Institute of Paper Science
and Technology

IMPROVED UNDERSTANDING OF WEB PREHEATING TECHNOLOGY
PART I: METHODS, APPARATUS, AND PRELIMINARY DATA

Project 3470/F001

Report 10

to the

MEMBER COMPANIES OF THE INSTITUTE OF PAPER SCIENCE AND TECHNOLOGY

October 31, 1994

Atlanta, Georgia

INSTITUTE OF PAPER SCIENCE AND TECHNOLOGY
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- to provide high quality students with a multidisciplinary graduate educational experience which is of the highest standard of excellence recognized by the national academic community and which enables them to perform to their maximum potential in a society with a technological base; and
- to sustain an international position of leadership in dynamic scientific research which is participated in by both students and faculty and which is focused on areas of significance to the pulp and paper industry; and
- to contribute to the economic and technical well-being of the nation through innovative educational, informational, and technical services.

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A Progress Report

to the

MEMBER COMPANIES OF THE INSTITUTE OF PAPER SCIENCE AND TECHNOLOGY

By

T. Patterson and D. Orloff

October 31, 1994

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I. Executive Summary

The Institute's program in the fundamentals of drying is focused on facilitating the commercialization of impulse drying technology. The work is in part funded by Institute member companies and in part by the U.S. Department of Energy. DOE is supporting experimental and theoretical work that addresses the long term durability of the press roll surface and press felts, and third press drying simulations using commercial furnishes. Institute member company funding is being used to conduct research directed at better understanding the phenomena of flashing and extending impulse drying to a wide range of furnishes. Institute funds are also being used to support work to improve understanding of and to optimize web preheating technology.

Web preheating is as important for impulse drying as it is for conventional pressing. It is generally agreed that in conventional pressing, increasing the temperature of web decreases the viscosity of the water in the web, and results in increased water removal. Previous work shows that the impulse dryer is more efficient when the sheet is preheated. In addition, the earlier work also shows that impulse drying efficiency increases with incoming web dryness. Hence, it is important to optimize the performance of the presses upstream of the impulse dryer by adequately preheating the web before each press. Thus, a thorough understanding of the variables affecting the preheating process is needed to optimize both impulse drying and conventional pressing.

In current practice, steam boxes are used to preheat webs in the press section of the paper machine. While there are many commercially available steam boxes, there are two main design types; those that employ superheated steam and higher steam velocities at the steam box exit and those that employ saturated steam and lower steam velocities at the steam box exit. In addition, depending on the steam box manufacturer and the structure (grade) of the web, vacuum boxes may or may not be recommended to be placed on the side of the felt opposite the side that carries the web. Hence, the Institute's investigations of web preheating technology have focused on evaluating the variables of: superheated steam, saturated steam, and vacuum.

The work presented here utilized the Steam Box Comparator or "Rocket Sled", which was built by IPST during the spring of 1994. There were two objectives; first, to develop the methods and apparatus needed to make the Steam Box Comparator an effective research tool and second, to perform a number of shakedown experiments which would provide useful data. The work consisted of hardware modifications to improve sled durability and performance, both hardware modifications and procedure development to create a workable system of sample attachment and handling, and a series of shakedown tests that culminated with the final tests detailed in this report. The steam box used was a general purpose Measurex-Devronizer owned by IPST.

Several conclusions can be drawn from this study:

- A steam box, with a vacuum box, produces a higher and more even temperature distribution in a single ply sheet than without a vacuum box.
- A vacuum box effect can be created by a passive device, a foil is one such device.
- Consistency appears to alter the ability of a steam box to heat the web.

Steam boxes and vacuum boxes represent relatively low capital investments, yet can potentially have a significant effect on paper machine efficiency. A study, or series of studies, using the Rocket Sled can provide the information needed to utilize a steam box and/or vacuum box in the most advantageous manner. If the objective is to improve the performance of a specific paper machine, a determination needs to be made as to which of the studied parameters:

vacuum
web consistency
felt construction

and which additional parameters:

steam flow rate
steam superheat

web residence time (web speed or Box MD Length)
vacuum location
steam box design
web furnish

can most easily be changed on the paper machine in question. If the parameters are prioritized as to the paper machine operators willingness to change them, then the selected parameters can be investigated one at a time. The results of each investigation can be applied to the machine and evaluated before the next series of tests is begun.

The apparatus can also be used for more in depth basic engineering studies. There are currently two Master students projects underway which are directed at characterizing the convection and conduction properties of the steam box and web combination. Other possible areas of study include; a detailed investigation of the effect of sheet structure on heating efficiency, an investigation of optimum steam jet velocities, and an investigation of passive vacuum devices.

II. Introduction

The study presented in this report utilizes a new and unique experimental apparatus. The apparatus is officially referred to as the Steam Box Comparator and unofficially referred to as the Rocket Sled. Although, there is no rocket associated with the device, the unofficial name is somewhat more descriptive of the operation of the apparatus. It consists of a sled (see Figure 1), a track (see Figure 2), a steam box (or other heating device), and a vacuum box (if specified). A single instrumented sheet is mounted on the sled and the sled is propelled, at typical paper machine speeds, down the track under the steam box. The purpose is to expose the single instrumented sheet to the same conditions, both thermodynamic and aerodynamic, that a continuous web experiences on a paper machine.

The Rocket Sled has the ability to:

1. Simulate paper machine speeds from 500 fpm to 3000 fpm.
2. Accommodate any steam or vacuum box which can be adapted to the 25" wide sled track. The system can be modified to accept steam boxes wider than 25"; however the test sample will be exposed to only a 25" section of the steam box.
3. Accommodate any grade of paper and sheet sizes up to 12" x 12". Larger sizes can be used, but the front edge of the sheet will not experience the same aerodynamic conditions as the trailing edge.
4. Accommodate any type of felt.
5. Provide steam quality ranging from saturated to superheated (330 deg F, 30 psig).
6. Steam flow rate measurements compensated for temperature and pressure.
7. Use 7 sample mounted thermocouples, 1 sled mounted pressure transducer, 1 sled mounted vacuum transducer, and a vacuum box manifold mounted vacuum transducer.

The Rocket Sled apparatus was completed in late May 1994. In preparation for future experimental studies the apparatus was subjected to a number of tests. These tests revealed several problems. The problems fell into two separate areas: sled durability and performance, and sample attachment and handling.

Solving the sled durability and performance problems required a concentrated effort during June and early July 1994. During this time the sled was redesigned and rebuilt, the braking system was redesigned and rebuilt, and the cable propulsion system was strengthened.

The original sample attachment system proved to be inadequate. It did not securely hold the sample, nor did it provide for simple and quick attachment and detachment of the sample. During July and August 1994, an iterative approach led to some additional sled modifications which solved these problems. The result was a felt extending the full length of the sled and a cloth cover for maintaining the sled upper surface boundary layer. Zippers are used for quick installation of the felt.

The solution of the sample handling problem also required a significant effort. Prior to the start of this work there were no defined procedures for forming a multi-ply sheet with embedded thermocouples, pressing such a sample, maintaining the sample moisture content, or handling the sample prior to testing without damaging the assembly. Efficient sample handling required answers to the following questions:

1. Do the interfaces between the plies of a multi-ply sheet cause the sheet to heat differently than a two-ply sheet? If a multi-ply sheet has different heating characteristics compared to a two-ply sheet then a significantly greater number of test runs are required. Producing a comprehensive and valid temperature profile using only two-ply sheets requires four or five test runs per test condition compared with one test run for a multi-ply sheet.

2. How fast does moisture evaporate from a felt under different ambient conditions? The ambient conditions during testing may vary and it is desired to maintain the felt moisture content at a level consistent with actual use.

3. How fast does moisture evaporate from a sheet under different ambient conditions? The ambient conditions during testing may vary and it is desired to maintain the felt moisture content at a level consistent with actual production conditions.

4. What is the best method for embedding thermocouples in the sheet?

The techniques for solving these problems were developed during May, July, and August 1994.

II. Static Experiments

A. PURPOSE

A series of static steaming experiments were conducted. The experiments had two goals: determine if multi-ply and two-ply sheets produce the same temperature profiles when exposed to a steam jet, and determine if 17 g/m^2 or 34 g/m^2 ply top sheets should be used in future steam box comparator tests. If multi-ply sheets have the same temperature profile as two-ply sheets (i.e., the layers do not effect heat transfer) then fewer test runs are required to produce a complete temperature profile. If 34 g/m^2 sheets provide adequate data then fewer thermocouples are required per test.

B. EXPERIMENTAL SETUP AND PREPARATION

The term "static steaming tests" is used because there was no attempt made to produce a moving boundary layer on the surface of the paper. In order to expedite the experiments a simple and easily constructed steaming apparatus was devised. The experiments make use of the steam system and data acquisition system that are normally used for the MTS Impulse Drying Simulator. A sketch is shown in Figure 3. The steam jet produced is directed upward to avoid dripping condensate on the paper sample. The paper sample and felt are oriented upside-down with the "top" of the paper sample and the "top" of the felt facing downward.

These experiments employed two types of multi-ply sheets, 5 types of two ply sheets, and several single ply sheets. The intended basis weight of each complete sheet was 204 g/m^2. Figure 4 shows a matrix of the types of sheets made and the basis weight of each ply used. The individual plies were produced using a hand sheet mold and 450 CSF, virgin pulp. The composite sheets were not formed until just prior to the experiment. This was done to assure that the internal water did not migrate and so that the thermocouple assemblies could be reused.

The composite sheets were formed using a hand operated hydraulic press. Thermocouples were embedded between each ply. Figure 5 shows the intended positioning of the thermocouples. The actual positioning tended to vary in the horizontal direction, although the pattern was maintained. The procedure for forming the composite sheets was to spray each ply with de-ionized water lay it on the lower surface of the press, position the corresponding thermocouple on top of the sheet, and then wet and place the next ply on top of the thermocouple. The process was repeated until all plies and thermocouples were in place. Once all layers were in place the press was lowered, locked in position, and the pressure raised to 100 psi and held for 1 minute. This produced sheets that were slightly drier than required (i.e., 30 % solids). Prior to the experiment the sheets were sprayed to increase the moisture content.

The fabrication techniques used in these experiments are presented below. The techniques were developed through trial and error.

1. After mounting the thermocouple wire in the thermocouple plug connector, the entire length of the thermocouple wire, except that portion that was to be embedded in the paper, was encased between two layers of masking tape. Each thermocouple was a separate assembly. The tape made handling easier and reduces the chance of electrical shorting.

2. Without special precautions, all but the most gentle handling of the sample resulted in the thermocouples pulling out of the sample. Therefore, in these experiments a clamping device was developed to maintain the positioning of the thermocouples. The device consisted of two pieces of 1/8 inch aluminum and several small clamps. The aluminum pieces were clamped onto the edge of the paper where the thermocouple wires emerge from the paper, securely holding the thermocouples in place.

These methods proved to have significant shortcomings. Management of the individual thermocouples was extremely tedious and the clamping device was awkward and difficult to use.

C. EXPERIMENTAL PROCEDURE

The actual experiment required only a short time. Preparation accounted for the majority of the work. The experimental procedure was as follows:

1. Record the weights of the thermocouples and clamping device.

2. Initialize the data acquisition system.

3. Weigh the paper sample/thermocouple/clamping device assembly and estimate the solids content of the paper. Spray the sample with deionized water or let it dry to adjust the solids as required. Desired solids content was 30%.

4. Turn on the steam to preheat the steaming device and reduce condensate production. Adjust steam pressure to 0.4 psig. During this process a bucket is held over the steam outlet to prevent the steam from heating or wetting the test stand.

5. Place the paper sample and backing felt on the test stand and hold in place with a ring shaped weight. Plug in the thermocouple connectors.

6. Start the data acquisition process.

7. Remove the bucket to let the steam impinge on the paper sample.

8. After 15 sec shut off the steam, remove the paper sample and weigh it.

9. Reset the data acquisition system.

Typically each paper sample was used for three tests, although one multi-ply sheet was used for 6 tests. Coordination of these activities required two people.

D. EXPERIMENTAL RESULTS

A total of 33 tests were performed using 11 different test samples. Figure 6 gives the matrix of tests. The test names indicate the type of sheet used. A T indicates two-ply sheet, M - multi-ply sheet, and S - single ply sheet. The number immediately after the letter indicates the basis weight of the top ply. The number following the dash indicates the number of the test with that type of sheet.

In some of the tests there were either data dropouts caused by temporary thermocouple shorts or complete failures on individual thermocouples caused by crossed thermocouple wires. Intermittent thermocouple shorts caused the data on tests T34-02, T68-02, and T102-02 to be unusable. In tests M34-01, M34-02, and M34-03 the thermocouple at the 68 g level had crossed wires making the data from that thermocouple unusable. In tests M34-04 and M34-05 the thermocouple at the 102 g level had crossed wires. In test M34-06 the wires on the thermocouples at the 34 g and 68 g had intermittent shorts that made the data unusable. Test M17-01 produced unusable data on the thermocouple at the top of the sheet. In these multi-ply sheets, the data from the thermocouples that were not shorted were retained and used. The thermocouple mounted between the paper and the felt showed the least consistent output. This may be due to it not being permanently attached to the paper sample. Tests M17-04 through M17-08 used sheets of 20% solids. Since these were the only tests at 20% solids, there is no data at the 68g level. This type of sheet did not have a ply interface at that level. In test M17-09 the steam pressure was tripled to 1.2 psig. No data were taken for the 68g level in this test. No data were taken during test M17-01, so it is not included in the matrix. In test T34-03 the sample was tested upside down.

A summary of the data is shown in Figures 7 through 13. The first six of these figures are graphs that compare thermocouple readings at the same level within the sheet. There is a graph for the 17, 34, 51, 68, 102, and 204 g/m^2 levels (See Figure 5). The intent of these graphs is to illustrate the difference, if any, between multi-ply and two-ply sheets. The graphs were produced by averaging the results from similar tests. As an example, in Figure 4 the data labeled two-ply (17/187) is the average of tests M17-02 and M17-03 and the data labeled multi-ply (17/17/17/51/51/51) is an average of tests M17-01, M17-02, and M17-03. Each graph starts at 0.05 seconds before the steam first impacted the sheet surface. This point in time was determined by the response of a thermocouple positioned at the "top" surface of the sheet. These graphs show several results:

1. The use of multi-ply sheets does not cause a temperature profile that is significantly different from that of a two-ply sheet.

2. The use of higher pressure steam does heat the sheet faster.

3. There probably was a correlation between percent solids and heating rate.

Figure 13 shows a graph of temperature profile for a multi-ply sheet with a 17 g/m^2 top ply. Profiles at increasing times are given. The graph simply connects data points, no attempt was made to curve fit. This graph shows that 17 g/m^2 plies at the top of the sheet are required to obtain an accurate temperature profile for the initial steaming pulse. This was expected to be more of a requirement in a dynamic study as the length of the steam pulse will be measured in fractions of a second. In Figure 13, the temperature at the 34g level is higher than that at the 17 g level for the times greater than 3.5 sec. This is probably due to data averaging and the limited number of samples used.

E. CONCLUSIONS

The two principal conclusions from this series of experiments were: First, it is acceptable to use a multi-ply sheet to collect temperature profile data. The ply boundaries do not appear to effect the heat transfer. This will greatly reduce the number of test runs required to produce a complete temperature profile. Second, sheets with 17 g/m^2 top plies are required in cases where a complete temperature profile during the initial phases of the steam pressure pulse is desired. The experiments also produced two secondary results: higher pressure steam increases the heating rate throughout the sheet and the percent solids probably effects the heating rate. The variation in percent solids did not produce the same magnitude changes in heating rate as the variation in steam pressure and may be skewed by the limited cases studied.

III. Felt Evaporation Test

A. PURPOSE

A series of tests were conducted to ascertain the relative rates of moisture evaporation under different ambient and felt water content conditions. The rationale for these tests was:

1. Any experiments should duplicate as closely as possible actual paper machine conditions, this required that felt moisture levels be maintained at an appropriate level for all experiment runs.

2. The ambient conditions at the test site vary with the outside weather; therefore, it was necessary to know the effect of varying ambient conditions on felt moisture.

3. If it could be shown that felt moisture evaporation was predictable, then it would be a simple matter to develop experimental procedures to maintain felt moisture levels during the experiments.

B. EXPERIMENTAL PROCEDURE

The testing method was simple. A clean dry (under typical ambient conditions ~27 deg C, ~70% RH) felt was cut and weighed on a Mettler PM4000 scale. The felt sample was then saturated with water and shaken vigorously to remove excess moisture until a target water content was reached. The felt sample was placed on the scale and its mass measured over time. The ambient conditions were measured during the test with a combination electronic thermometer/hygrometer.

Two tests were conducted at location of the Rocket Sled. An additional test was conducted in one of the TAPPI controlled environment rooms at IPST. The testing methods were identical for all three tests.

C. RESULTS

Figures 14 and 15 show the results in tabular and graphical form. The slightly higher evaporation rate for the second trial is attributed to forced convection evaporation due to an air conditioning draft evident at the test location. The linear and approximately parallel data series plots indicate that the felt moisture evaporation rate is slow, linear, and manageable across a range of conditions. The results show that felt moisture content will not change appreciably during the time span of one test (approximately 2 minutes) but may change during the interval between tests. At the time of these experiments it was planned to make up for water evaporation by using a calibrated water spray bottle. Attachment of the felt to the sled using zippers made it possible to remove the felt after each test, to add water, and weigh the sample prior to the next test.

IV. Sheet Assembly Trials

A. PURPOSE

The static steaming tests demonstrated the need for an alternative method of forming, embedding thermocouples, and handling the sample. Thermocouple management presented a difficult problem during the fabrication and pressing of the sample. Handling of the sample also created problems: the clamping device was difficult to use, thermocouples occasionally pulled out of the sample, and the thermocouple wires occasionally crossed resulting in an electrical short. Efficient testing of numerous samples required development of alternative methods. These methods needed to ensure that:

1. The thermocouple wires and connector plugs remain in one place and in one orientation throughout all forming and handling procedures.
2. The thermocouple wires could not pull out of the sample at any time.
3. The sample could be pressed with the thermocouples embedded in the sample and the thermocouple connectors attached to the thermocouple wires. The task of attaching the wires to the connectors is extremely tedious and time consuming.
4. The pressed sample could be weighed to check its moisture content.
5. The pressed and weighed sample could be sealed from the environment to maintain its moisture content.
6. The sealed containment of the sample could be quickly and easily removed so that the sample could be mounted on the sled and exposed to steam and vacuum.
7. The forming and handling of each layer was as simple as possible. This was important as a large number of samples were formed and the thermocouple z-direction placement was determined by the basis weight of each layer.
8. The sample, after pressing was as close as possible to its target moisture content, minimizing additional moisture addition or removal.

B. RESULTS AND METHODS

The first issue considered was sheet construction for a 204 g/m^2 sheet, i.e., the number and basis weight of each layer. The static steaming tests showed that low basis weight layers (17 g/m^2) were required at the top of the sheet. The samples used in the static tests had constructions of 34-34-34-51-51 and 17-17-17-51-51-51 g/m^2. While the second of these provided good resolution at the top of the sheet, neither provided for adequate resolution throughout the rest of the sheet. An alternative construction was 17-17-25-25-51-69 g/m^2. This construction had several advantages: adequate temperature resolution through the entire sheet, relatively easy formation (hand sheet forming and individual ply handling), and easily used for different applications. A 17 g/m^2 ply was about the lowest basis weight ply that could reasonably be formed. The two top plies could be made from top sheet pulp and the remaining plies from base sheet pulp, thus form a true "two ply" sheet. The same construction readily lends itself to uniform sheets or sheets with higher basis weight top sheets.

The next issue was thermocouple management and sheet handling. Trial and error resulted in the development of the following techniques, methods, and procedures.

Thermocouple Assembly: The thermocouple assembly consisted of five thermocouples, five thermocouple male connectors, and a 6"x 8" plastic bag used as a backing. One lead of each thermocouple wire was fished through a small diameter plastic tube. The tube was just long enough to allow placement of the thermocouple junction near the center of the sample without the tube interfering with the sample. The plastic bag was cut along the seam opposite the zip seal. The thermocouple lead without the plastic tube was feed through the bag to the zip seam. The lead with the plastic tube was laid on top of the plastic bag, the free end at the zip seal edge. Both leads were taped in place with masking tape. The free ends of the thermocouples were attached to the thermocouple connector terminals. The thermocouple connectors were spaced on 1" centers and clamped to the zip seal edge of the plastic bag. Each connector had a small screwed on cover used to shield the thermocouple wire terminals, this cover was used to clamp the connector to the plastic bag. The free thermocouple junctions were folded back onto the backing bag and held in place with small pieces of tape. This assembly kept all the thermocouple in place, maintained the orientation of the connectors, and greatly minimized the chance of thermocouple electrical shorts. These assemblies were durable and easily reused.

Sample Containment Bag: A second plastic bag was used to contain the sample and thermocouple assembly. A bag measuring 16" x 12" with the zip seal on one 12" edge was cut to 16" x 8". This eliminated one of the seams adjacent to the zip seal. The seam opposite the zip seal was cut so the bag could be opened like a book, the one remaining seam acted as the binding. Using a template, and with the bag unopened, an equilateral triangle was cut in both layers of the bag. The triangle was located approximately 3" from the zip seal, one side parallel to the remaining bag seam. Each side of the triangle was 5" long (See Figure 1). The bag was opened, like a book, and the thermocouple assembly was positioned so that the line of thermocouple connectors was parallel to the zip seal and along the edge opposite the zip seal. The thermocouple assembly was taped in place using masking tape. The bag was closed, each triangle cutout was covered with a piece of additional plastic which was taped in place. The plastic cover pieces were removed just prior to testing to expose the sample to the steam and vacuum.

Sample Assembly: All of the sheet plies were made prior to assembling the sample using a standard TAPPI hand sheet mold. A hand sheet mold must be used for forming sheets of basis weight 25 g/m^2 and less. Using the Formette Dynamique results in poor formation of the sheets. After forming, the sheets were die cut to 5" diameter circles, sealed in plastic bags, and placed in cold storage. The procedure for fabricating the sample began by weighing and recording the containment bag weight. The bag was then opened and placed on a large cardboard template. The template was used for positioning of the sample. The bottom ply was removed from its storage bag, sprayed with deionized water, and placed on the same side of the opened containment bag as the taped down thermocouple assembly. The tape holding down the first thermocouple junction was removed and the junction placed approximately at the center of the ply. It was held in that position. The next ply was removed from its storage bag, sprayed, and gently placed on top of the thermocouple and the previous ply. This process was repeated until all plies are in place. The embedded thermocouples were numbered from bottom to top 2, 3, 4, 5, and 6. (Thermocouples 1 and 7 were placed beneath and on top of the sample at the time of the test run). The bag was then folded closed and positioned on a press so that only the sample portion was in the press. The press was closed and the sample pressed. Afterward the sample was weighed to ensure it was at the desired moisture content. Deionized water was added or allowed to evaporate as needed. The zip seal of the containment bag was then sealed and the two open edges of the bag sealed with masking tape. The sealed bag was weighed and the weight recorded. The containment bag was small enough that sample movement was restricted, preventing the thermocouples from pulling out. The thermocouple assembly remained stationary relative to the sample with the connectors all in the proper orientation and order. Corresponding plugs were mounted on the sled allowing for quick connections and disconnections. The bag remained sealed until just prior to the test, maintaining the moisture content of the sheet.

A number of samples were assembled using the above techniques. A certain amount of practice was required to become proficient at the sample assembly process. Pressing at 80 psig for 40 seconds resulted in good adhesion between plies and reasonable moisture content.

V. Sheet Moisture Test

A. PURPOSE

A series of tests were conducted to ascertain the relative rates of moisture evaporation from representative sample sheets under different ambient conditions. The rationale for these tests was:

1. Any experiments should duplicate as closely as possible actual paper machine conditions; this required that sheet moisture levels be maintained at an appropriate level for all experiment runs.

2. The ambient conditions at the test site vary with the outside weather, therefore it was necessary to know the effect of varying ambient conditions on sheet moisture content.

3. If it could be shown that sheet moisture evaporation was predictable, then it would be a simple matter to develop experimental procedures to maintain moisture levels during the experiments.

B. EXPERIMENTAL PROCEDURE

A number of samples were formed using the 17-17-25-25-51-69 g/m^2 construction. These samples were pressed at 80 psig for 40 seconds with a target moisture content of 30% solids. The samples did not contain embedded thermocouples. The testing method was the same as used for the felt moisture evaporation tests. Five tests were conducted, trials 1, 2, and 3 were conducted in a TAPPI environment controlled room and trials 4 and 5 at the Rocket Sled location.

C. RESULTS

Figures 16 and 17 show the results in tabular and graphical form. The results do show some dependence of evaporation rate on relative humidity. However, the primary result was that for various conditions the evaporation was relatively constant. Given these results, it was not expected that exposing a sample to ambient conditions for only a few minutes would significantly alter its moisture content. The sample containment bag and thermocouple assembly made it possible to run a complete test in just a few minutes. During the Rocket Sled runs done as part of the shakedown, the duration of a test from starting the data acquisition system to removal of the sample from the sled was approximately two minutes. The sample was exposed to the atmosphere for less than this total time.

VI. Shakedown Trials

A. PURPOSE

During June and July a large number of Rocket Sled Test runs were conducted. These runs had the objective of refining the sled structural design, the braking system, the propulsion system, felt and sample attachment, and determining requirements for specific sled speeds. This work showed a number of short comings in the original design.

During late July and August a large number of shakedown Rocket Sled runs were made. These runs had the following objectives:

1. Show that the thermocouples and transducers were able to withstand the loads produced during a test run and that the data produced was usable.

A removable data cable and thermocouple mounting bracket were developed. The bracket mounted on the sled and securely held both the thermocouple connectors and the data cable. It allowed the thermocouple assembly to be connected and disconnected quickly. The data cable was over 30 feet long and laid in a gutter beneath the track. The end opposite the thermocouple bracket was connected to a data acquisition board at the computer. A pressure transducer (Omega PX-603) and a vacuum transducer (Omega PX-605) were mounted on the sled. Each had a small capillary tube attached to the sensing end of the transducer. The free ends of these tubes were mounted in the same manner. A cut out measuring 1/4" x 1/4" x 1/8" deep was made 1/2" from the 1-1/4" long edge of a 1-1/4" x 3" piece of cardboard. This created a small square cavity in the cardboard, the cavity did not extend through the cardboard. The free end of the capillary tube was inserted into the cardboard, parallel to the plane of the cardboard. It was fed through until it just protruded into the square cavity. The cardboard for the vacuum transducer was secured to the sled so the cavity opening faced downward and was against the felt surface. This allowed the transducer to measure the vacuum on the upper surface of the felt, i.e., the vacuum experienced by the bottom of the sample. The cardboard for the pressure transducer was secured so that the cavity opening faced upward and away from the felt surface. This allowed the transducer to measure the pressure on the upper surface of the sample. A second vacuum transducer (Omega PX-605) was mounted in the vacuum box manifold approximately 1 foot from the vacuum box. This transducer, in combination with the sled mounted vacuum transducer, allowed the measurement of the pressure drop across the felt. The transducers were all calibrated against analog gauges. This arrangement worked well during the tests.

2. Show that the data acquisition system works adequately.

   The current data acquisition system had a number of limitations. A great deal of effort was expended to develop an adequate means of collecting data. A data acquisition system configuration was found which provided for 7 thermocouples, 1 pressure transducer, 2 vacuum transducers, 2 photo eyes, and a data rate of 125 Hz. We are currently investigating improvements to this system.

3. Show that the sheet is exposed to a vacuum.

   This issue was addressed, see below.

4. Show that the Rocket Sled is a viable experimental tool capable of producing useful data.

   This issue was addressed by running a series of complete tests in late August 1994. These tests incorporated hand sheet forming of the individual plies, sample construction with 0.002 " Type E thermocouples, use of the thermocouple assemblies and sample containment bags, and various steam and vacuum test conditions. The details of these tests are given below.

B. STATIC VACUUM TESTS

While it was possible to analytically show that a boundary layer of appropriate thickness will form on the top surface of the sled, it was not so easily shown that a vacuum seal is produced on the underside of the sled. The static test described here was the first step in demonstrating that such a seal was produced.

The vacuum line for the Rocket Sled incorporated a variable opening vent which allows the vacuum level to be regulated. In this test a piece of felt was place directly on the vacuum box. The manifold vacuum transducer was left in place. The sled vacuum transducer assembly was removed and the cardboard/capillary sensing end secured to the felt. The cavity, containing the capillary, was mounted against the felt and facing towards the vacuum box i.e., the transducer was mounted to detect the vacuum level on the top surface of the felt, the same vacuum experienced by the bottom surface of a paper sample. The difference between the vacuum transducer outputs was equivalent to the pressure drop across the felt.

The vacuum system was turned on and the vacuum level varied in stages. The data acquisition system was used to record the transducer signals.

Figure 18 shows the results. The graph shows that the maximum vacuum in the manifold was approximately 10 in Hg. It also shows that for the felt used, the maximum vacuum on the bottom side of a sheet was approximately 2.75 in Hg. Thus, the pressure drop across the felt was 7.25 in Hg.

C. DYNAMIC VACUUM AND PRESSURE TESTS

The next step in verifying that the Rocket Sled produces a vacuum seal was a dynamic test. For this test only a felt was used. The vacuum and pressure transducers were mounted in a manner similar to that described above.

At the time of these test only one vacuum transducer was available. Therefore, two identical tests were run, the first with the transducer mounted on the vacuum box manifold and the second with the transducer mounted on the sled. The conditions for the tests were: no steam, full vacuum, and sled speed of 2600 fpm. Figure 19 combines the results of the two tests. These tests show that the maximum vacuum produced in the line is approximately 5.3 in Hg, although the average is closer to 5 in Hg. The length of the manifold vacuum pressure pulse corresponded almost exactly to the length of the sled, i.e., the vacuum pressure pulse started almost exactly when the front of the sled reached the vacuum box and ended when rear of the sled passed the vacuum box. The sled vacuum pressure pulse reached a maximum level of approximately 1.75 in Hg. The test proved that a vacuum seal is created with a pressure drop of 3.25 to 3.55 in Hg across the felt.

D. FINAL SHAKEDOWN TESTS

The most important shake down tests were conducted on 26 August 1994. The steam box used was a general purpose Measurex-Devron which IPST owns. These tests were run with the intent of collecting useful data.

The sheet construction for these test was:

- 600 CSF, virgin kraft fiber.
- 204 g/m^2.
- 6 ply sheet.
- Construction top to bottom, 17, 17, 25, 25, 51, 69 g/m^2.
- Samples pressed at 80 psig for 40 seconds.

The tests were all run at a sled speed of 2000 fpm and with the following variables:

- Constant steam flow, 150 kg/hr, 0.490 bar, 112 deg C.
- Four vacuum levels, full, 2/3, 1/3, 0.
- Two solids contents, ~30%, ~37%.

Full vacuum is approximately 5 in Hg. The vacuum level was adjusted by opening a vent in the vacuum line. The experimental procedures for these tests are typical of those used for the rocket sled. A minimum of two people were required to run the tests. In order, the steps were as follows (it is assumed that the data acquisition computer is turned on and the data acquisition software is activated):

1. Person 1 brings the sled to its start point, i.e., the end of the track opposite the motor.

2. Person 1 positions the braking bar and Person 2 turns the brake on. Persons 1 and 2 tension the sled pull cables and turn the cable drum brake on.

3. Person 1 checks the operation of each photo eye. The eyes provide a speed gate 7 feet long for measuring the sled speed, photo eye 1 is positioned 37.5" in front of the steam box and photo eye 2 is 33.5" behind the steam box. The eyes are also wired in series and are essential to safe operation of the sled. When the circuit is interrupted the sled cable pull clutch is disengaged.

4. Person 2 weighs the felt to ensure it is at its target weight, water is added or allowed to evaporate as needed. The felt is rolled up and placed on a scale.

5. Person 2 turns on the steam system and adjusts it for the desired test conditions. If vacuum is required Person 1 activates the vacuum system.

6. Person 2 records the steam flow parameters, flow rate, pressure, and temperature, and the weight of the felt.

7. Person 1 activates the data acquisition system. There is a three minute window for data capture.

8. Person 2 carries the felt to the sled and holds the front edge in place while Person 1 zips in the front edge. The zipper ends are then secured with duct tape. The half of the zipper which is attached to the front of the sled is sewn to the cloth top cover. The top cover is sewn with a loop which wraps around and secures it to the front cross piece.

9. Person 1 passes the free end of the felt under the main cross piece and holds the rear of the felt in place while Person 2 zips in the rear edge. The half of the zipper which is attached to the rear of the sled is sewn into a piece of neoprene which loops around the rear sled cross piece. At the rear edge of the felt are sewn two 1" nylon straps. Person 1 or 2 pulls these straps under the rear sled cross piece and lays them on top of the rear cross piece.

10. Person 1 secures the rear zipper with duct tape and Person 2 gets the test sample in its sample containment bag and thermocouples 1 and 7 (thermocouples 2, 3, 4, 5, and 6, from bottom to top, are embedded in the sheet) from a nearby table.

11. Person 2 begins plugging in the thermocouple assembly and thermocouples 1 and 7, while Person 1 begins removing the tape holding the plastic over the triangular holes in the containment bag. Thermocouples 1 and 7 have each been fished through small diameter plastic tubes so that only the junction is exposed. This reduces the chance of shorts and makes handling easier.

12. Person 2 helps remove the last of the tape and Person 1 collects all the pieces and puts them in one place.

13. Persons 1 and 2 pull the cloth cover over the main cross piece and extend it down the sled to its full extension. The cover extends to just short of the rear sled cross piece and is as wide as the felt. There is a cut out to expose the sample and a small hole to expose the pressure transducer capillary. There are also two 1" nylon straps which loop around the front cross piece and extend the length of the sled along the edges of the cloth cover. The nylon straps attach, with plastic clips, to the two straps that were placed on the top of the rear sled cross piece in step 9. Person 1 and Person 2 secure the cover cloth with the nylon straps and tension the straps. This relieves some of the stress on the felt zipper.

14. If vacuum is used, Person 1 turns on the lube shower. Person 2 secures thermocouples 1 and 7 with small pieces of tape and checks that the pressure and vacuum capillaries are positioned correctly.

15. When Person 1 returns to the safe area by the sled, Person 2 turns on the motor.

16. When the motor and flywheel have reached full speed, Person 2 presses and holds down the run button engaging the pull cable clutch and sending the sled down the track. When the sled stops, Person 2 releases the run button, turns off the steam, and disengages the brake cable and pull cable brakes.

17. Person 2 collects the pieces removed from the plastic containment bag, walks to the sled, removes the sample by unplugging the thermocouples, and takes the sample to the scale for weighing.

18. Person 1 turns off the lube shower and vacuum, removes the felt from the sled, and takes it to the scale for weighing.

19. The weights are recorded. The data acquisition system times out and the data is checked.

If a third person is available, that person assumes some of the jobs of both Person 1 and Person 2. This speeds up the process of running multiple tests.

Figure 20 gives the conditions for each of the shakedown runs conducted. In these tests the sample reached the steam box at 0.200 seconds, exited the steam box at 0.230 seconds and hit the brake bar at 0.384 seconds. The braking bar was positioned 4 feet past the second photo eye. These times are based on the triggering of the first photo eye and may vary slightly from test to test. The data rate was 125 Hz.

Figures 21 through 26 show the thermocouple responses for each of the tests. Figures 27 through 32 show 2-D temperature profiles through the sheet. In each 2-D profile there are six profiles each separated in time by 0.032 seconds. The first profile is just as the sample enter the steam box and the last profile is just before the sled hits the braking bar. In all cases, the order of the thermocouples from top of the sheet to the bottom was 7, 6, 5, 4, 3, 2, 1. Figure 33 shows a non-dimensional response, referred to as Weighted Heat Average Temperature (WHAT), for all six runs. The WHAT response is calculated as

$$WHAT = \left\{ \begin{array}{l} \left[(TC1+TC2)/2\right]*69g+\left[((TC2+TC3)/2)\right]*51g \\ +\left[((TC3+TC4)/2)\right]*25g+\left[((TC4+TC5)/2)\right]*25g \\ +\left[((TC5+TC6)/2)\right]*17g+\left[((TC6+TC7)/2)\right]*17g \end{array} \right\} /(204g*100C).$$

E. SUMMARY OF RESULTS

In reviewing the temperature responses, one can see that the graphs show occasional sudden high or low temperature outputs. Two possible causes are; random thermocouple outputs caused by noise in the signal and/or temporary electrical shorts or a disturbance to the sample which causes the thermocouple to move relative to the sample plies. The former is more likely since the spikes generally consist of only one data point and after the spike the data trace returns to near its earlier level. In addition, the data rate for all the test runs was 125Hz, or one data point every 0.008 seconds, and the Type E, 0.002 thermocouples used in these experiments have a response time of approximately 0.002 seconds. The samples did suffer some delamination during the impact with the braking bar, but this did not occur until approximately 0.38 seconds and does not account for spikes before that time.

A comparison of Runs 2, 4, 5, and 6 shows the effect of vacuum. In these runs the vacuum levels were progressively reduced, from full, to 2/3, to 1/3, and to 0. Runs 2 and 4, with full and 2/3 vacuum show almost identical heating. However, close examination of the thermocouple responses does show a difference. Despite reaching the same peak temperatures at the top of the sheet, the lower portion of the sheet, as indicated by thermocouple 2, was not heated as well in Run 4 as it was in Run 2. Both the temperature response and temperature profile graphs show that the sheet in Run 4 cooled faster. Runs 5 and

6, with vacuum levels of 1/3 and 0, respectively, show the effects of further reducing the vacuum. Both runs show lower peak temperatures at all levels in the sheet, and lower temperatures at braking bar impact. In these runs full vacuum was approximately 5 in Hg as measured in the vacuum box manifold. The vacuum at the bottom of the sheet was approximately 1.75 in Hg, giving a pressure drop across the felt of approximately 3.25 in Hg. There are a number of questions about how the vacuum produces this effect: Does the vacuum cause a downward z-direction displacement of water, thus, providing vacant pore spaces for the steam to condense in? How much of a role do conduction and convection play? Does the vacuum reduce air in the sheet and thereby increase the thermal conductivity of the sheet? Does a two ply sheet behave differently and if so why?

The primary difference between Runs 1 and 2 is the percent solids of the samples; in the first case it is 38% and in the second it is 31%. The temperature profile graphs show that the 38% sheet reached slightly higher temperatures and that the higher temperatures extended deeper into the sheet. Another interesting effect that is evident on both the thermocouple response and temperature profile graphs, is that the 38% sheet appears to have cooled faster.

Runs 3 and 6 illustrate an interesting and potentially useful effect. In Run 3, the plastic was left on the bottom of the sample, thus isolating it from the vacuum. In Run 6 there was no active vacuum applied. In both cases the vacuum box remained mounted on the track. The temperature profile and thermocouple response graphs demonstrate that the Run 3 sheet had lower peak temperature at all sheet levels. Given the results of Runs 2, 4, 5, and 6, which show that increasing vacuum levels increase the level and depth of sheet heating, it appears that the presence of the vacuum box in Run 6 produced a passive vacuum. Run 2, which produced a thorough heating of the sheet, used a relatively low vacuum level of ~5 in Hg. The combination of these results suggest that it may be possible to construct a passive device capable of producing a vacuum large enough to thoroughly heat the sheet. Note, that in Run 3, the bottom thermocouple slipped out from under the sample.

The last graph, Figure 33, is the WHAT response. This graph is useful in obtaining an overall comparison of the runs. Due to the averaging used in its calculation some effects are minimized, but it still provides a reasonable accurate and concise view of the test results.

IX. Conclusions

A review of the test results leads to several general conclusions:

1. The steam box comparator is capable of producing experimental data under conditions similar to those that exist in commercial paper machines.

2. Using a vacuum box with the current steam box improves heat transfer to the sheet, although the exact mechanism that causes the improvement is not known.

3. Lower sheet moisture content improves the heat transfer, although it appears that the lower moisture content sheet will also cool faster.

4. It appears that a vacuum box with no active vacuum source can apply a passive vacuum to the sheet.

X. Recommendations

In this study the vacuum box is 9" long while the steam box is 12" long. The vacuum box was centered underneath the steam box. The question arises, is there an optimum vacuum box length for a given steam box and is there an optimum position for the vacuum box in relation to the steam box? Are two short vacuum boxes more efficient than one long vacuum box? Can a passive device provide a large enough vacuum? Given the limited space available in a paper machine it would be worthwhile learning if a short length vacuum box or passive device perform as well as a long vacuum box.

The shakedown tests showed that for a sheet made entirely of 600 CSF fiber that increasing vacuum levels increased steam box performance. Is there a level where this effect drops off? Does it hold true for all webs, including multi-ply webs?

Is there an advantage to using a different felt? The current instrumentation set up allows the measurement of the pressure drop through the felt. Test methods exist for measuring felt permeability. Thus, the capability exists to evaluate felts both from the stand point of water absorption and maximizing the vacuum exerted on the web.

In addition, there is the consideration of steam box design. The Measurex-Devron steam box used in this study was a general purpose design. It was useful in establishing general trends but it does not have the same performance as a box designed for a specific application. Also, the design philosophy behind the Measurex box is not the same as that for boxes made by other manufacturers.

It is well known that heating the web with steam prior to pressing improves the performance of the press. Improvements in web heating directly effect the press performance. The steam box and vacuum box are relatively low cost compared to the rest of the paper machine. There is the potential of gaining press section performance for a small capital investment. Given the results of the testing to date, the following parameters effect steam box performance:

1. Vacuum.
3. Web Consistency.

It is assumed that several other factors effect the steam box performance:

1. Vacuum Location.
2. Steam Box Design.
3. Steam Flow Rate.
4. Steam Superheat.
5. Web Residence Time.
6. Web Speed.
7. Web Furnish.
8. Felt Construction.

If the objective is to improve the performance of a specific paper machine, the question needs to be asked, i.e. Which of these parameters can most easily be changed on the paper machine in question? If the parameters are prioritized as to the paper machine operators willingness to change them, then the selected parameters can be investigated one at a time. The results of each investigation can be applied to the machine and evaluated before the next series of tests is begun. An example of this type of work is: the evaluation of the actual preheat capabilities on a specific commercial paper machine. This would involve mounting a representative steam box on the rocket sled and running sample made from the pulp used on the commercial machine. Actual temperature profile of the sample can then be used to evaluate the effectiveness of the preheat system.

If the objective is a generic investigation, such a study would investigate most of the parameters listed above. Its intent would be less application oriented, and more concerned with describing and explaining the physical processes which occur in the sheet and the interactions with the steam and vacuum boxes. An example of this type of study is a laboratory experiment to determine the impact of preheat on the complete press section, including an impulse dryer. This type of experiment could use either the standard closed top sheet-open bottom sheet combination or the open top sheet-closed bottom sheet combination that works best for impulse drying.

Another potential subject for a more general study is design optimization. There is almost no current, publicly accessible, literature on the design of steam and vacuum boxes.

XII. Figures and Tables

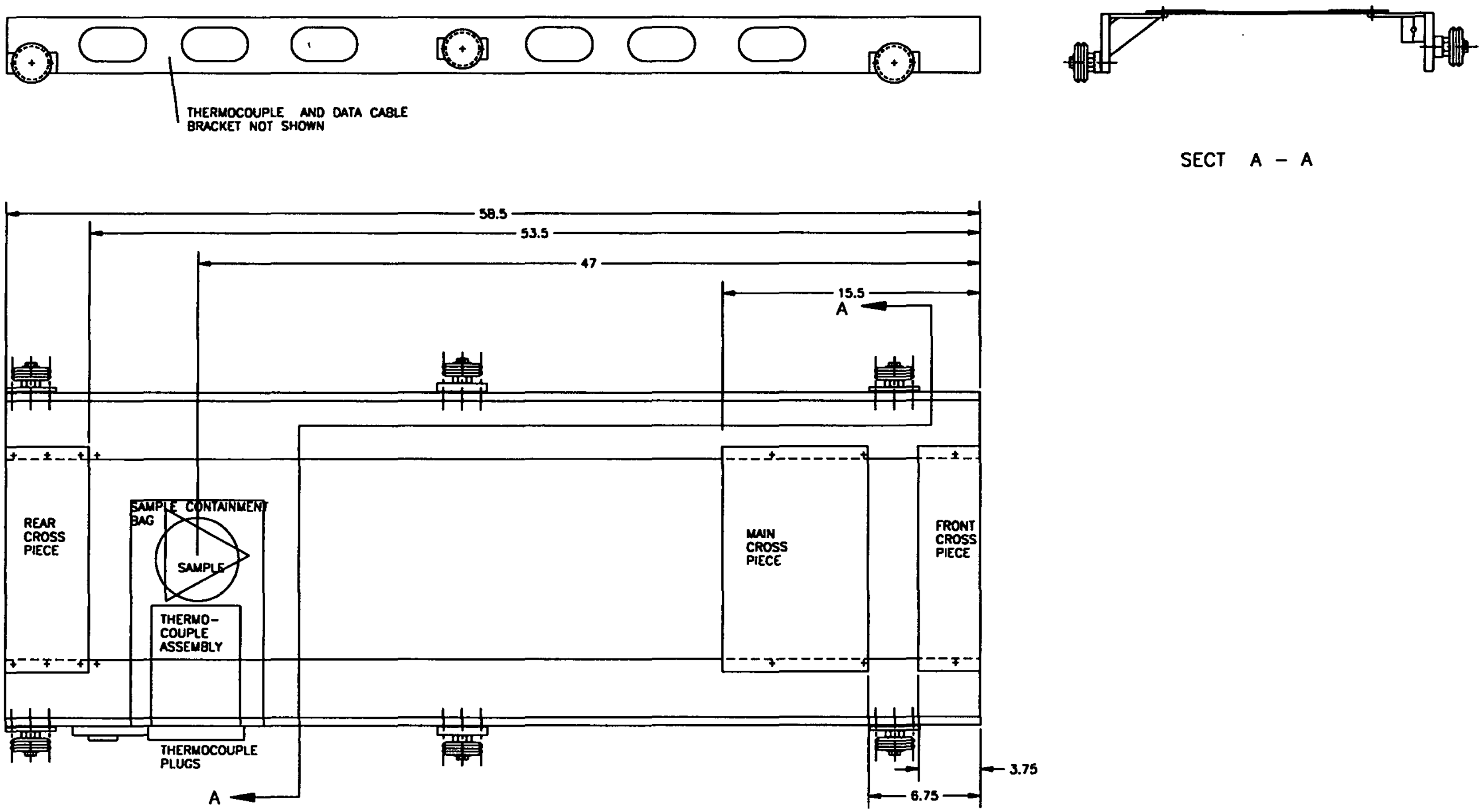


FIGURE 1. THE ROCKET SLED

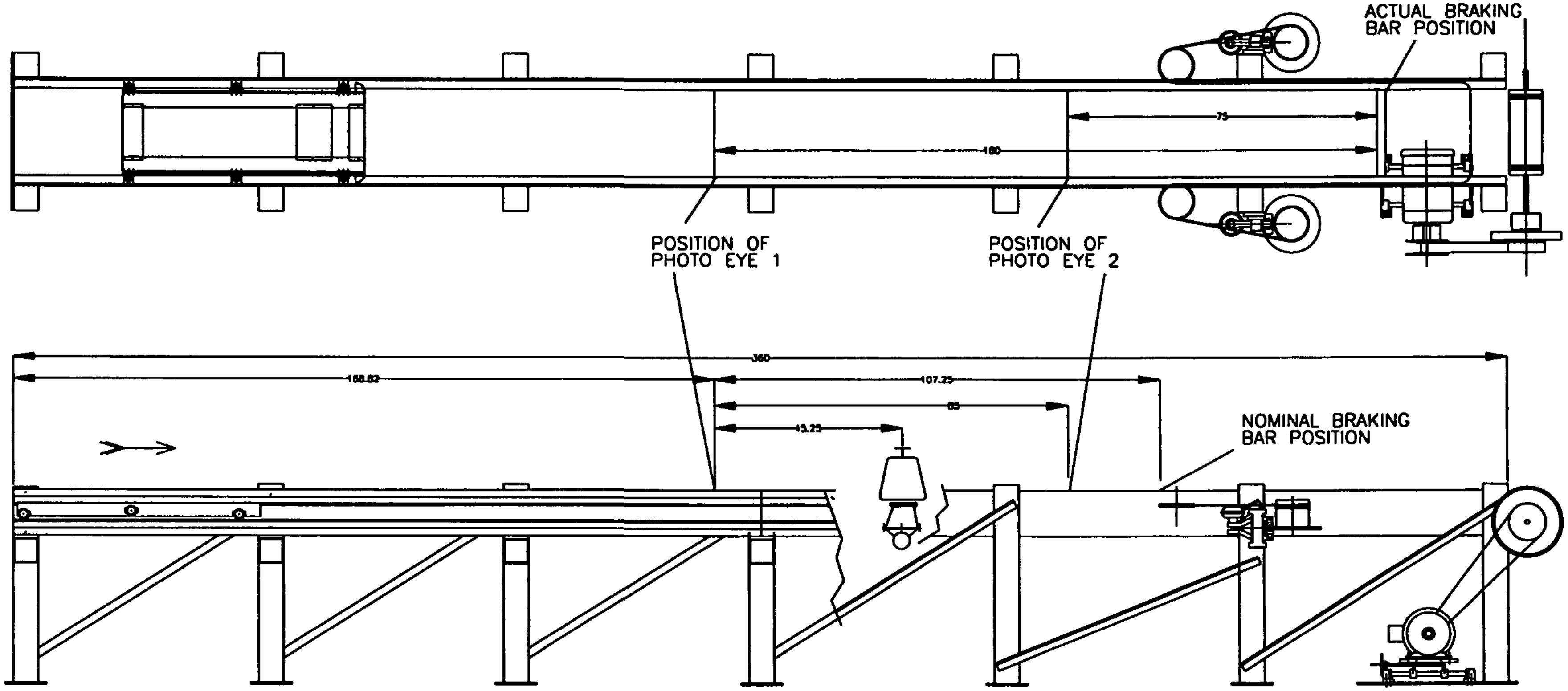


FIGURE 2. THE ROCKET SLED TRACK

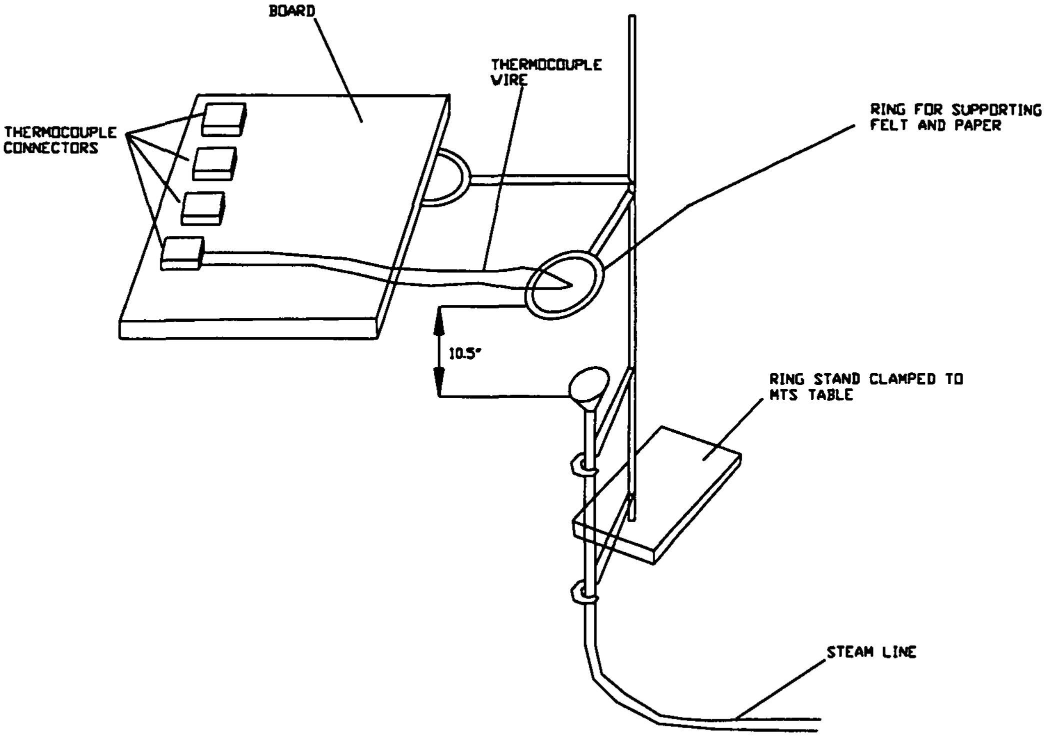
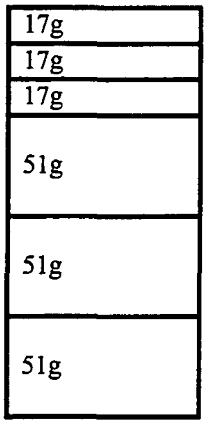
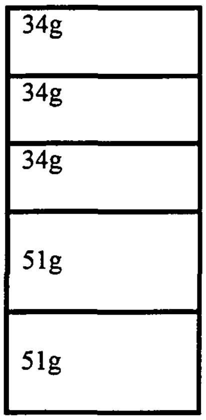


FIGURE 3. STATIC STEAMING APPARATUS



Type 1



Type 2

Multi-Ply

Type	Samples	17g	34g	51g	# thermo.
1	3	3x3=9	0	3x3=9	3x5=15
2	3	0	3x3=9	2x3=6	3x4=12

Two Ply

Type	Samples	Top	Bottom	# thermo.
3	3	17g (3)	187g (3)	1
4	3	34g (3)	170g (3)	1
5	3	51g (3)	153g (3)	1
6	3	68g (3)	136g (3)	1
7	3	102g (3)	102g (3)	1

Figure 4. Matrix of Sample Types

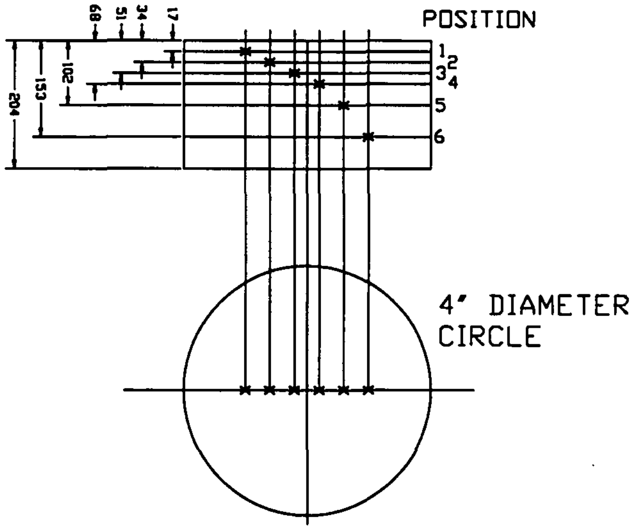


FIGURE 5. THERMOCOUPLE POSITIONS FOR STATIC STEAMING

Figure 6. Summary of Static Steaming Tests

Test #	Sample	% Solids	Basis Weight	Comments
T17-02	1	39.98	208.33	
T17-03	1	31.20	208.33	Drop outs on TC2.
T34-01	2	32.27	199.82	
T34-02	2	40.17	199.82	Spike on TC2.
T34-03	2	29.32	199.82	Upside down.
T34-04	2	29.03	199.82	
T51-01	3	35.20	207.84	
T51-02	4	38.66	191.68	
T51-03	4	28.23	191.68	
T68-01	5	25.98	196.61	
T68-02	5	25.63	196.61	Bump on TC2.
T68-03	5	26.33	196.61	
T102-01	6	27.77	191.93	
T102-02	6	27.68	191.93	Drop outs on TC2.
T102-03	6	28.15	191.93	
S205-01	7	31.11	208.33	
S205-02	7	30.59	208.33	
S205-03	7	30.99	208.33	
M34-01	8	30.00	188.47	TC3 bad.
M34-02	8	27.70	188.47	TC3 bad.
M34-03	8	27.90	188.47	TC3 bad.
M34-04	9	28.47	190.57	TC4 bad.
M34-05	9	28.49	190.57	TC4 bad.
M34-06	9	27.47	190.57	Bump on TC2,3.
M17-01	10	28.82	198.34	TC1 bad.
M17-02	10	29.00	198.34	
M17-03	10	28.55	198.34	
M17-04	11	22.58	207.47	Bump on TC 2.
M17-05	11	22.46	207.47	
M17-06	11	22.44	207.47	Bump on TC 2.
M17-07	11	22.58	207.47	
M17-08	11	22.55	207.47	Bump on TC 2.
M17-09	11	22.22	207.47	1.2 psig steam.

Figure 7. Multi-ply and Two-ply 17g Level

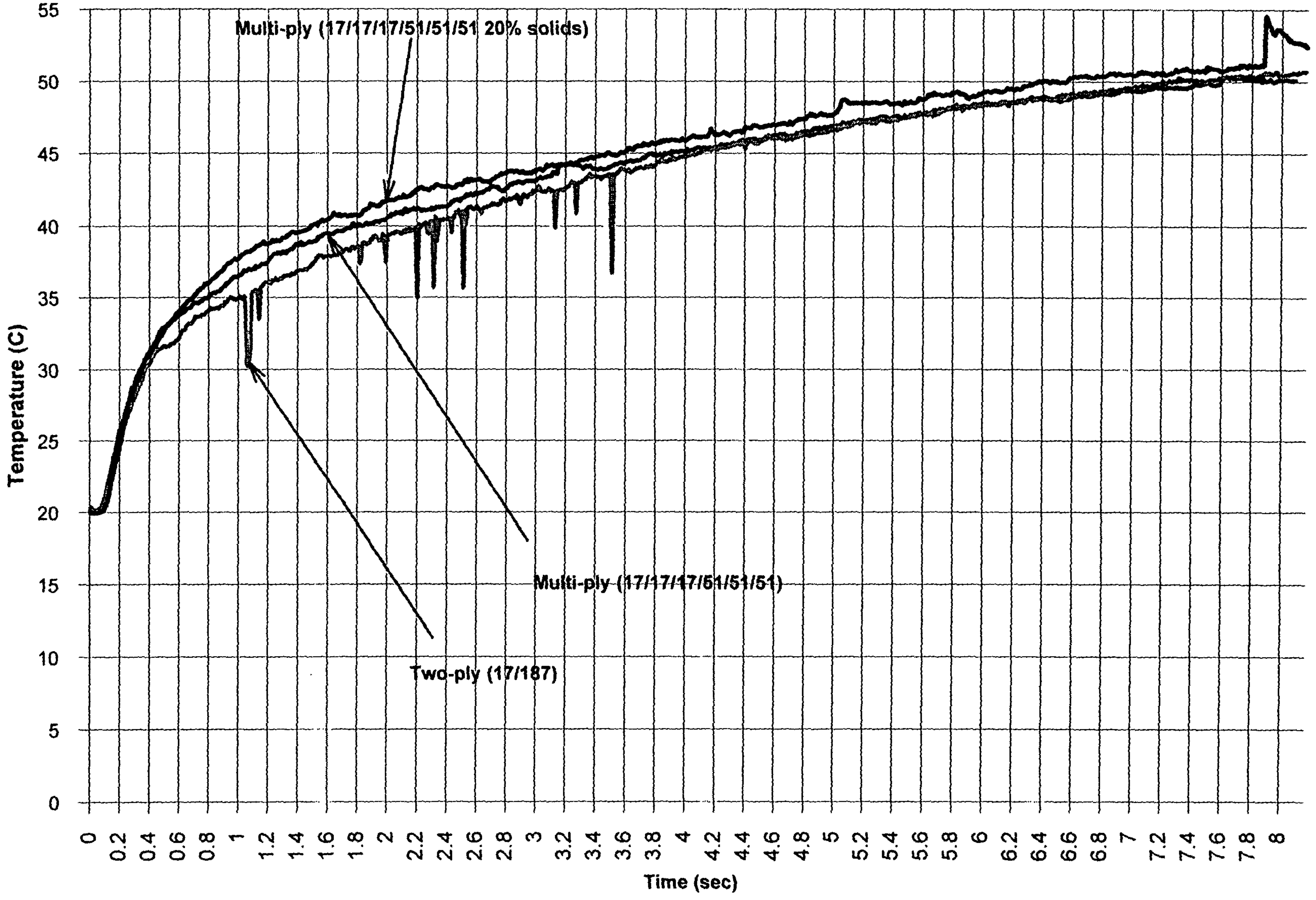


Figure 8. Multi-ply and Two-ply 34g Level

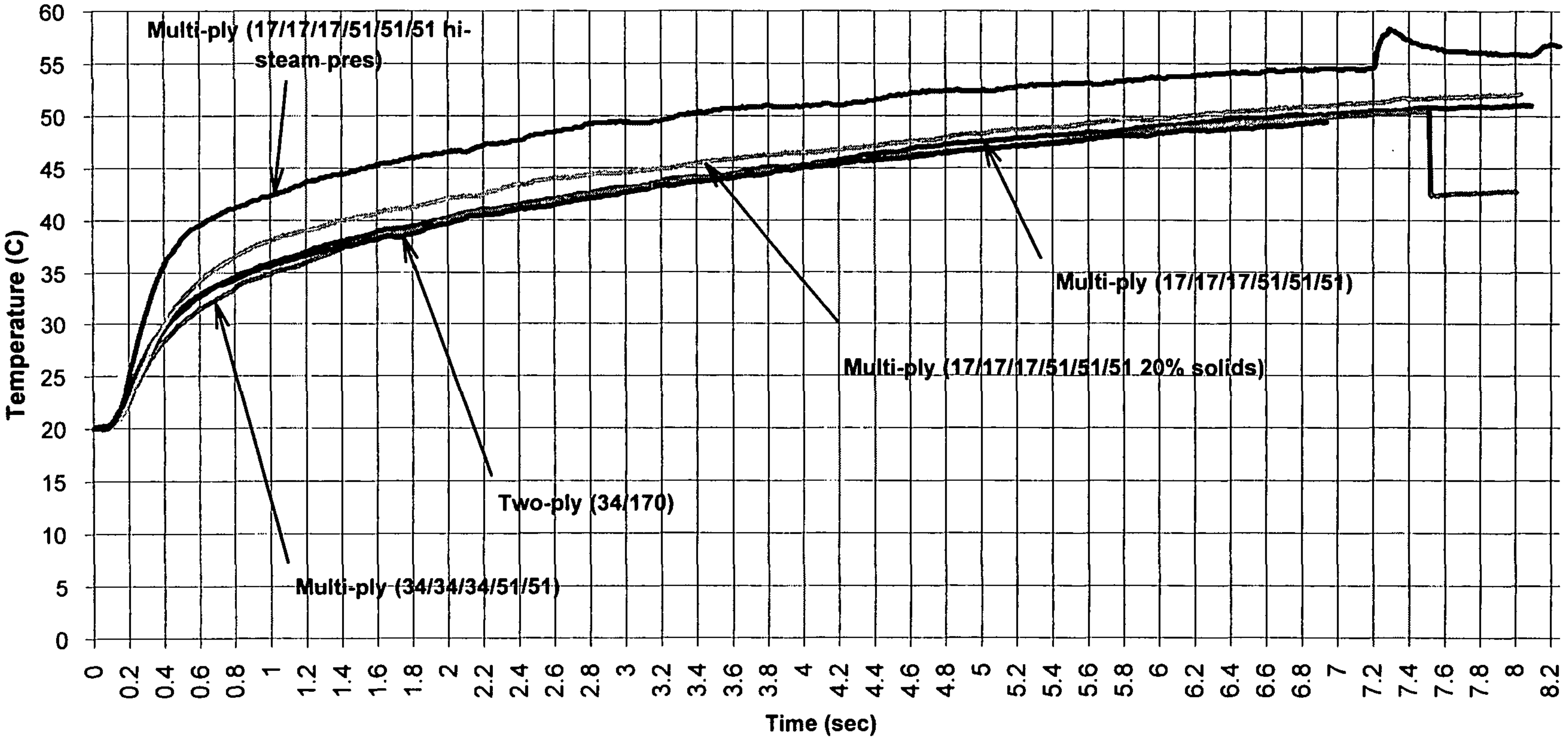


Figure 9. Multi-ply and Two-ply 51g Level

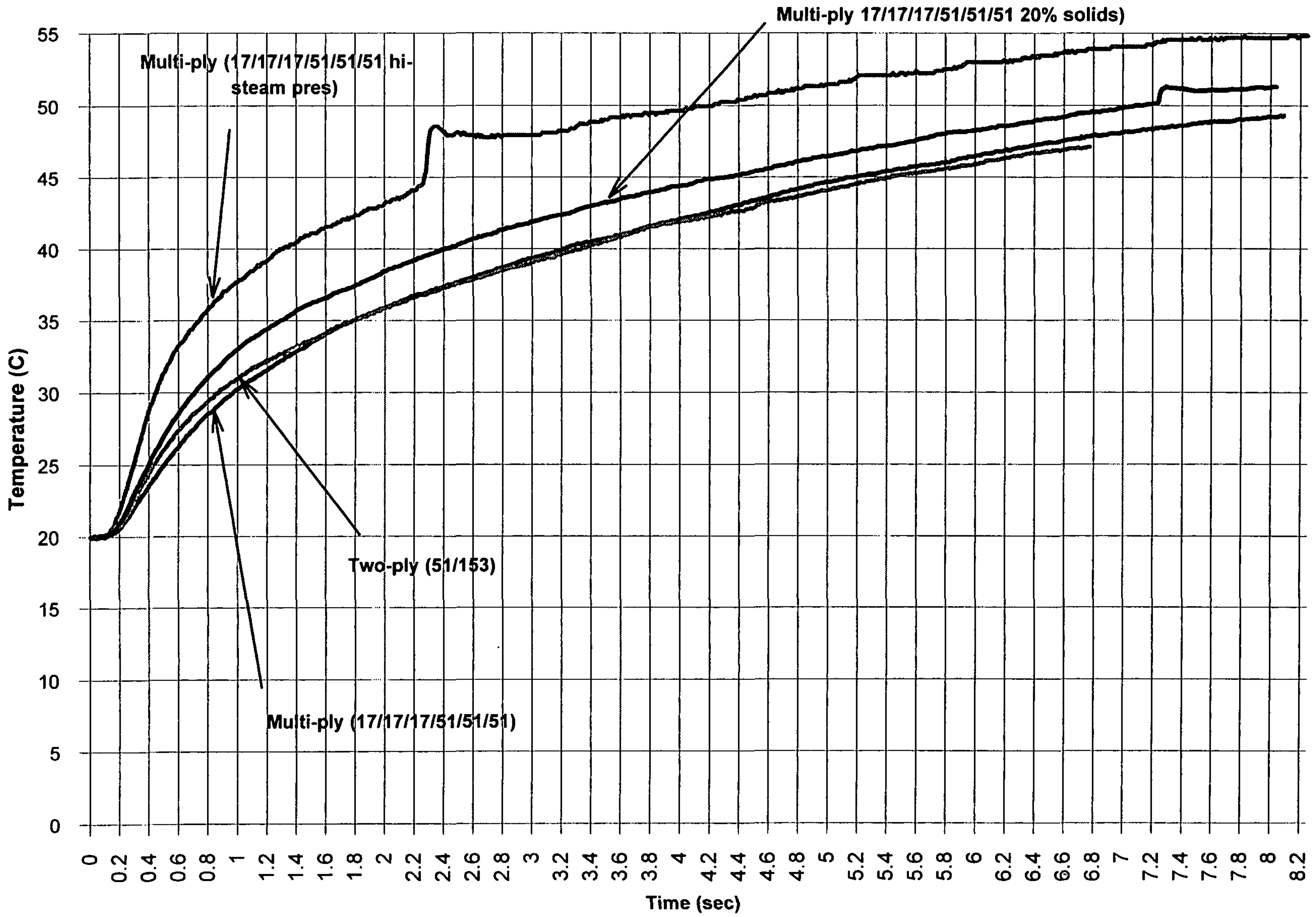


Figure 10. Multi-ply and Two-ply 68g Level

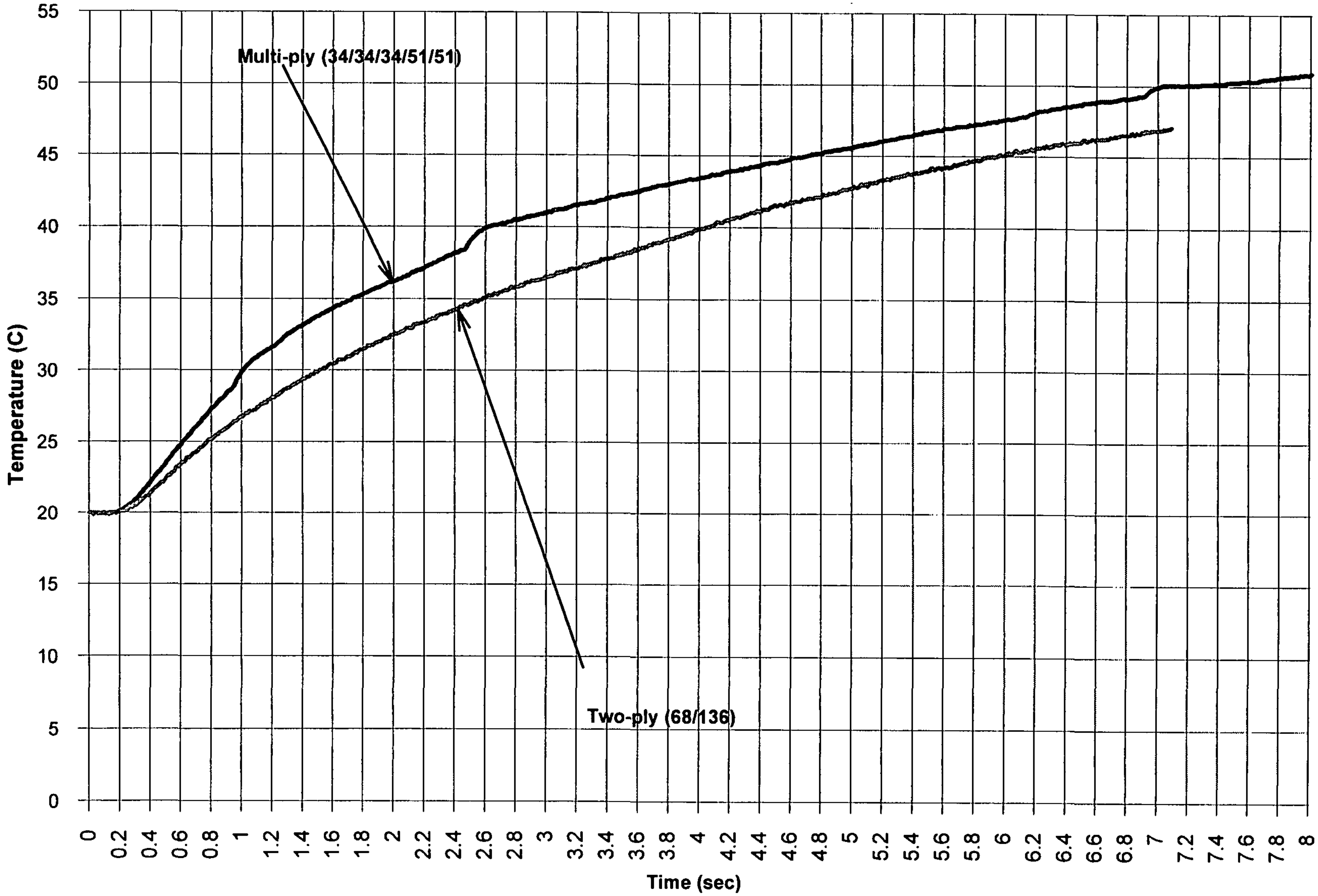


Figure 11. Multi-ply and Two-ply 102g Level

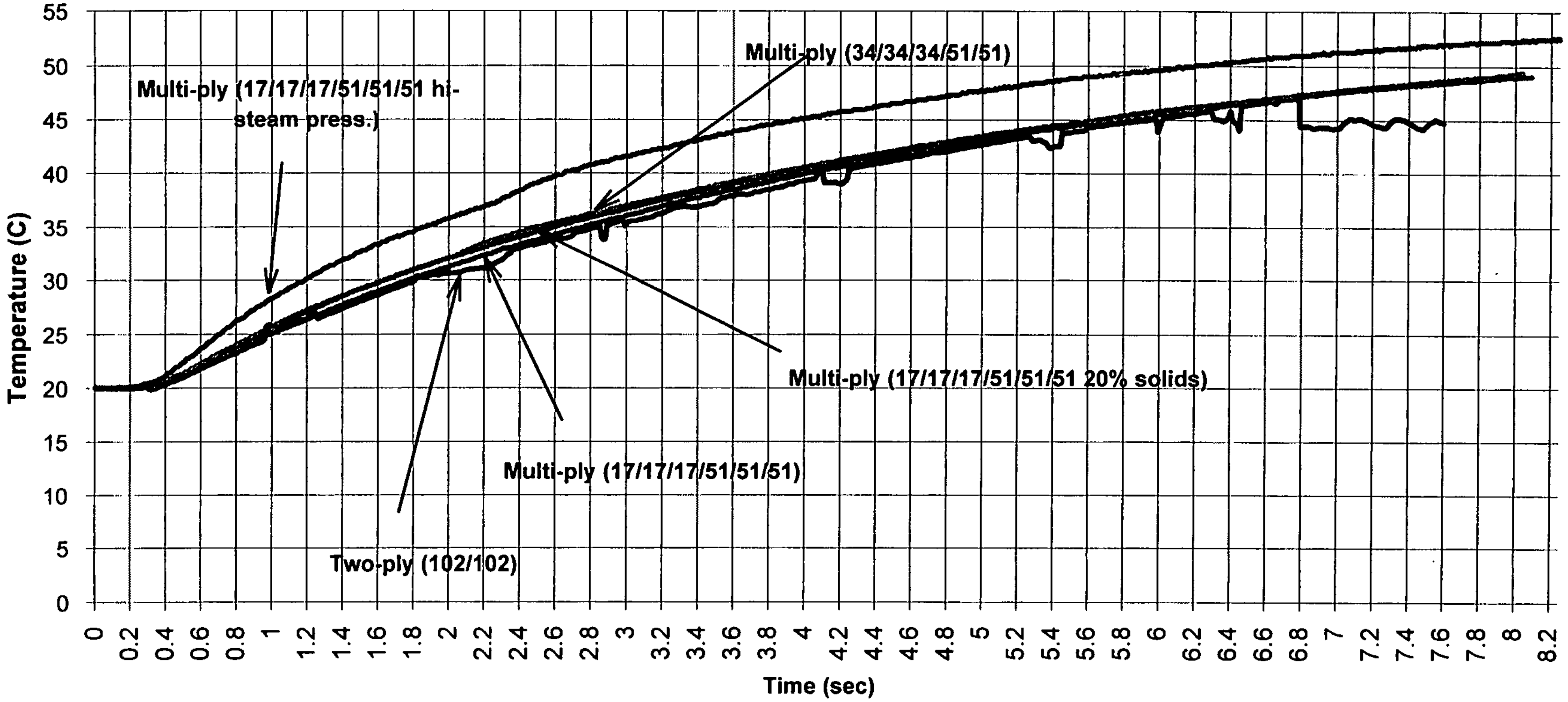


Figure 12. Multi-ply and Single-ply 205g Level

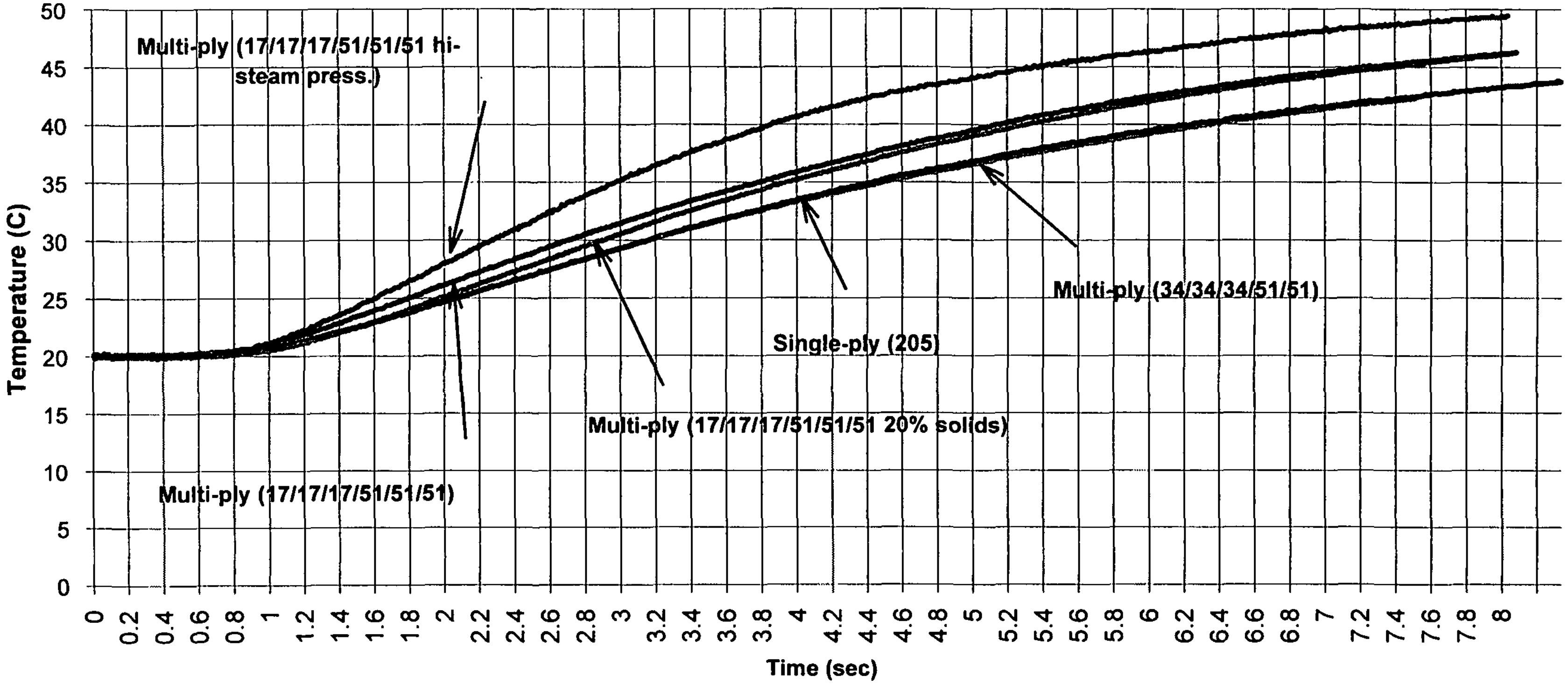


Figure 13. Thermocouple Profile 17-17-34-34-51-51-51 sheet

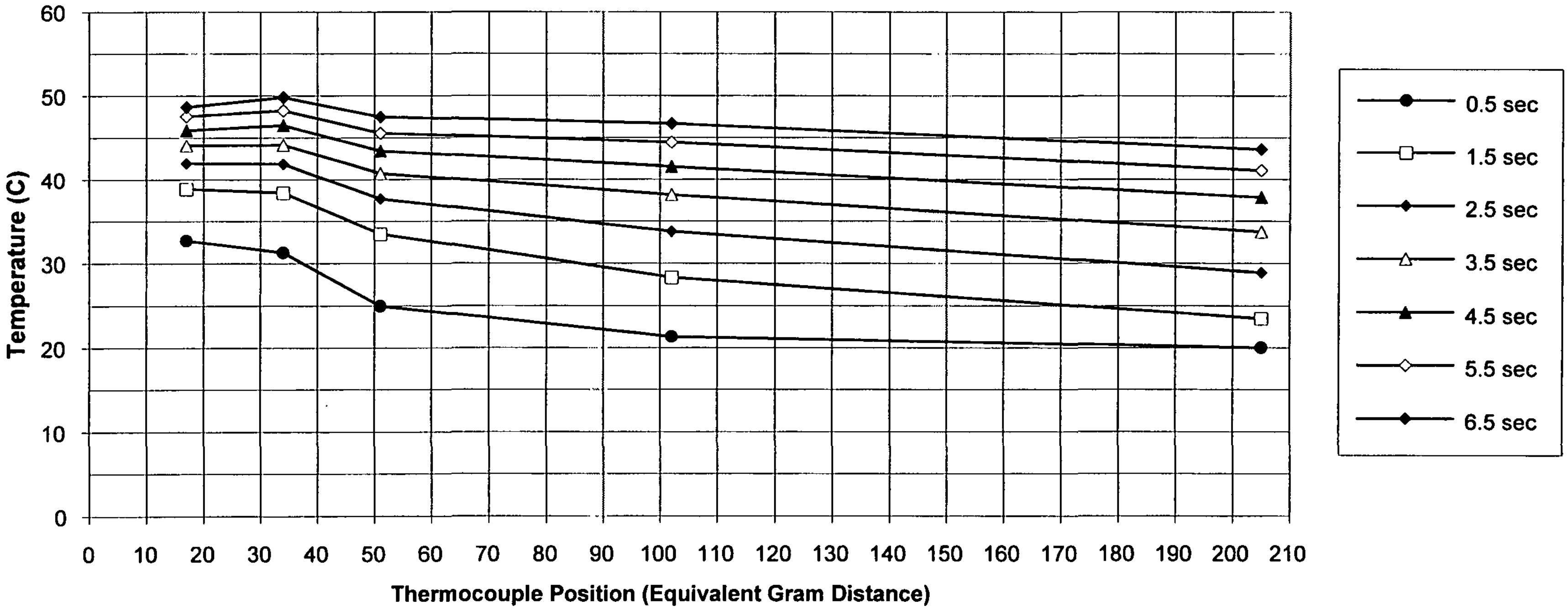


Figure 14. Felt Evaporation Trials

Time (min)	Trial 1	Ambient	Trial 2	Ambient	Trial 3	TAPPI
	Felt Weight (grams)	Temperature/ Rel. Humidity	Felt Weight (grams)	Temperature/ Rel. Humidity	Felt Weight (grams)	Temperature/ Rel. Humidity
0	214.50	27.2 C/ 72.4%	156.30	28.7 C / 68.3%	169.15	23.0 C / 54.3%
5	213.80		155.56		168.53	
10	213.27		154.79		167..80	
15	212.65		153.97		167.09	
20	212.06		153.17	29.3 C / 65.8%	166.33	22.8 C / 53.0%
25	211.44		152.34		165.57	
30	210.80		151.48		164.10	
35	210.18		150.70		163.36	
40	209.53		149.90	29.6 C / 64.3%	162.61	22.6 C / 52.6%
45	208.87		149.05		161.85	
50	208.18		148.16		161.10	
55	207.56		147.30		160.35	
60	206.90	28.4 C / 68.4%	146.42	29.5 C / 63.9%	159.59	22.7 C / 52.8%
65	206.18		145.53		158.83	
70	205.46		144.75		158.04	
75			143.87		157.33	
80			143.02	29.6 C / 64.0%	156.48	22.5 C / 53.0%
85			142.24		155.71	
90			141.37	29.6 C / 64.9%		
Net loss	9.04		14.93		13.44	
Evaporation rate	0.129		0.166		0.149	
Nominal felt dry weight: 104g						

Figure 15. Felt Evaporation Trials

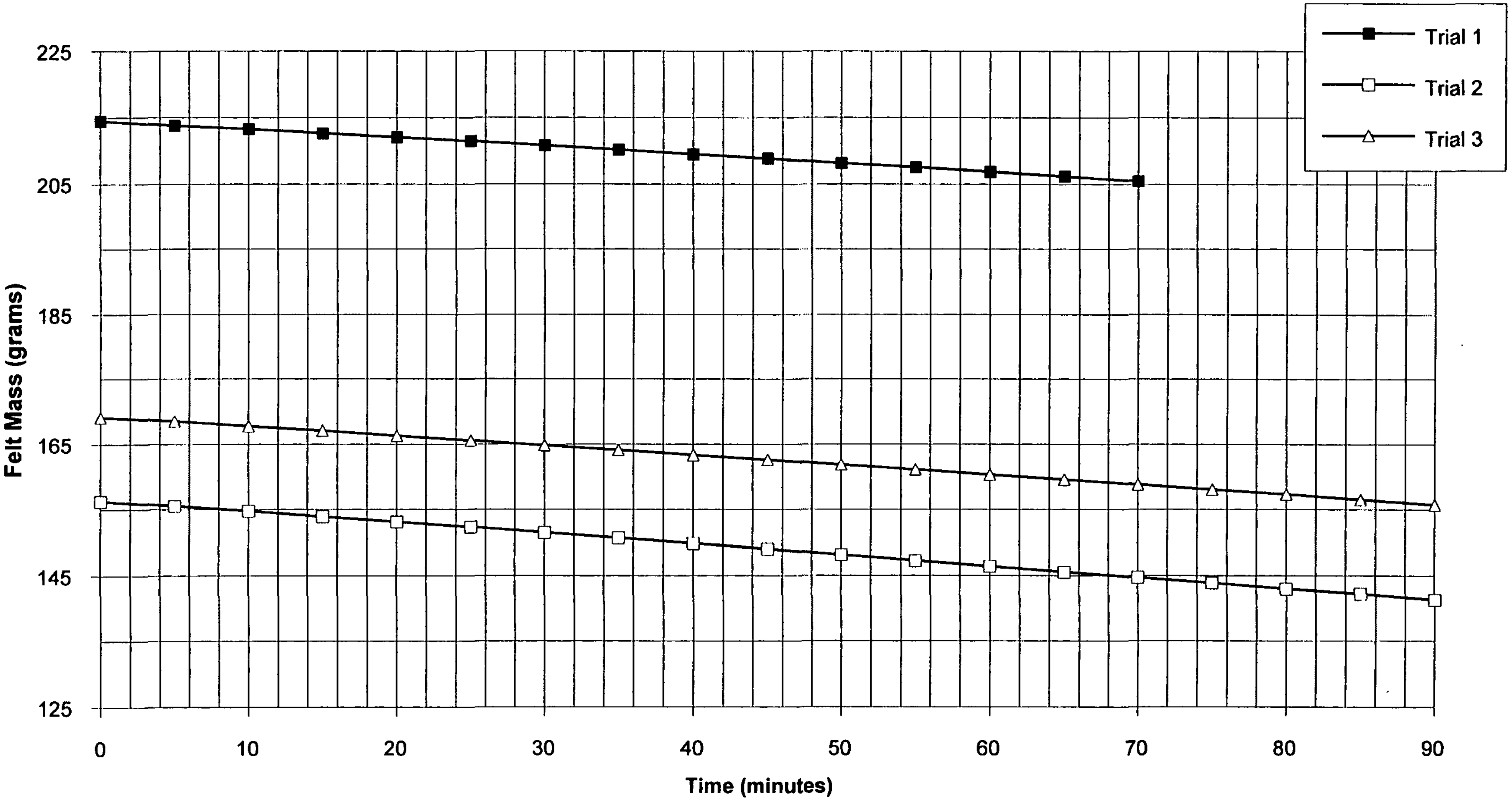


Figure 16. Sheet Assembly Evaporation Testing

Time	Trial 1		Trial 2		Trial 3		Trial 4		Trial 5	
(min)	weight (gram)	%solids	weight (gram)	%solids	weight (gram)	%solids	weight (gram)	%solids	weight (gram)	%solids
0	8.57	25.5	9.79	22.0	8.54	25.2	9.28	23.3	8.42	25.1
5	8.38	26.1	9.61	22.4	8.41	25.6	9.11	23.8	8.26	25.6
10	8.18	26.7	9.47	22.8	8.34	25.8	8.98	24.1	8.14	26.0
15	8.07	27.1	9.28	23.2	8.21	26.3	8.87	24.4	8.01	26.4
20	7.91	27.6	9.16	23.5	8.08	26.7	8.76	24.7	7.88	26.9
25	7.78	28.1	8.95	24.1	7.95	27.1	8.67	25.0	7.77	27.2
30	7.62	28.7	8.80	24.5	7.84	27.5	8.57	25.3	7.63	27.7
35	7.49	29.2	8.63	25.0	7.70	28.0	8.47	25.6	7.49	28.3
40	7.33	29.8	8.50	25.4	7.56	28.5	8.37	25.9	7.34	28.8
45	7.20	30.4	8.32	25.9	7.42	29.1	8.27	26.2	7.18	29.5
50	7.02	31.1	8.17	26.4	7.27	29.7	8.17	26.5	7.03	30.1
55	6.89	31.7	8.03	26.8	7.13	30.2	8.05	26.9	6.88	30.8
60	6.74	32.4	7.88	27.4	6.98	30.9	7.93	27.3	6.74	31.4
Avg. Temp.	22.8		22.9		23.0		27.5		29.1	
Avg. Rel. Humidity	50.4		50.1		50.3		68.8		62.2	
Net Loss	1.83		1.91		1.56		1.35		1.68	
Loss Rate	0.0305		0.0318		0.0260		0.0225		0.028	
o.d.wt.	2.19		2.16		2.16		2.17		2.12	

Figure 17. Sheet Evaporation Trials

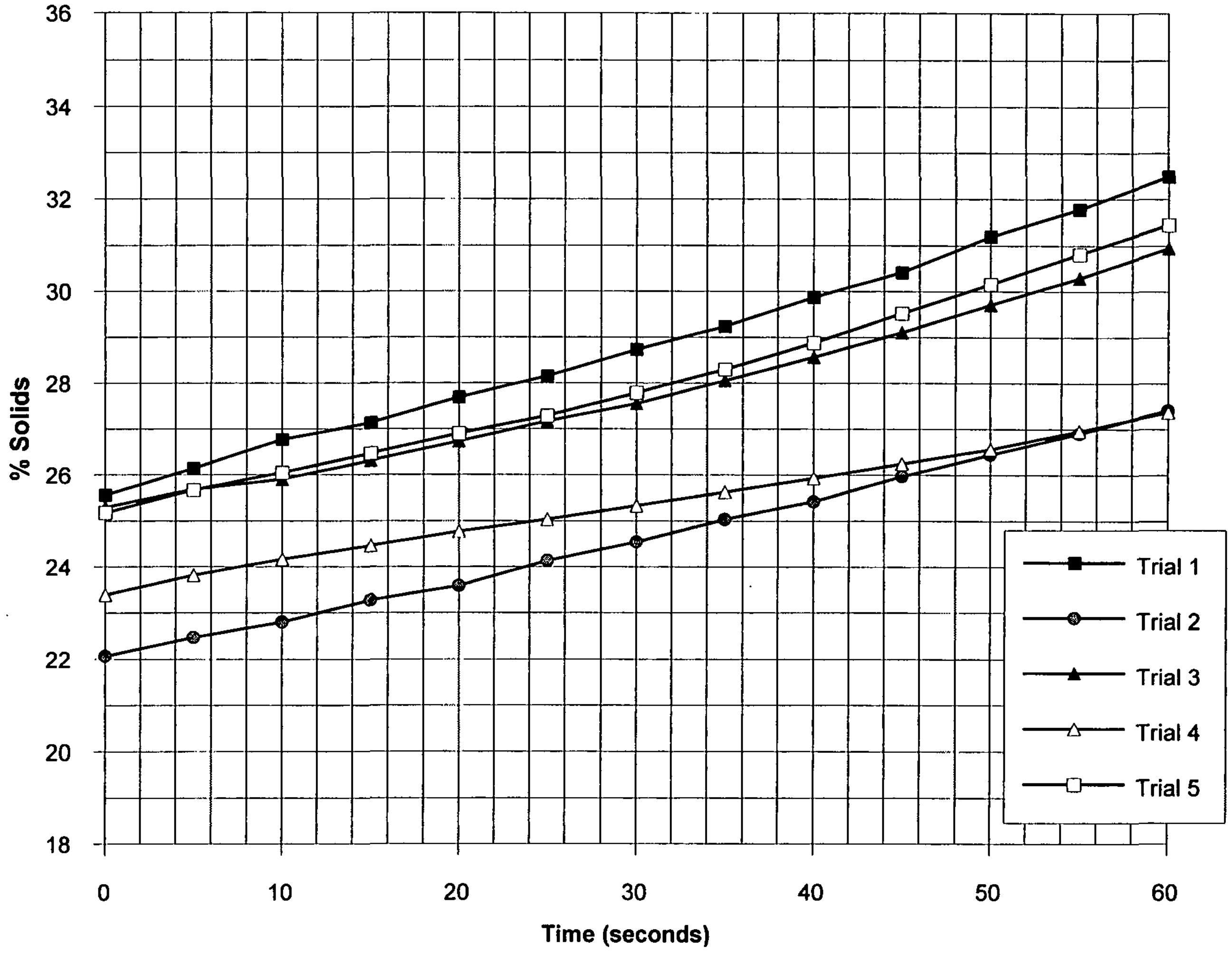


Figure 18. Static Vacuum Test

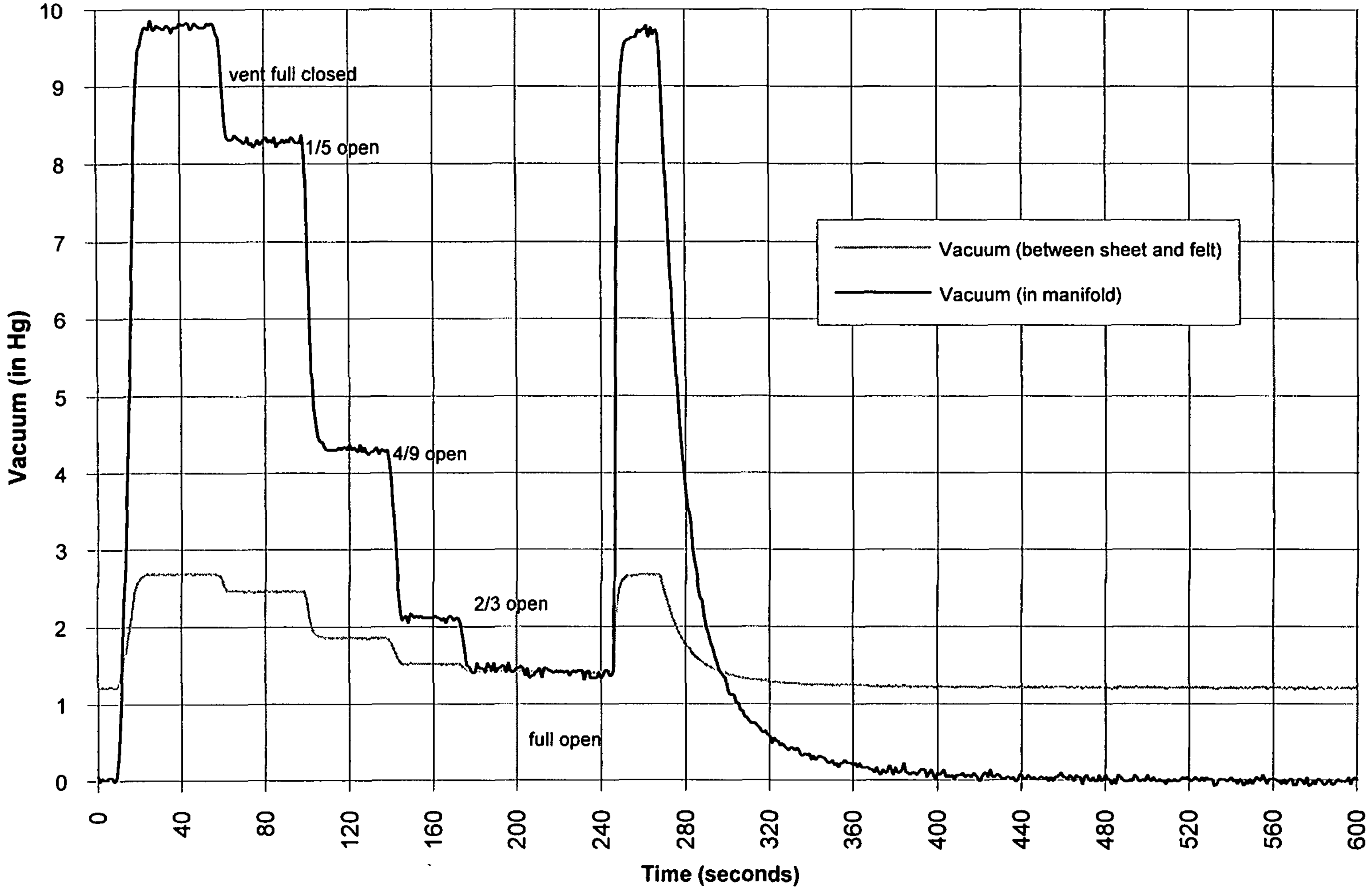


Figure 19. Dynamic Vacuum and Pressure Test

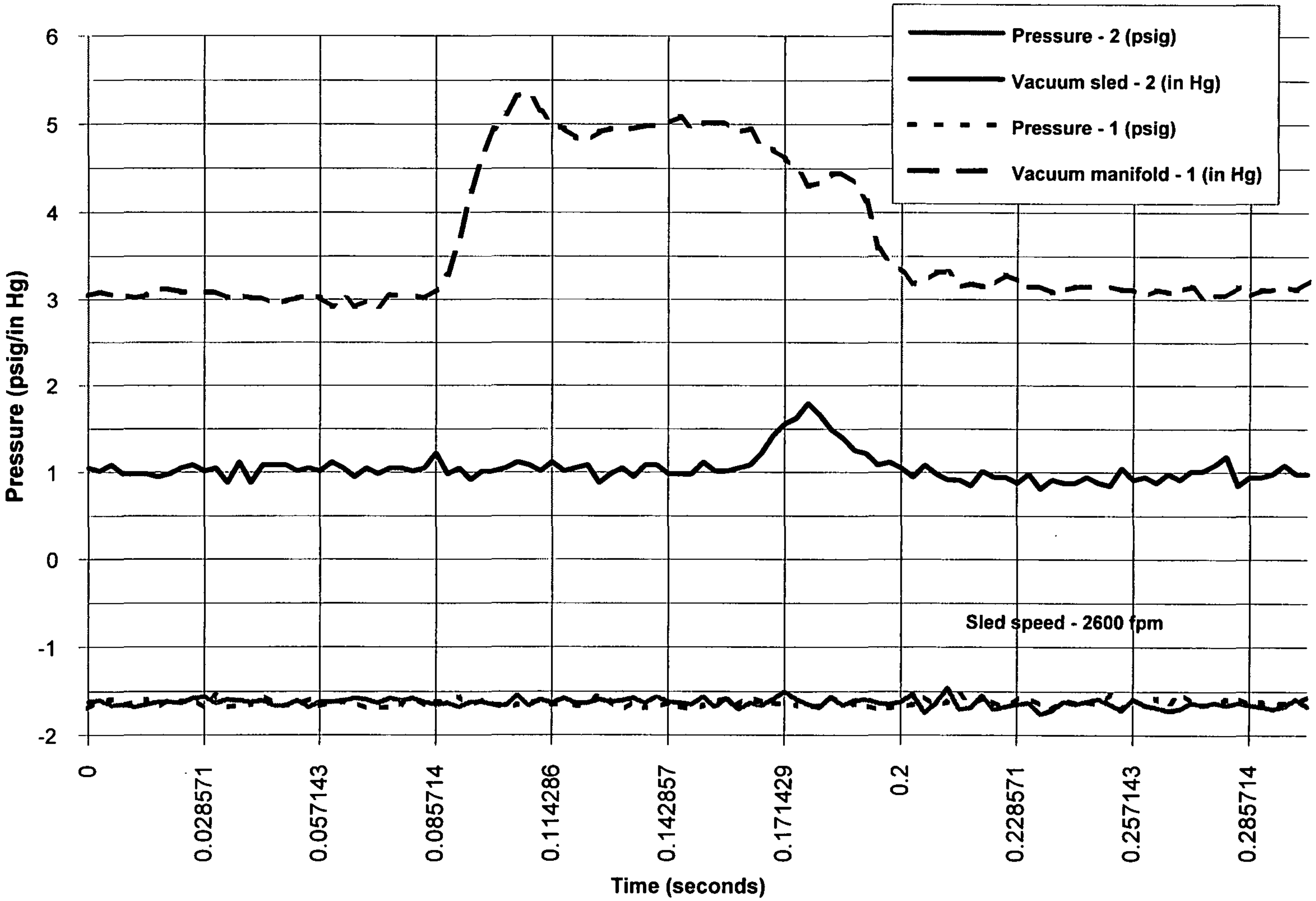


Figure 20. Final Shakedown Run Test Conditions

Run	Data File	Vacuum	Steam Flow	Steam Temp	Steam Pressure	% Solids	Comments
1	0826bb9	Full	152 kg/hr	112 C	.488 bar	38	
2	0826bb10	Full	152 kg/hr	112 C	.499 bar	31	
3	0826bb11	Full	153 kg/hr	112 C	.497 bar	37	plastic kept on bottom of sheet
4	0826bb13	2/3	149 kg/hr	112 C	.498 bar	31	
5	0826bb14	1/3	152 kg/hr	112 C	.485 bar	29	
6	0826bb15	0	153 kg/hr	112 C	.490 bar	30	

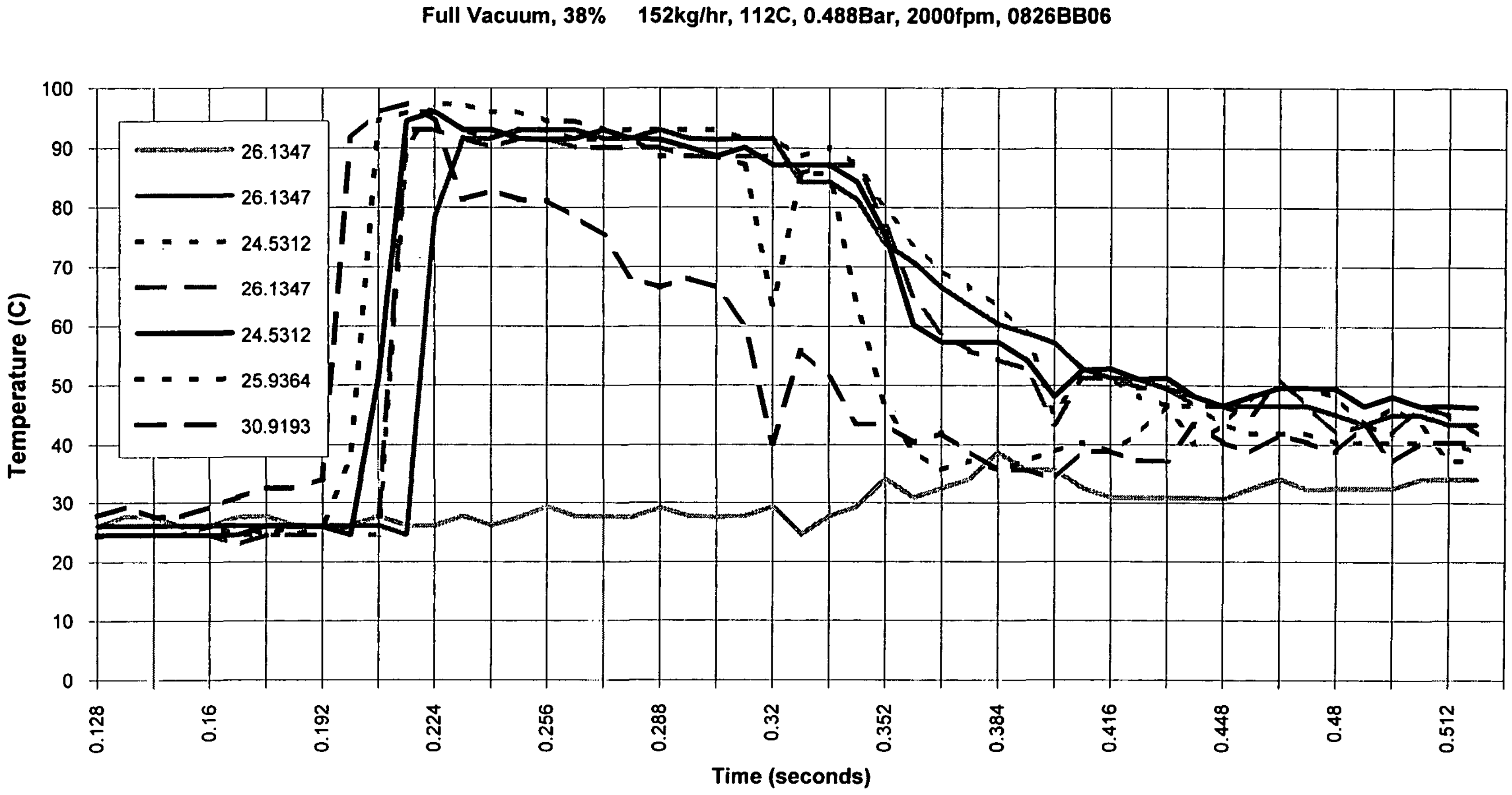


Figure 21. Shakedown Run 1: Thermocouple Response

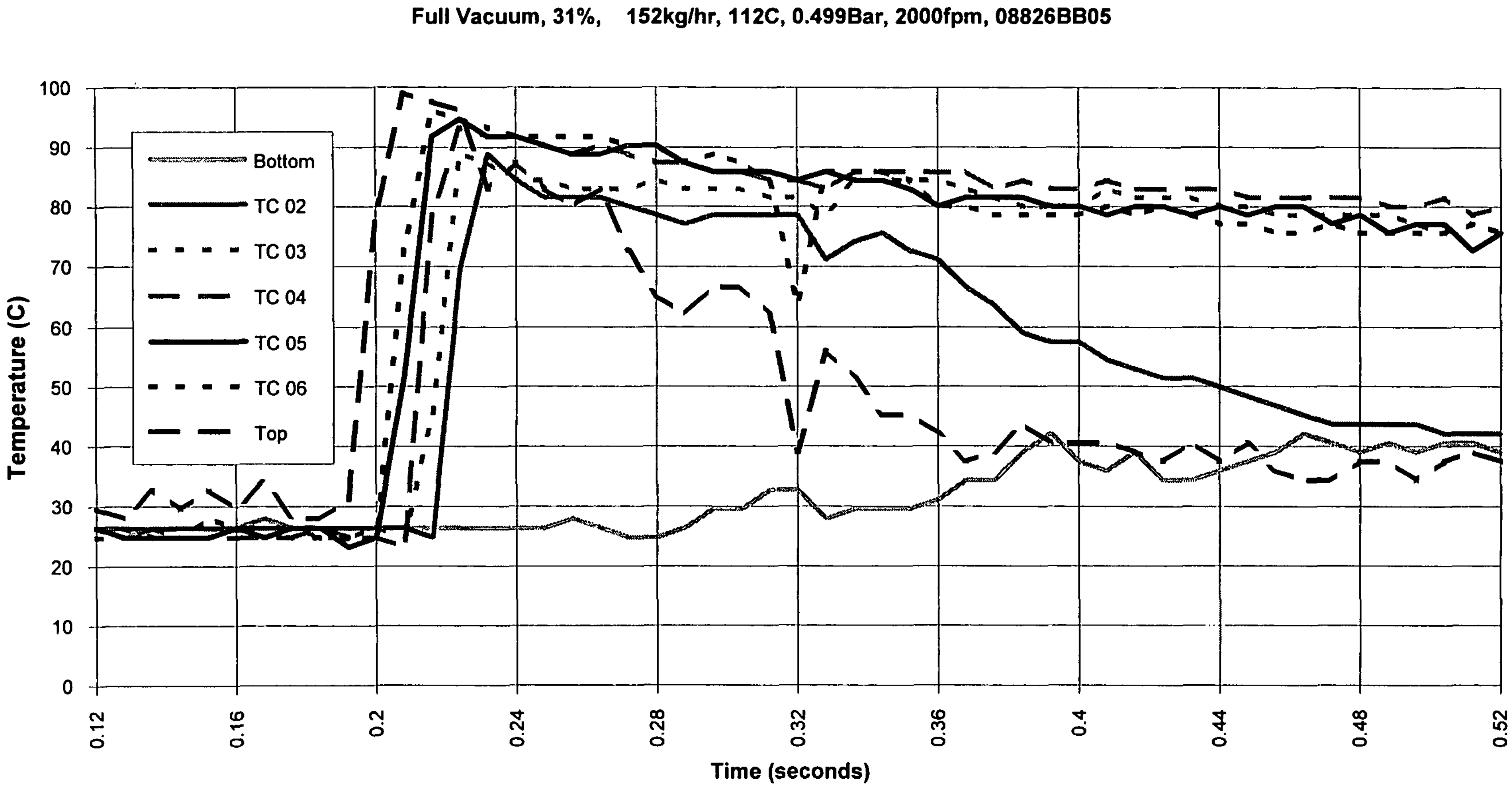


Figure 22. Shakedown Run 2: Thermocouple Response

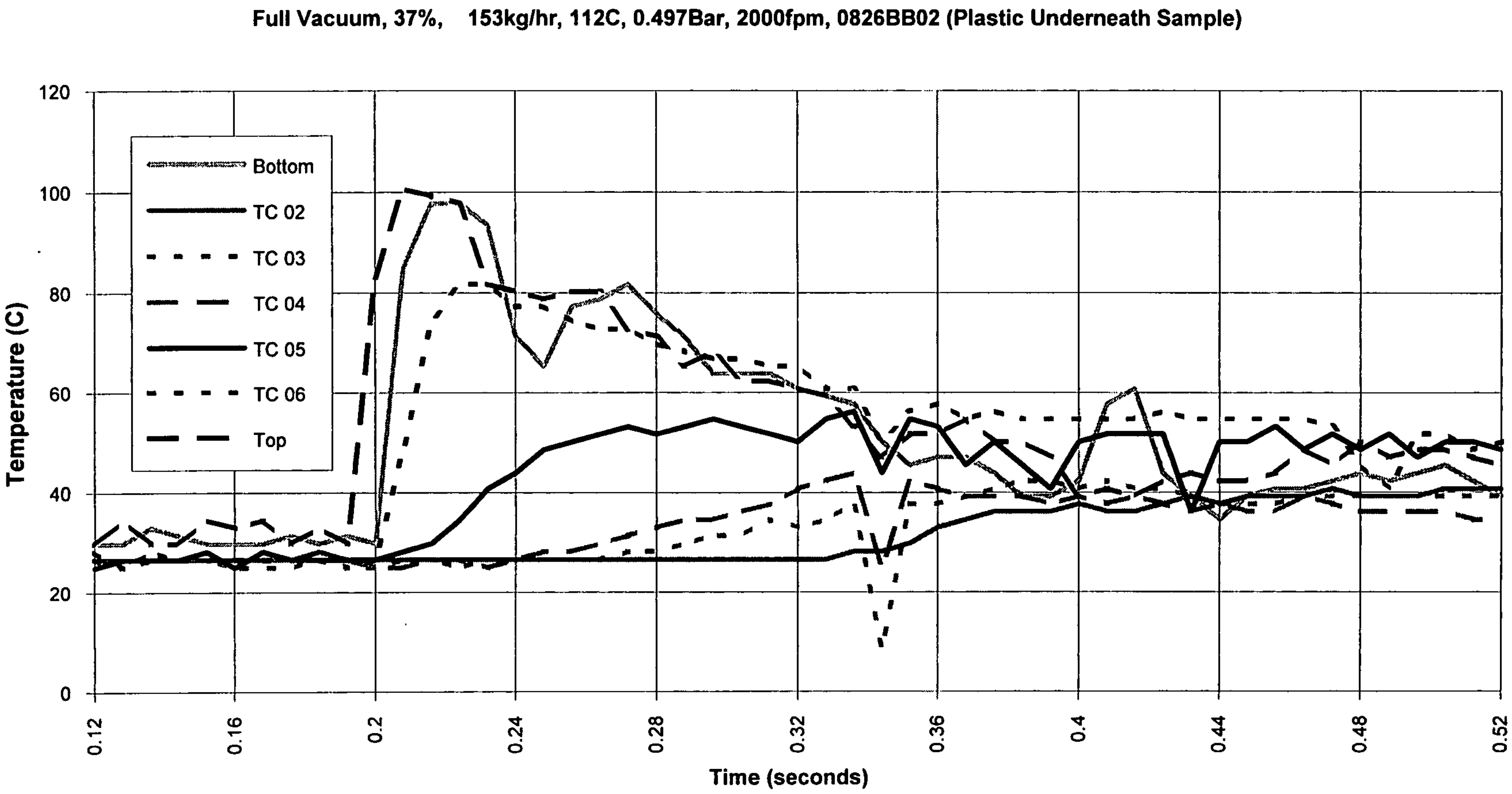


Figure 23. Shakedown Run 3: Thermocouple Response

[0826BB.XLW]0826T13.XLC

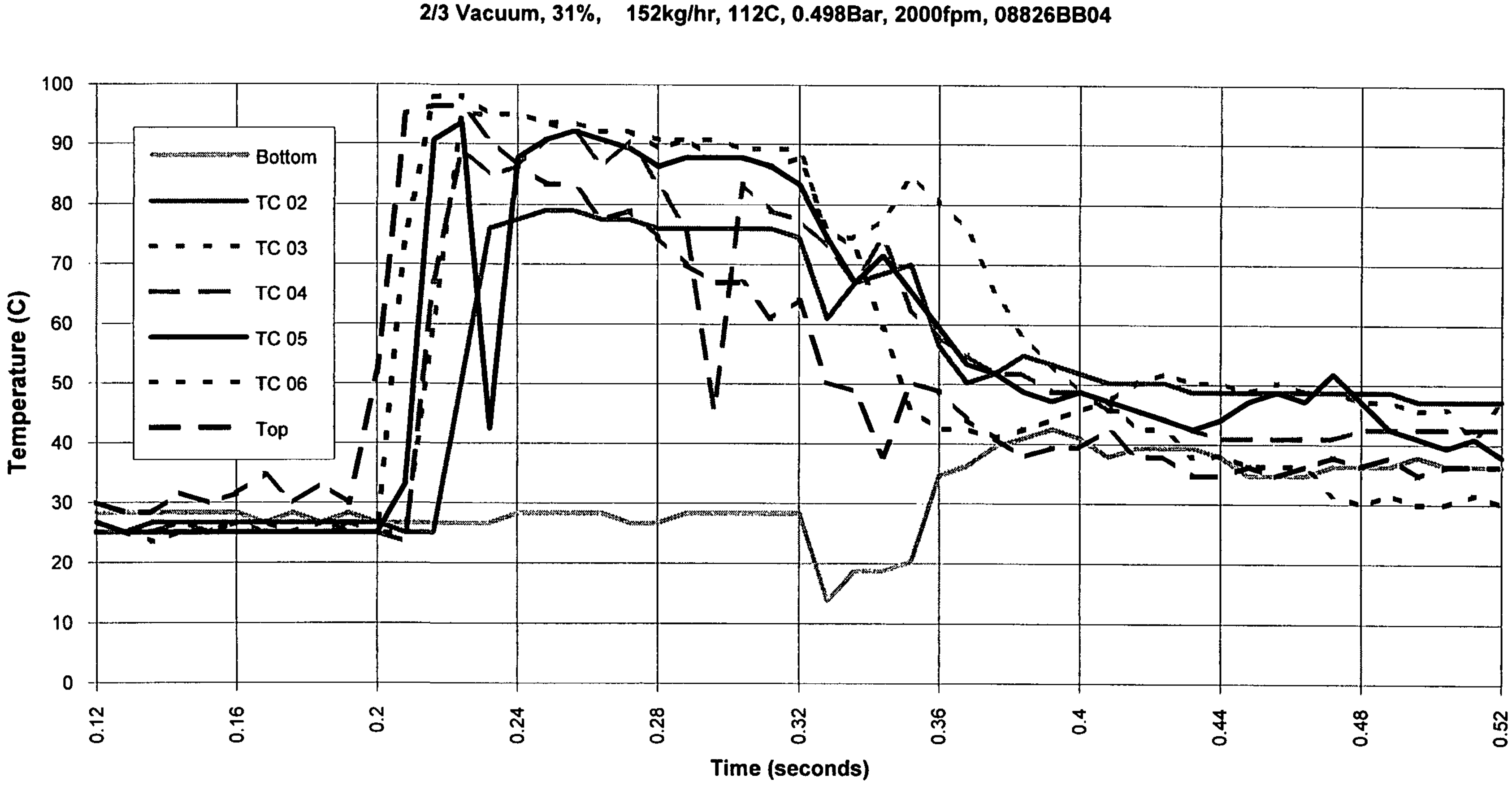


Figure 24. Shakedown Run 4:   Thermocouple Response

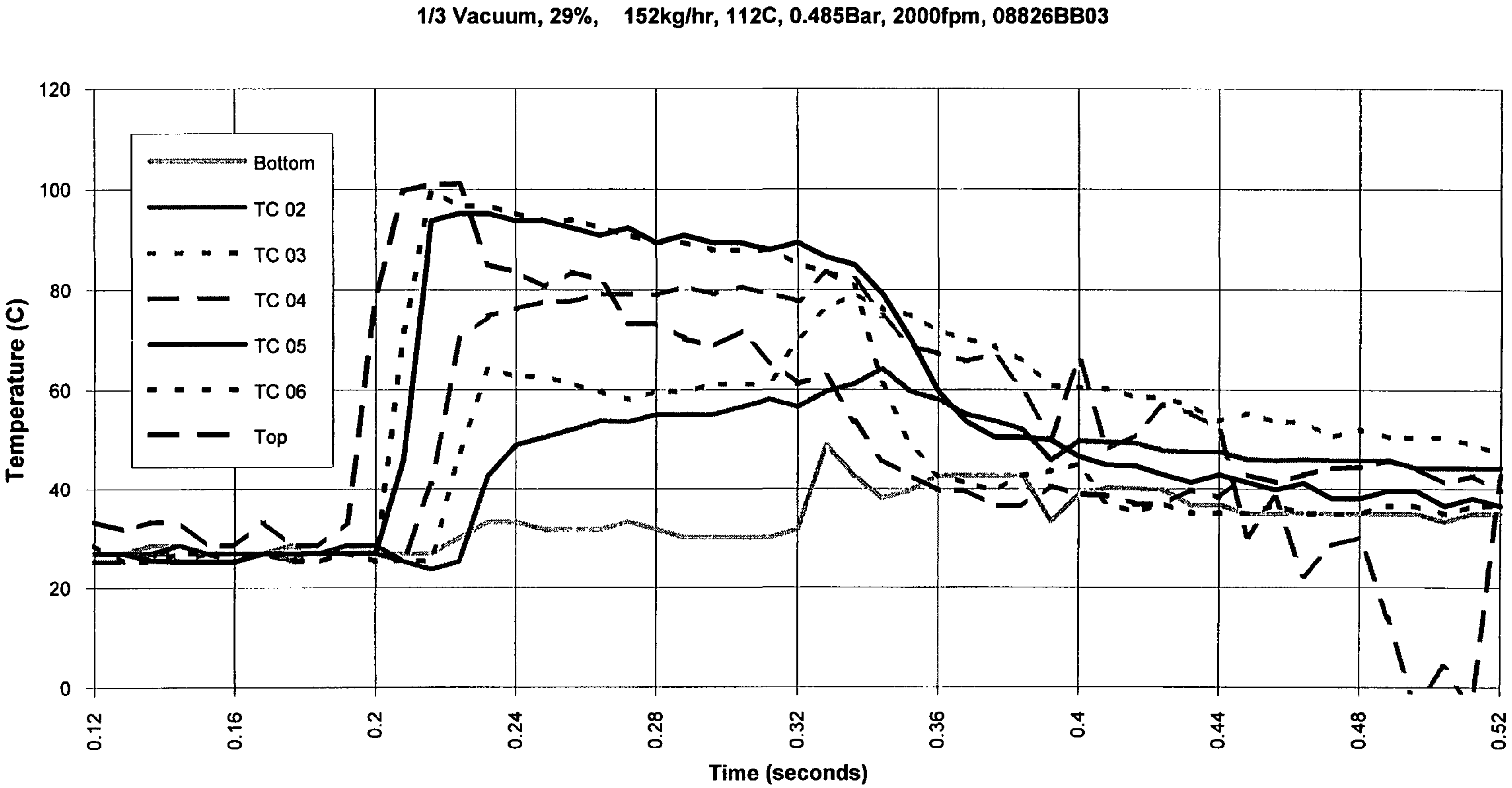


Figure 25. Shakedown Run 5: Thermocouple Response

[0826BB.XLW]0826T15.XLC

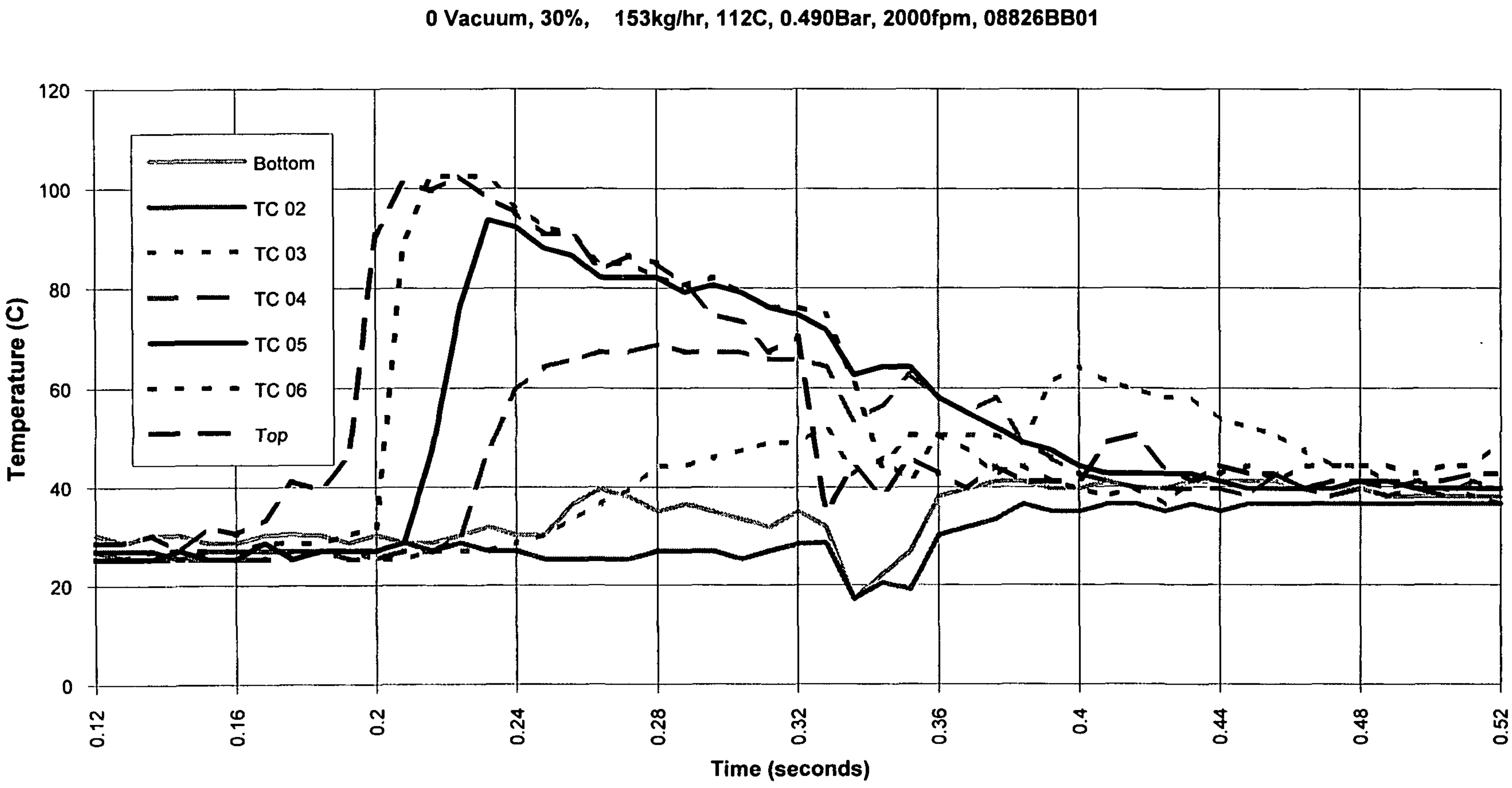


Figure 26. Shakedown Run 6: Thermocouple Response

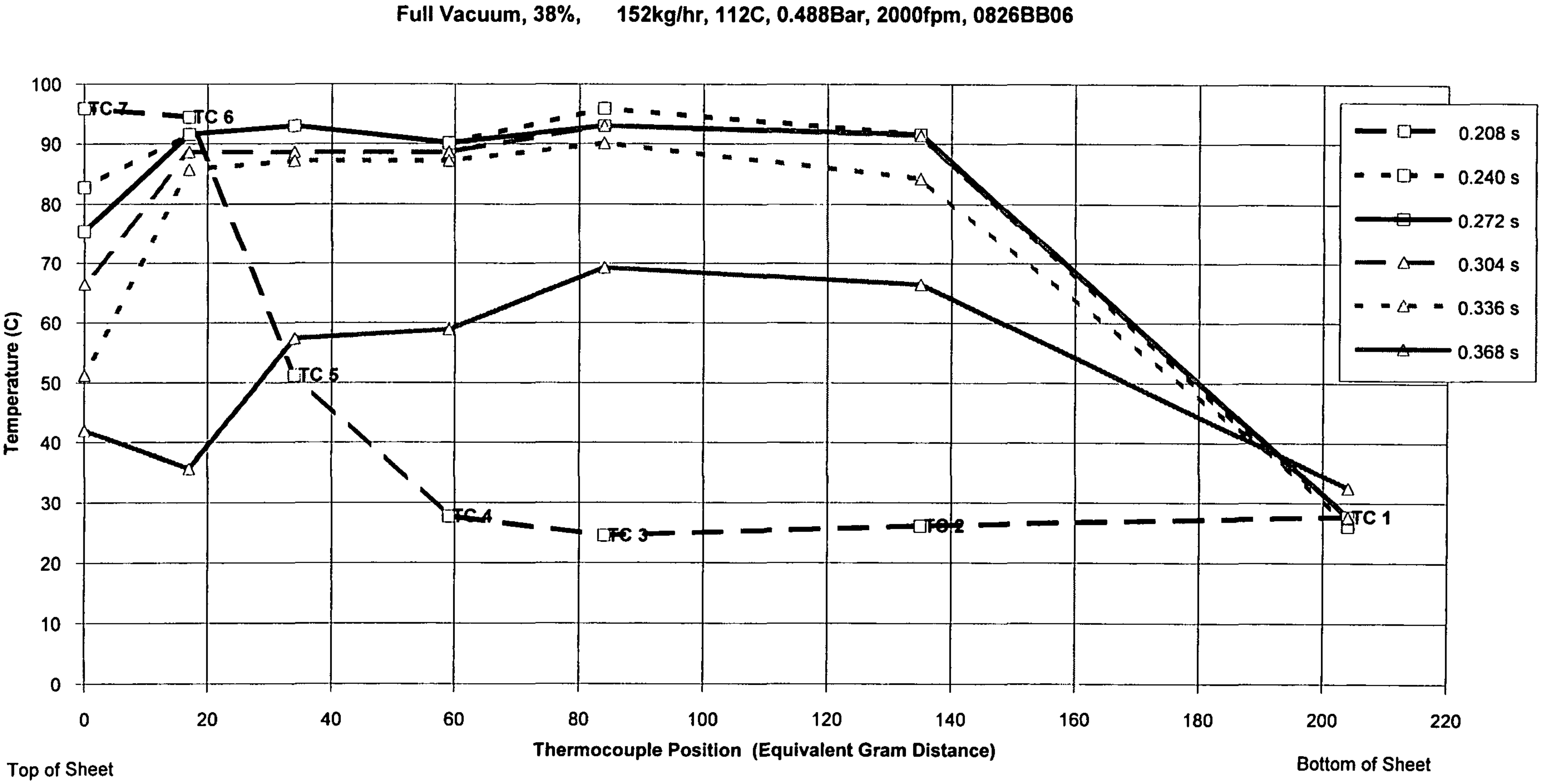


Figure 27. Shakedown Run 1: 2-D Temperature Profile

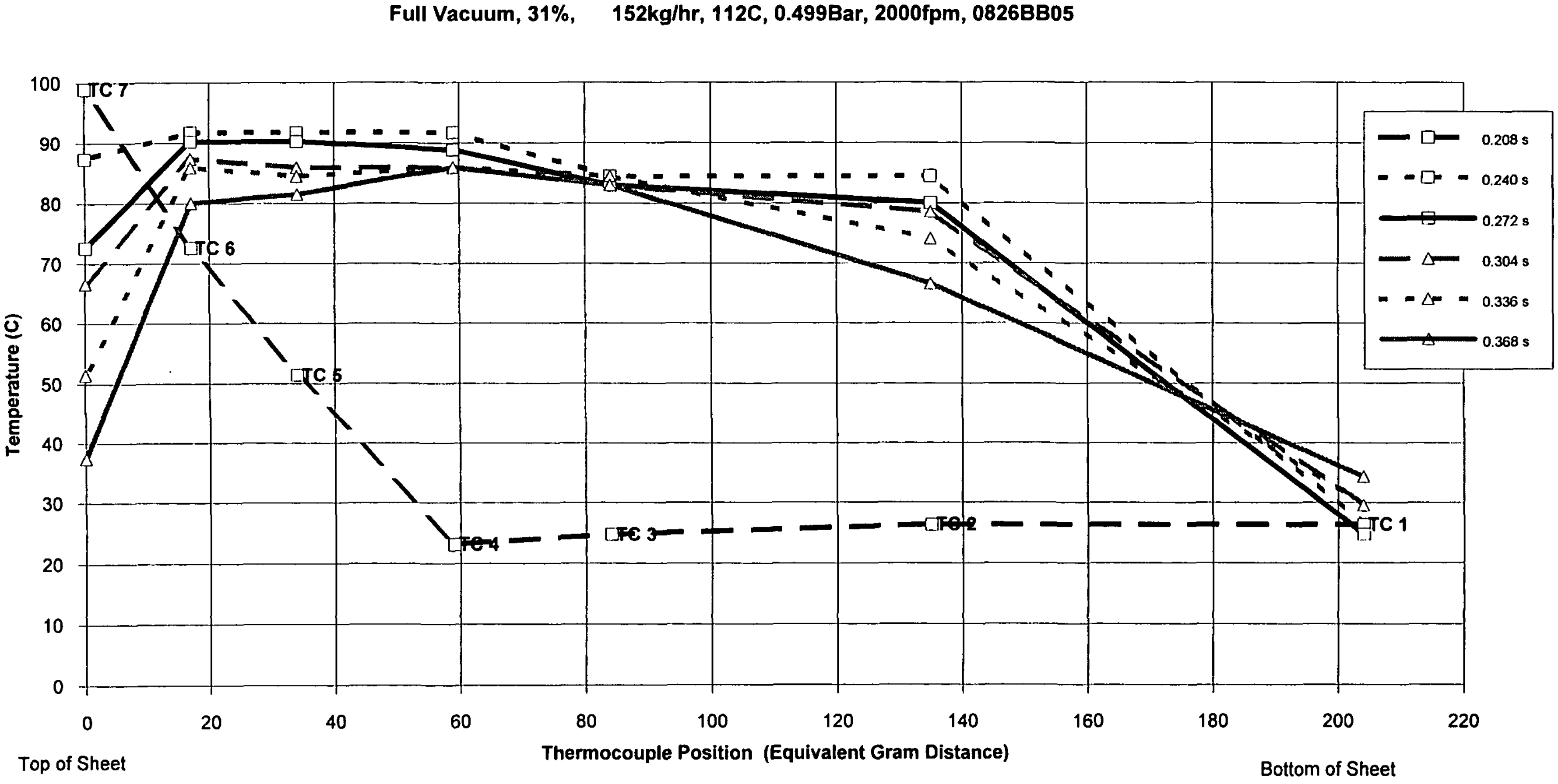


Figure 28. Shakedown Run 2: 2-D Temperature Response

[0826BB.XLW]0826G11.XLC

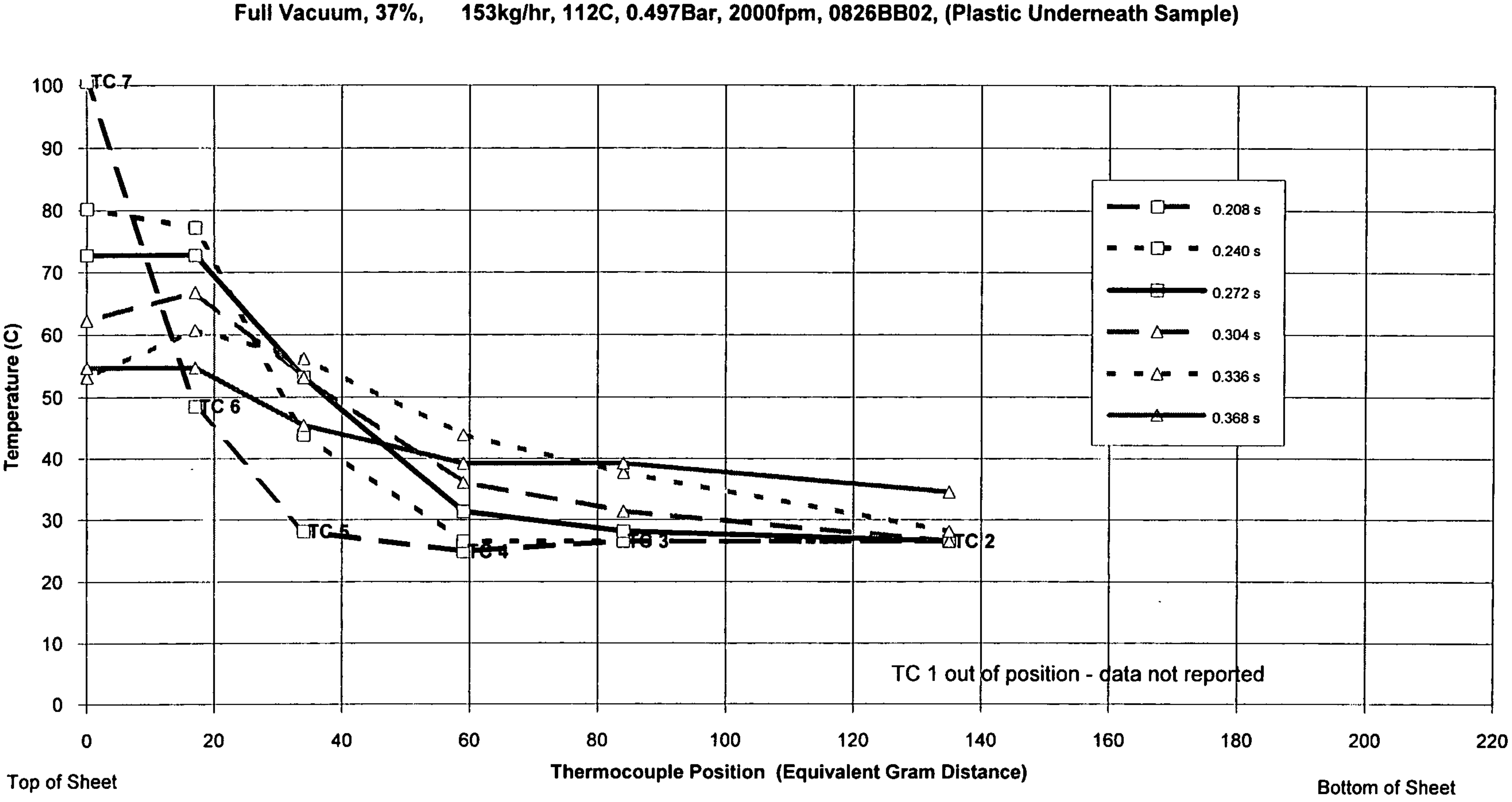


Figure 29. Shakedown Run 3: 2-D Temperature Profile

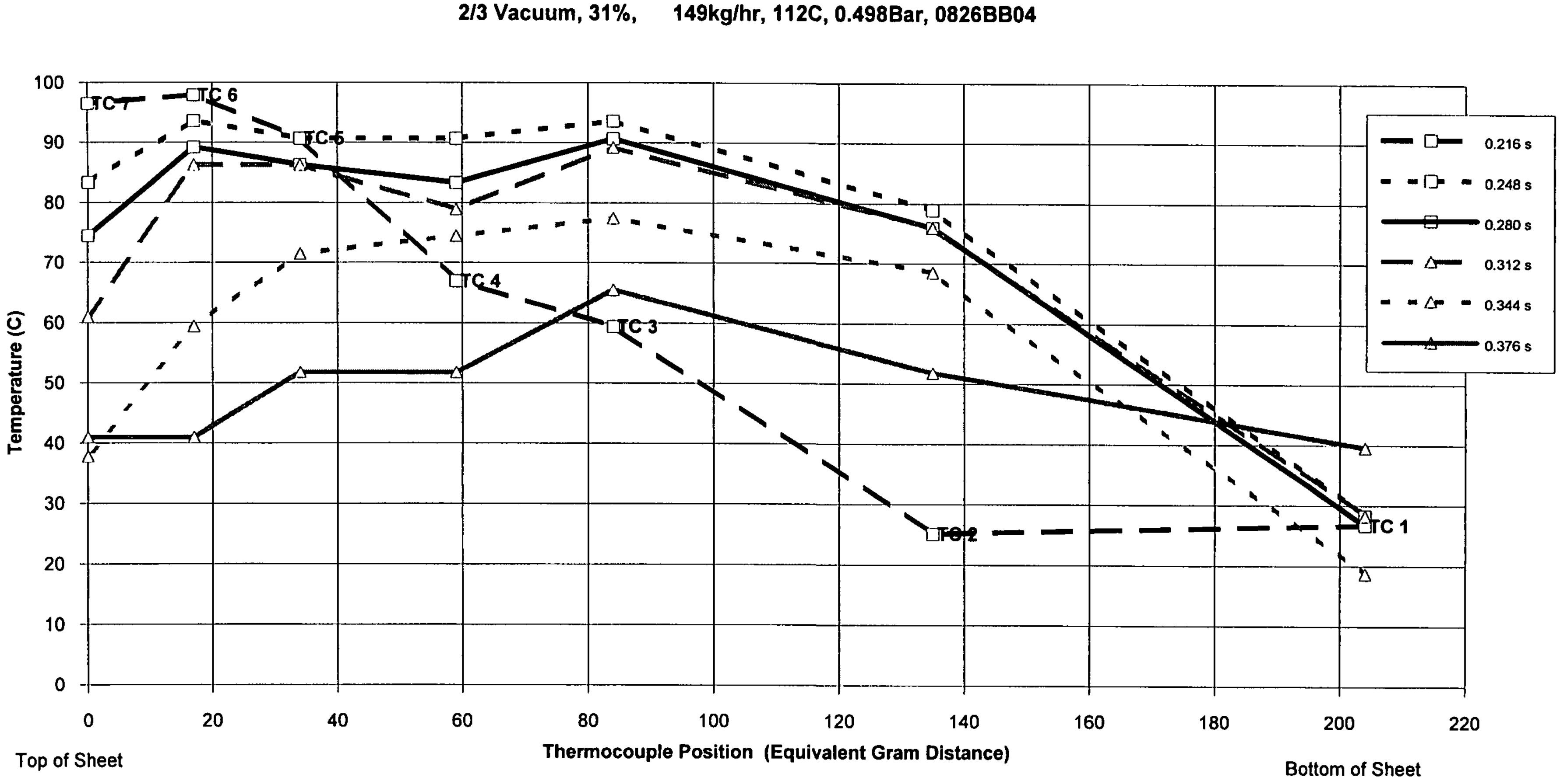


Figure 30. Shakedown Run 4: 2-D Temperature Profile

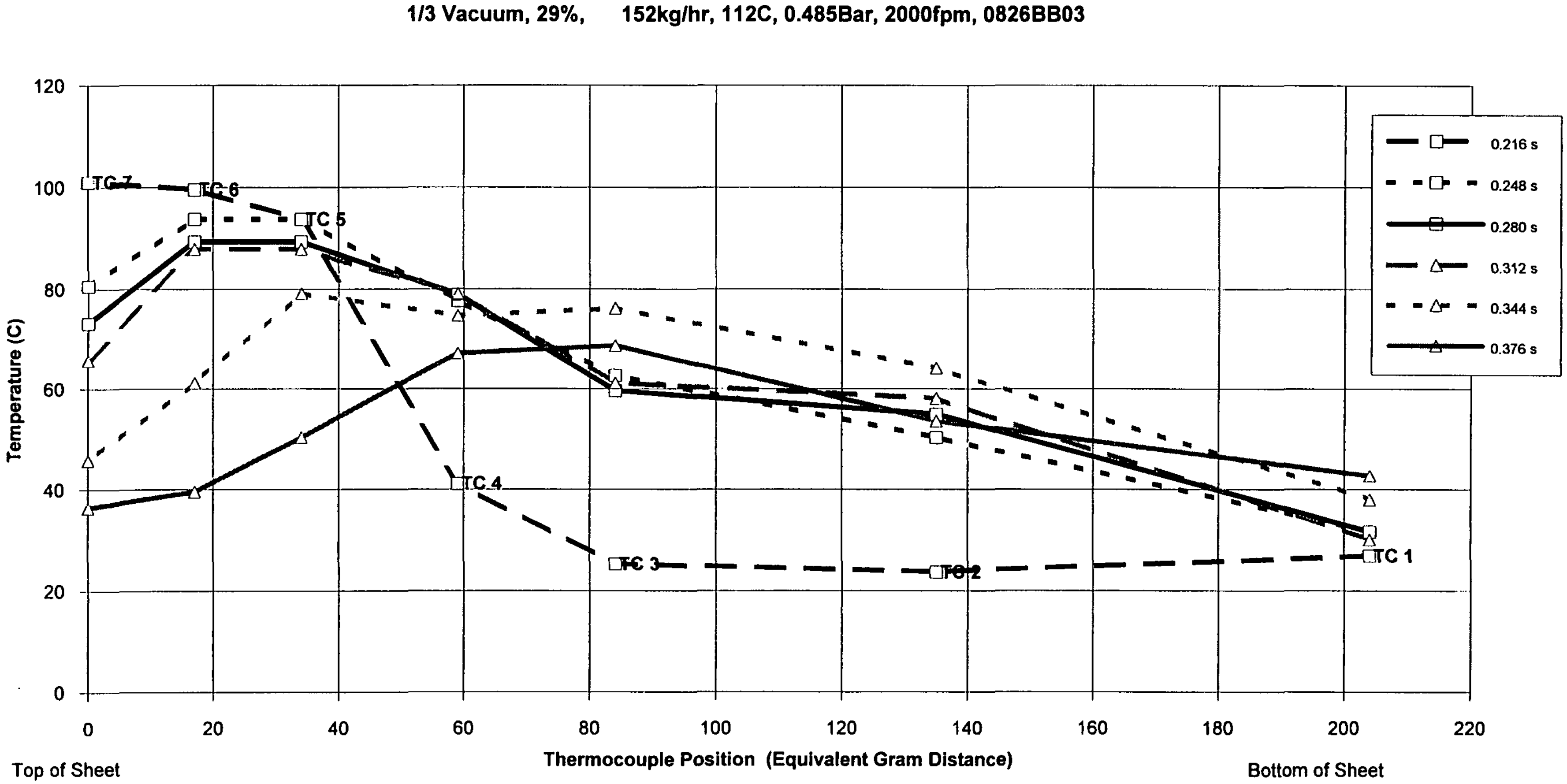


Figure 31. Shakedown Run 5: 2-D Temperature Profile

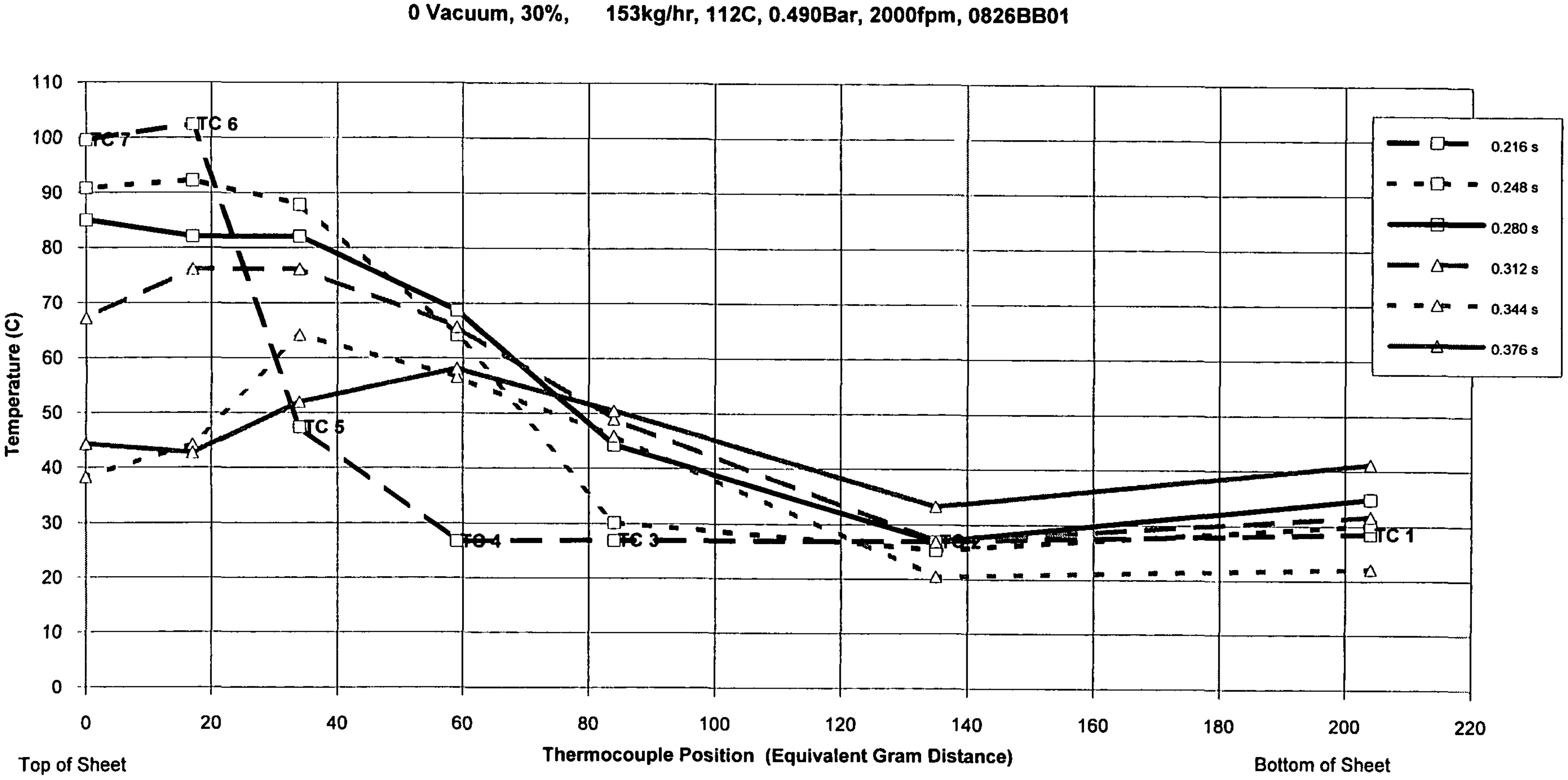


Figure 32. Shakedown Run 6: 2-D Temperature Profile

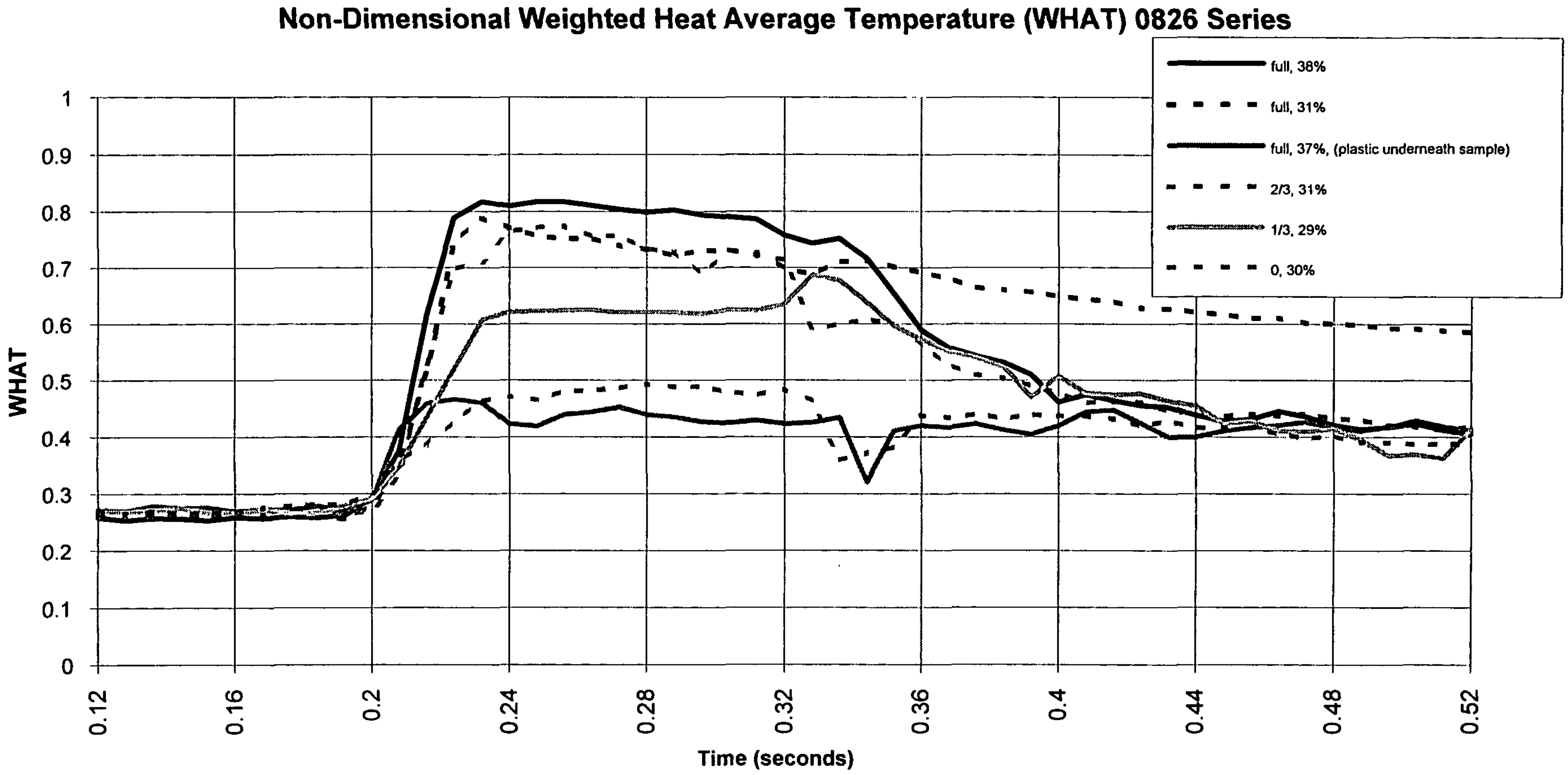


Figure 33. Shakedown Runs: WHAT Response

XIII. Acknowledgments

The work presented in this report would not have been possible without the efforts of Mark Strand. Mark Strand is currently a second year Master Student at IPST. Since he has considerable industry experience, he substituted a summer at IPST engaged in research for his "summer industrial work experience". During his time spent working on the Rocket Sled and on this project Mark proved himself to be a extremely capable researcher.

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Timothy Patterson

Timothy Patterson, Ph.D., Associate Engineer

David Orloff

David I. Orloff, Ph.D., Professor of Engineering and
Director of Engineering and Paper Materials Division

APPENDIX A

VACUUM BOX AND STEAM BOX VENT CONFIGURATIONS

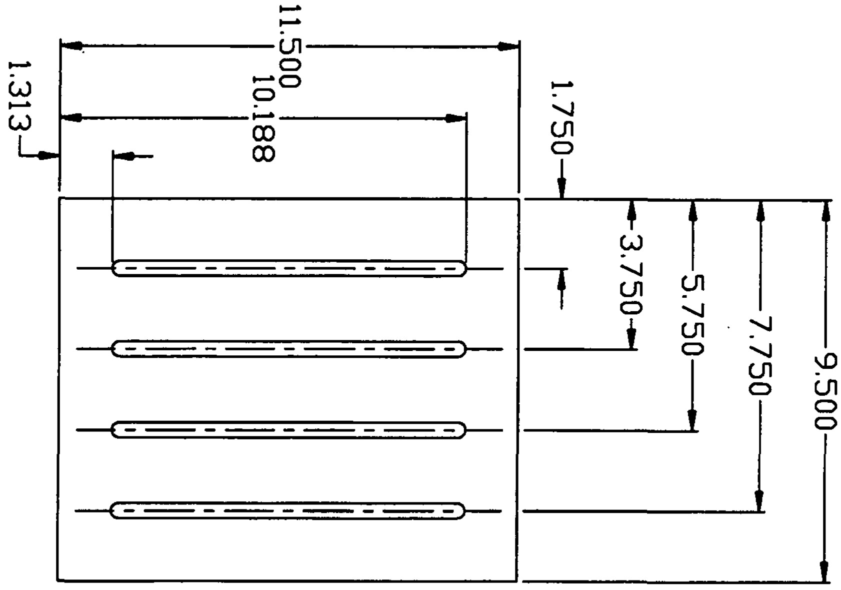

FIGURE A-1. VACUUM BOX VENT HOLE DIAGRAM

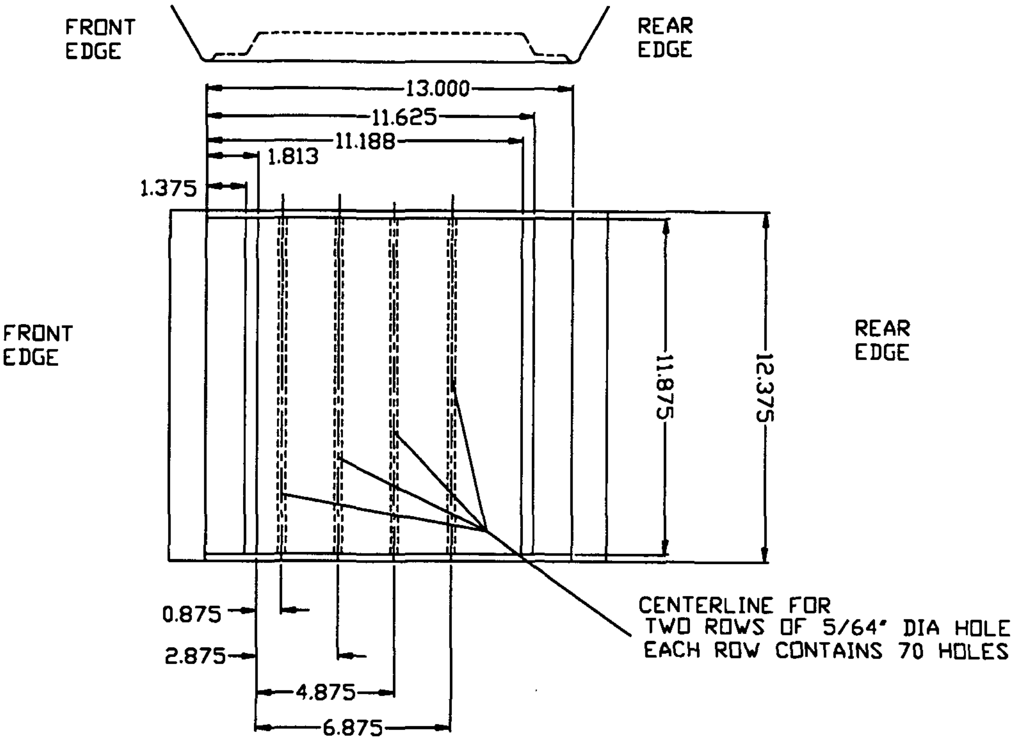

FIGURE A-2. STEAM BOX DELIVERY HOLE DIAGRAM