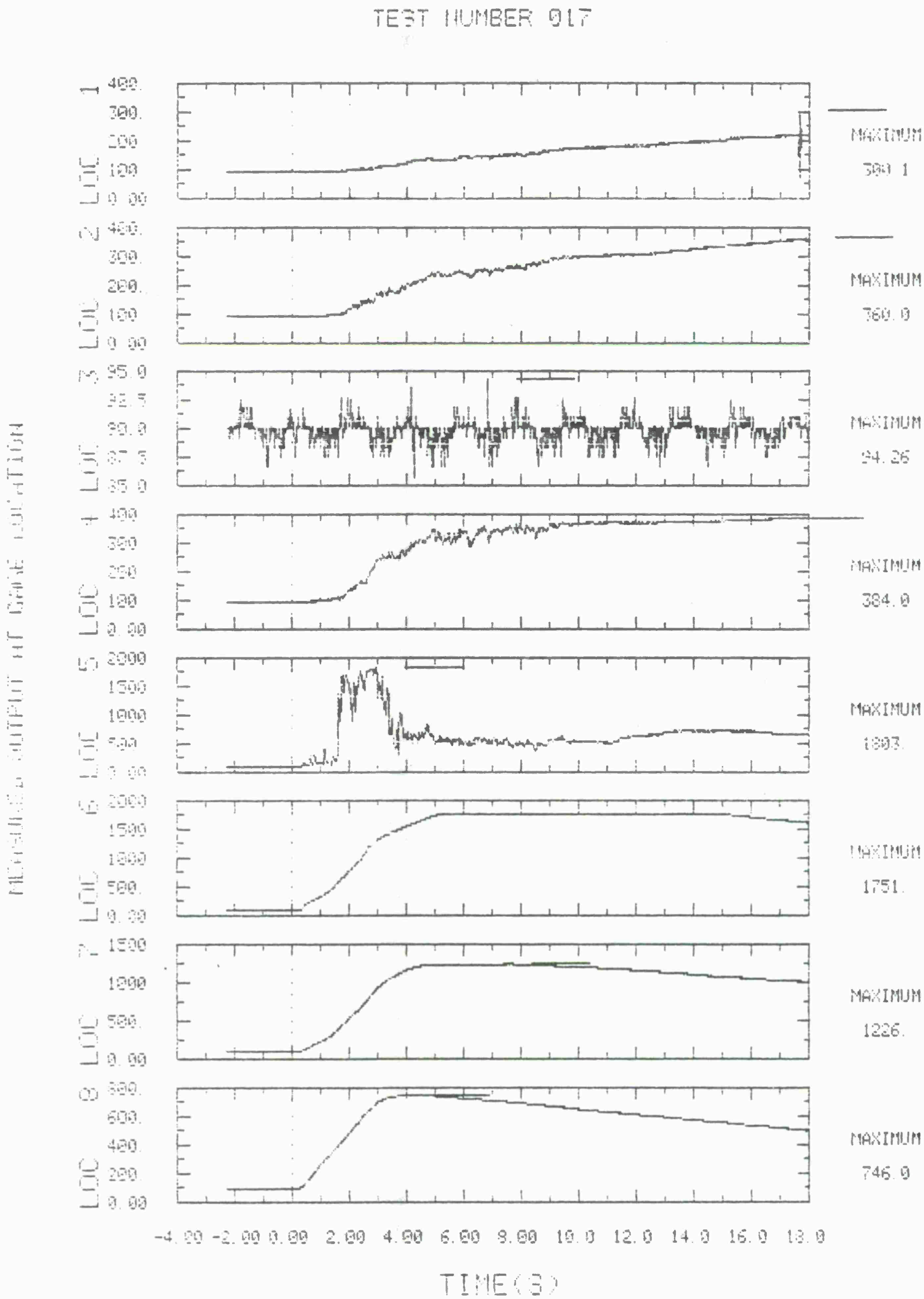


Figure A-13 (Continued)

The plume velocity was calculated using the pressures measured by the Keil probes positioned at the door. Keil Probe 1 which is at the top of the door measured a plume pressure of 0.105 in. of water at 1.4 sec after ignition. The plume temperature at this time was 140°F. The resultant velocity calculated was 23.1 ft/sec. Probe 2 measured a pressure of 0.115 in. of water at 1.4 sec after ignition and at a temperature of 135°F. This pressure converts to a velocity of 24 ft/sec. Probes 3 and 4 did not detect any air intake verifying the fact that there was no air being ingested into the cube. The low air velocity measured by Probes 1 and 2 and the lack of intake air also indicate that the plume did not reach the thermocouple rake and rose between the cube and the thermocouple rake. A review of the video tape recording of this test showed that the plume was not very dynamic and did indeed rise before reaching the external thermocouple rake.

A.3.4 Test 17--Four ALA-17 Flares

This test consisted of four flares placed inside the metal ammuntion box and then placed inside the cube. This test also used the ammunition box with side vents. Figure A-14 presents the temperature profiles for the 14 thermocouples. As can be seen in Figure A-14, instrumentation problems occurred with Thermocouple 3 and all that was recorded was a high frequency noise signal. Thermocouple 5, which is at the roof of the cube, measured a maximum temperature of 1803°F; however, these data are also suspect because the temperature drops down to around 500°F shortly thereafter (approximately 2 sec later) and stays around 500°F for most of the remainder of the test. Thermocouple 6, which is at the top of the door, measured a maximum temperature of 1751°F, at approximately 5 sec after ignition. The temperature remains constant for the next 10 sec and it appears that the doorway temperature reached a steady state condition. However, to ensure that the cube reached a steady state condition and that it was not a case of the Type K thermocouple reaching its maximum temperature reading capability (Type K thermocouples are good up to 2500°F) or a case of saturating the electronics used to record the temperature data, a repeat of this test was performed. This repeat test was performed with additional instrumentation, specificaly Type B thermocouples (which are good up to temperatures in excess of 3000°F) placed at the doorway in addition to the existing Type K thermocouples already at the door. The electronics were checked to ensure that saturation did not occur. The ability to measure mass loss rates would be very beneficial to the determination as to whether the cube goes into a steady state condition. However, at this time we do not have the capability to measure mass loss rates inside the cube. Thermocouple 7 also goes into an apparent steady state condition at a temperature of 1226°F approximately 4-1/2 sec after ignition. The thermocouple sees this high temperature for approximately 5 sec. All of the door thermocouples saw extremely high temperatures as shown in Figure 5 and even the thermocouple at the bottom of the door (Thermocouple 8) saw a temperature of 746°F where on previous tests it has only seen temperatures in the 300°F range. The thermocouple rake mounted 3 ft away from the cube also saw very high



TEST NUMBER 017
LOC 1
LOC 2
LOC 3
LOC 4
LOC 5
LOC 6
LOC 7
LOC 8
MEASURED OUTPUT AT GAGE LOCATION
MAXIMUM 300.1
MAXIMUM 360.0
MAXIMUM 94.26
MAXIMUM 384.0
MAXIMUM 1803.
MAXIMUM 1751.
MAXIMUM 1226.
MAXIMUM 746.0
-4.00 -2.00 0.00 2.00 4.00 6.00 8.00 10.0 12.0 14.0 16.0 18.0
TIME(S)

Figure A-14.

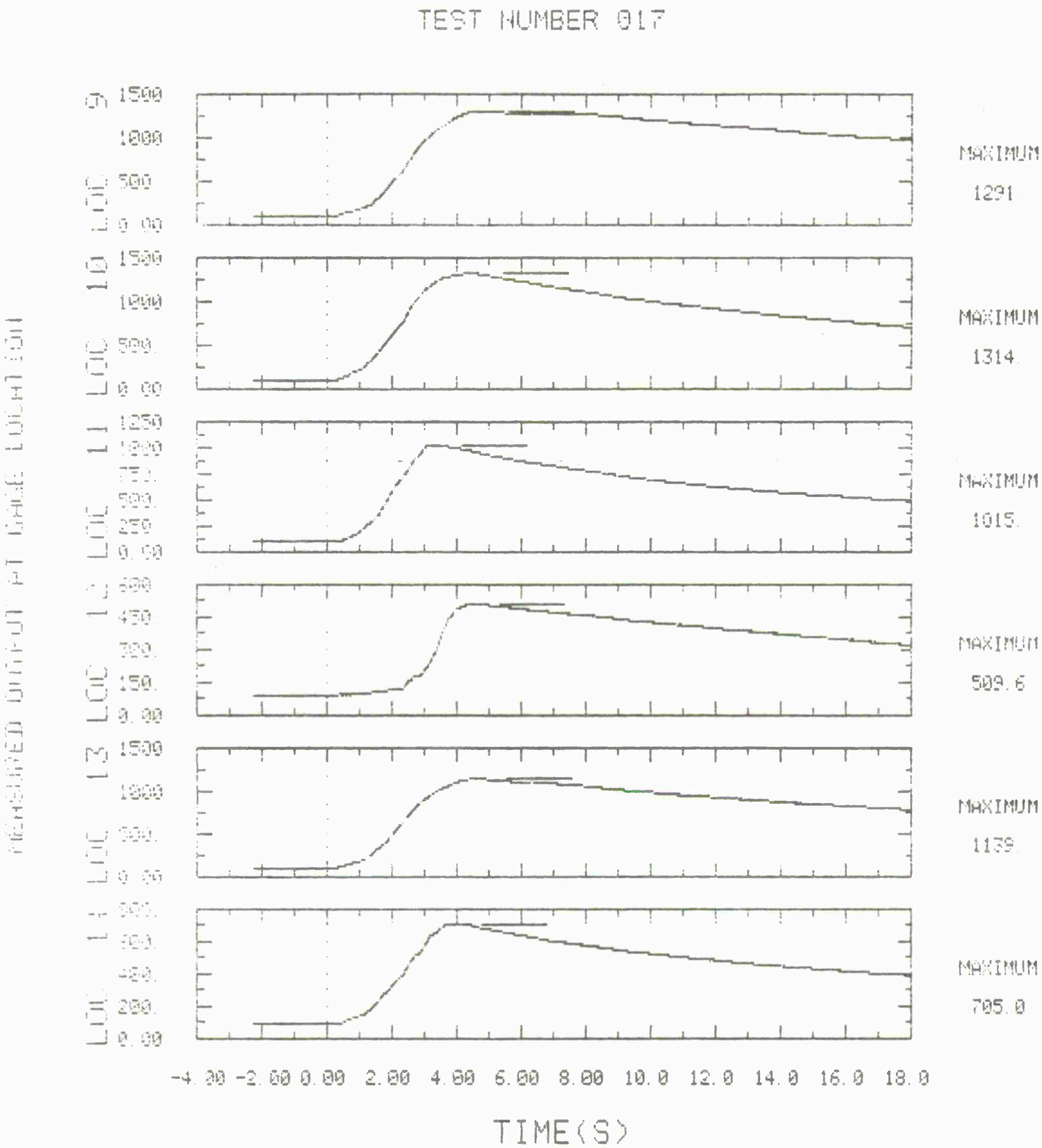


Figure A-14 (Continued)

temperatures specifically at the bottom of the rake, Thermocouple 11. This measured a maximum plume temperature of 1015°F. The other two thermocouples, 12 and 14, measured 510 and 705°F, respectively. The very high temperature at Thermocouple 11 indicates that the plume is flat, with sufficient velocity to reach the rake.

The plume velocity was in fact calculated using the Keil probe data measured by the four probes in the door. Probe 1 measured a maximum plume pressure of 0.5 in. of water at 2.3 sec after ignition and at a plume temperature of 950°F. The resultant velocity is 77.3 ft/sec. Probe 2 measured 0.45 in. of water at 1.7 sec after ignition and at a temperature of 450°F. The corresponding velocity of the plume was 58.5 ft/sec. Probes 3 and 4 saw much lower pressures and the resultant velocities were much lower, 16.7 ft/sec and 10.1 ft/sec, respectively.

A review of the video tape recording of Test 17 showed that the plume was exiting the door at a high rate and with a very flat shape. The plume carried well past the rake and the aforementioned high rake temperature verify it. It was noticed for the first time in any of our tests that a considerable amount of firebranding was occurring. Firebrands were burning visibly in the plume itself and also being thrust out of the cube and burning on the ground.

A.3.5 Test 21--Four ALA 17 Flares

This test was a repeat of Test 17 with the flares placed inside of the vented ammunition box. Figure A-15 presents the temperature profiles for the 14 thermocouples. Those thermocouples that were questionable on the previous tests were replaced with new Type K thermocouples and were checked out with a propane torch prior to the test. As can be seen in Figure A-15, all of the thermocouples with the exception of Probe 5 responded as was expected. Thermocouple 6 which is at the top of the door measured a maximum temperature of 1344°F which is somewhat lower than that measured in Test 17 (1751°F). All of the doorway thermocouples saw high temperatures ranging from 1344°F at the top of the door down to 415°F at the bottom of the door. Thermocouples 12, 13 and 14 mounted on the rake 3 ft away from the door also saw high temperatures; however, the higher temperatures occurred at the top of the rake. Probes 12 and 13 measured temperatures of 321°F and 381°F, respectively, indicating that the plume was starting to rise.

A review of the video of this test showed a secondary ignition (which implies that not all of the flares ignited simultaneously) at approximately 7.7 sec after the first ignition. A considerable amount of firebrands were observed in the effluent plume. This occurred shortly after the first ignition and again after the second ignition. A third ignition was observed at approximately 17 sec after the first ignition. The third ignition was barely noticeable on the video recording, and only a small amount of firebrands were emitted during the final burning stages of the test. The delayed multiple ignitions can also be seen in the

TEST NUMBER 21

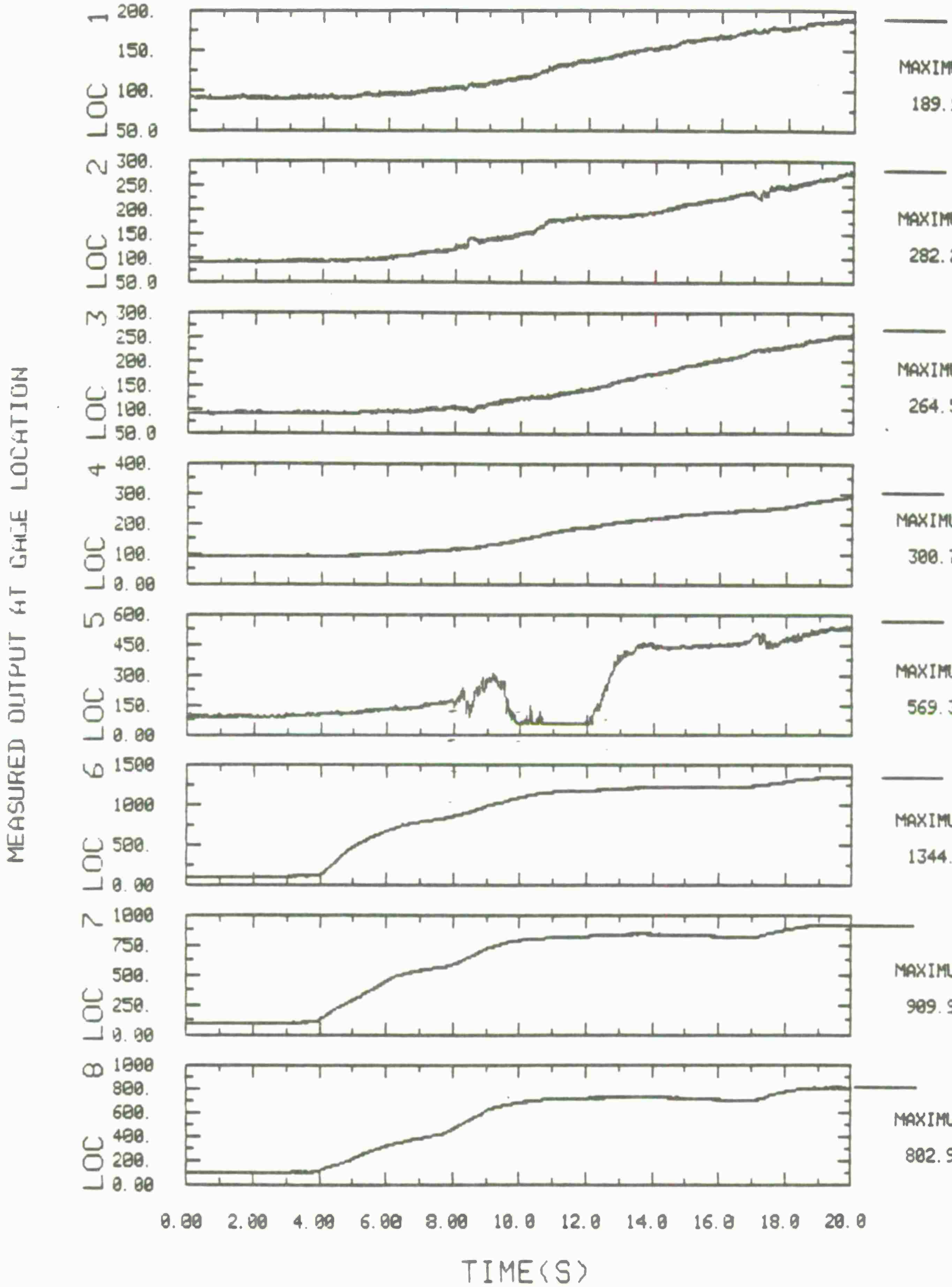


Figure A-15.

TEST NUMBER 21

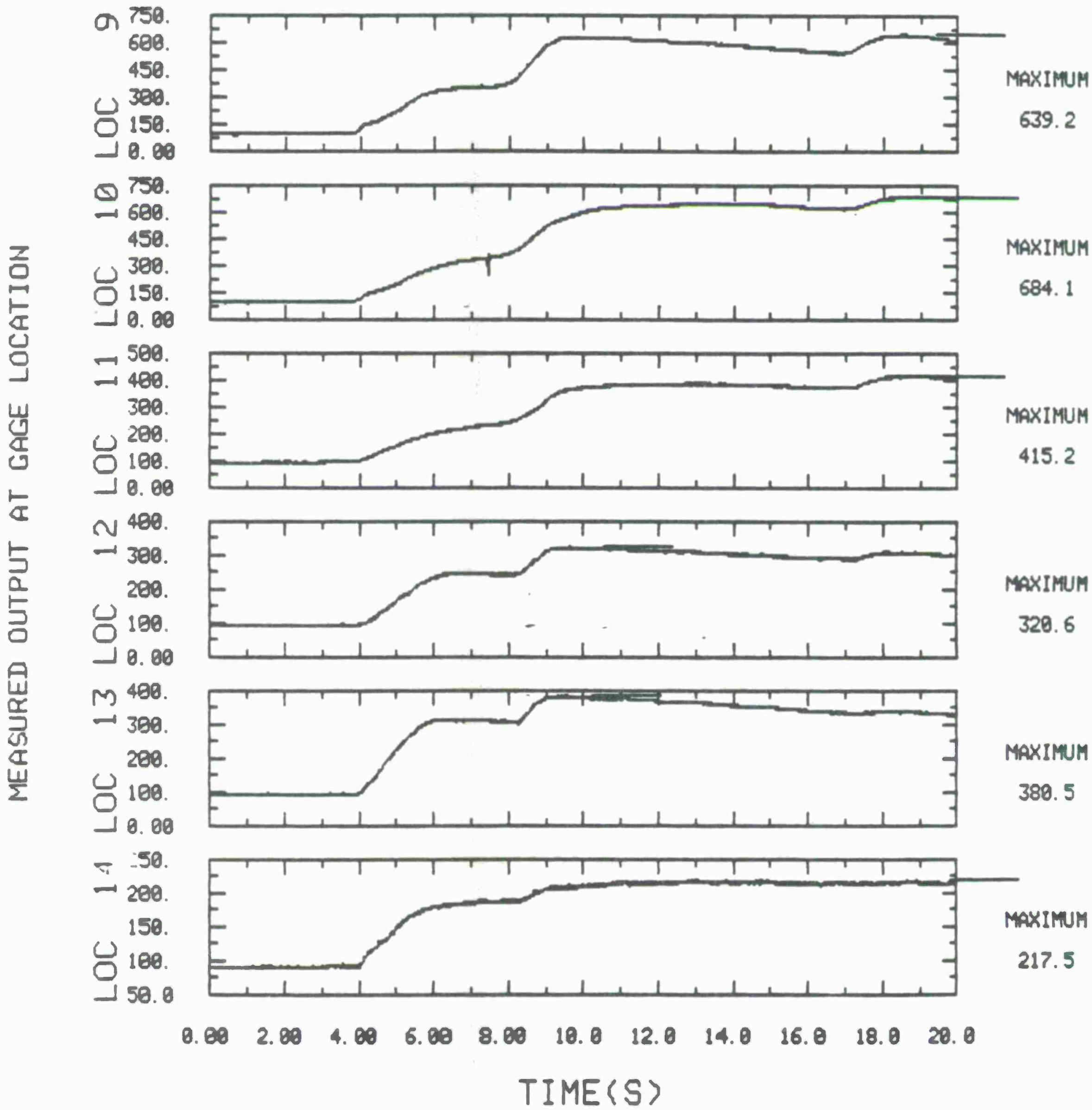


Figure A-15 (Continued)

thermocouple data presented in Figure A-15. If one looks at the thermocouple temperature traces (in particular Probes 6 through 14), a change in the slope occurs at approximately 8 sec and again at 17.5 sec with the rate of temperature rise becoming steeper at each change. Since all of the flares were initially ignited simultaneously, there is no real explanation for the delays in the ignition other than the fact the flares did not ignite as they are designed to.

The plume velocity was calculated for this test using the Keil probe data measured by the four probes at the door. Probe 1 measured a maximum pressure of 0.18 in. of water at a time of 3.9 sec after ignition and at a plume temperature of 900°F. The resultant velocity is 45.4 ft/sec. Probe 2 measured a maximum pressure of 0.22 in. of water at 3.9 sec after ignition and at a temperature of 600°F. The corresponding velocity of the plume was 44.3 ft/sec. Probe 3 measured 0.10 in. of water at 4.7 sec after ignition at a plume temperature of 480°F. This results in a calculated velocity of 28.2 ft/sec. Probe 4 measured 0.19 in. of water at 4.2 sec after ignition at a plume temperature of 250°F which results in a velocity of 33.7 ft/sec. A correlation between plume exit velocity, rate of heat release and visual observance of firebrand emission might provide information for plume modeling and/or prediction of full-scale burning behavior.

A.3.6 Test 22--Four ALA 17 Flares

This test was a repeat of Test 21 to determine if the flares could be ignited simultaneously or whether delayed ignitions would again occur. The four flares were placed in the vented ammunition box and placed in the cube. The flares were remotely initiated and it appears from reviewing the video that most if not all the flares ignited simultaneously. The ignition of the flares resulted in a thermally induced overpressure condition that caused irreparable damage to the Marinite cube. Figures A-16 and A-17 are pictures showing the extent of the damage to the cube and the vented ammunition box that contained the four flares. All of the instrumentation in the cube was lost after approximately 2.4 sec after ignition and limited temperature data was obtained for this test (see Figure A-18). The steel support frame for the cube survived the test; however, it was decided not to rebuild the cube this late in the program.

The limited temperature data recorded prior to failure of the cube was used to calculate the rate of heat release up to the time of failure. Table A-1 provides a comparison of this data with values obtained for Test 17 which also involved four ALA 17 flares. This comparison indicates that the burning rate for Test 22 was three to four times higher than for Test 17 while a peak of 9500 Btu/100 msec and 2750 Btu/100 msec was obtained for Test 22 and Test 17, respectively. This gross variation in burning rate would have to be evaluated through tests in a substantial cubicle before any conclusions can be made on the burning behavior of multiple flares igniting and burning simultaneously.

Figure A-16. Damaged Cube After Test 22

Figure A-17. Vented Ammunition Box Used to Contain the Four Flares

TEST NUMBER 22

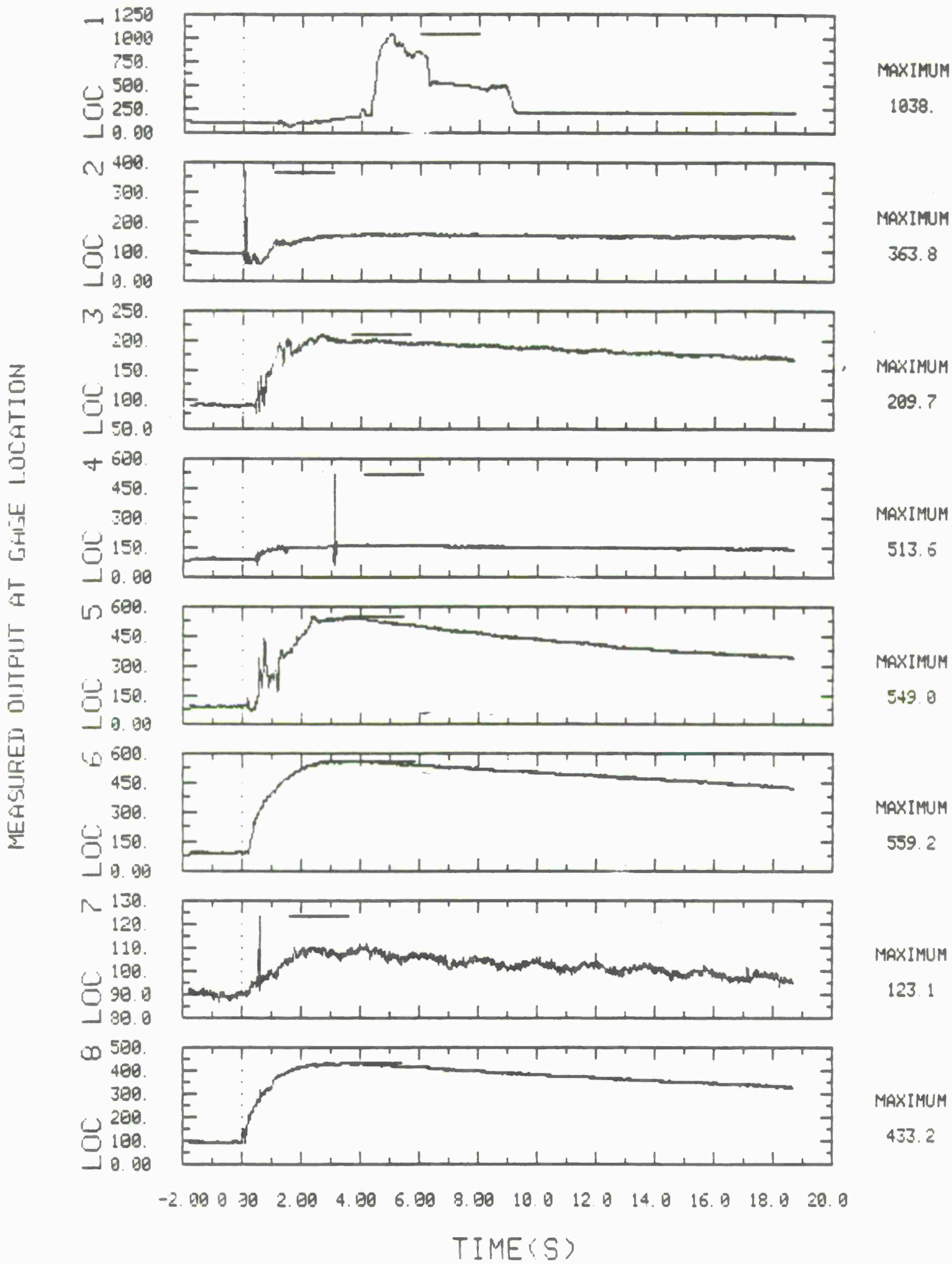


Figure A-8.

TEST NUMBER 22

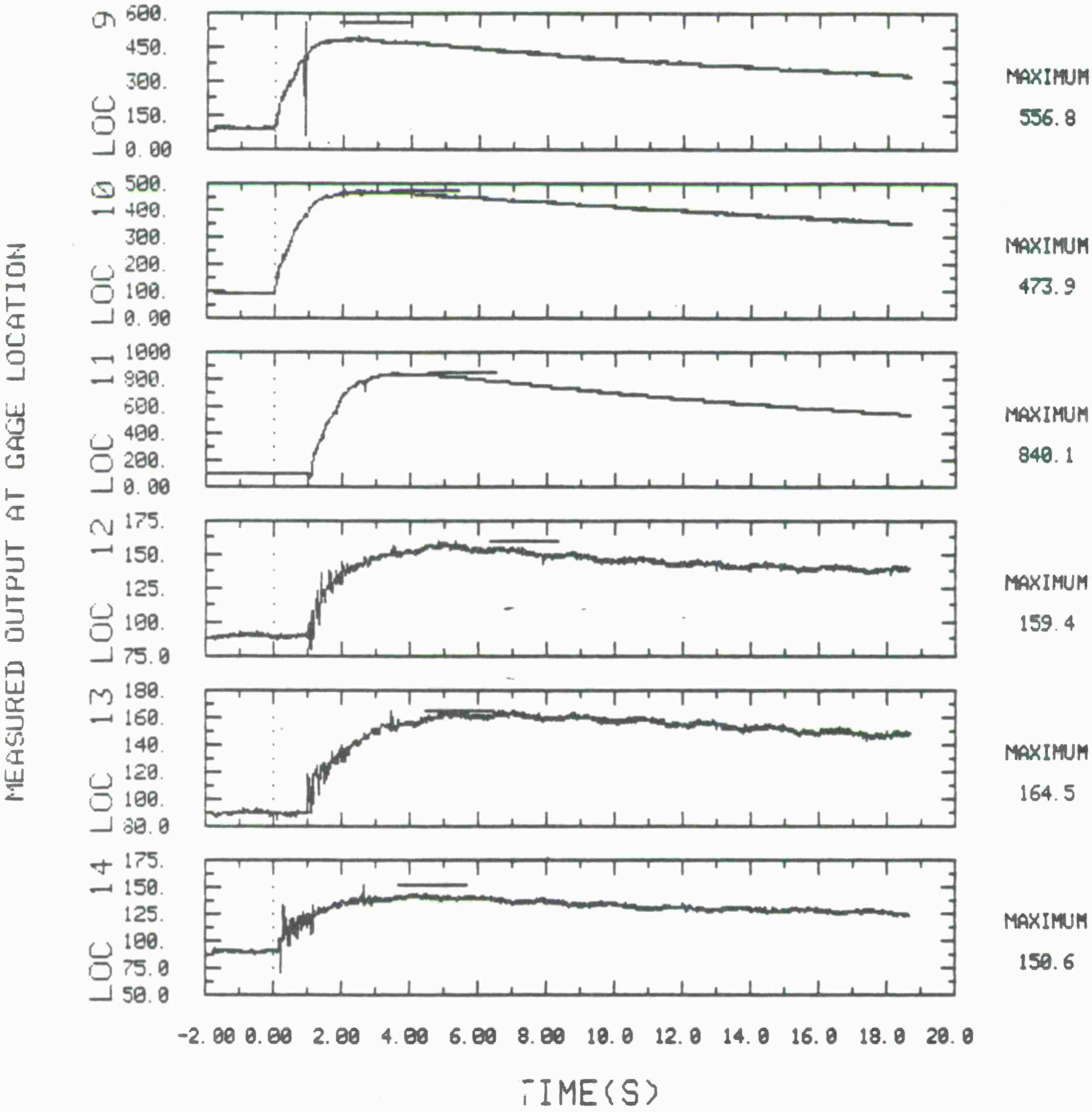


Figure A-18 (Continued)

TABLE A-1. COMPARISON OF RATE OF HEAT RELEASE FOR TESTS 17 AND 22--4 ALA 17 FLARES

Time seconds	Test 17 $\dot{Q}$ Btu/100 msec/sec	Test 22 $\dot{Q}$ Btu/100 msec/sec
0-1	1000	3300
1-2	1500	4100
2-2.5	700	(5000)*
0-2.5	900	3360

* Data becomes questionable after 2.4 sec.

APPENDIX B

1/10th SCALE MODEL IGLOO TEST DESCRIPTIONS

Page

B.1 M1 PROPELLANT TESTS

B.1.1 Test 1--M1 Propellant (1.5 lb)

The first propellant test utilizing the M1 propellant was performed using 1.5 lb of propellant in a single sealed cardboard canister. The propellant canister was placed in the center of the 1/10th scale model igloo and was initiated using an electric match placed at the top of the propellant. The igloo was instrumented with eight Type K thermocouples for measuring the heat generated inside the igloo. Four thermocouples (1 through 4) were located in the roof of the igloo equally spaced from front to back. Four thermocouples (5 through 8) were located 45° down from the roof on the shell equally spaced from the front to the back. Two rakes each containing three thermocouple probes and two Keil probes were located outside of the igloo door. The first rake (Probes 9 through 11, top to bottom) was located 7 in. from the door and the second rake (Probes 12 through 14, top to bottom) was located 3 ft from the door. Temperature profiles for the 14 thermocouples are presented in Figure B-1. Also presented in this figure is the output of the load cells which is labeled "Location 15." The load cells were used to measure mass loss rate. As shown in Figure B-1, the maximum temperature in the igloo was at Locations 3 in the roof and 6 in the side of the igloo. These two probes are located towards the center of the igloo. The maximum plume temperature measured was 845°F at Location 9 which is the top probe on the first rake. Probes 10 and 11 also measured high temperatures, 815°F and 809°F, respectively. The second rake located 3 ft away also saw high plume temperatures, however, not as high as those at the door. The maximum temperature measured at the second rake was 715°F at the top of the rake. The high temperature measured by the thermocouples on the second rake indicate that the plume is flat and with sufficient velocity to reach the rake.

Due to instrumentation problems with the video camera dedicated to the Keil probes, pressures were not recorded and plume velocities could not be calculated.

B.1.2 Test 2--M1 Propellant (3.0 lb)

The second propellant test was performed using 3 lb of M1 propellant contained in two sealed cardboard canisters. The canisters were centered in the 1/10th scale model igloo and simultaneously ignited using an electric match in each canister. Figure B-2 presents temperature profiles for the 14 thermocouples and also the output of the load cells. As shown in this figure, the two central thermocouples (Probes 3 and 7) recorded the highest internal temperatures, 777°F and 718°F, respectively. The thermocouples mounted on the first rake (Probes 9, 10 and 11, top to bottom) measured higher temperatures than those measured inside the igloo, 983°F, 903°F and 855°F, respectively. The thermocouples mounted on the second rake (Probes 12, 13 and 14) were 3 ft away from the igloo door and measured even higher temperatures, 1069°F, 1028°F and 924°F, respectively. This phenomena would indicate that unburned particles are exiting the igloo in the plume and are burning outside of the igloo.

TEST NUMBER 1

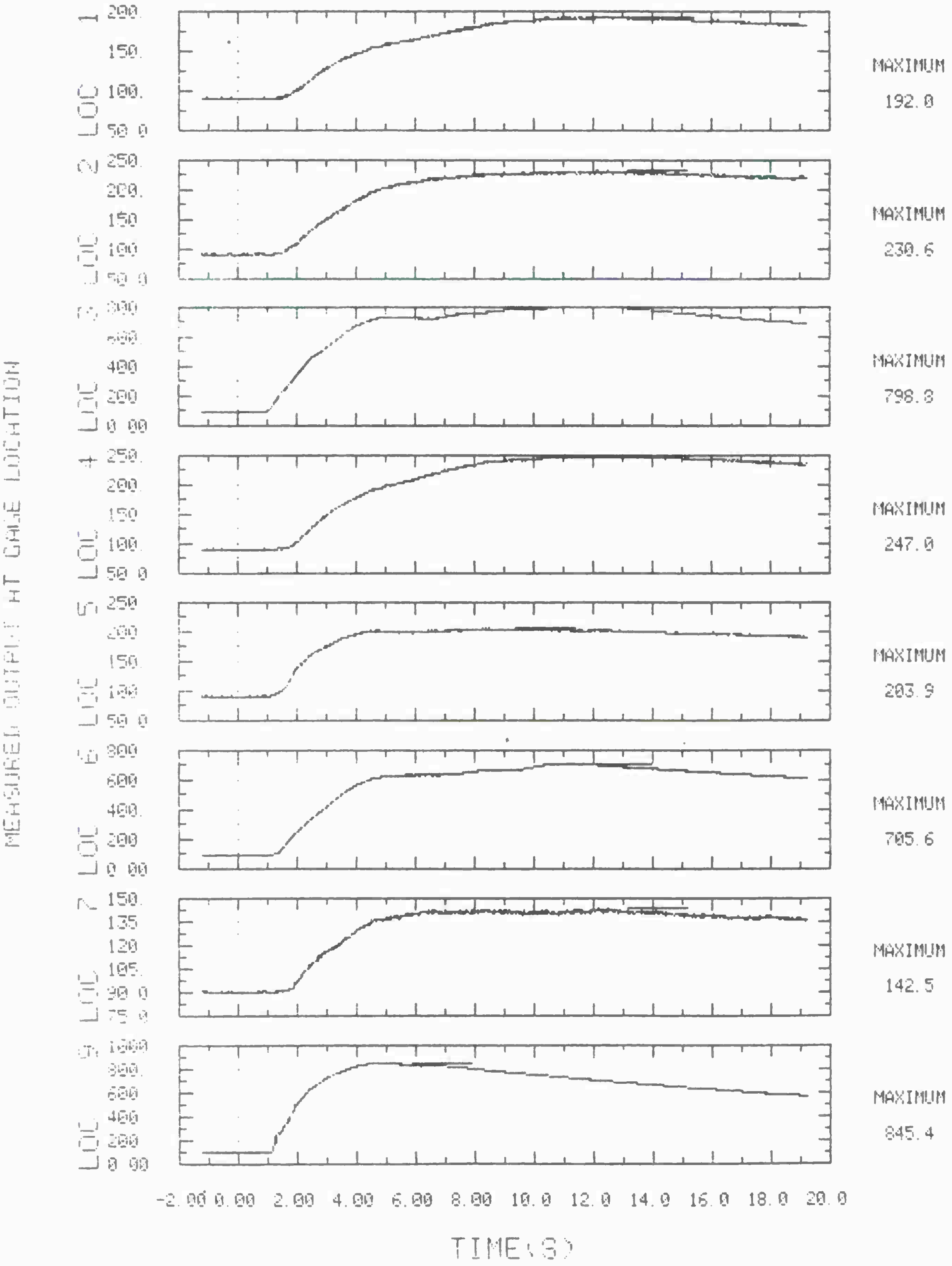


Figure B-1.

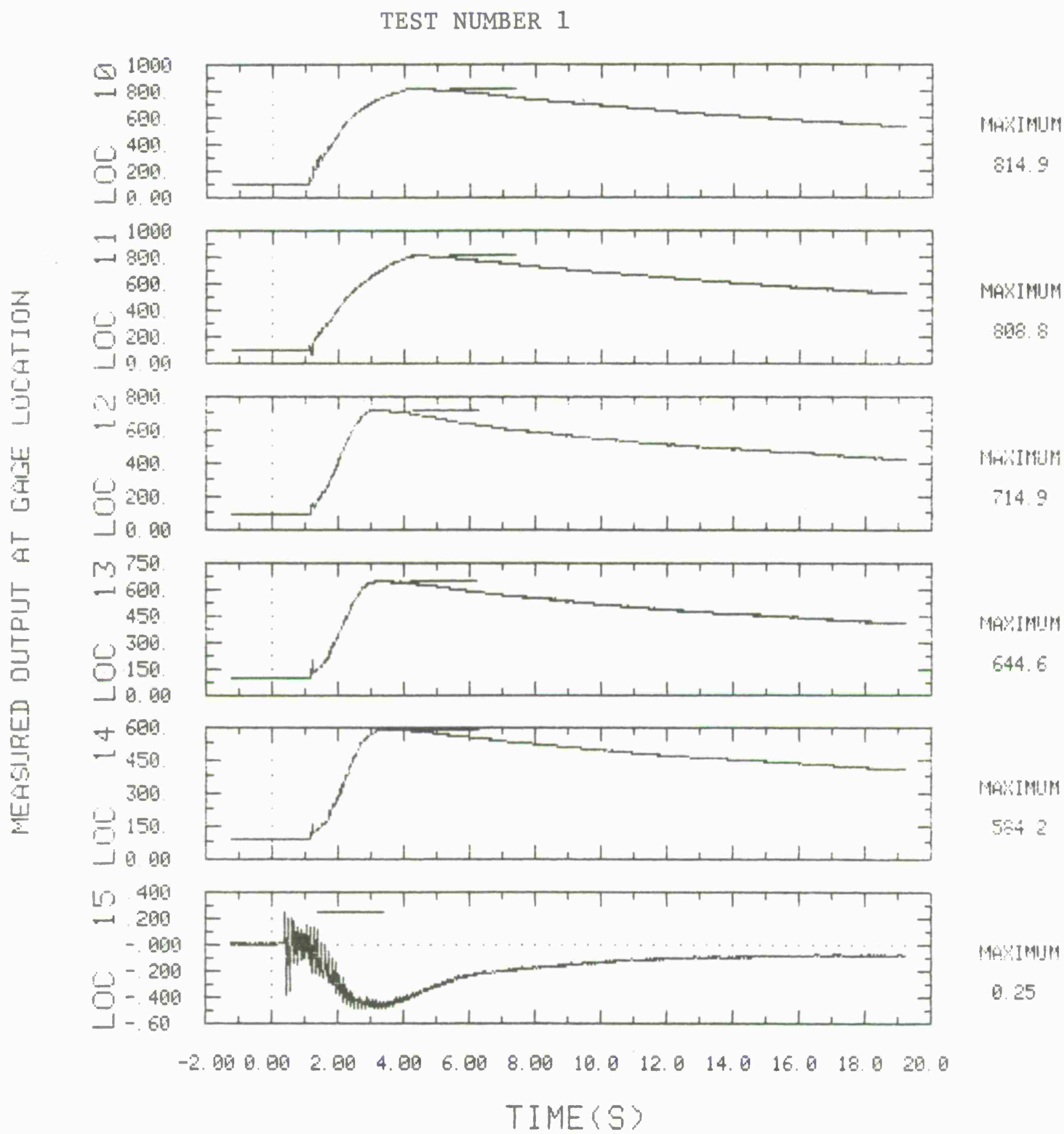


Figure B-1 (Continued)

TEST NUMBER 2

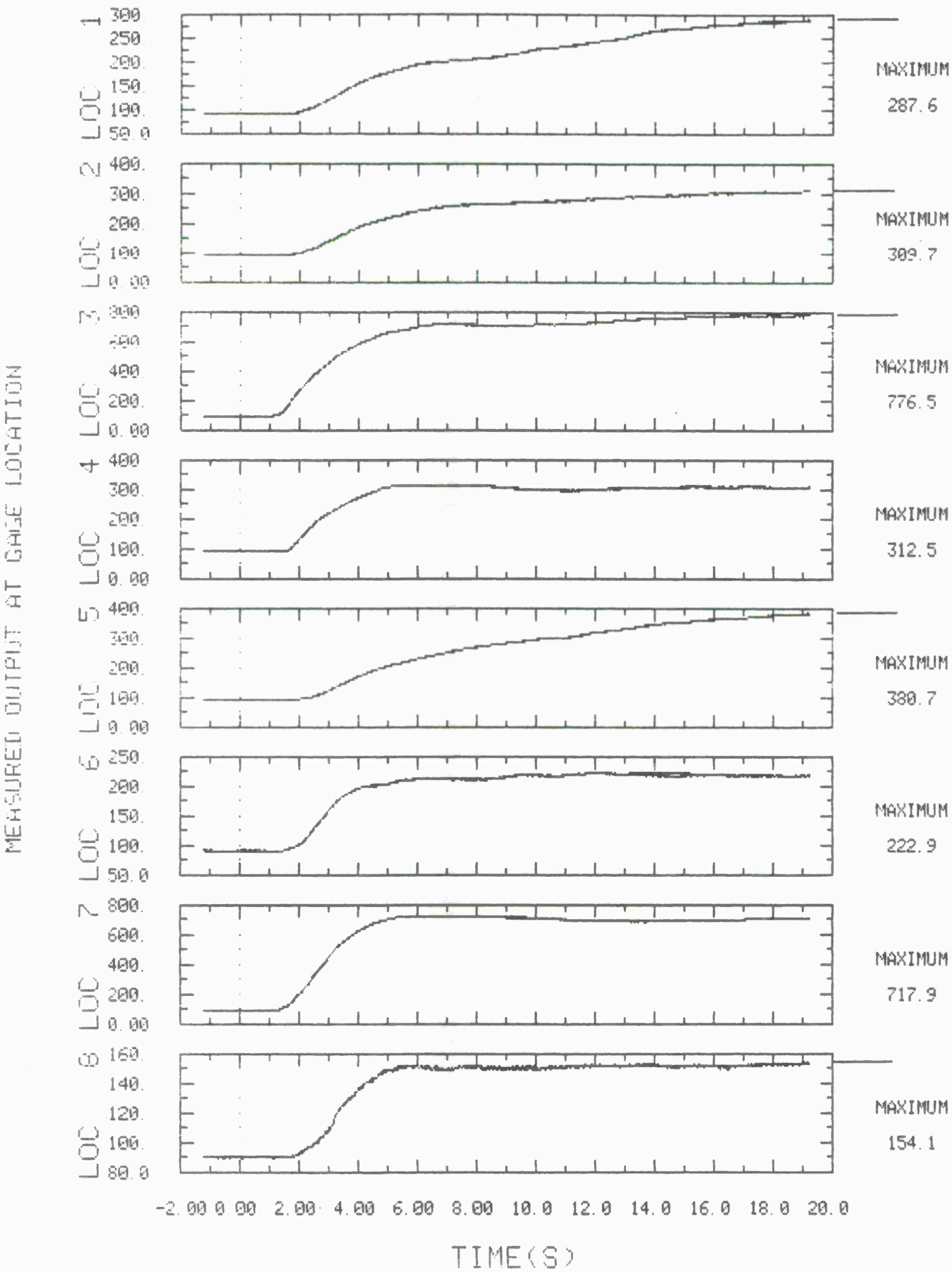


Figure B-2.

TEST NUMBER 2

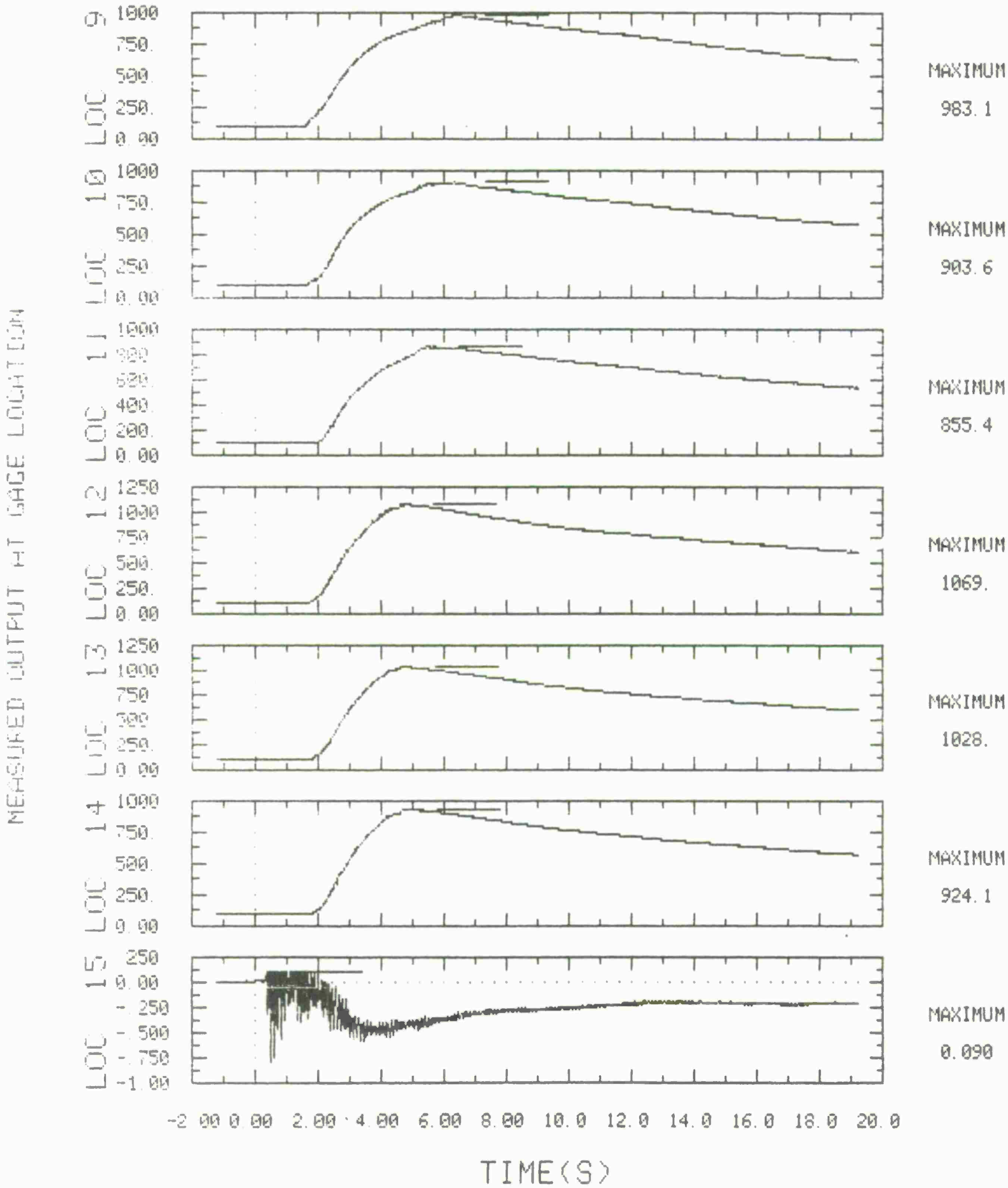


Figure B-2 (Continued)

Plume velocities were calculated for this test using the keil probe data. Keil Probe 1, which is at the top of the first rake, measured a pressure of 0.19 in. of water at 3.2 sec after ignition. The plume temperature at this time was 625°F and the resultant plume velocity was 42 ft/sec. Keil Probe 2 which is at the middle of the first rake measured a pressure of 0.22 in. of water at 3.2 sec after ignition and at a plume temperature of 625°F. This data can be converted to a velocity equal to 45 ft/sec. Probe 3 at the top of the second rake measured a plume pressure of 0.18 in. of water at 3.2 sec after ignition and at a plume temperature of 625°F. The resultant velocity was calculated to be 40.6 ft/sec. The probe at the middle of the second rake, Probe 4, measured 0.19 in. of water pressure at 3.2 sec after ignition and the plume temperature at this time was 625°F. The resultant plume velocity at this position is 42 ft/sec.

B.1.3 Test 3--M1 Propellant (4.5 lb)

Test 3 was performed using 4.5 lb of propellant in three 1/65th volumetric scale model cardboard canisters. The three canisters were centered in the igloo and simultaneously ignited using electric matches. The propellant was ignited at the top. Figure B-3 presents temperature-time profiles for each of the 14 thermocouples. The load cell output is presented in Figure B-3, see Location 15, and presents the dynamic mass loss data. As shown in this figure, the thermocouples mounted in the igloo three-fourths of the way back from the door, Locations 3 and 7, measured the highest internal temperatures, 1148°F and 753°F, respectively. The thermocouples mounted on the first rake, Probes 9, 10 and 11, also measured very high temperatures. Probe 9 measured 975°F, while Probe 10 measured 1038°F and Probe 11 measured 1127°F. This higher outside temperature indicates that unburned particles are again exiting in the plume and burning outside. The fact that Probe 11, which is at the bottom of the rake, measured the highest temperature of the rake thermocouples would indicate that the plume is very flat and has not started to rise. The probes on the second rake saw high temperatures, 570°F at the top probe, however not as high as the first rake.

Velocity of the plume was calculated using the Keil probe data. Probe 1 measured a plume pressure of 0.18 in. of water at 1.7 sec after ignition. The plume temperature was 375°F at this time and the resultant velocity was 35.6 ft/sec. Probe 2 measured a plume pressure of 0.2 in. of water at a time of 3.2 sec after ignition and at a plume temperature of 375°F. The velocity of the plume was calculated to be 37.5 ft/sec. Probe 3, which is on the second rake, measured a pressure of 0.12 in. of water at 1.7 sec after ignition and at a temperature of 375°F. The resultant velocity was calculated to be 29 ft/sec. Probe 4, also on the second rake, measured a pressure of 0.10 in. of water at 1.7 sec and at 375°F. The velocity calculated was 26.5 ft/sec.

B.1.4 Test 4--M1 Propellant (6.0 lb)

Test 4 was performed using 6 lb of M1 propellant in four 1/65th volumetric scale model cardboard canisters. Each canister was ignited

TEST NUMBER 3

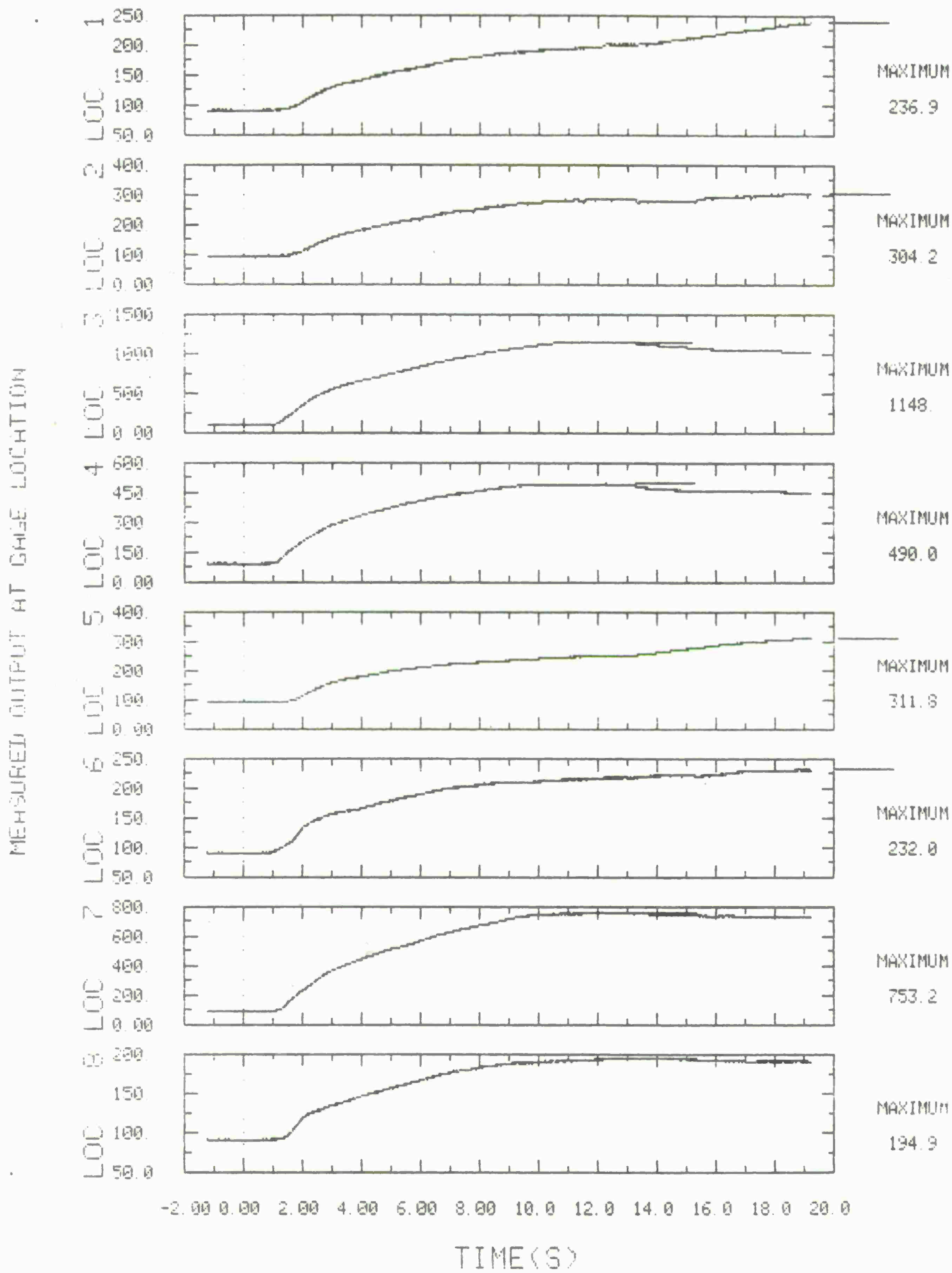


Figure B-3.

TEST NUMBER 3

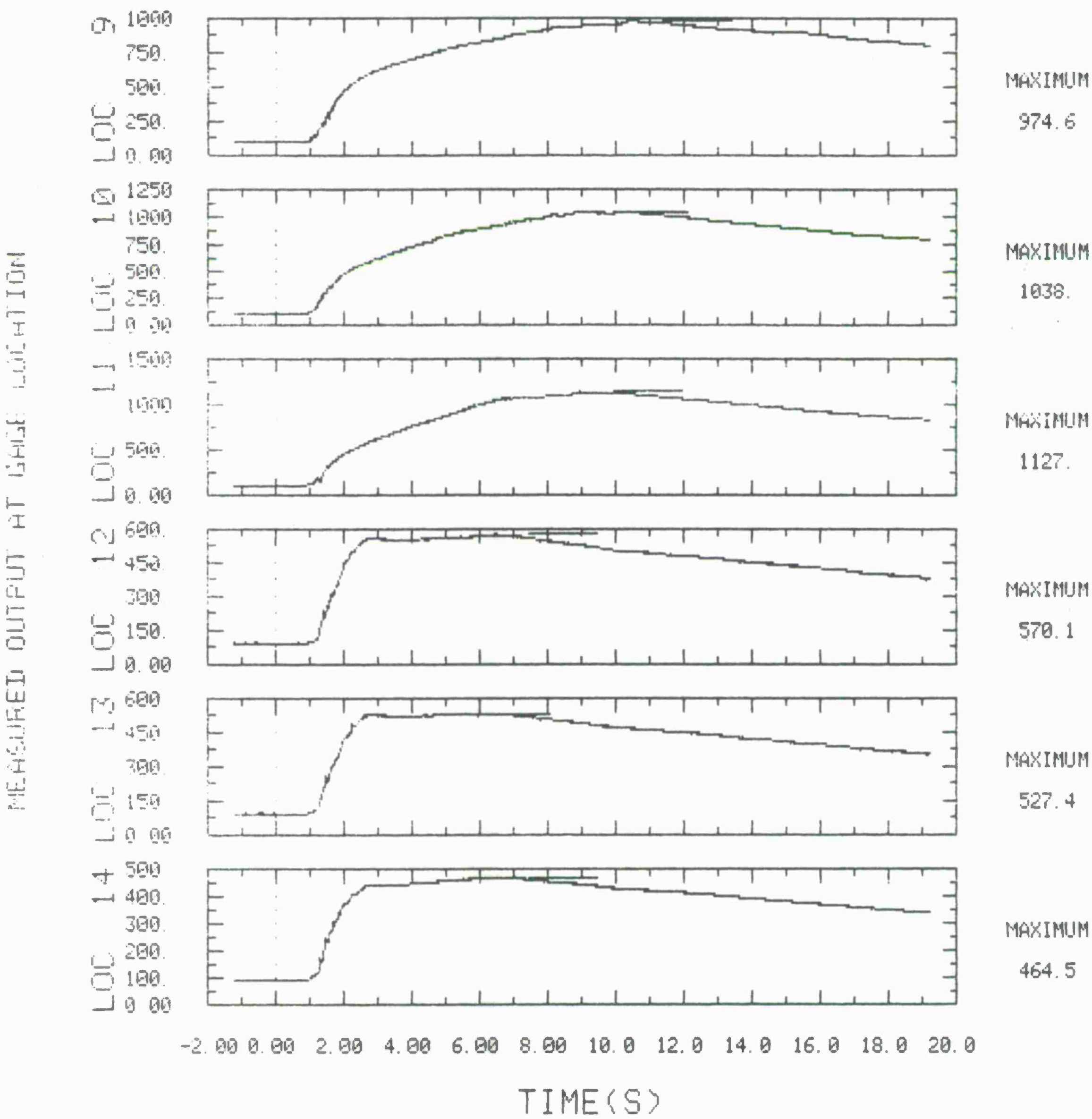


Figure B-3 (Continued)

using an electric match placed at the top of the propellant. The four canisters were placed in the igloo and simultaneously ignited. Figure B-4 presents the temperature versus time profiles for the 14 thermocouples. The load cell output is also included as Location 15. As was the case in the previous tests, Thermocouples 3 and 7 measured the highest inside temperatures, 1014°F and 740°F, respectively. The thermocouples in the first rake measured high temperatures ranging from 1057°F at Thermocouple 10 to 1099°F at Thermocouple 9. The second rake, however, measured even higher temperatures with Thermocouple 12 which is at the top measured 1194°F and Thermocouple 13 which is at the middle measuring 1145°F. Since the thermocouples outside of the igloo measure temperatures much higher than those inside the igloo, it appears that unburned particles are being ejected out of the igloo in the plume and these particles are burning outside. The fact that the second rake which is 3 ft away from the igloo measures higher temperatures than the first rake which is 7. in. away from the igloo indicates that the unburned particles are burning as they get further away from the door.

The plume velocity was calculated for the first rake and the second rake. Keil Probe 1 measured a plume pressure of 0.5 in. of water at 2.2 sec after ignition and at a temperature of 650°F. The velocity calculated using this data was 68.4 ft/sec. Probe 2 measured 0.5 in. of water at 2.2 sec after ignition and at a temperature of 800°F. The resultant velocity at Probe 2 was 73.0 ft/sec. Probe 3 measured 0.5 in. of water at 2.2 sec and at a plume temperature of 800°F. The velocity at Probe 3 was also 73 ft/sec. Probe 4 also measured 0.5 in. of water at 2.2 sec and at a plume temperature of 800°F and the resultant plume velocity was also 73 ft/sec.

B.1.5 Test 13--M1 Propellant (0.5 lb)

Test 13 was performed using 0.5 lb of M1 propellant placed in a 1/65th scaled cardboard canister. The canister was ignited using an electric match placed at the top of the propellant. The canister was centered in the igloo and then ignited. Figure B-5 presents the temperature profiles for the eight thermocouples monitored during this test. The highest internal doorway temperature was measured by Thermocouple 5 and was 242°F. The maximum temperature of the plume as measured at the first and closest rake was 450°F as measured by Thermocouple 9 at the top of the rake. This temperature is higher than the internal temperatures recorded. This would once again imply that the bulk of the propellant is being consumed inside the igloo and not being carried out in the plume as would be implied if the second rake temperatures were higher than the internal temperatures.

Velocities of the plume at both rakes were calculated using the pressures measured by the Keil probes and their corresponding plume temperatures. Keil Probe 1 measured a pressure of 0.05 in. of water at a plume temperature of 300°F which calculated out to be a velocity of 18 ft/sec. Probe 2 measured 0.04 in. of water at a plume temperature of 250°F

TEST NUMBER 4

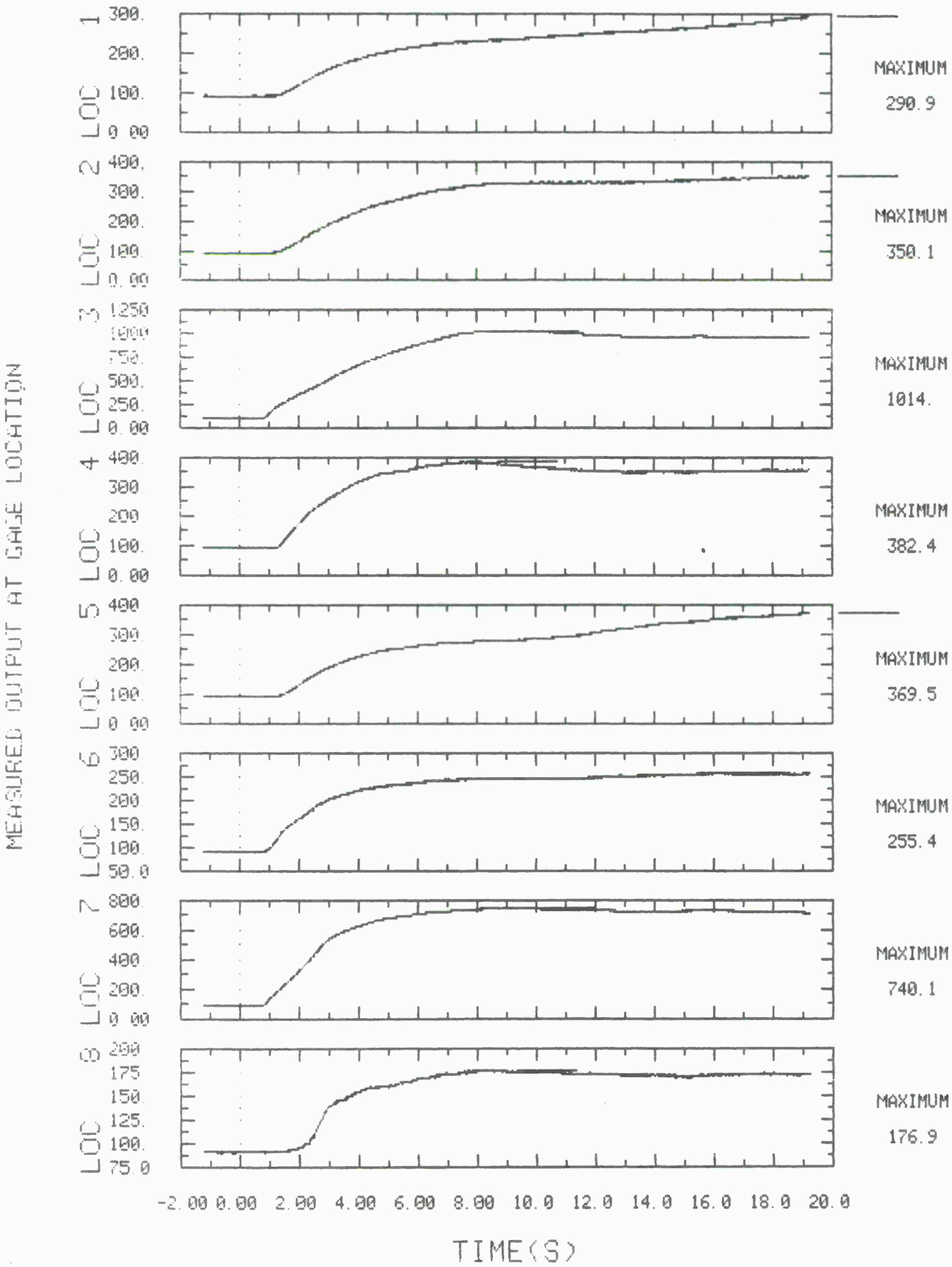


Figure B-4.

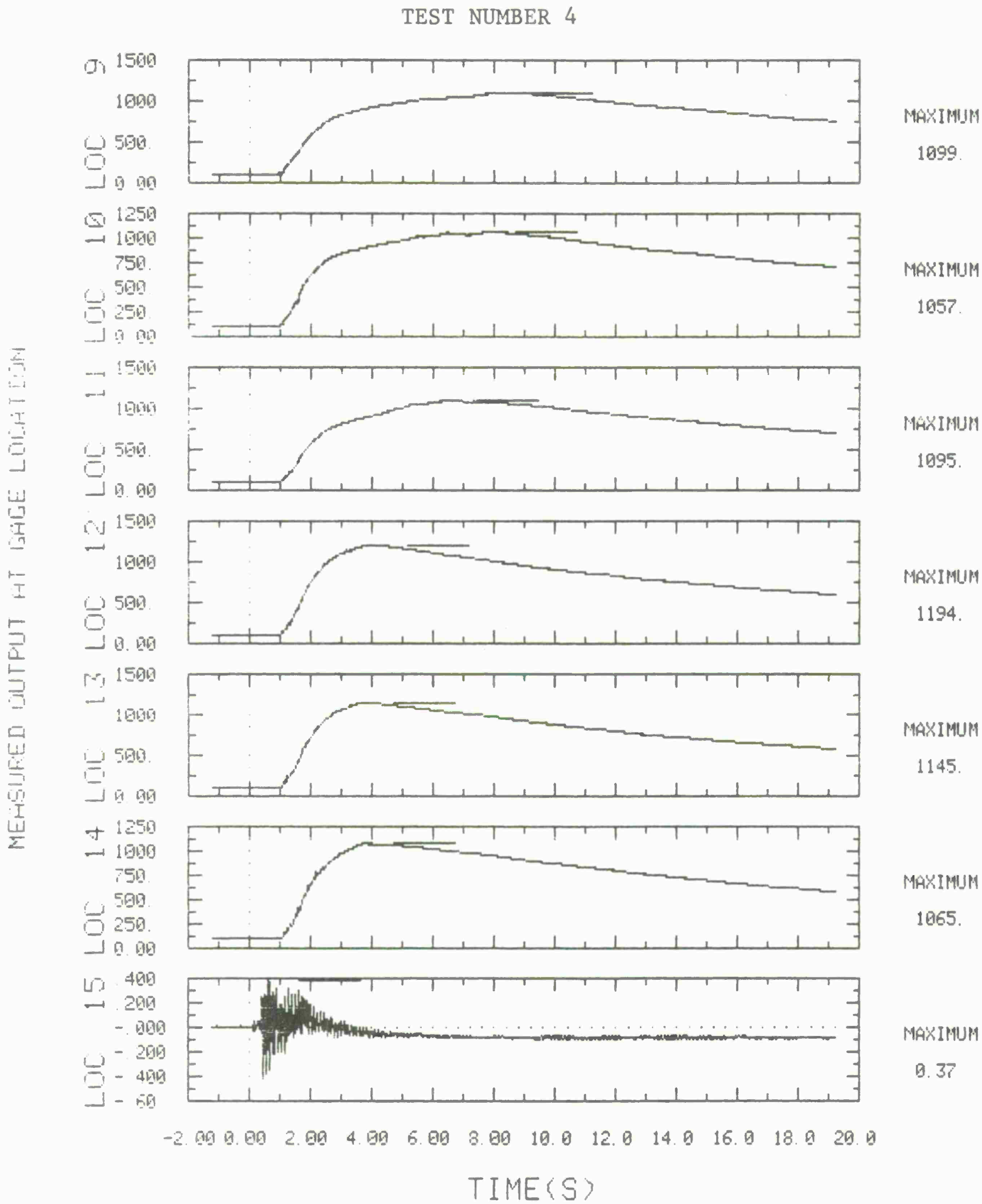


Figure B-4 (Continued)

TEST NUMBER 13

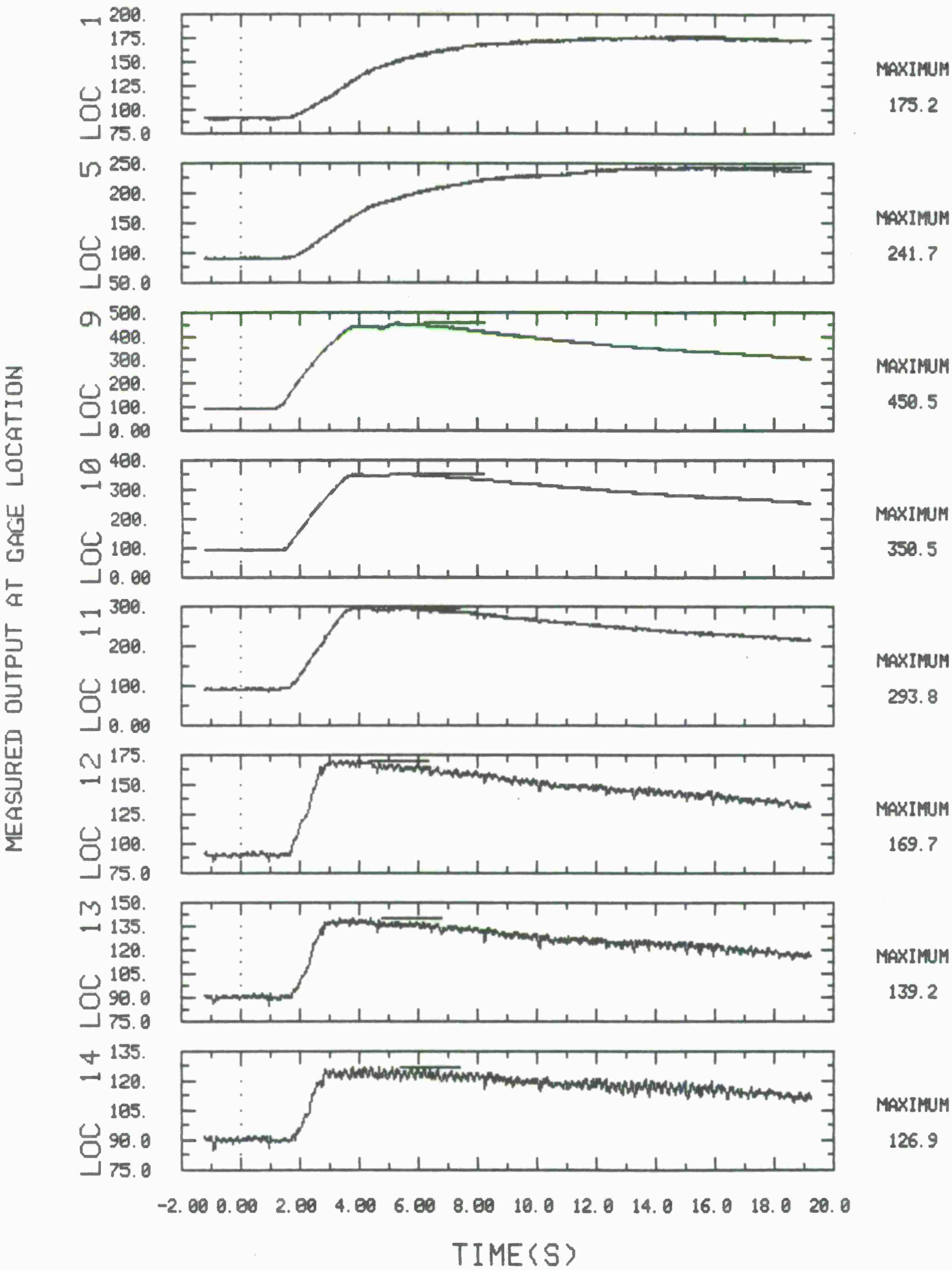


Figure B-5.

and the resultant velocity is 15.5 ft/sec. Probes 3 and 4 measured 0.02 in. of water at temperatures of about 150°F which converts to approximately 10.5 ft/sec.

B.1.6 Test 14--M1 Propellant (1.0 lb)

Test 14 was performed using 0.1 lb of M1 propellant. The propellant was placed in a single scaled canister and centered in the igloo. Ignition was achieved using an electric match placed at the top of the propellant. Once again, only eight thermocouples were used and temperature profiles for these thermocouples is provided in Figure B-6. As can be seen in this figure, the maximum internal doorway temperature was 291°F recorded by Thermocouple 5. All of the temperatures measured at the first rake, Thermocouples 9, 10 and 11, easily exceeded this temperature (584°F, 502°F and 469°F, respectively). The temperature measured by the top thermocouple on the second rake was 299°F (Thermocouple 12) which just barely exceeded the internal temperature. The other two thermocouples, 13 and 14, measured 242°F and 223°F which is below the internal temperature but by the smaller difference than on the previous tests. This closeness in internal and external temperatures indicates that the threshold of total consumption of the propellant in the igloo or venting of burned propellant in the plume which will burn outside was quickly being reached. This was further verified by reviewing the temperatures for Test 1 which used 1.5 lb of propellant. On Test 1, the temperature outside were higher than those inside the igloo.

Velocities of the plume were calculated for each of the two Keil probes attached to the rakes. Keil Probe 1 measured a pressure of 0.12 in. of water at a temperature of 450°F. The resultant velocity was calculated to be 30.4 ft/sec. Keil Probe 2 measured 0.11 in. of water pressure at a plume temperature of 400°F which calculated out to be a velocity of 28 ft/sec. Keil Probe 3 measured a pressure of 0.065 in. of water at a temperature of 250°F which converts to a velocity of 19.7 ft/sec. Probe 4 measured a pressure of 0.065 in. of water at a temperature of 200°F which calculates to be a velocity of 19 ft/sec.

B.2 IMR-5010 Propellant Test

B.2.1 Test 5--IMR-5010 Propellant (2.0 lb)

The first IMR-5010 propellant test was performed using 3 lb of propellant contained in a sealed cardboard canister. The canister was centered in the 1/10th scale model igloo and ignited using an electric match. Figure B-7 presents temperature profiles for the 14 thermocouples and also the output of the load cells. As shown in this figure, the two central thermocouples (Probes 3 and 7) recorded the highest internal temperatures, 984°F and 780°F, respectively. The thermocouples mounted on the first rake (Probes 9, 10 and 11, top to bottom) measured higher temperatures than those measured inside the igloo, 1100°F, 1033°F and 997°F, respectively. The thermocouples mounted on the second rake (Probes

TEST NUMBER 14

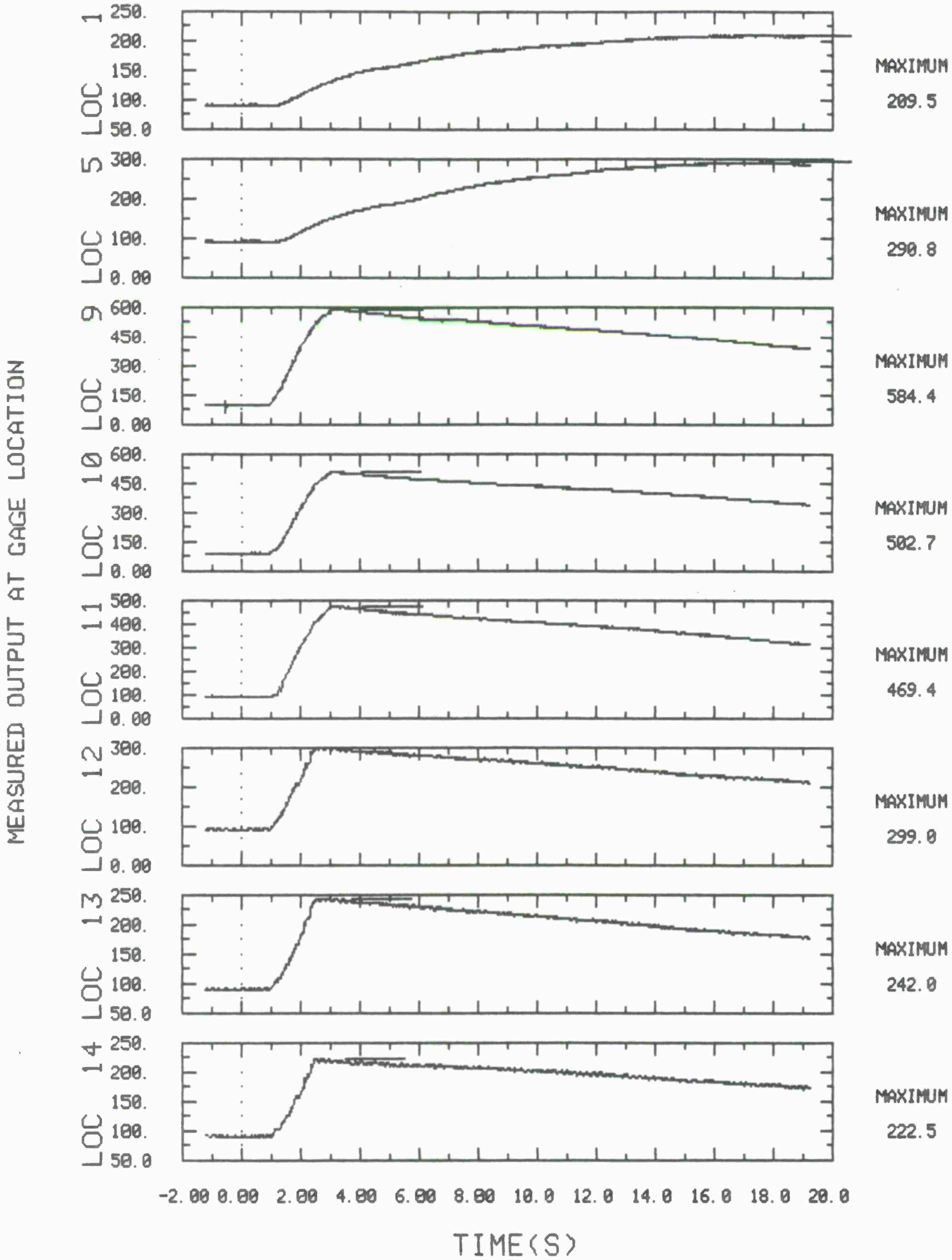


Figure B-6.

TEST NUMBER 5

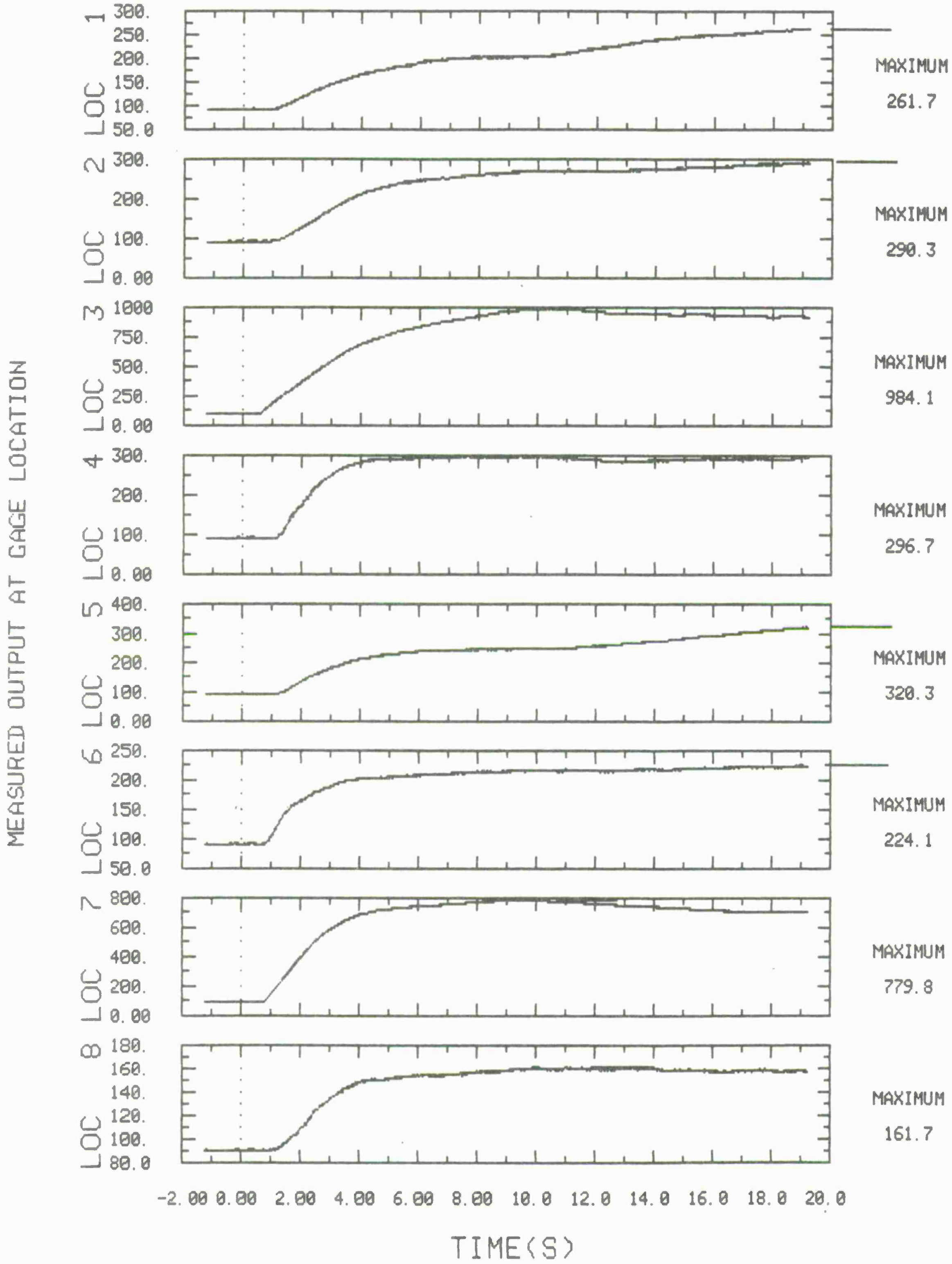


Figure B-7.

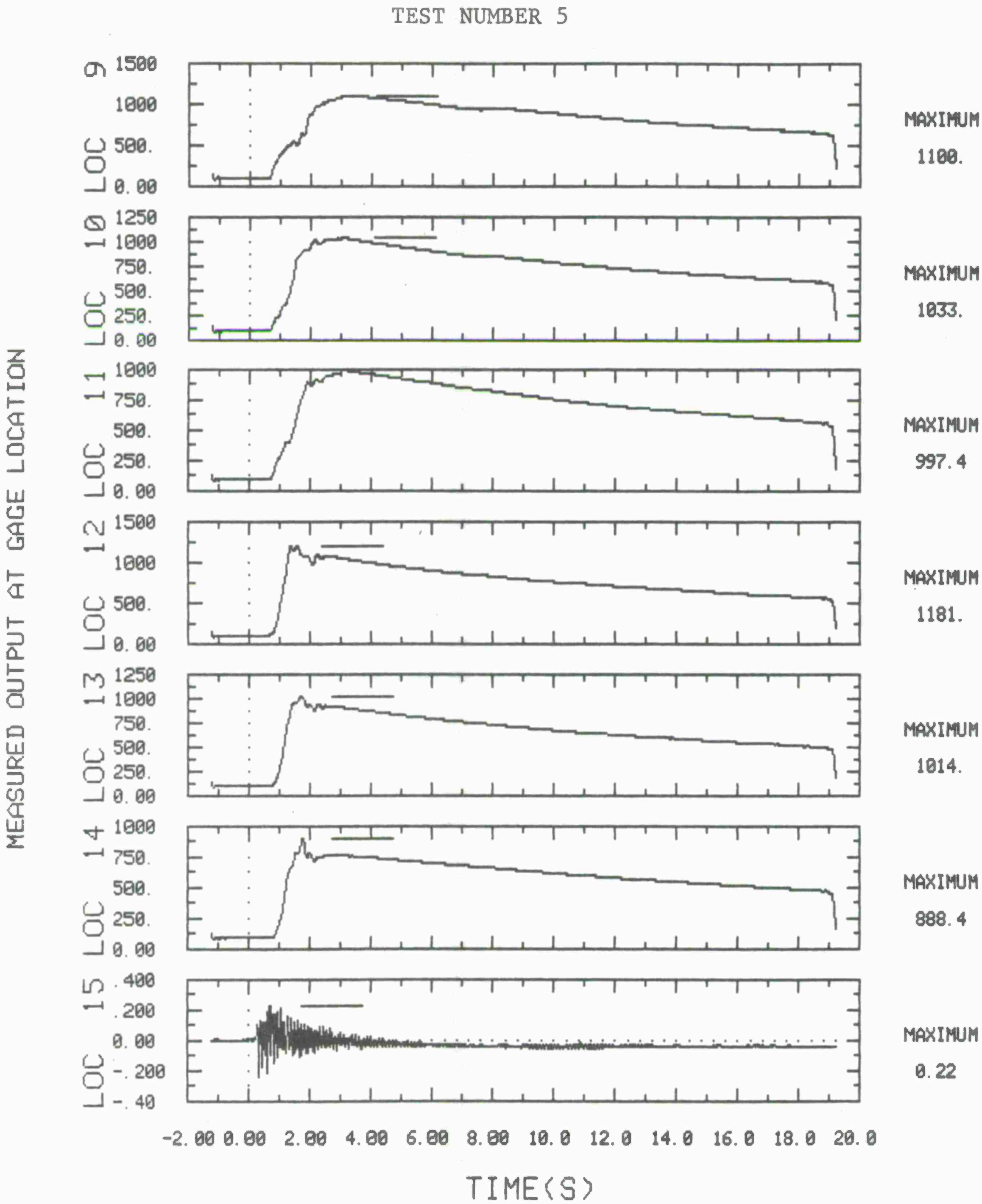


Figure B-7 (Continued)

12, 13 and 14) were 3 ft away from the igloo door and also measured very high temperatures, 1181°F, 1014°F and 888°F, respectively.

Plume velocities were calculated for this test using the Keil probe data. Keil Probe 1, which is at the top of the first rake, measured a pressure of 0.25 in. of water at 1.9 sec after ignition. The plume temperature at this time was 800°F and the resultant plume velocity was 52 ft/sec. Keil Probe 2 which is at the middle of the first rake measured a pressure of 0.25 in. of water at 1.9 sec after ignition and at a plume temperature of 900°F. This data can be converted to a velocity equal to 54 ft/sec. Probe 3 at the top of the second rake measured a plume pressure of 0.22 in. of water at 1.9 sec after ignition and at a plume temperature of 1000°F. The resultant velocity was calculated to be 52.0 ft/sec. The probe at the middle of the second rake, Probe 4, measured 0.20 in. of water pressure at 1.9 sec after ignition and the plume temperature at this time was 900°F. The resultant plume velocity at this position is 48 ft/sec.

B.2.2 Test 6--IMR-5010 Propellant (4.0 lb)

The second propellant test was performed using 4 lb of IMR-5010 propellant contained in two scaled cardboard canisters. The canisters were centered in the 1/10th scale model igloo and simultaneously ignited using an electric match in each canister. Figure B-8 presents temperature profiles for the 14 thermocouples and also the output of the load cells. As shown in this figure, the two central thermocouples (Probes 3 and 7) again were the ones that recorded the highest internal temperatures, 1070°F and 973°F, respectively. The thermocouples which were mounted on the first rake (Probes 9, 10 and 11, top to bottom) measured higher temperatures than those measured inside the igloo, 1231°F, 1230°F and 1284°F, respectively. The thermocouples mounted on the second rake (Probes 12, 13 and 14) were 3 ft away from the igloo door and measured even higher temperatures, 1704°F, 1504°F and 1397°F, respectively. This phenomena would again imply that unburned particles are exiting the igloo in the plume and are burning outside of the igloo.

Plume velocities were calculated for this test using the keil probe data. Keil Probe 1, which is at the top of the first rake, measured a presure of 0.35 in. of water at 2.6 sec after ignition. The plume temperature at this time was 1000°F and the resultant plume velocity was 66 ft/sec. Keil Probe 2 which is at the middle of the first rake measured a pressure in excess of 0.5 in. of water at 2.6 sec after ignition and at a plume temperature of 1000°F. This data can be converted to a velocity equal to 78 ft/sec. Probe 3 at the top of the second rake measured a plume pressure of 0.39 in. of water at 2.6 sec after ignition and at a plume temperature of 1400°F. The resultant velocity was calculated to be 78 ft/sec. The probe at the middle of the second rake, Probe 4, measured 0.4 in. of water pressure at 2.6 sec after ignition and the plume temperature at this time was 1250°F. The resultant plume velocity at this position is 76 ft/sec.

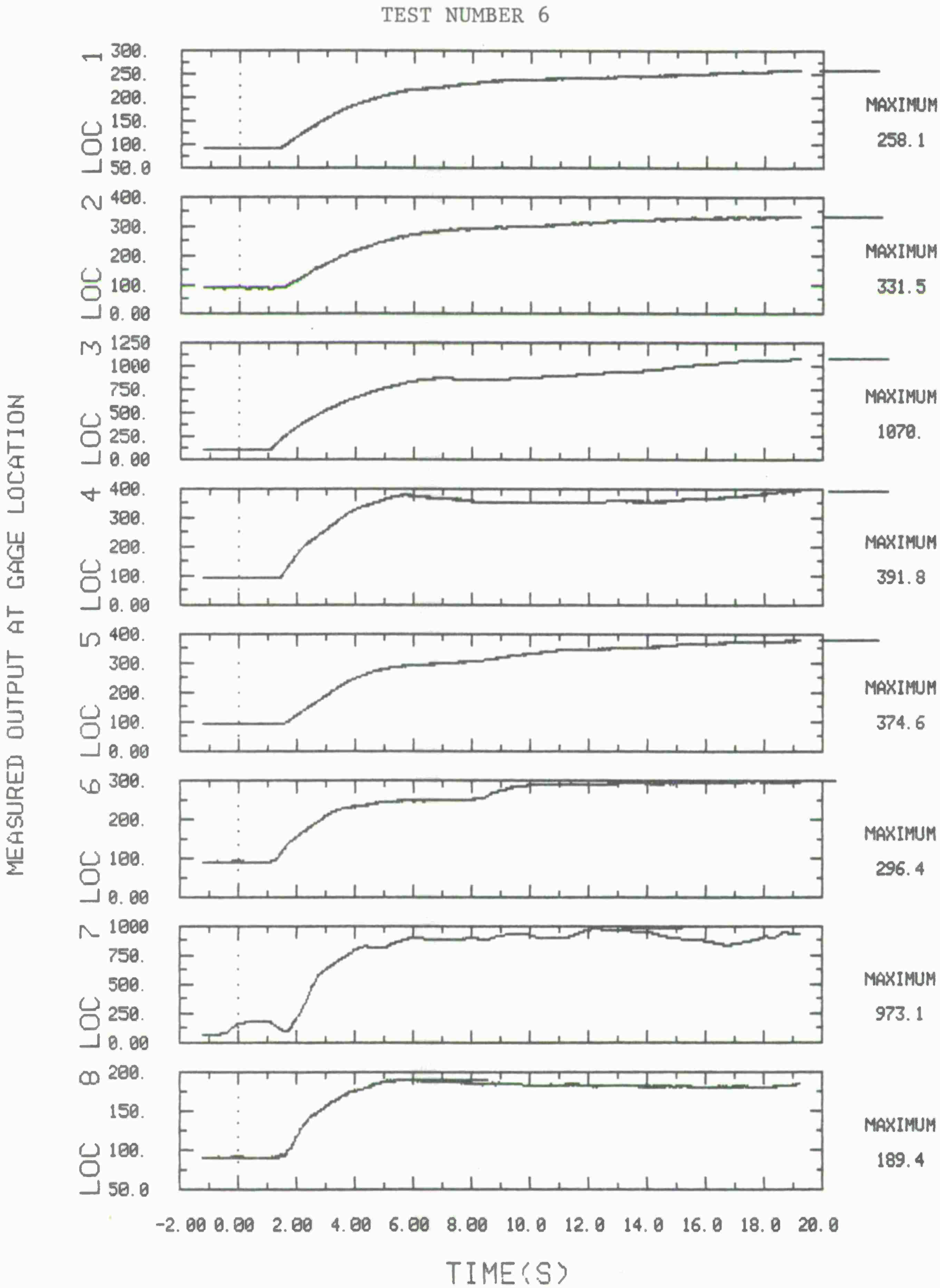

TEST NUMBER 6
MEASURED OUTPUT AT GAGE LOCATION
LOC 1
LOC 2
LOC 3
LOC 4
LOC 5
LOC 6
LOC 7
LOC 8
MAXIMUM
258.1
MAXIMUM
331.5
MAXIMUM
1070.
MAXIMUM
391.8
MAXIMUM
374.6
MAXIMUM
296.4
MAXIMUM
973.1
MAXIMUM
189.4
-2.00 0.00 2.00 4.00 6.00 8.00 10.0 12.0 14.0 16.0 18.0 20.0
TIME(S)

Figure B-8.

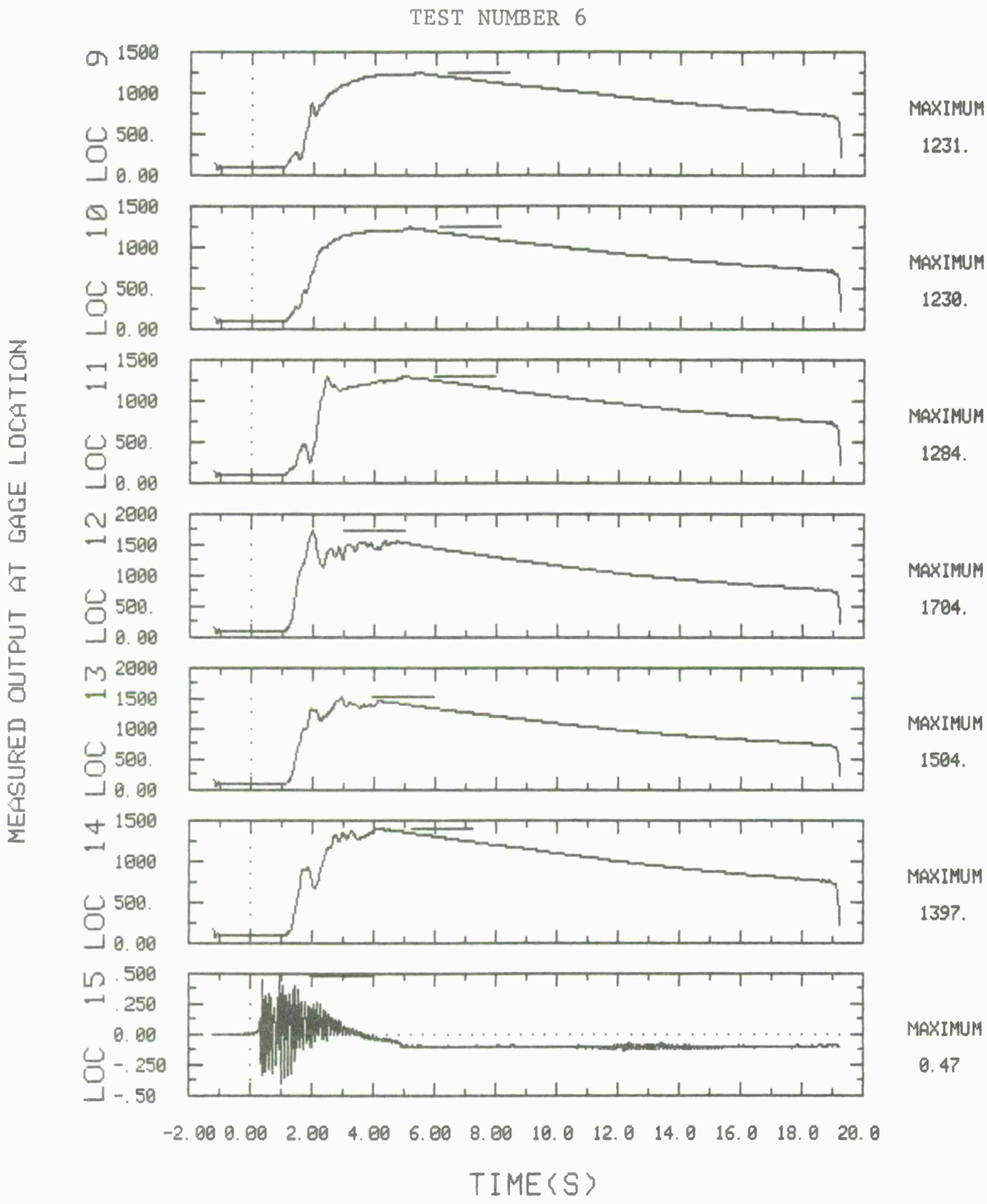


Figure B-8 (Continued)

B.2.3 Test 7--IMR-5010 Propellant (6.0 lb)

Test 7 was performed using 6 lb of propellant in three volumetric scale model cardboard canisters. The three canisters were centered in the igloo and simultaneously ignited using electric matches. The propellant was ignited at the top. Figure B-9 presents temperature-time profiles for the 14 thermocouples and also the output of the load cells at Location 15 as well as the dynamic mass loss data. As shown in this figure, the thermocouples mounted in the igloo three-fourths of the way back from the door, Locations 3 and 7, measured the highest internal temperatures, 1299°F and 1021°F, respectively. The thermocouples mounted on the first rake (Probes 9, 10 and 11, top to bottom) measured high temperatures, 1824°F, 1877°F and 1837°F, respectively. This higher outside temperature indicates that unburned particles are again exiting in the plume and burning outside. The fact that Probe 11 which is at the bottom of the rake measured the highest temperature of the rake thermocouples would indicate that the plume is very flat and has not started to rise. The probes on the second rake also saw high temperatures, 1672°F at the top probe, 1644°F at the middle probe and 1555°F at the bottom of the rake. These temperatures were slightly lower than those measured at the first rake.

Plume velocities were calculated for this test using the Keil probe data. Keil Probe 1 measured a pressure of 0.33 in. of water at 2.6 sec after ignition. The plume temperature at this time was 1750°F and the resultant plume velocity was 78.4 ft/sec. Keil Probe 2 measured a pressure in excess of 0.5 in. of water at 2.6 sec after ignition and at a plume temperature of 1750°F. The velocity of the plume was calculated to be 97 ft/sec. Probe 3, which is on the second rake, measured a plume pressure of 0.35 in. of water at 2.6 sec after ignition and at a plume temperature of 800°F. The resultant velocity was calculated to be 61 ft/sec. Probe 4, also on the second rake, measured 0.35 in. of water pressure at 2.6 sec after ignition and the plume temperature at this time was 800°F. The resultant plume velocity at this position is 61 ft/sec.

B.2.4 Test 15--IMR-5010 Propellant (0.5 lb)

This test involved 0.5 lb of propellant placed in a scaled cardboard canister. The canister was centered in the igloo and the propellant ignited using an electric match. Eight thermocouples were used on this test, two just inside the igloo doorway and six thermocouples mounted on two rakes outside of the igloo. Temperature profiles for the eight thermocouples are presented in Figure B-10. As shown in this figure, the maximum internal temperature was measured by Thermocouple 5 and was 225°F. The temperatures measured at the first and closest rake greatly exceeded the internal temperature. The temperatures measured at the second rake, which was 3 ft away, just barely exceeded the internal temperatures. As was the case in Test 14 using the M1 propellant it appears that for this test, the threshold of whether the propellant all burns inside the igloo or whether some propellant gets carried out in the plume and burns outside is quickly being approached. It would appear that any larger quantity of

TEST NUMBER 7

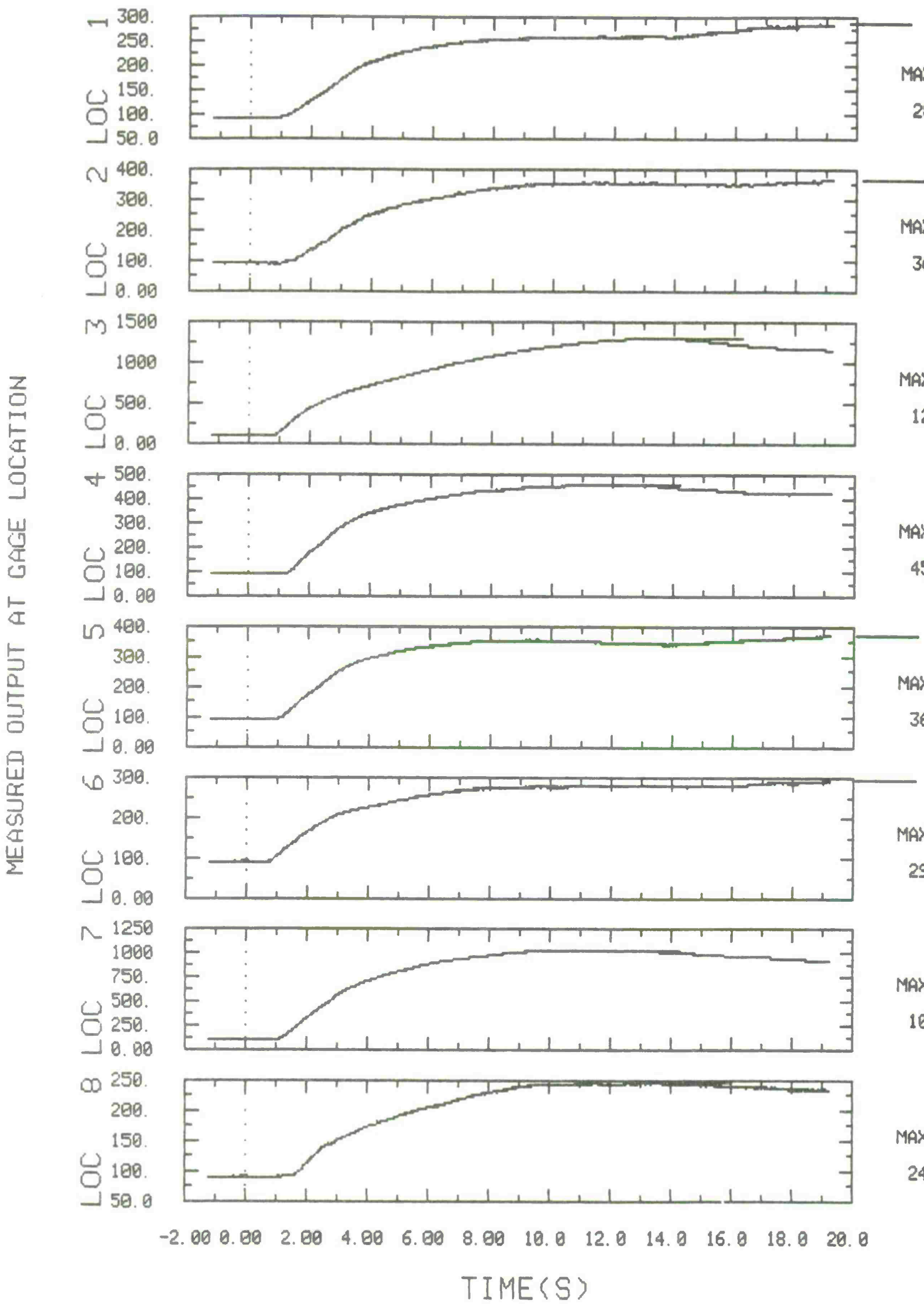


Figure B-9.

TEST NUMBER 7

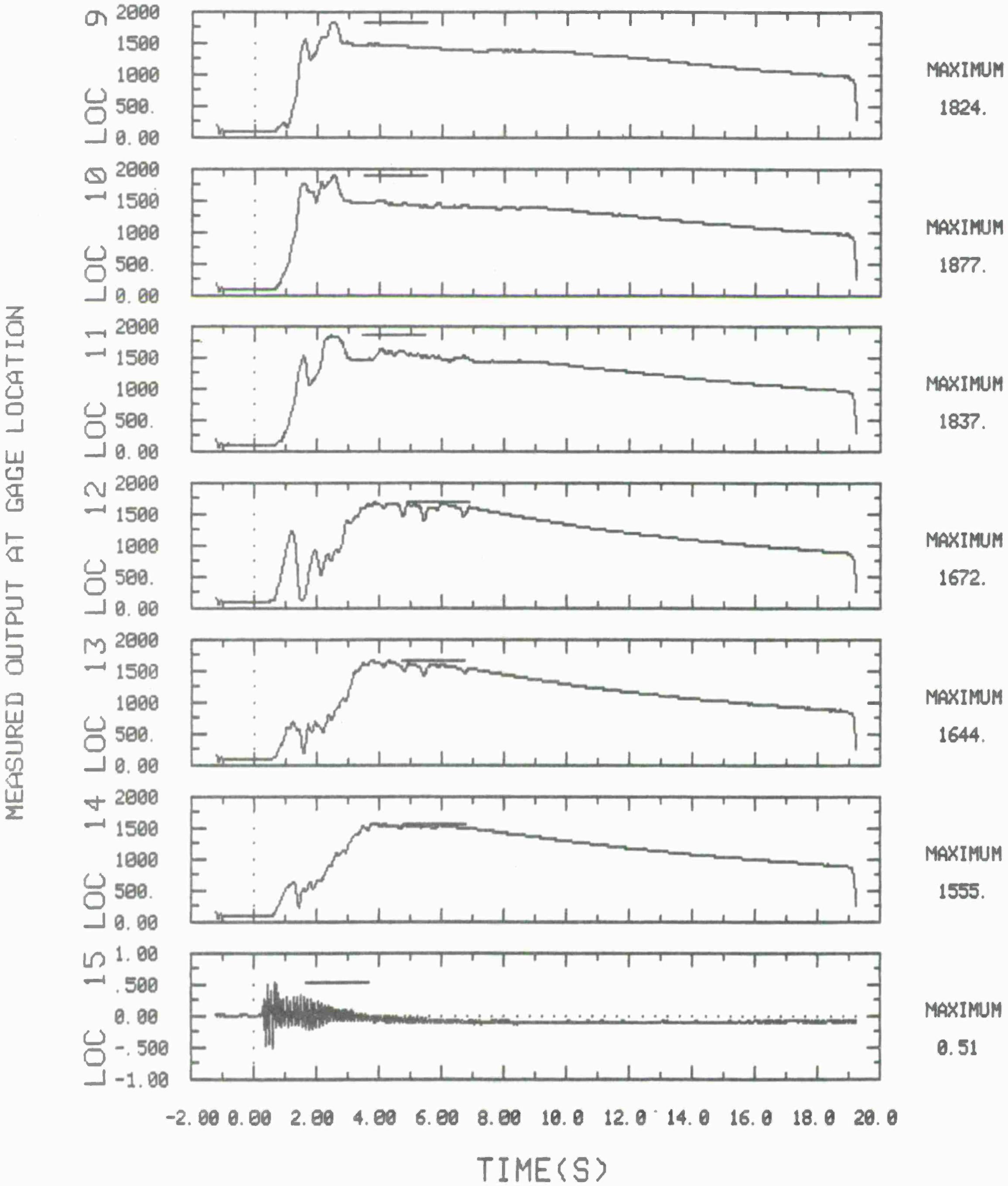
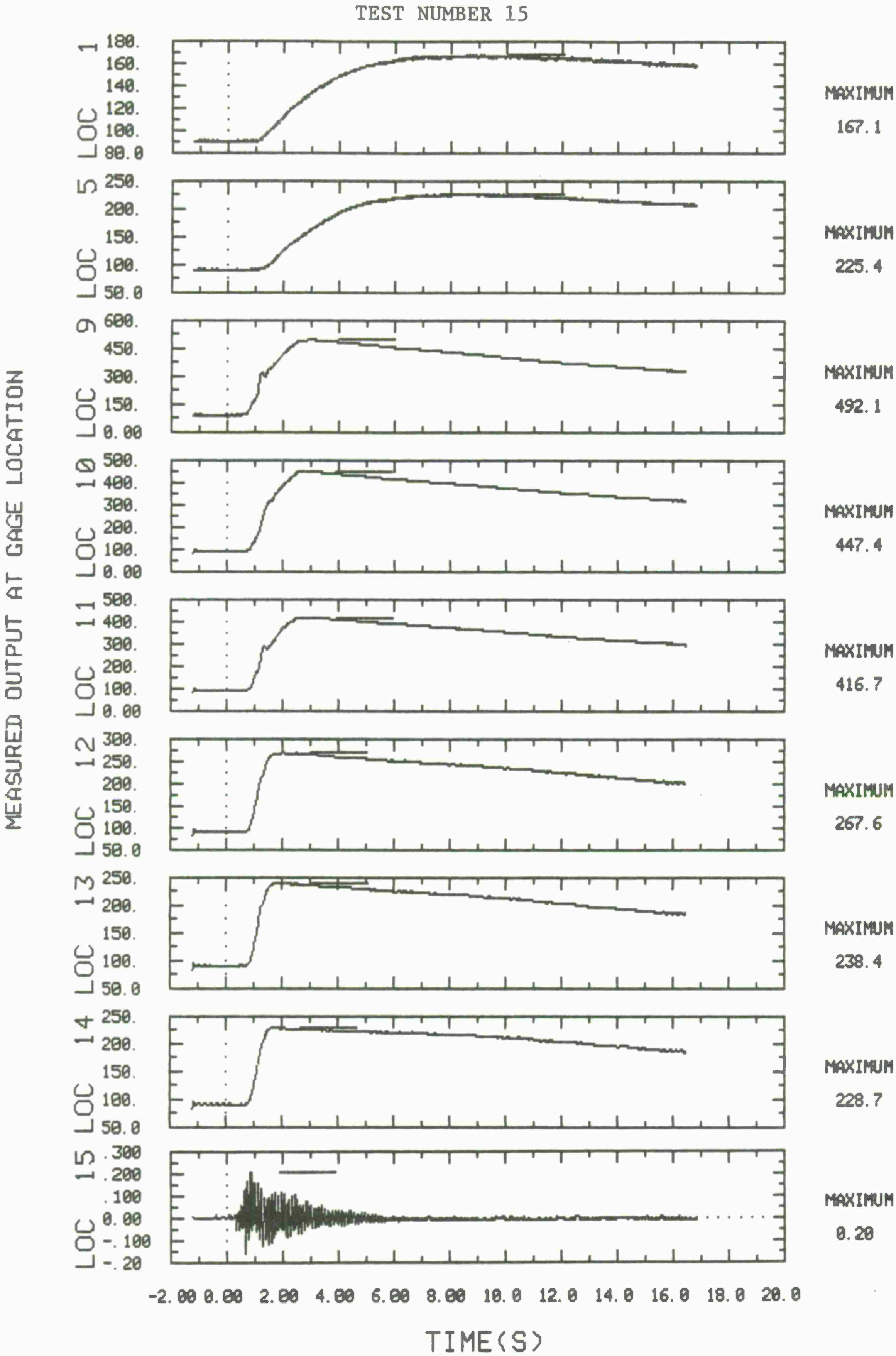


Figure B-9 (Continued)



TEST NUMBER 15
MEASURED OUTPUT AT GAGE LOCATION
LOC 1
LOC 5
LOC 9
LOC 10
LOC 11
LOC 12
LOC 13
LOC 14
LOC 15
MAXIMUM 167.1
MAXIMUM 225.4
MAXIMUM 492.1
MAXIMUM 447.4
MAXIMUM 416.7
MAXIMUM 267.6
MAXIMUM 238.4
MAXIMUM 228.7
MAXIMUM 0.20
-2.00 0.00 2.00 4.00 6.00 8.00 10.0 12.0 14.0 16.0 18.0 20.0
TIME(S)

Figure B-10.

propellant will result in partial burning inside of the igloo and some burning outside and this phenomena is verified in Test 5.

Plume velocities were calculated using the Keil probes mounted to the two rakes. Keil Probe 1 measured a pressure of 0.18 in. of water at a plume temperature of 300°F which converts to a velocity equal to 34 ft/sec. Keil Probe 2 measured a pressure of 0.16 in. of water at a plume temperature of 250°F. The resultant velocity was 31 ft/sec. Probes 3 and 4 which were on the second rake measured pressures of 0.11 in. of water and 0.09 in. of water, respectively. The temperatures recorded were 200°F and 175°F. The calculated velocities were 25 ft/sec for Probe 3 and 22 ft/sec for Probe 4.

B.2.5 Test 16--IMR-5010 Propellant (1 lb)

This test was performed using 1 lb of propellant to see if the propellant would be carried out in the plume. The propellant was placed in a scaled cardboard canister and centered in the igloo. Ignition as achieved using an electric match placed at the top of the propellant. Figure B-11 presents temperature profiles for the eight thermocouples. As can be seen in this figure, the majority of the thermocouples show a second step in temperature at approximately 9 sec after ignition. The video recording for this test was reviewed and a second ignition is visible; however, why this second ignition occurred is not known. The resultant temperatures are lower than expected and the data does not appear to be usable in our analysis.

Plume velocities were calculated for this test; however, the temperatures at which the Keil probes measured a maximum pressure correspond to the first step and the velocities are therefore low. The first probe, Keil Probe 1, measured 0.06 in. of water at a temperature of 300°F which calculated to a velocity of 19.6 ft/sec. Keil Probe 2 measured 0.05 in. of water at a temperature of 275°F which converts to a velocity of 17.6 ft/sec. Probes 3 and 4 saw very little pressure and the resultant velocities were 11 ft/sec and 10 ft/sec, respectively.

B.3 IMR-8208 Propellant Tests

B.3.1 Test 8--IMR-8208 Propellant (2.0 lb)

The first test performed using the IMR-8208 propellant involved 2 lb of propellant in a single scaled cardboard canister. The propellant canister was placed in the center of the igloo and was initiated using an electric match placed at the top of the propellant. Figure B-12 presents temperature profiles for the 14 thermocouples used in the test and also presents the load cell output. As shown in this figure, the highest temperatures recorded inside the igloo were 1102°F and 915°F recorded by Thermocouples 3 and 7, respectively. The temperatures measured at the first rake were high; however, they were lower than the maximum internal temperature of 1102°F. The temperatures measured at the second rake which

TEST NUMBER 16

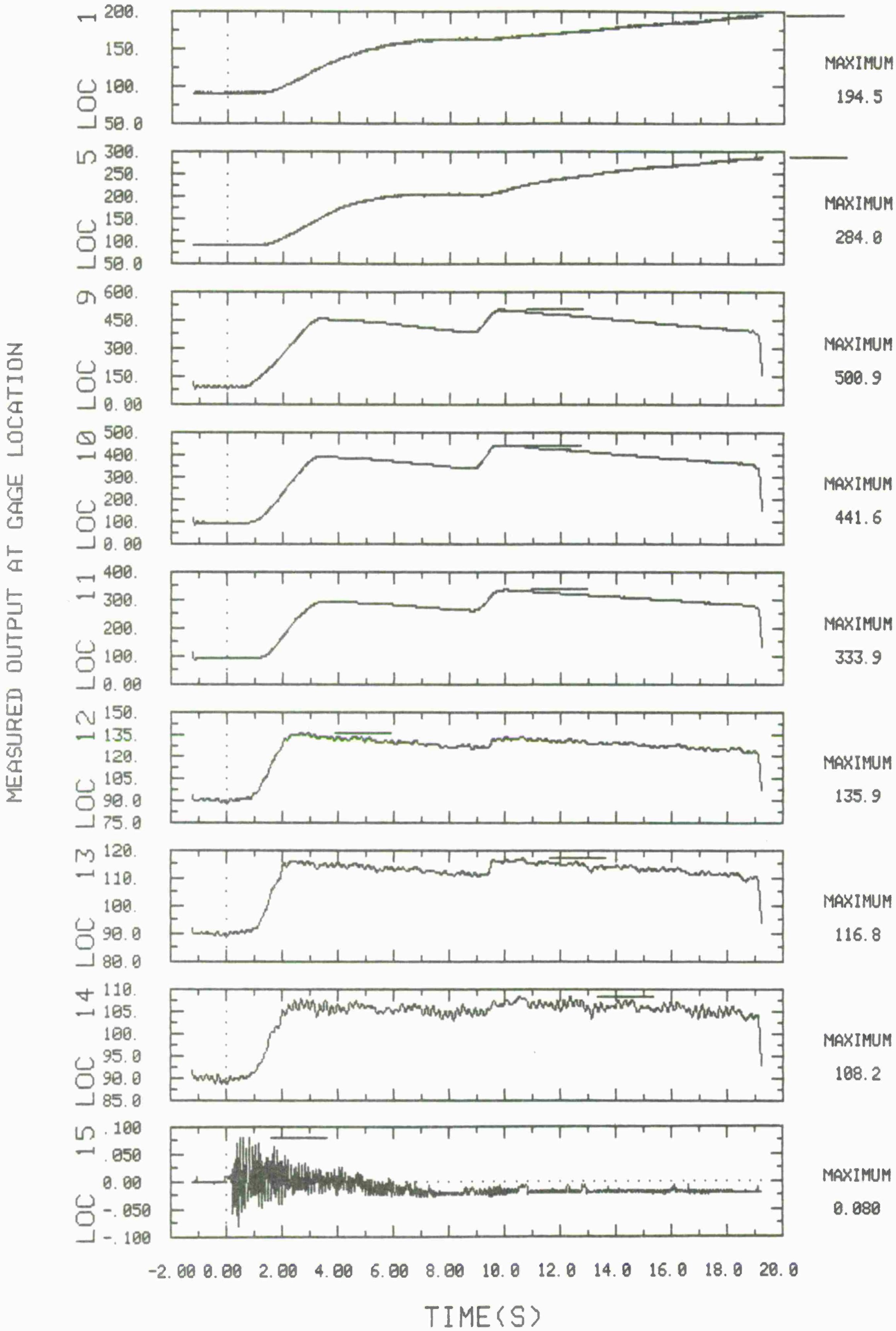


Figure B-11.

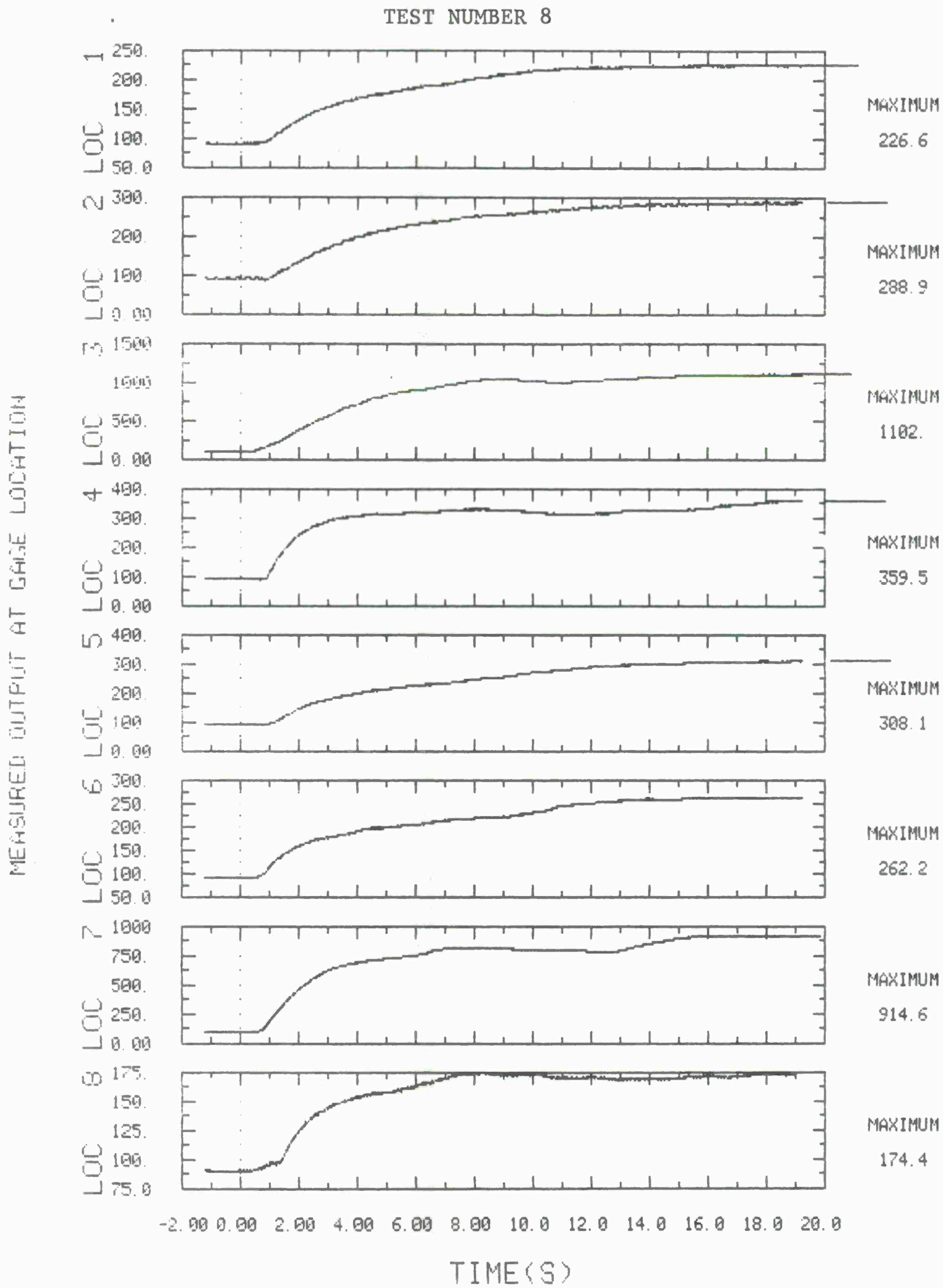

TEST NUMBER 8
MEASURED OUTPUT AT GAGE LOCATION
LOC 1
250.
200.
150.
100.
50.0
MAXIMUM
226.6
LOC 2
300.
200.
100.
0.00
MAXIMUM
288.9
LOC 3
1500
1000
500.
0.00
MAXIMUM
1102.
LOC 4
400.
300.
200.
100.
0.00
MAXIMUM
359.5
LOC 5
400.
300.
200.
100.
0.00
MAXIMUM
308.1
LOC 6
300.
250.
200.
150.
100.
50.0
MAXIMUM
262.2
LOC 7
1000
750.
500.
250.
0.00
MAXIMUM
914.6
LOC 8
175.
150.
125.
100.
75.0
MAXIMUM
174.4
-2.00 0.00 2.00 4.00 6.00 8.00 10.0 12.0 14.0 16.0 18.0 20.0
TIME(S)

Figure B-12.

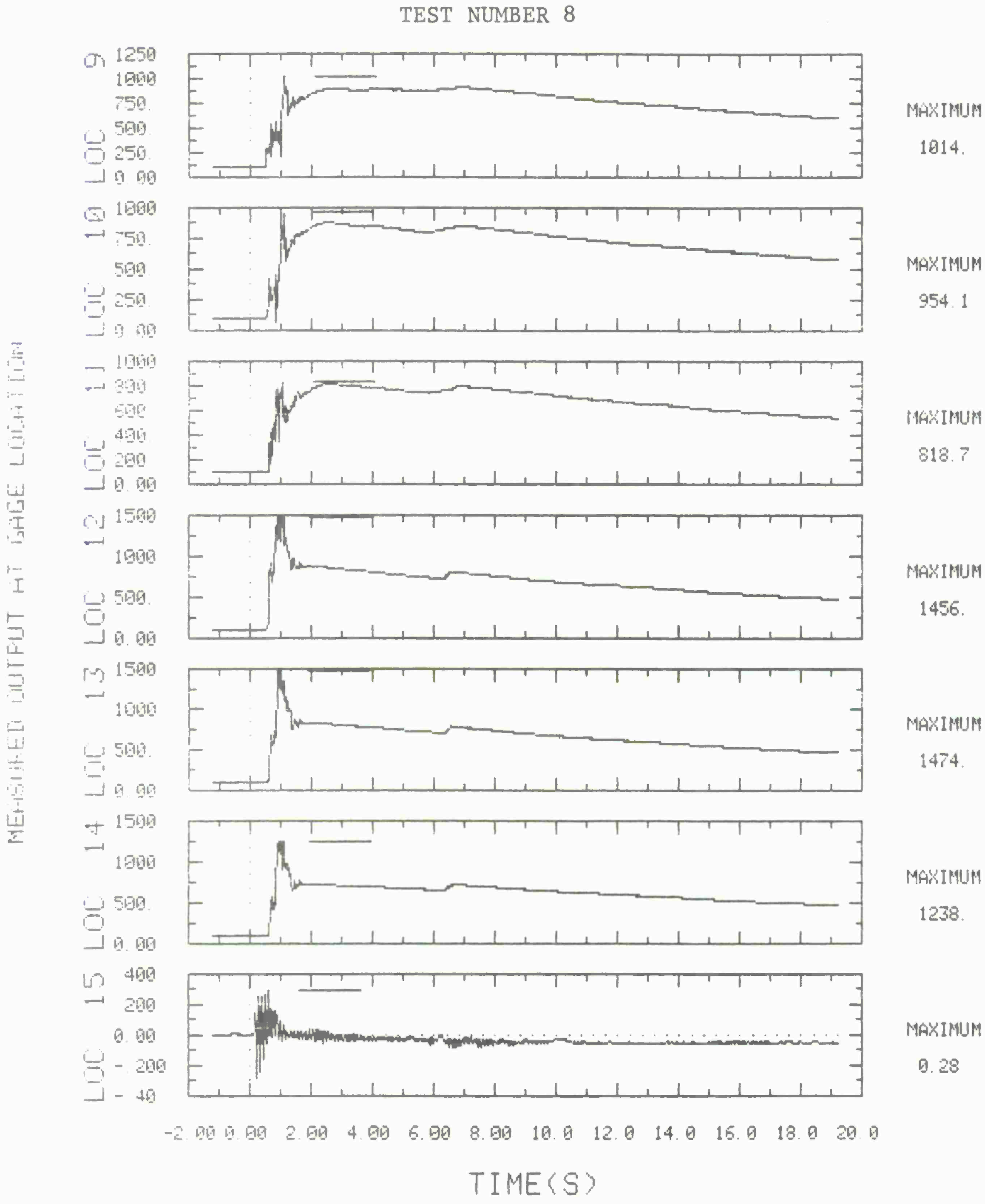


Figure B-12 (Continued)

was 3 ft away were much higher than the maximum internal temperature. These higher temperatures 3 ft away from the cube indicate that unburned propellant was being carried out of the igloo by the plume and burning outside.

Plume velocities were calculated for this test using the Keil probe data recorded at the two rakes. Probe 1 at the top of the first rake measured a pressure of 0.28 in. of water at 1.1 sec after ignition and at a plume temperature of 800°F. This data converts to a plume velocity of 54.5 ft/sec. Keil Probe 2 measured a pressure of 0.32 in. of water, 1.1 sec after ignition and at a plume temperature of 800°F also. The resultant plume velocity was calculated to be 58.3 ft/sec. Probe 3 which was at the top of the second rake measured 0.27 in. of water pressure also at the time of 1.1 sec after ignition. The plume temperature was 1250°F and the resultant plume velocity is 62.4 ft/sec. Probe 4 also on the second rake measured a pressure of 0.22 in. of water at a time of 1.3 sec after ignition. The plume temperature was measured at 1000°F and the resultant calculated plume velocity was 52 ft/sec.

B.3.2 Test 9--IMR-8208 Propellant (4.0 lb)

The second propellant test was performed using 4 lb of IMR-8208 propellant contained in two scaled cardboard canisters. The canisters were centered in the igloo and simultaneously ignited using an electric match in each canister. Figure B-13 presents temperature profiles for the 14 thermocoules and also the output of the load cells. As shown in this figure, the two central thermocouples (Probes 3 and 7) recorded the highest internal temperatures, 675°F and 597°F, respectively. The thermocouples mounted on the first rake (Probes 9, 10 and 11, top to bottom) measured higher temperatures than those measured inside the igloo, 1439°F, 1301°F and 1243°F, respectively. The thermocouples mounted on the second rake (Probes 12, 13 and 14) were 3 ft away from the igloo door and measured even higher temperatures, 1469°F, 1360°F and 1087°F, respectively. This phenomena would indicate that unburned particles are exiting the igloo in the plume and are burning outside of the igloo.

Plume velocities were calculated for this test using the Keil probe data. Keil Probe 1 which is at the top of the first rake measured a pressure of 0.5 in. of water at 2.0 sec after ignition. The plume temperature at this time was 1250°F and the resultant plume velocity is 85 ft/sec. Keil Probe 2 which is at the middle of the first rake also measured a pressure of 0.5 in. of water at 2.0 sec after ignition and at a plume temperature of 1000°F. This data can be converted to a velocity equal to 78.4 ft/sec. Probe 3 at the top of the second rake measured a plume pressure of 0.5 in. of water at 2.0 sec after ignition and at a plume temperature of 1100°F. The resultant velocity was 81 ft/sec. The probe at the middle of the second rake, Probe 4, measured 0.5 in. of water pressure at 2.0 sec after ignition. The plume temperature at this time was 1000°F. The resultant plume velocity at this position is 78.4 ft/sec.

TEST NUMBER 9

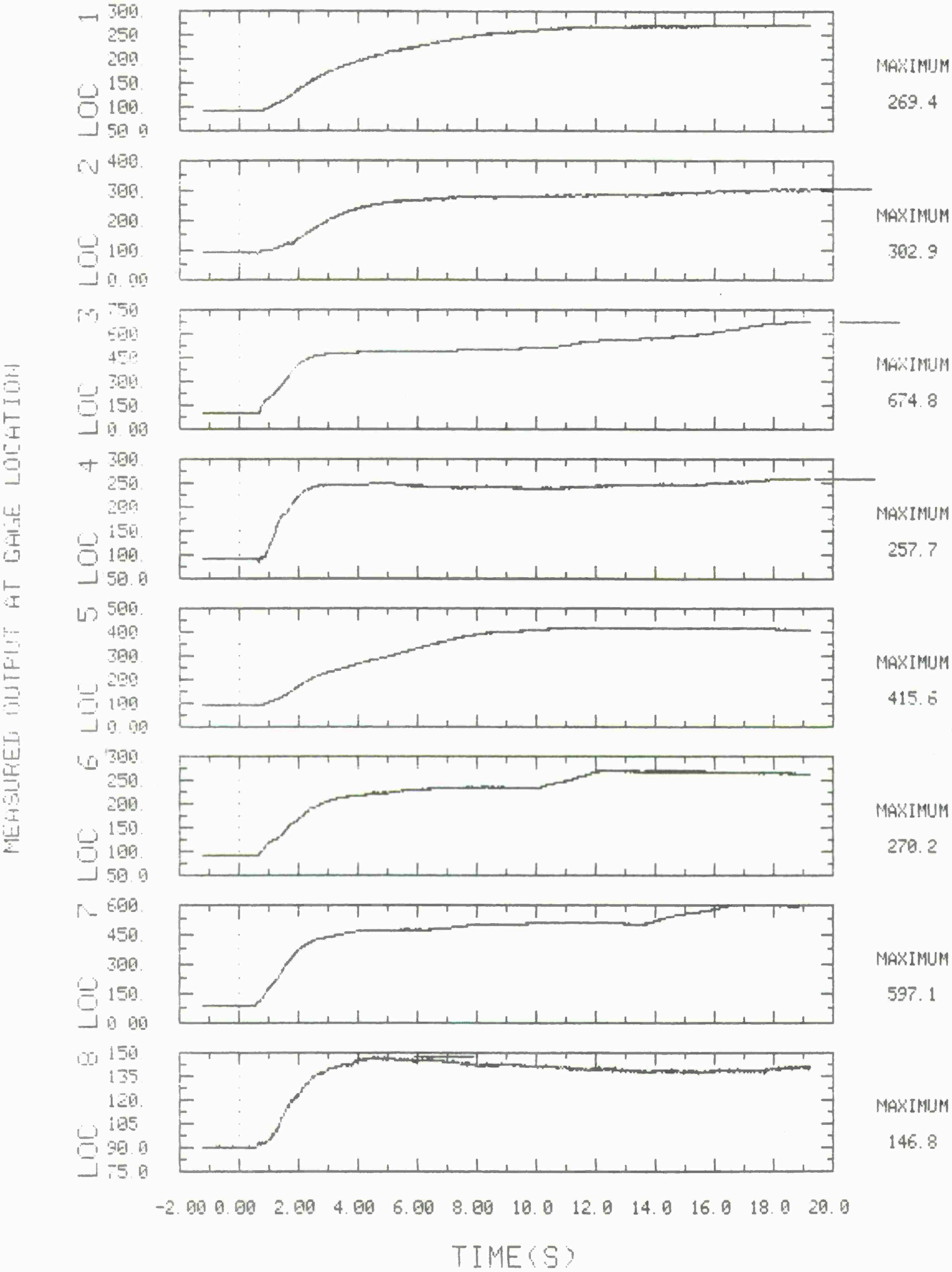


Figure B-13.

TEST NUMBER 9.

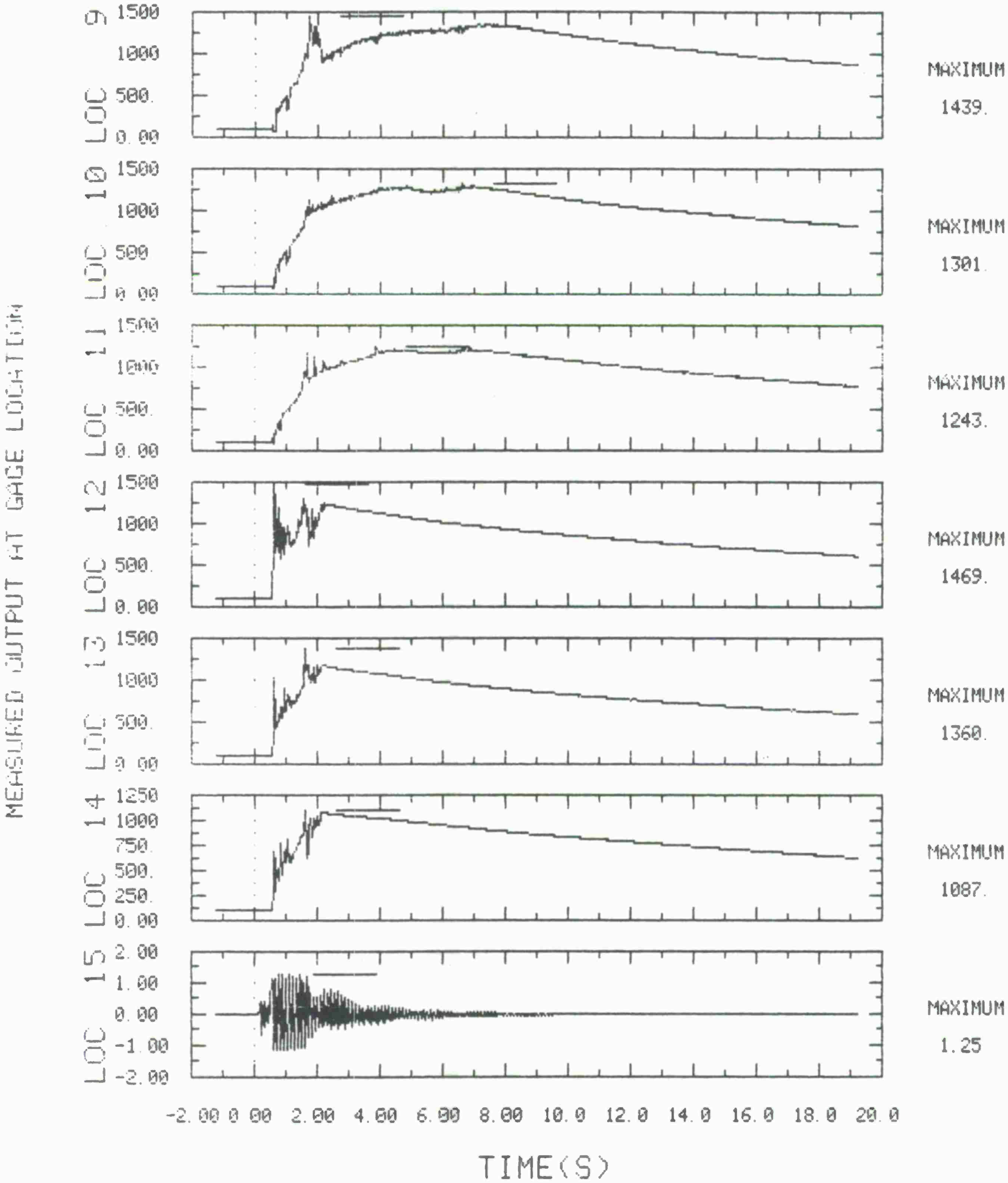


Figure B-13 (Continued)

B.3.3 Test 10--IMR-8208 Propellant (6.0 lb)

Test 10 was performed using 6.0 lb of propellant in three 1/50th volumetric scale model cardboard canisters. The three canisters were centered in the igloo and simultaneously ignited using electric matches. The propellant was ignited at the top. Figure B-14 presents temperature-time profiles for each of the 14 thermocouples, the load cell putput, Location 15, and the dynamic mass loss data. As shown in Figure B-14, the thermocouples mounted in the igloo three-fourths of the way back from the door, Locations 3 and 7, measured the highest internal temperatures, 1231°F and 794°F, respectively. The thermocouples mounted on the first rake, Probes 9, 10 and 11, also measured very high temperatures, 1315°F, 1287°F and 1102°F, respectively. This higher outside temperature indicates that unburned particles are again exiting in the plume and burning outside. The fact that Probe 11 which is at the bottom of the rake measured the highest temperature of the rake thermocouples would indicate that the plume is very flat and has not started to rise. The probes on the second rake saw even higher temperatures, 1633°F at the top probe, 1393°F at the middle probe and 1265°F at the bottom probe.

Velocity of the plume was calculated using the Keil probe data. Probe 1 measured a plume pressure of 0.5 in. of water at 1.2 sec after ignition. The plume temperature as 1250°F at this time and the resultant velocity was 85 ft/sec. Probe 2 measured a plume pressure of 0.5 in. of water at a time of 1.2 seconds after ignition and at a plume temperature of 1100°F. The velocity of the plume was calculated to be 81 ft/sec. Probe 3 which is on the second rake measured a pressure of 0.5 in. of water at 1.2 sec after ignition and at a temperature of 1100°F. The resultant velocity was calculated to be 81 ft/sec. Probe 4 also on the second rake measured a pressure of 0.5 in. of water at 1.2 sec and at 1200°F. The velocity calculated was 83.6 ft/sec.

B.3.4 Test 11--IMR-8208 Propellant (0.5 lb)

This test involved 0.5 lb of IMR-8208 propellant in a 1/50th volumetric scale model canister. The canister was placed in the center of the igloo and ignited using an electric match placed at the top of the propellant. For this test, only the two internal doorway thermocouples and the six rake-mounted thermocouples were monitored. Figure B-15 presents the temperature profiles for the eight thermocouples. The purpose of this test was to determine if for the smaller quantities of material the plume temperature outside of the igloo would be drastically higher implying that unburned propellant was being carried out in the plume and burning outside. As shown in this figure, the maximum doorway temperature is 244°F at Thermocouple 5 while the maximum temperature at the first rake was 445°F at Probe 9. The maximum temperature of any thermocouple on the second rake was 176°F which is lower than the internal temperatures. This would imply that all of the propellant was burned inside the igloo and none was carried out in the plume.

TEST NUMBER 10

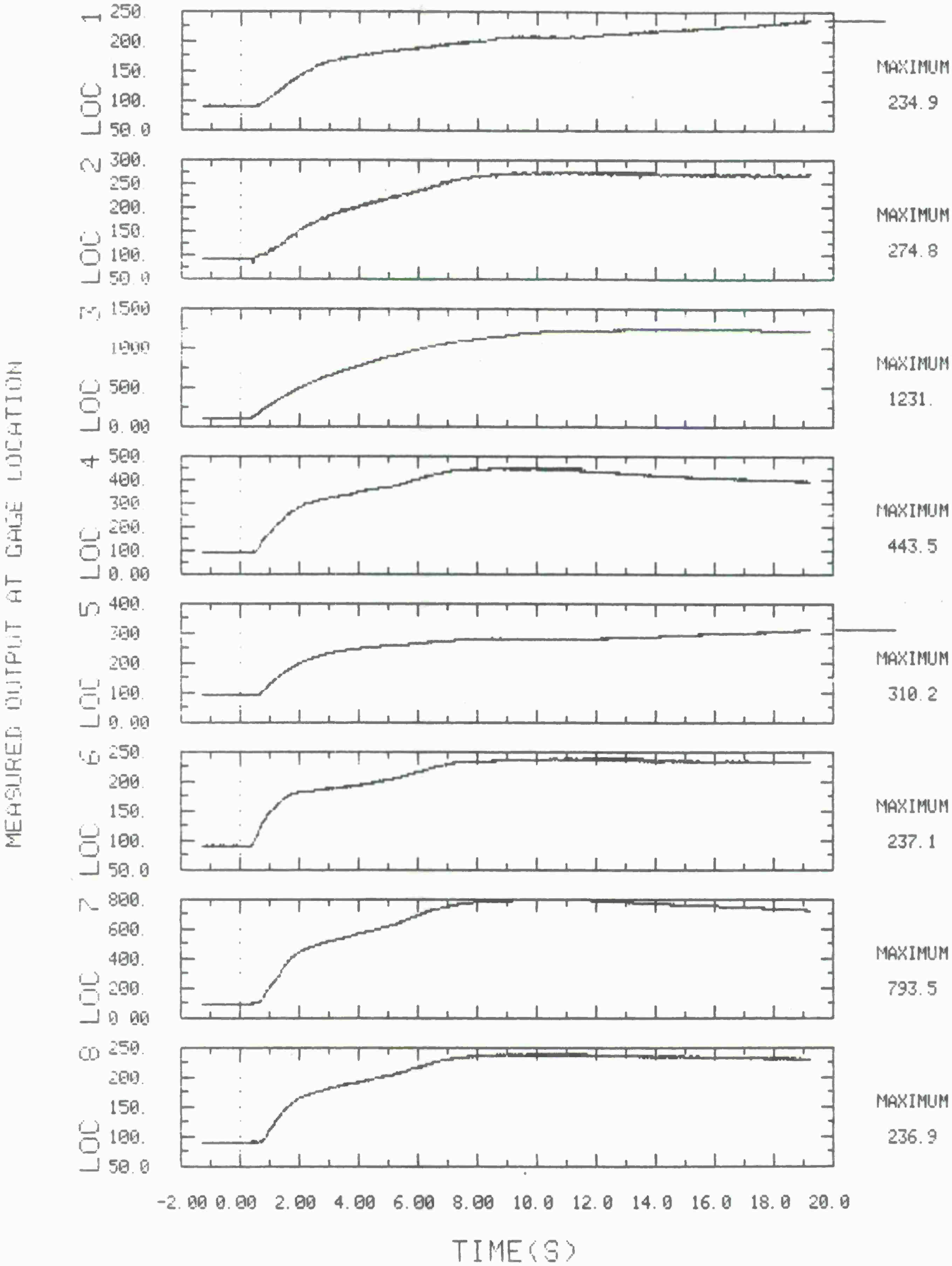


Figure B-14.

TEST NUMBER 10

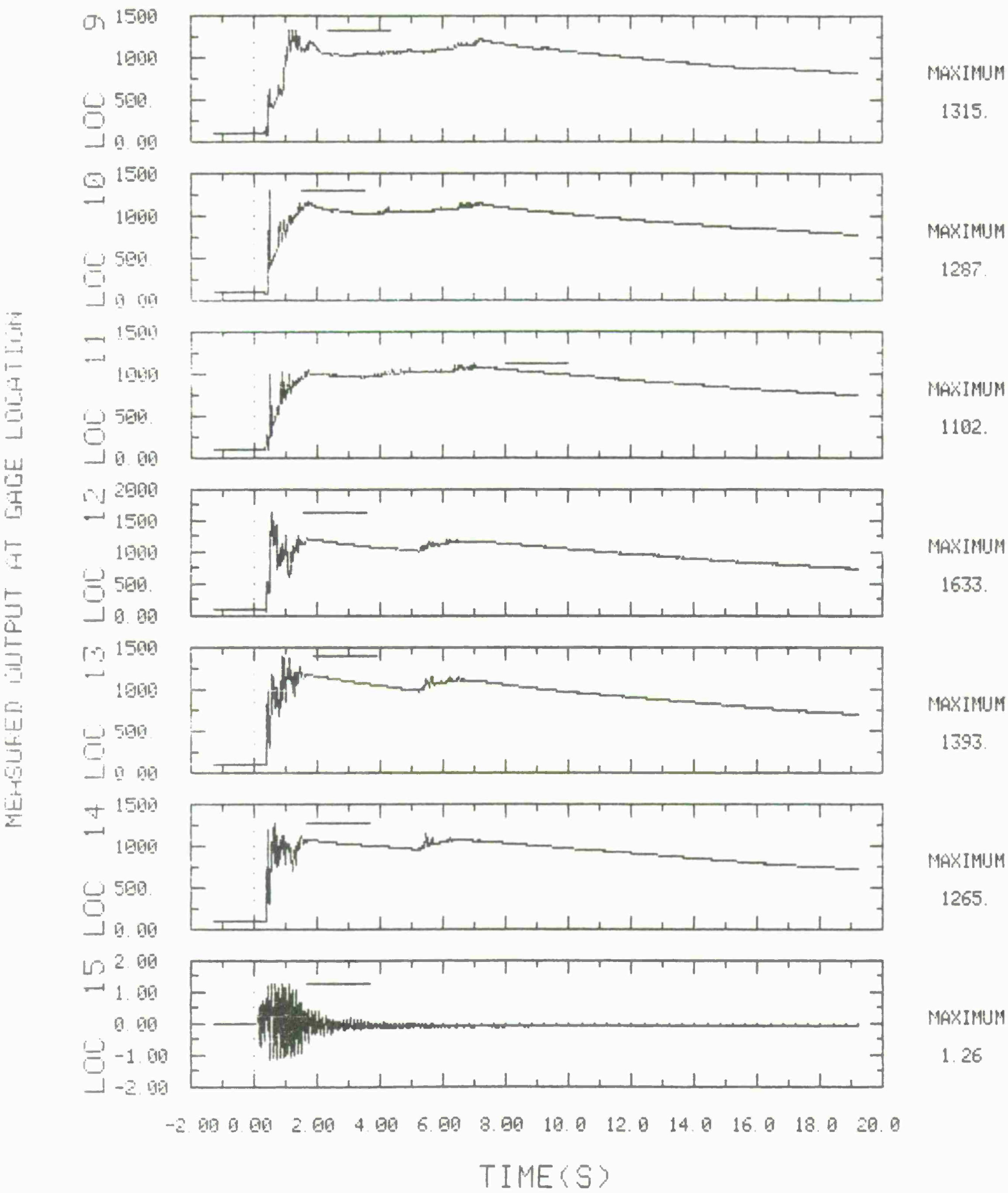


Figure B-14.

TEST NUMBER 11

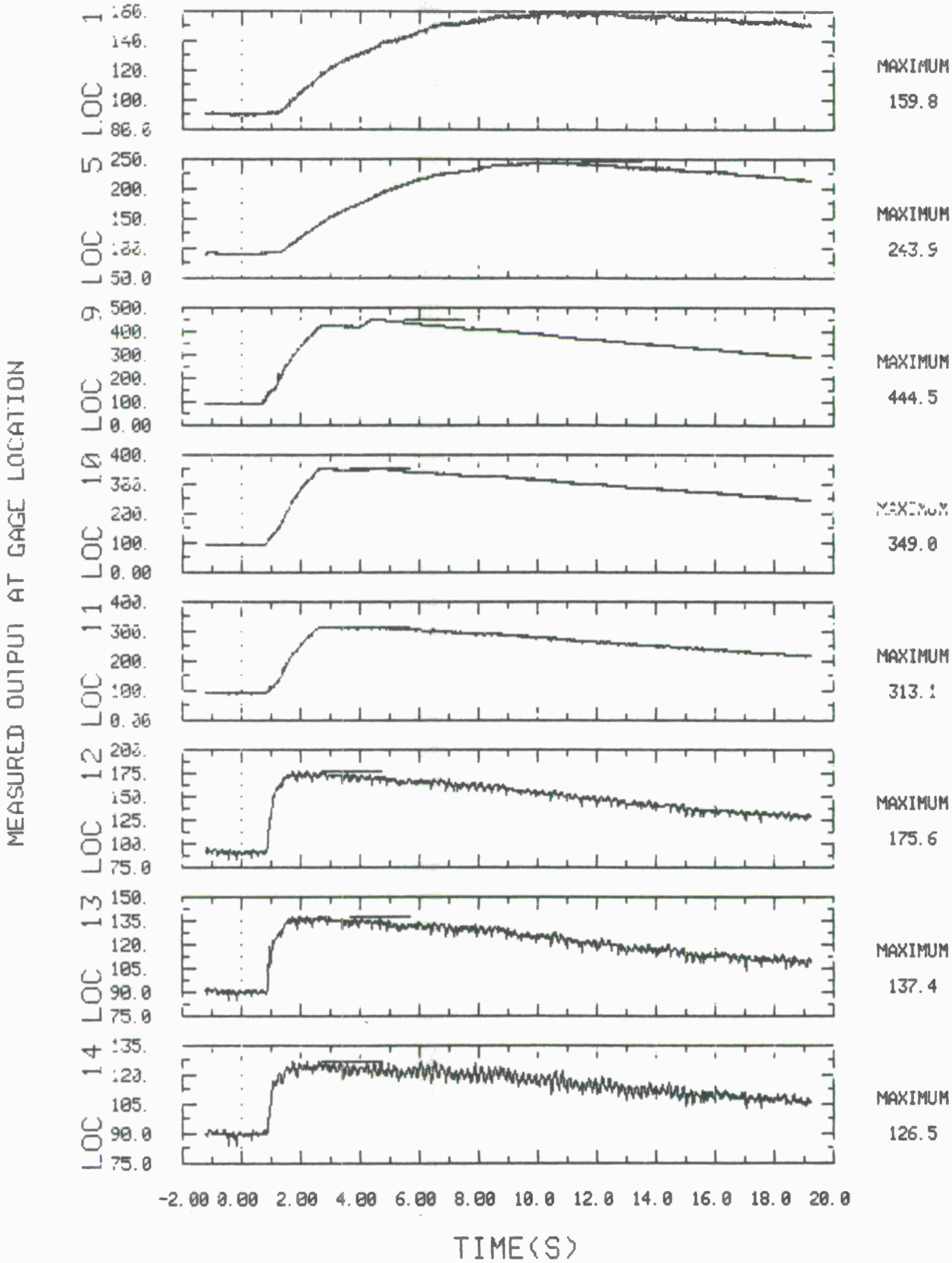


Figure B-15.

Plume velocities were calculated using the Keil probes attached to the two rakes. Keil Probe 1 which was at the top of the rake nearest to the igloo measured a pressure of 0.08 in. of water 1.1 sec after ignition. The plume temperature at this time was measured at 150°F and the resultant velocity is 20.3 ft/sec. Keil Probe 2 measured 0.07 in. of water at the same time 1.1 sec after ignition and with a plume temperature of 140°F. The resultant velocity was calculated to be 18.8 ft/sec. Probes 3 and 4 saw very little pressure, 0.03 in. of water and at plume temperatures of approximately 140°F. The velocity calculated from this data was 12.3 ft/sec.

B.3.5 Test 12--IMR-8208 Propellant (1.0 lb)

This test involved 1.0 lb of propellant placed in a 1/50th scaled canister. The cardboard canister was centered in the igloo and ignited using an electric match. Temperature profiles for the eight thermocouples monitored is presented in Figure B-16. The maximum temperature measured at the internal doorway thermocoules (Probes 1 and 5) was 228°F measured at Probe 5. The first rake measured a maximum plume temperature of 414°F at the top, Thermocouple 9. This temperature is higher than the internal temperatures recorded; however, the temperatures recorded at the second rake were lower than the internal temperatures. The maximum temperature recorded at the second rake was only 196°F. This would again imply that the bulk of the propellant is being consumed inside the igloo and unburned particles are not being carried out in the plume.

Velocities of the plume at both rakes were calculated using the Keil probe data measured at each rake. Probe 1 which is at the top of the first rake measured 0.11 in. of water at a plume temperature of 200°F which results in a calculated velocity of 25 ft/sec. Keil Probe 2 measured 0.09 in. of water and a plume temperature of 175°F. The velocity at this point is 22 ft/sec. Keil Probe 3 measured 0.05 in. of water and a plume temperature of 150°F which converts to a velocity equal to 16 ft/sec. Probe 4 measured 0.04 in. of water and a plume temperature of 120°F which converts to a velocity of 14 ft/sec.

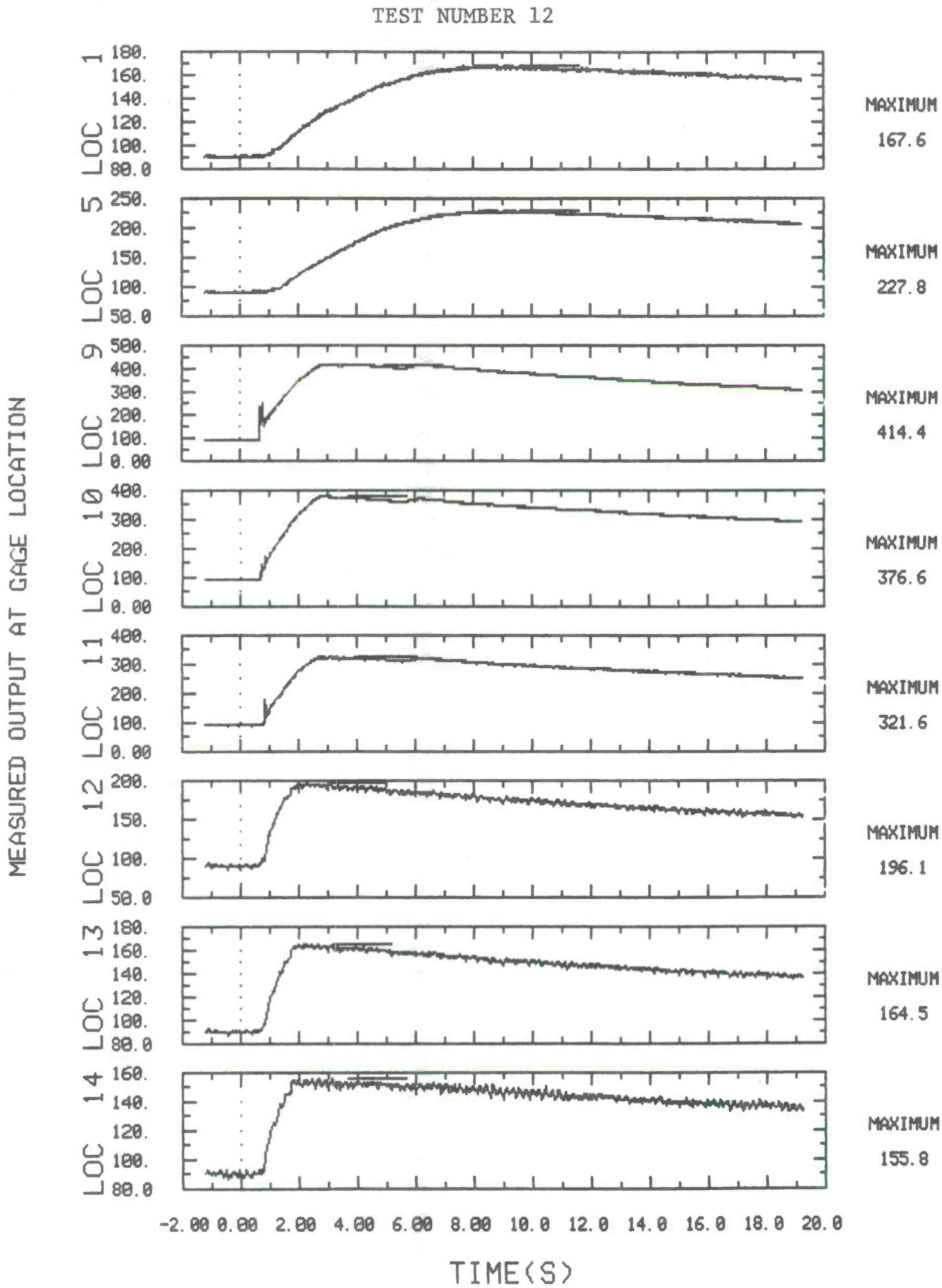

TEST NUMBER 12
MEASURED OUTPUT AT GAGE LOCATION
LOC 1
180.
160.
140.
120.
100.
80.0
MAXIMUM
167.6
LOC 5
250.
200.
150.
100.
50.0
MAXIMUM
227.8
LOC 9
500.
400.
300.
200.
100.
0.00
MAXIMUM
414.4
LOC 10
400.
300.
200.
100.
0.00
MAXIMUM
376.6
LOC 11
400.
300.
200.
100.
0.00
MAXIMUM
321.6
LOC 12
200.
150.
100.
50.0
MAXIMUM
196.1
LOC 13
180.
160.
140.
120.
100.
80.0
MAXIMUM
164.5
LOC 14
160.
140.
120.
100.
80.0
MAXIMUM
155.8
-2.00 0.00 2.00 4.00 6.00 8.00 10.0 12.0 14.0 16.0 18.0 20.0
TIME(S)

Figure B-16.

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