# INTERIM REPORT – VRTC-DCD2037 (EA02-034)

## Tests of the Bosch Brakes (ZOPS) on a 2001 Monaco Holiday Rambler Ambassador Motorhome

## 1.0 INTRODUCTION

This test program was performed at the Vehicle Research and Test Center (VRTC) in response to a request by the Office of Defects Investigation (ODI), National Highway Traffic Safety Administration (NHTSA). The ODI has received complaints alleging brake overheating on the Bosch "Zero-Offset Pin Slide" (ZOPS, aka International Diamondlife) caliper brake system on various vehicles. Many complainants have alleged that these brakes apply normally, and then fail to fully release, resulting in overheated wheel-ends and fires on various vehicles, including school buses.

## 2.0 BACKGROUND DISCUSSION

The primary objective of this portion of the test program was to document the condition and performance of the ZOPS brake system on a Monaco Holiday Rambler Ambassador motorhome that had just been repurchased by Monaco. An additional front axle that had been previously replaced under warranty by Monaco was also tested later on the motorhome.

## 3.0 TEST VEHICLE AND A WARRANTY-REPLACEMENT AXLE

The test vehicle, designated MH1, was a 2001 Monaco Holiday Rambler Ambassador with VIN 1RF12041012012312 and the odometer reading was 9,946 miles at the start of testing. The weight placard on the 36-ft long vehicle listed 10,500 lb for the front Gross Axle Weight Rating (GAWR), 15,500 lb for the rear GAWR, and 26,000 lb for the Gross Vehicle Weight Rating (GVWR). A placard on the front axle identified it as a Westport Model No. F5W-1200. The vehicle had been repurchased by Monaco after multiple thermal events were reported on the rear axle. The last reported event was a brake fire on the right rear wheel-end. A photograph of the vehicle is shown in Figure 1 in the Appendix. All tables and figures for this report are presented in the Appendix.

The warranty-replacement front axle, designated AXL1, procured from Monaco, was reportedly replaced under warranty because owner had reported a left front brake fire. Subsequently, the left rotor temperature was measured, with a handheld optical pyrometer, at the dealership at over 1,000°F. This warranty-replacement axle had been removed from another 2001 Monaco Holiday Rambler Ambassador with VIN 1RF12041512012855 and the odometer reading was reported to have been 11,891 miles. The axle was stored by Monaco for approximately three months before it was procured by the VRTC. A placard on the axle identified it as a Westport Model No. F5W-1200. A photograph of the axle, as received by VRTC, is shown in Figure 2.

## 4.0 TEST EQUIPMENT AND PROCEDURES

The instrumentation package used to record the performance of each of the four wheel-ends included sensors for brake line pressure (inboard of the flexible brake hose), the inner brake pad temperature (thermocouples installed from the edge so as to avoid disturbing the "as received" brake condition), and the brake fluid temperature inside the caliper (probe inserted through the bleeder valve). The vehicle stopping distance, vehicle speed and deceleration, and brake pedal force and travel were also monitored. Videotape cameras, mounted near the centerline of the vehicle looking outboard, were used to record events at each wheel-end. The front axle views of the caliper and rotor were slightly restricted by the front axle, and the rear axle views of the caliper and rotor were significantly restricted by the suspension trailing arm and splash shields. A halon fire-suppression system was built and installed on the motorhome with two nozzles positioned at each caliper. This system included a backup halon gas cylinder for longer duration fire suppression (if needed) and a control panel that allowed fire suppression at either a single wheel or all wheels simultaneously. The equipment used for the instrumentation, the videotape, and the fire suppression systems are listed in Table 1 and shown in Figures 3 through 11. Note: the Parker Corp. solenoids, selected for the fire suppression system, were later found to be incompatible with halon gas and are not recommended.

The first test was conducted on the Skid Pad at the Transportation Research Center (TRC). The Skid Pad has a one-mile straightaway for brake testing and loops at each end, as shown in Figure 12. The driver performed a stop from 40 mph at a deceleration rate of 0.3 g, and then resumed driving at 40 mph with repeated 0.3-g stops and cool-down periods sufficient to maintain post-stop pad temperatures of 200°F, then 300°F, then 400°F, and finally 500°F. In general, three stops were made at each temperature level before targeting the next post-stop temperature.

Another test conducted was similar, except the vehicle was snubbed from 40 mph to 15 mph at a 0.3-g deceleration rate. Additional tests were conducted on the Vehicle Dynamics Area (VDA) and High Speed Test Track (HSTT) when necessary to accommodate TRC scheduling conflicts.

As a diagnostic tool, the torque required to rotate each wheel was measured after the vehicle was lifted from the ground. A bound caliper would be indicated by a high turning torque reading. The torque required to cause the wheels to start moving and to maintain the spinning or running torque were found. This torque on the wheel was measured by installing a torque wrench onto a wheel lug nut with the longitudinal axis of the torque wrench handle aligned as closely as possible with the center of the wheel. Then a correction factor was applied to convert the center of rotation from the lug nut position to the center of the wheel, as shown below.

$$Ta = Tm[(A+L)/L]$$

where Ta = actual wheel turning torque
Tm = measured wheel torque with torque wrench on lug stud and radially aligned through center of wheel
A = distance from center of wheel to lug stud
L = distance from center of torque wrench handgrip to center of the socket adapter at the lug site

## 5.0 INSPECTION AND TEST RESULTS

The vehicle had been repurchased by Monaco and the VRTC took immediate possession of the vehicle from the dealership in Alabama. No work had been performed on the vehicle since the reported brake fire at the right rear wheel-end. The vehicle appeared to be in good condition and the brakes operated normally when the vehicle was received, except the ABS-warning lamp was illuminated. The measured weights were 7,840 lb on the front axle, 14,040 lb on the rear axle, and 21,880 lb for the total weight.

As soon as the vehicle was lifted in the shop, the wheels were turned by hand and the force required to rotate each wheel seemed reasonable. The brake components appeared to be in good working order, except the right rear ABS wheel-speed sensor (the location of the reported fire) was found to be severely melted and had fallen out of the interference-fit socket, as shown in Figure 13. The sensor on the Wabco ABS was not repaired until later in the test program. Tests using the Markey Vapor Lock Indicator found the brake fluid boiling points were 375°F to 398°F at the wheel-ends and 425°F at the master cylinder reservoir, indicating the brake fluid was relatively new. Once the instrumentation was installed, the brake system was thoroughly inspected for "trapped" brake line pressure that could cause a dragging brake. The items checked included fluid exchange malfunctions between the master cylinder and reservoir, binding at the brake pedal linkage, overboost in the hydroboost system, swelling of ABS internal seals, and restrictions in the metal brake lines or flexible rubber hoses.

The torque required to rotate each wheel on MH1 was measured just before the first driving test. After three spike applications on the brake pedal (with the engine running), the static breakaway torques required to rotate the wheels were determined to be 12/12 ft-lb (left/right front) and 51/26 ft-lb (left/right rear). The dynamic (continuously running) torques were 7/7 ft-lb (left/right front) and 40/30 ft-lb (left/right rear). The increased torque required was expected on the rear axle due to the differential and drivetrain drag.

During the first test, the weather conditions included an ambient temperature of 33°F, a 5-mph wind from the northeast, 87% humidity, and sleet, snow, and rain. The test surfaces were wet, but clear of ice and snow, except for portions of the north and south loops of the Skid Pad, where braking did not occur. After 20 normal 0.3-g stops, with intentionally increasing post-stop temperatures, the post-stop temperatures of the inner-brake pads were 526/526/585/518°F (LF/RF/LR/RR). At this point, the goal was a 500°F post-stop brake lining temperature. The testing had to be stopped for 5 minutes to change the videotapes and wipe the moisture from the camera box lenses. After resuming the brake applications, the left rear wheel temperature was noticeably deviating from the other wheels (510/520/**650**/520°F) after four stops. For the next 4 minutes, the vehicle was driven, without braking, between 20 mph in the loops and 40 mph on the straightaways and the rotor started to glow red, as shown in Figure 14. The temperatures dropped on three of the wheels, but continued to climb at the left rear wheel (398/359/**1,095**/430°F). At this point, the brakes were catching on fire, as shown in the videotape submitted with this report. The driver had no indication of any problems. Throughout the event, the vehicle did not yaw, exhibit noticeable drag during acceleration, and there was no smoke or odor noted in the passenger compartment.

The vehicle was then stopped for 1 minute and all four wheel temperatures started to drop. As the vehicle was driven away, a wheel fire flamed up as shown in Figure 15. Note: In the upper view of the figure, the camera auto-iris circuitry had malfunctioned so the picture is relatively dark. The camera was replaced before the next test. The lower view in Figure 15, taken using from the replacement camera, shows the same field of view for comparison. The trailing arm is in the right bottom corner, the rear axle is across the left side, and one-half of the caliper is near the center of the picture. The video images are clearer than the picture transferred from the video for Figure 15.

The vehicle was driven a short distance and the temperature on the left rear wheel continued to rise during this portion of the test (368/328/**1,330**/398°F). Each time the vehicle stopped, all of the brake temperatures cooled down. Each time the vehicle started moving again, the left rear wheel fire would flare up. The data collection was normally retriggered every 10 minutes, but at this point, retriggering was inadvertently delayed for a 4-minute period. During this period, the real-time readout was pegged at 1,400°F, the limit of the instrumentation. The brake fluid temperature in the calipers had been between 70°F and 80°F. Each time the vehicle was stopped, the left rear wheel area would heat-soak, and the brake fluid temperature in the left rear caliper would rise. At this point, the fluid temperature at the left rear had risen to 169°F. The highest brake fluid temperatures recorded were 86/64/306/92°F, which may possibly cause boiling in a vehicle with hydroscopically-aged brake fluid. However, the brake fluid boiling point of this vehicle was about 400°F. While pulling away from a stop during the 4-minute period of data loss, a "pop" was heard from the left rear wheel area and the vehicle rocked forward slightly. This indicated that this piston probably expanded thermally and seized temporarily in the bore. The high thermal readings began to diminish, even after continuing the braking and driving sequence. When it was determined that the thermal event could not be repeated, it was too late to perform the planned on-track diagnostic tests to determine which subcomponent had failed to operate normally.

More information about this test is available from the test instrumentation. The individual 10-minute data collection files are shown in Figures 16 through 24. A composite plot of the four 10-minute data files during the thermal event is shown in Figure 25. The composite image shows the inner brake lining temperatures stepping upward with the initial testing, until the temperature of the left rear (green trace) deviates into an abnormal thermal event. The wide blank space is the area where the data collection system had not been triggered in a timely manner and where the lining temperature reached the peak (limit of data channel) of 1,400°F. There was no evidence of residual brake line pressures at any time during this test.

The original front axle, which did not demonstrate any abnormal activity during the previous test, was removed so that warranty-replacement axle, AXL1, could be installed on the motorhome for the next test. The AXL1 axle was an exact match for the original front axle and there were no problems during the installation. The axle appeared to be in good shape, with no obviously melted components, but the left rotor surface was corroded. The disc brake on the left side was where the owner reported a fire had occurred. The wheel torque required to rotate the wheels on MH1 equipped with AXL1 were measured just before the subsequent driving test. After three spike applications to the brake pedal, the static breakaway torques required to rotate the wheels were determined to be 20/12 ft-lb (left/right front) and 46-51 ft-lb (left/right rear). The dynamic (continuously running) torques were 15/10 ft-lb (left/right front) and 36/41 ft-lb (left/right rear). The increased torque required was expected on the rear axle due to the differential and drivetrain drag.

During the second test on MH1, the weather conditions included an ambient temperature of 29°F, a 10 mph wind from the east, 68% humidity, and cloudy. The test surfaces were wet, but clear of ice and snow, except for portions of the north and south loops of the Vehicle Dynamics Area (VDA), where braking did not occur. After 14 normal 0.3-g stops with intentionally increasing post-stop temperatures, the post-stop temperatures of the inner brake pads were 450/629/603/578°F. A composite plot of five 10-minute files during the time of the abnormal thermal event is shown in Figure 26. After the goal of 500°F post-stop brake lining temperatures was reached, the testing was stopped for 4 minutes to change the videotapes and wipe the moisture from the camera box lenses. As the vehicle was driven away from this stop, the driver noticed a slight pull to the right. One minute later, the right front brake-lining temperature was increasing noticeably without the brakes being applied (342/**552**/425/427°F). The vehicle was driven without braking and 3 minutes later, although the three other wheel-end temperatures were dropping, the right front temperature was rising (291/**755**/390/403°F). At this time, the rotor started to glow red, as shown in Figure 27. The driver still noticed a slight steering pull to the right and a hot-brake odor was entering the passenger compartment from the area of the right front door. The vehicle was driven without braking for 8 minutes at 40 mph (slower for the loops). The right front brake temperature exceeded 1,000°F (193/**1,016**/322/348°F) and then started to drop off. The vehicle was stopped for four more minutes and upon resuming driving, without brake applications, the right front brake temperature started to rise again (161/**1,262**/280/311°F). The brake fluid temperature in the right front caliper reached 217°F. Similar to the first test, there was no evidence of residual brake line pressures at any time during this test.

The test was terminated so that the planned on-track diagnostic component checks could be performed. The vehicle was driven 500 ft away from the VDA test route and the frame was lifted to remove the vehicle weight from the right front wheel. The breakaway torque required to rotate the wheel was 140 ft-lb (at the start of the test it was 12 ft-lb). The wheel was removed and locking pliers (Vise-Grips) were clamped on the brake pad backing plates (at the abutment ears) and used to attempt to "rattle" the inner and outer brake pads. If only the outer pad was tight, a slide pin problem could be indicated; and if both pads were tight, a piston problem could be indicated. In this case, both pads were tight. The slide-pin-mounting bolts were removed but the caliper was still tight on the rotor. The caliper was removed from the rotor and a flat metal bar was laid across the dual pistons. Then a C-clamp was used to attempt pushing the pistons back into the caliper housing, but the pistons would not move. Next, a 2-1/2 inch wooden block was laid in place of the rotor and pads and the brake pedal was slowly applied by hand. The leading piston was found to be immobile so the brakes were reassembled and the vehicle was driven back to the VRTC. It should be noted that some of the features of the Bosch ZOH-T design to improve the ZOPS caliper were added to prevent piston bore binding. The next morning when the brake components were examined, the caliper operated normally again.

The right front brake was replaced with new parts and five more tests (Dec 18-31) were conducted as shown in Table 2. The brake system worked as expected on the remaining tests.

The testing was followed by a systematic teardown to the brake component level. The individual components were stored in sealed plastic containers with desiccant for further testing. The brake equipment from each wheel-end was examined, the attachment of that component documented, and photographed. The condition of each component and the integrity of the attachment system is listed in Table 3. The photographs showing the condition of the brake equipment at each wheel-end are shown in Figures 28 through 37.

## 6.0 FINDINGS

The subject motorhome and components for this program included a 2001 Monaco Holiday Rambler Ambassador and an additional front axle previously replaced by Monaco under a warranty claim.

1) Upon initial inspection, the motorhome and brake components appeared to be in good working order, except the right rear ABS sensor was found melted and out of the interference-fit socket (a fire had been reported at this wheel-end), thus causing the ABS warning light to illuminate. The front and rear axle wheels could be turned with reasonable effort, indicating no abnormal drag.
2) A dragging brake could be caused by trapped brake line pressures at the wheel-ends. A thorough inspection of the brake system revealed none of the following possible problems: fluid exchange malfunctions between the master cylinder and reservoir, binding at the brake pedal linkage, overboost problem in the hydroboost system, swelling of ABS internal seals, and restrictions in the metal brake lines or flexible rubber hoses. No evidence of residual brake line pressures was indicated by the instrumentation at any time during these tests.
3) The first test on the "as received" motorhome resulted in a wheel-end fire at the left rear brake after a series of 0.3-g stops, followed by driving without braking at 20 to 40 mph. The fire lasted for 15 minutes before diminishing after a "pop" sound was heard from the left rear wheel area and a "rock-forward" of the vehicle was noted. This indicated that this piston probably expanded thermally and seized temporarily in the bore. The inner brake pad lining temperature exceeded 1,400°F and the brake fluid temperature at that wheel rose to 306°F.

Throughout the event, the vehicle did not yaw or exhibit noticeable drag during acceleration, and there was no smoke or odor noted in the passenger compartment.

4) The second test was conducted after installing a front axle previously replaced by Monaco under warranty. This test also resulted in an abnormal thermal event after a series of 0.3-g stops, followed by driving without braking at 20 to 40 mph. The right front rotor glowed red for approximately 20 minutes before the vehicle was stopped for a component diagnosis. The inner brake lining temperature reached 1,262°F and the brake fluid temperature inside the caliper reached 217°F. Field diagnosis of this event concluded that the leading piston, of the dual piston system, was seized in its bore, but only while the piston temperature was elevated. At room temperature, the next morning, the caliper operated normally.

# APPENDIX

## List of Items in the Appendix

## Table 1 – Equipment Used to Test the Monaco Holiday Rambler Ambassador

| | | |
|---|---|---|
| Electronic Data Collection Package | | |
| Data Acquisition Components | Model | Manufacturer |
| Computer Case | MB1PC5N | Cyber Research Inc |
| Pentium Computer | 90 MHz P1 | Cyber Research Inc |
| LCD Display | 10.4-in | Cyber Research Inc |
| Signal Conditioning Components | Model | Manufacturer |
| Temperature Modules | 3B47 | Analog Device Inc |
| Signal Conditioners | 3B18 | Analog Device Inc |
| 16-Channel Backplane | 3B01 | Analog Device Inc |
| DC Power Supply | KW40-12-15T797 | Polytron Devices Inc |
| [illegible] | [illegible] | [illegible] |
| Hi-Temp Probe J-type thermocouple, inserted through T-fitting welded to OEM bleed valve into caliper (4) | 20-HH40 | Marlin Mfg Corp |
| J-Type Thermocouple (for inner brake pads) (4) | J-20-1-305 | Watlow Gordon |
| Performance Monitor | 625 | Lab Equip Corp |
| Fifth Wheel (initial speed and stopping distance) | 5101 | Lab Equip Corp |
| Vehicle Decelerometer | 141 4G | Setra Corp |
| Brake Pedal Force Display for driver | 3100A | GSE Inc |
| Brake Pedal Force Transducer (300 lb) | 114350-01301 | GSE Inc |
| Brake Pedal Position Linear Potentiometer | M2078-6-10 | Maurey Instrument Corp |
| Brake Fluid Pressure Transducer (2500 psi) (4) | PSI 100 | PSI-Tronix Inc |
| | | |
| [illegible] | [illegible] | [illegible] |
| Digital CCD Color Camera (2) | KCC-31OND/PD | KoCom Co |
| Lenses - 2.8 to 12mm CS-mount (2) | 1:1.4 Ratio Auto Iris | Tamron USA Inc |
| Digital CCD Color Camera (2) | WV-CL352 | Panasonic |
| Lenses - 4.5mm Computar® CS-mount (2) | 1:1.4 Ratio Auto Iris | CBC (America) Corp |
| Multivision Quadprocessor (4-to-1 view splitter) | MV85 | Robot Corp |
| DV Cam Cassette Recorder | SDRV10 | Sony Corp |
| DV Cam Cassette Recorder | GVD900 | Sony Corp |
| DV CamCorder (used as cassette recorder) | DSR PD100A | Sony Corp |
| DV CamCorder (used as cassette recorder) | DSR PD100A | Sony Corp |
| DV CamCorder (used as cassette recorder) | DSR PD100A | Sony Corp |
| DV Cam Shoulder Camera | DSR 300A | Sony Corp |
| 13" Monitor (for fire suppression monitor) | CM8762074G | Magnavox/Phillips Elec |
| Power Supply (modified to limit to 12-vdc) | RS-35M | Astron Corp |
| | | |
| [illegible] | [illegible] | [illegible] |
| [illegible] | Model | Manufacturer |
| Handheld Extinguisher, 20 lb halon, modified by VRTC with manual T-handle shutoff valves and ducted to solenoids for fire suppression package (2) | 398 Halotron | Amerex |
| Solenoid Valves, to control halon bottles (6) | 02F20C1103A1F | Parker Corp |
| Pressure Switches, to monitor duct charge (2) | 10-C12 | United Elec Controls Co |
| Cone Jet Nozzles, brass, two per caliper (8) | 2101315 | TSC Co |
| Fire Suppression Control Panel | 1 | VRTC |
| Handheld Extinguisher, 20 lb ABC dry chemical | A411 | Amerex |
| Handheld Extinguisher, 5 lb, CO2 (2) | 322 | Amerex |
| Handheld Extinguisher, 5 lb, Halotron | 3806T | Amerex |

**Figure 1 - 2001 Monaco Holiday Rambler Ambassador**

**Figure 2 – Front Axle (AXL1) As Received at the VRTC**

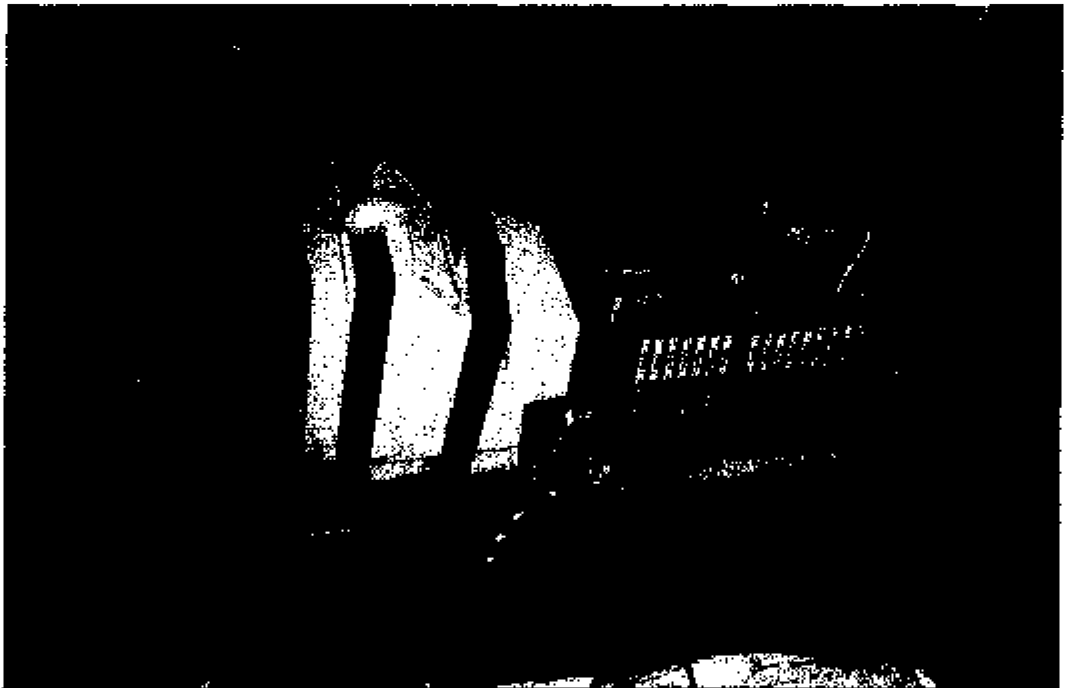

**Figure 3 – Instrumentation Package Showing Data Collection Computer, Signal Conditioners, LCD Monitor, and the Video Monitor for the Fire Suppression System**

**Figure 4 – Wheel-end Instrumentation Showing the Fire Suppression Nozzles and the Thermocouple Probe Inserted into the Caliper through a Modified Bleeder Valve**

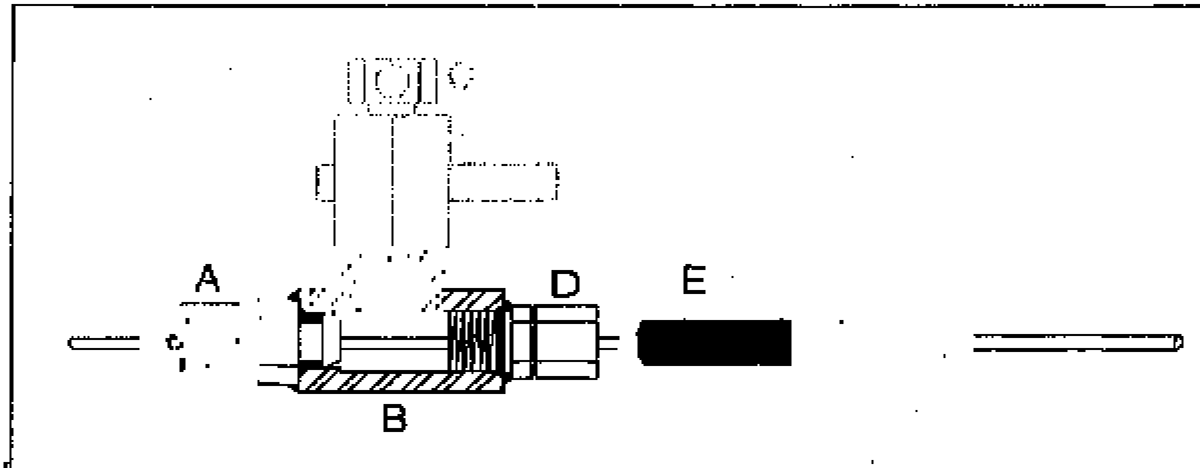


**Figure 5 – Installation of the Thermocouple to Measure Brake Fluid Temperatures Inside the Caliper; Probe Inserted through the Bleeder Valve**

Component Notes: (A) OEM Bleeder Valve Modified by Sealing the Hole on the Sidewall Below the Threads and Drilling a New Hole Through the Bottom (Left Side in the Picture) of the Valve for Passage of the Probe, (B) T-Fitting Silver Soldered onto the Bleeder Valve, (C) New Bleed Port, (D) Compression Fitting, (E) Thermocouple Probe

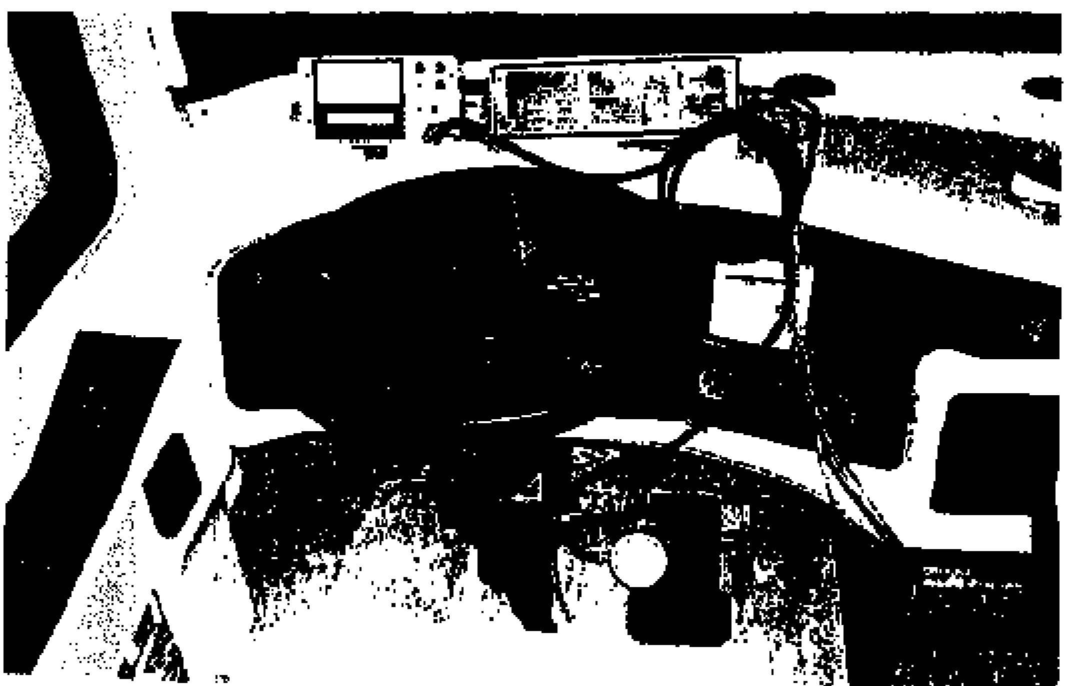

**Figure 6 – Instrumentation for the Brake Pedal Force and Travel and the Driver Display for Vehicle Speed/Distance and Brake Pedal Force**

**Figure 7 – Videotape Recorders (Used Three DV CamCorders as Recorders) and the Quadprocessor for the 4 (Wheel-ends)-into-1 Composite View**

**Figure 8 – Videotape Camera Position and Fire Suppression Nozzle Position for the Right Front Wheel**

**Figure 9 – Fire Suppression Package Consisting of the Halon Cylinders, Solenoids, and Pressure Valves Located in the Vehicle Storage Bay**

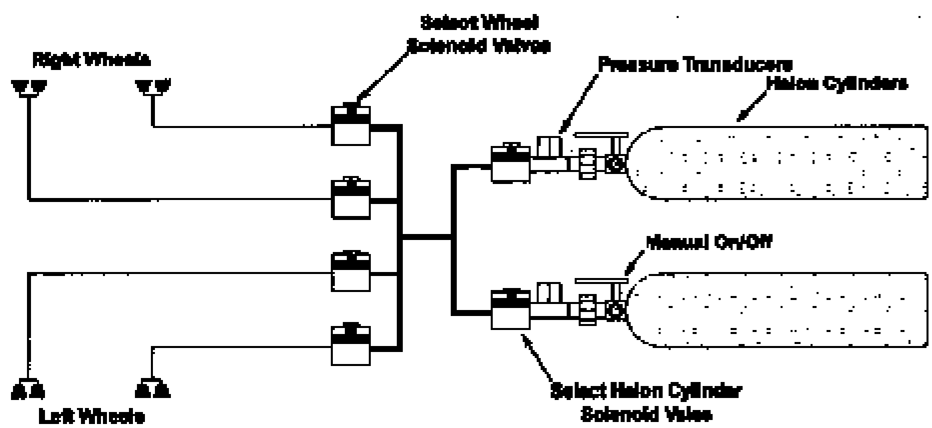


**Figure 10 – Schematic of the Fire Suppression System**

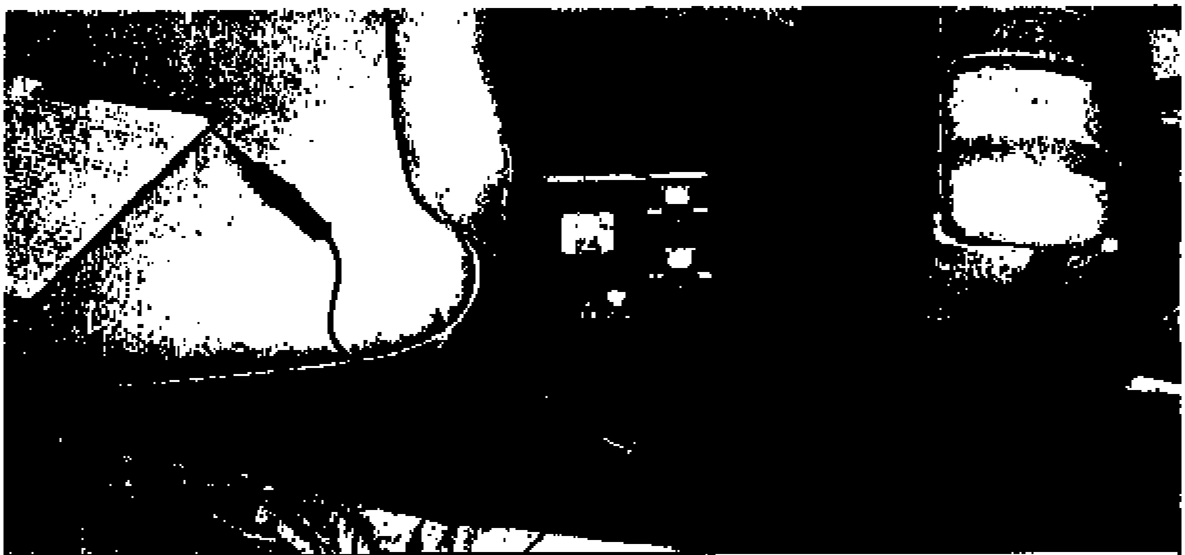

**Figure 11 – Control Panel with Master On/Off Toggle, Green Push Activation Buttons (One for Each Wheel), Yellow Lights to Indicate if the Primary and Secondary Halon Cylinders have Pressurized the Fire Suppression System, and Red Push Buttons to Activate Each Halon Cylinder**

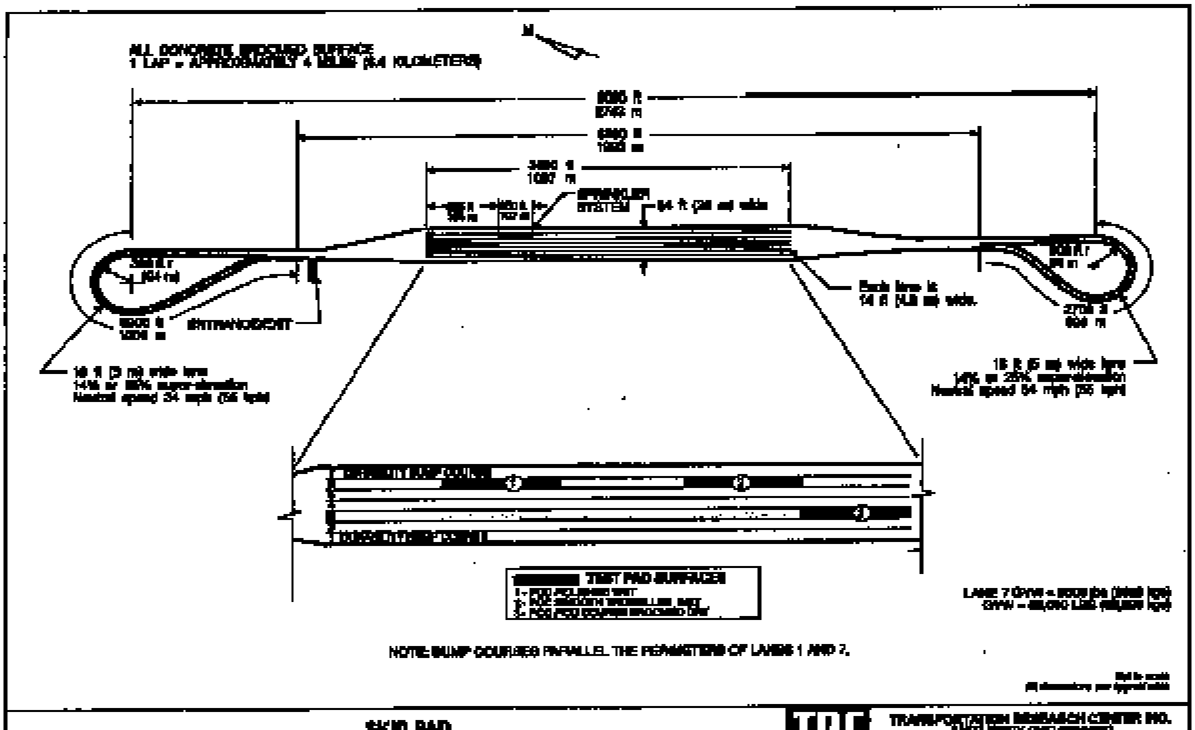


**Figure 12 – The TRC Skid Pad with the Straightaway Test Area and the North and South Turning Loops**

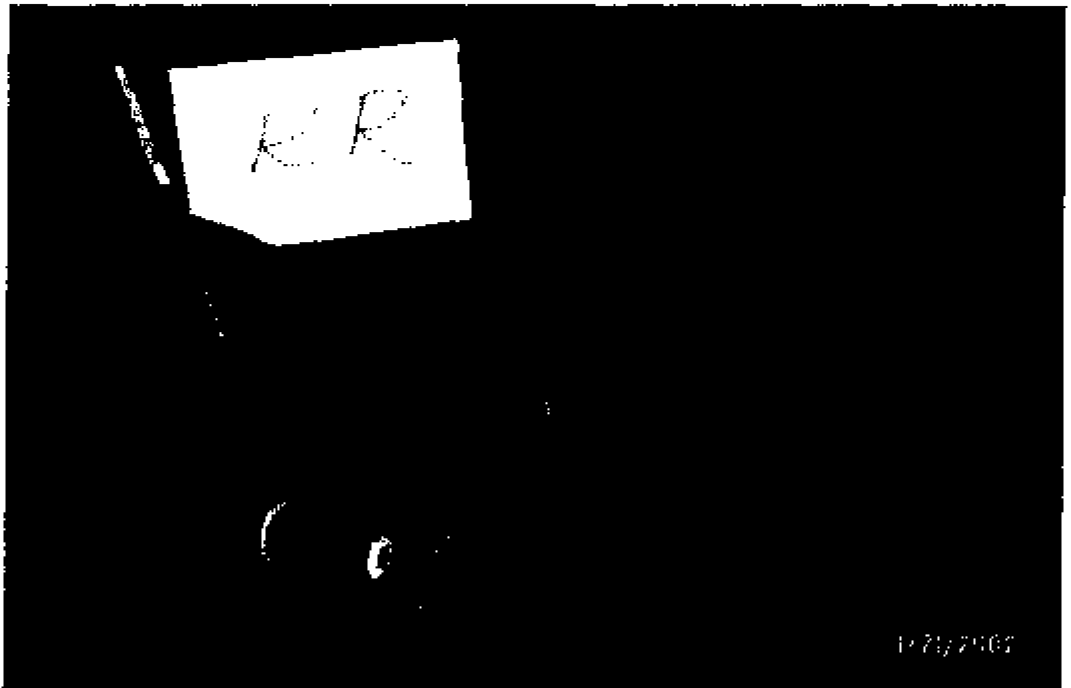


**Figure 13 – View of As Received Right Rear Wheel Showing the Melted ABS Sensor on the Wheel-end Reported to have had a Fire**

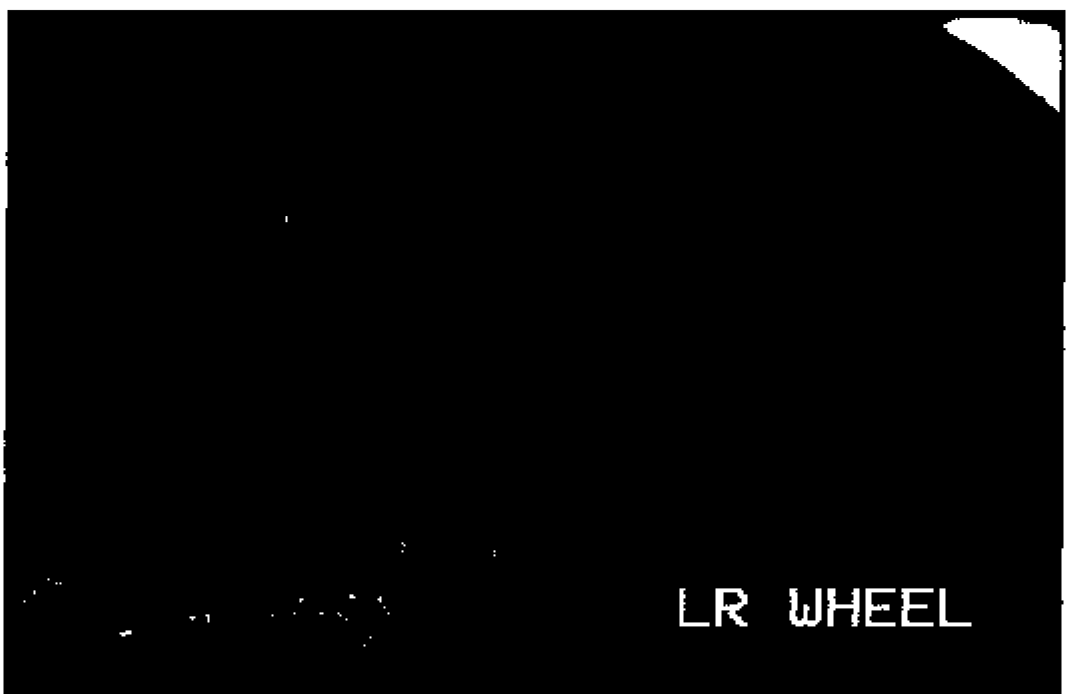


**Figure 14 - Left Rear Brake Rotor was Glowing Red at 50 Minutes into the First Test on MH1 (Most of the View of the Rotor is Blocked)**

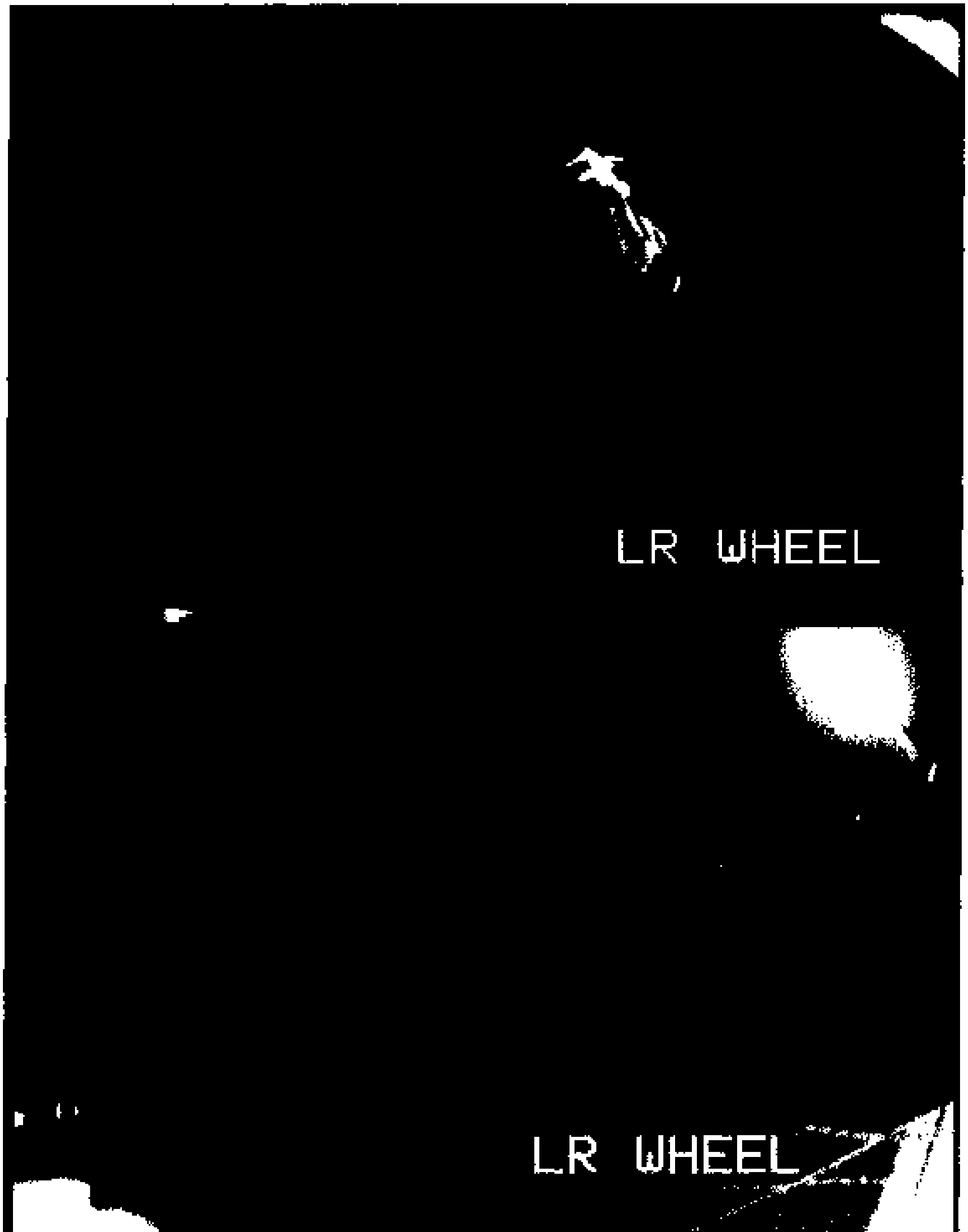


**Figure 15 – Left Rear Wheel Fire at 55 Minutes into the First Test on MH1**

Note: In the upper view, the auto-iris circuitry of the videotape camera malfunctioned during this test. The lower view, from the replacement camera, shows the same field of view for comparison.

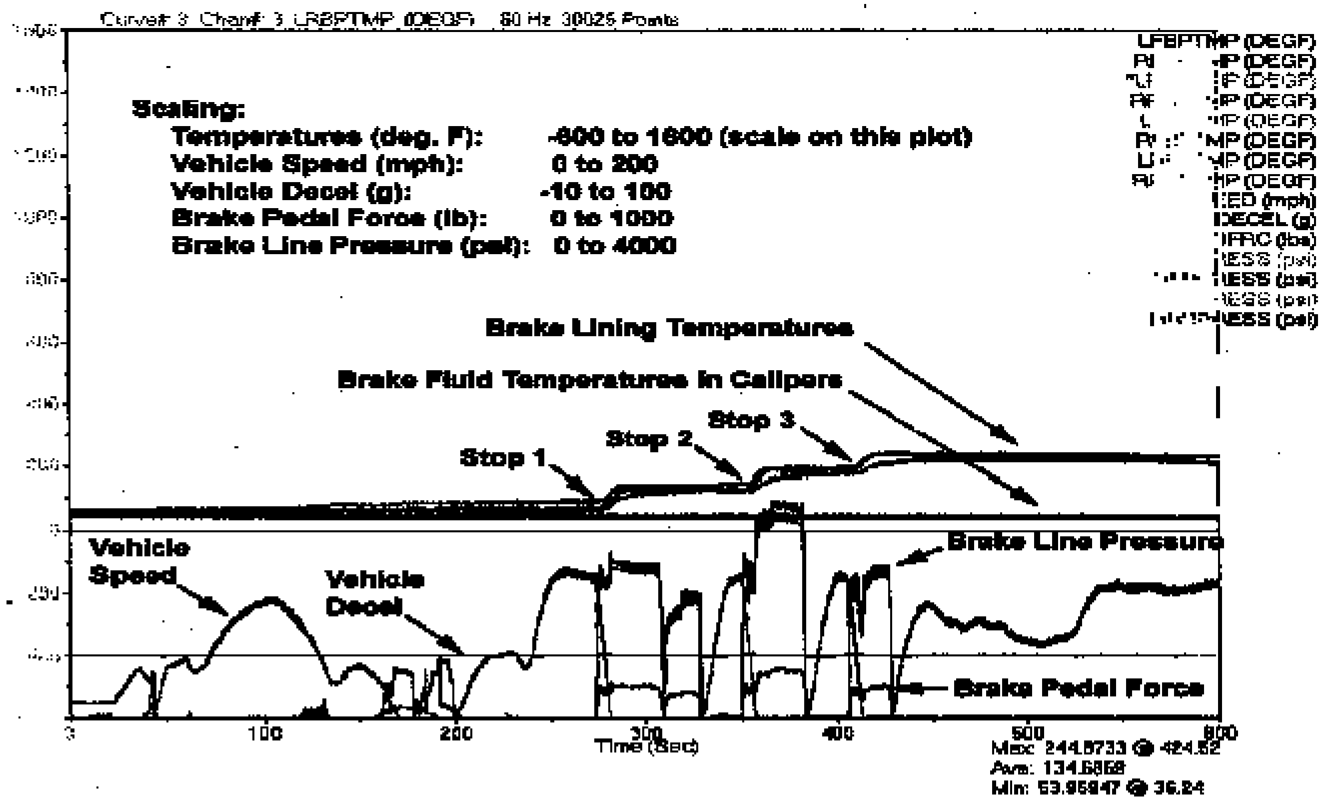


**Figure 16 – Data for First Test on MH1 Showing the Drive Out to the Skid Pad and the First 200°F Target Stops**

(Notice the rise of the inner brake lining temperatures compared to the four caliper fluid temperatures)

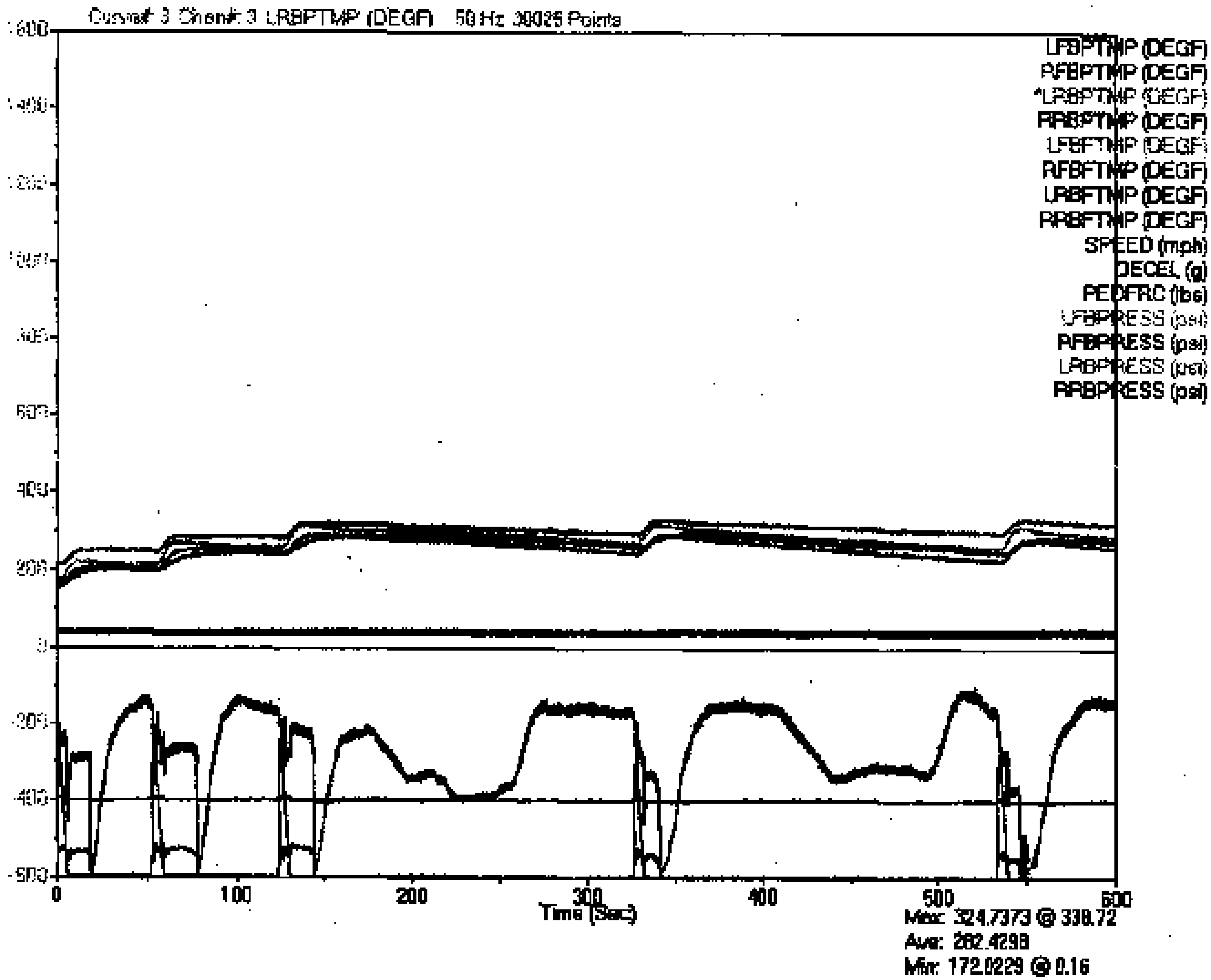


**Figure 17 – Data for First Test on MH1 Showing the 300°F Target Stops**
(Notice the left rear inner brake lining temperatures are running lower than the right rear and the brake fluid temperatures are 40 to 50°F)

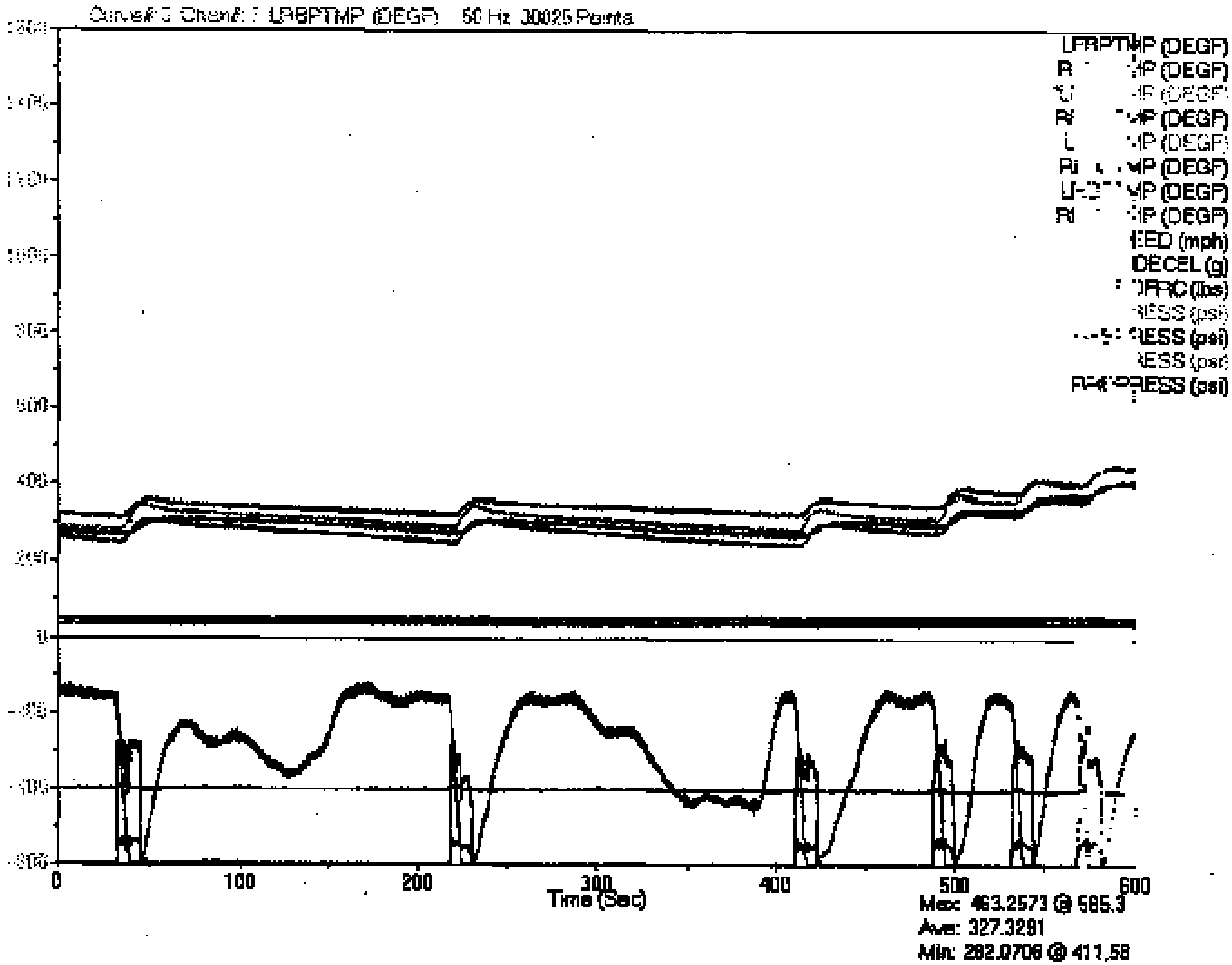


**Figure 18 – Data for First Test on MH1 Showing the 400°F Target Stops**
(Notice minimal heat buildup in the brake fluid inside the caliper)

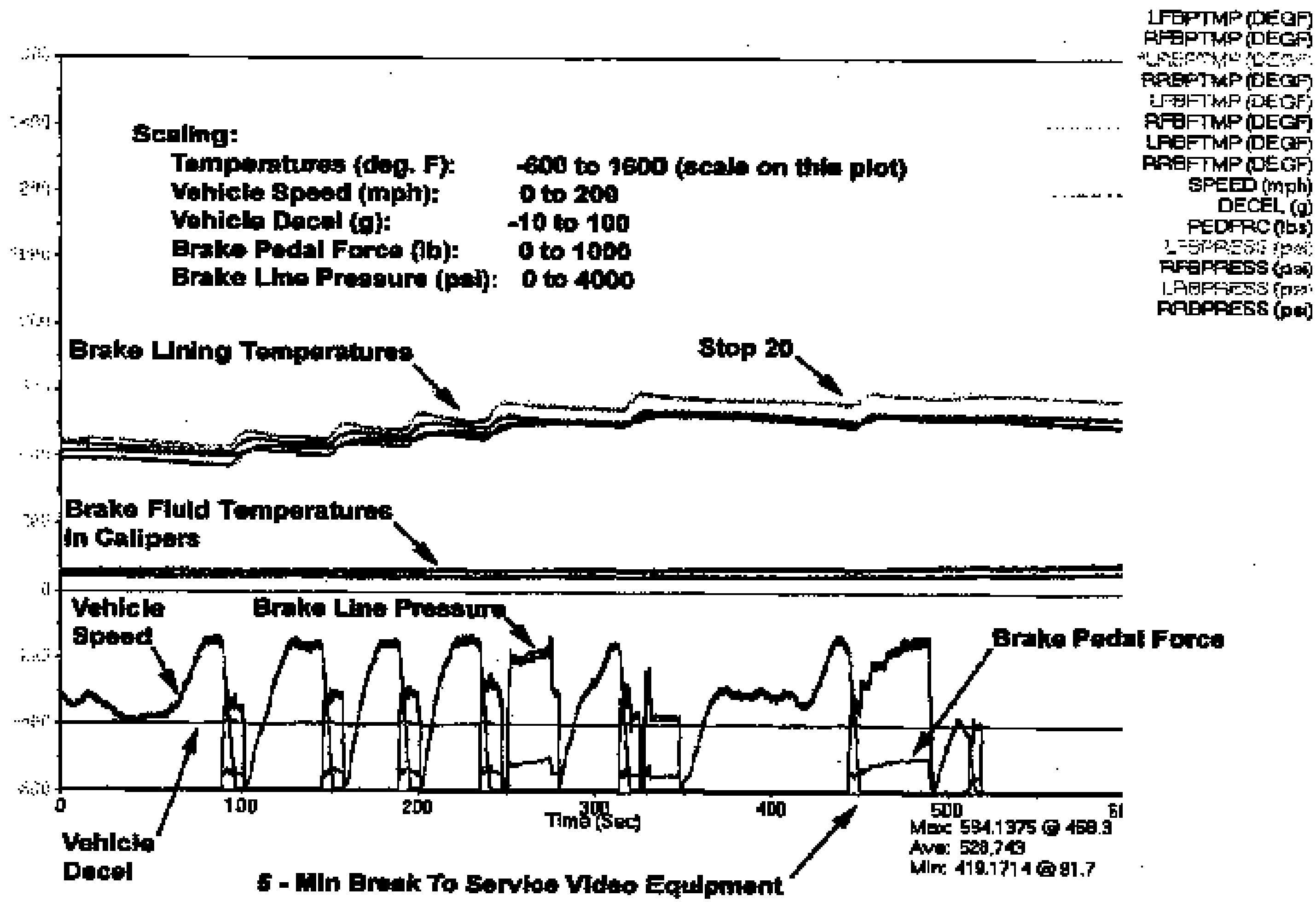


**Figure 19 – Data for First Test on MH1 Showing the 500°F Target Stops**

(Notice the left rear inner brake lining now has the highest temperature

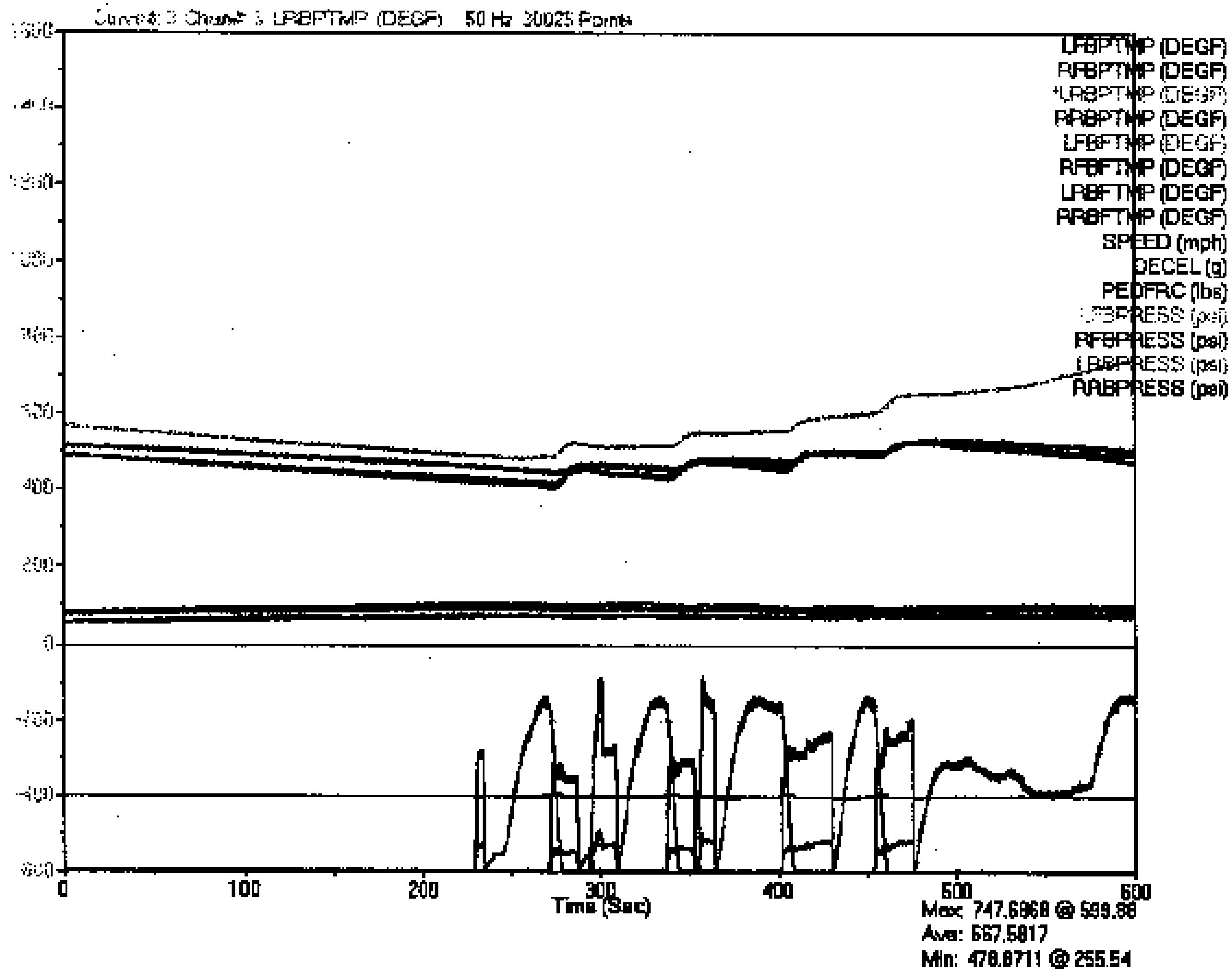


**Figure 20 – Data for First Test on MH1 Showing the End of the 5-Minute Break (for the Video Equipment), the Next Four Brake Applications, and the Beginning of the Abnormal Rise in the Left Rear Brake Lining Temperature**

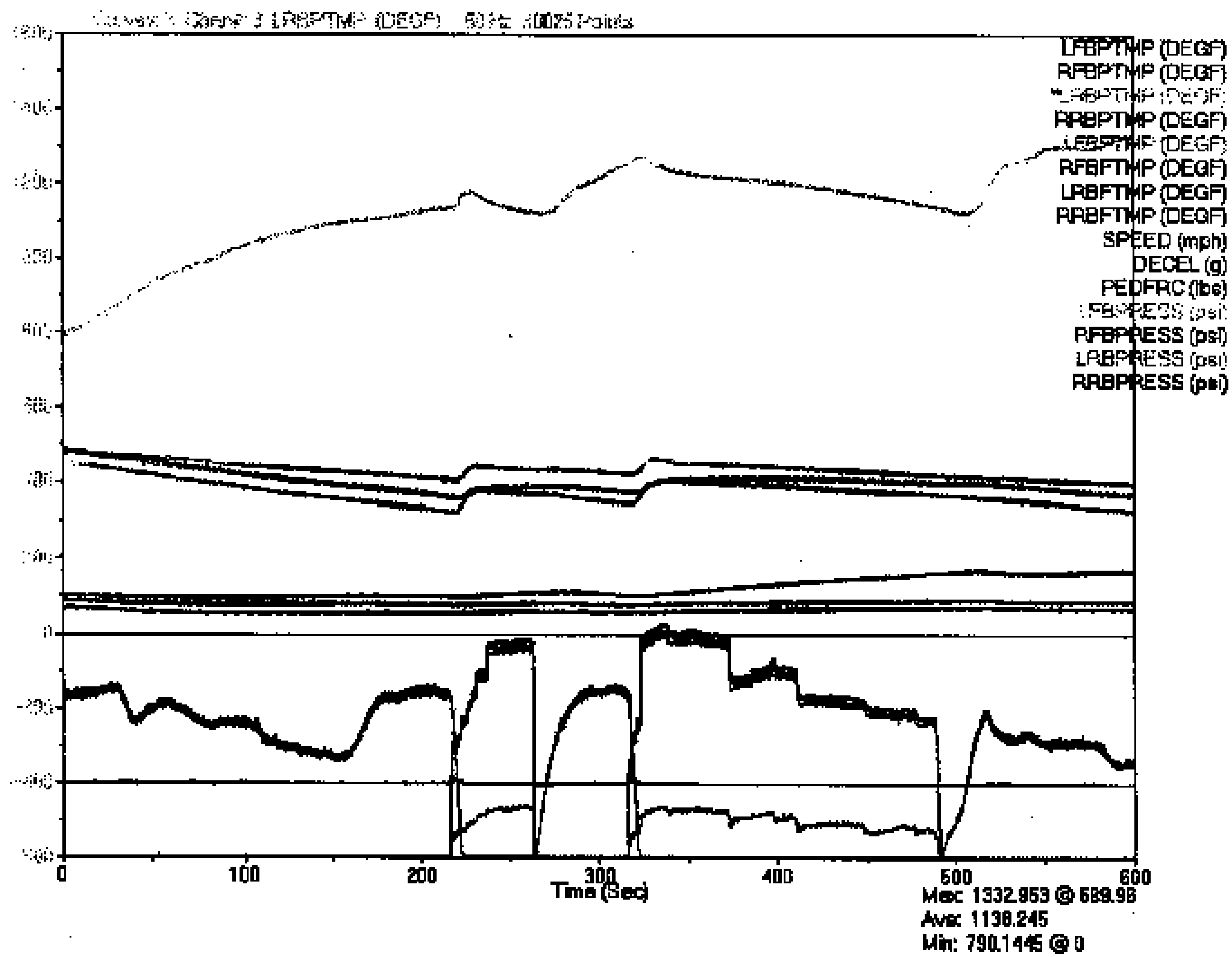


Figure 21 – Data for First Test on MH1 Showing the Abnormal Thermal Rise Continuing

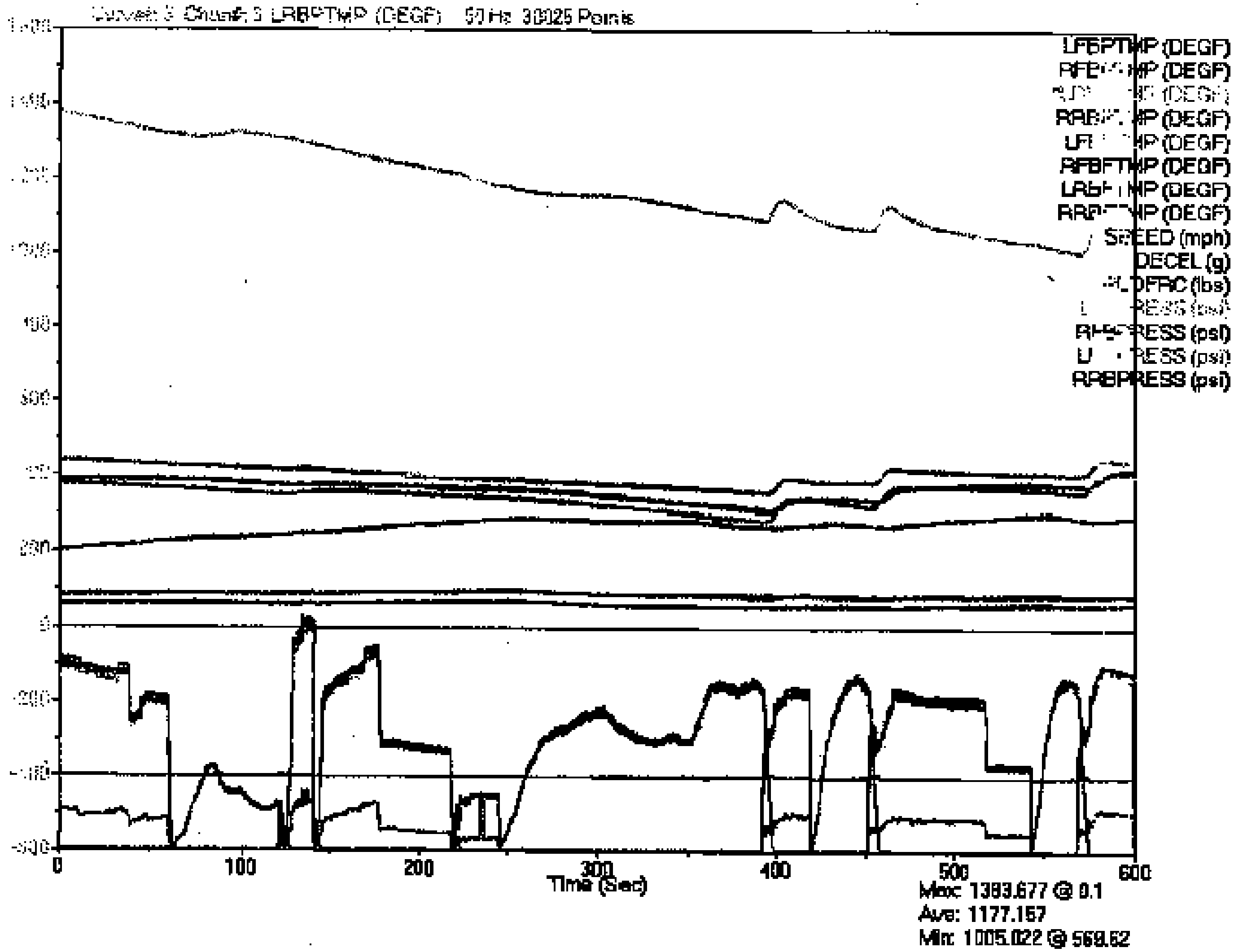


**Figure 22 –Data for First Test on MH1 Showing a Decline in the Abnormal Temperature on the Left Rear Lining**
(Notice more braking does not restart the abnormal thermal event)

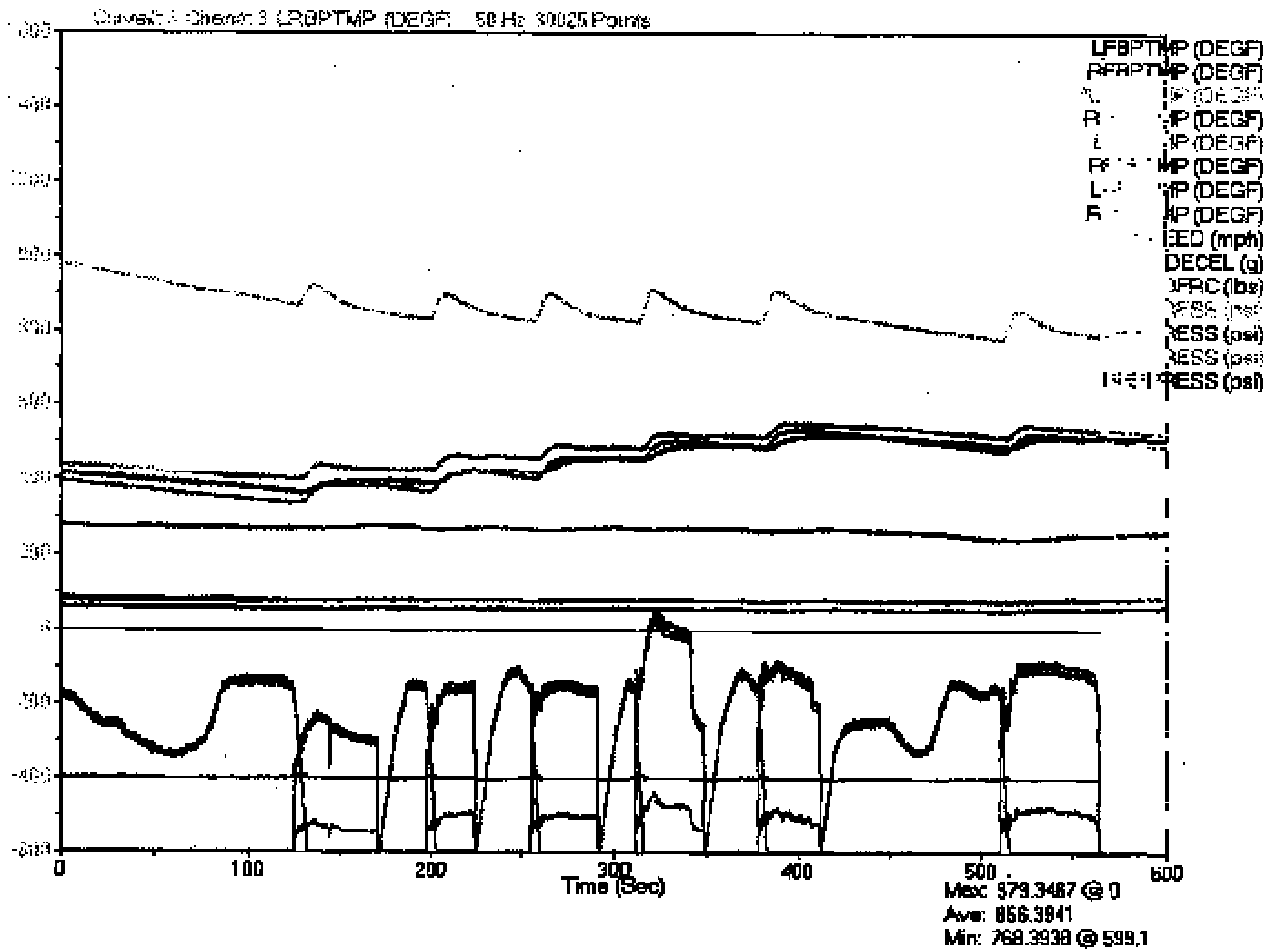


**Figure 23 –Data for First Test on MH1 Showing the Temperature of the Left Rear Lining Declining as Additional Braking Does Not Restart the Event**
(Notice the left rear brake fluid temperature rising to 306°F)

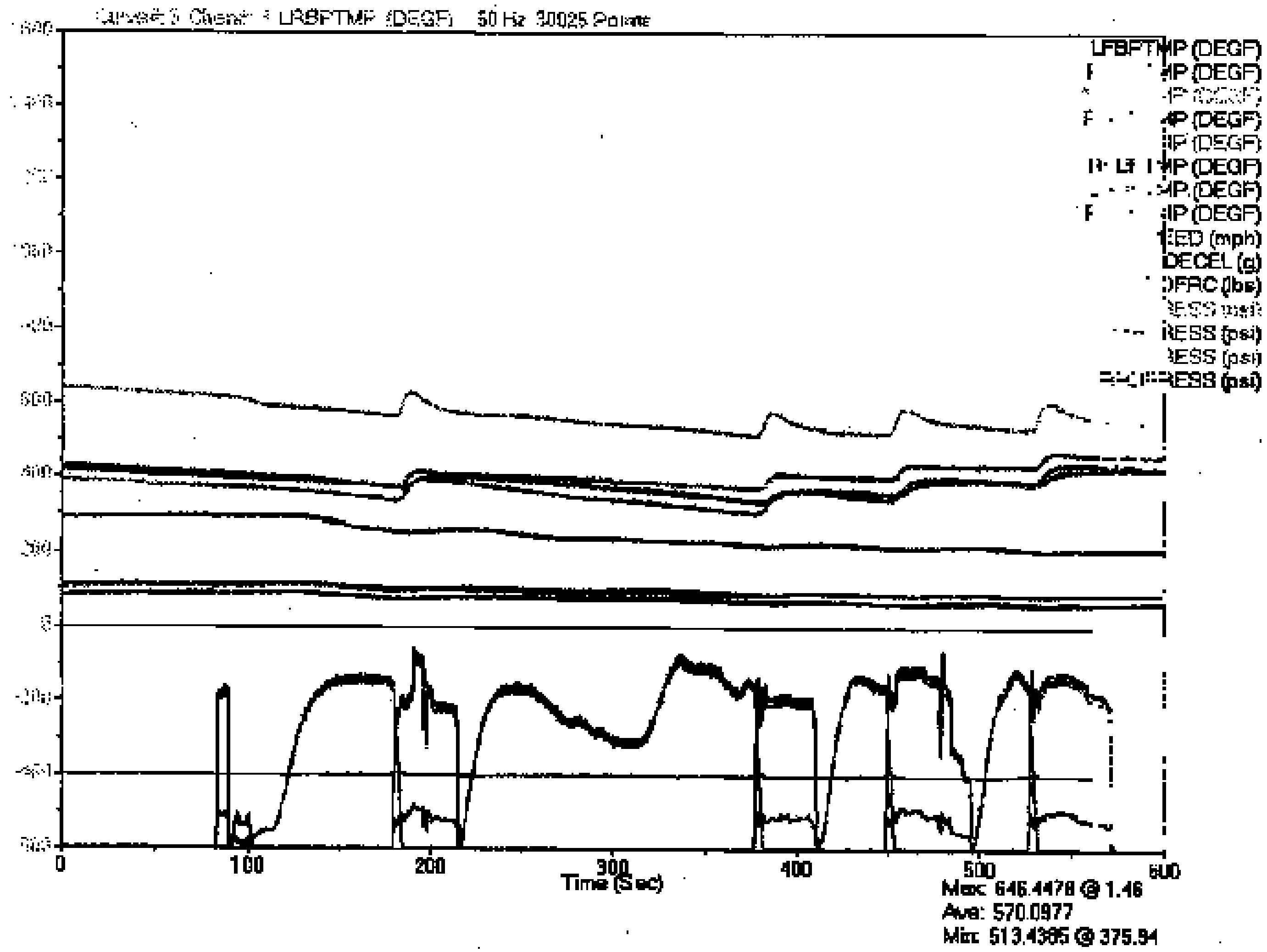


**Figure 24 – Data for First Test on MH1 Showing the End of the Abnormal Thermal Event before a Field Inspection of the Components Could be Conducted**

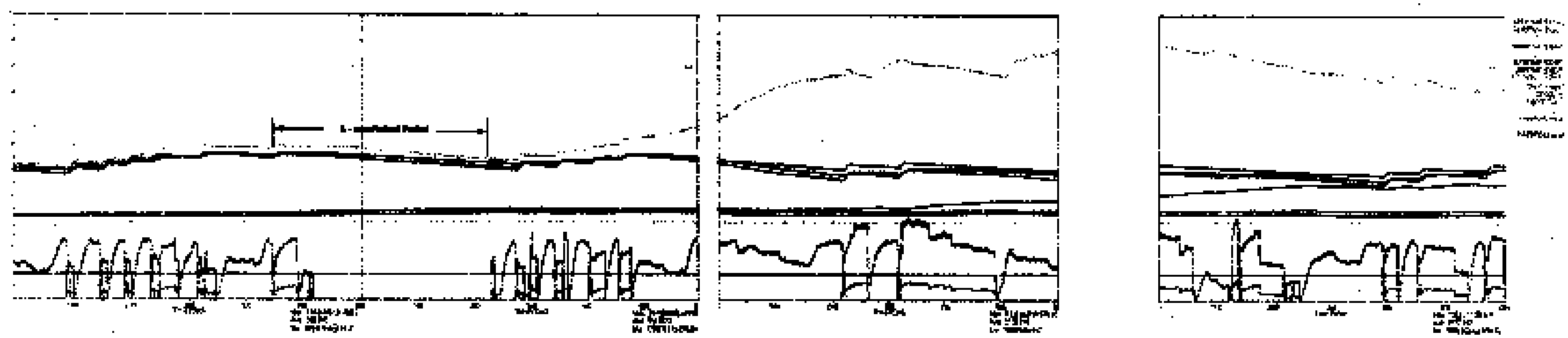

**Figure 25 – Composite Data for the First Test on MH1 Showing Normal Brake Stops, a 5-Minute Break or Parked Period (to Service Video Equipment), and the Thermal Deviation of the Left Rear Inner Brake Pad after Four More Brake Stops (Temperatures Reached 1,400+°F)**

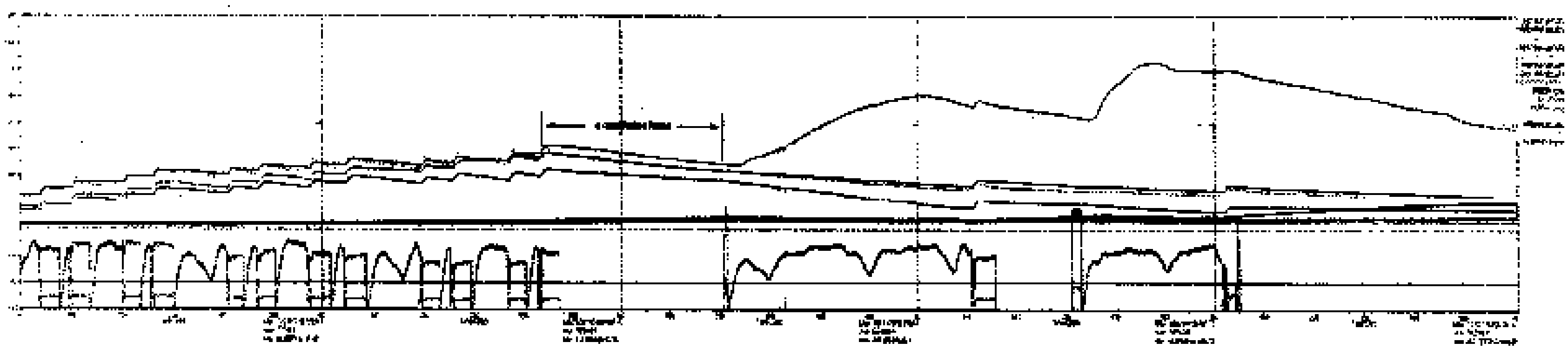

**Figure 26 – Composite Data for the Second Test on MH1 Equipped with AXL1 Showing Normal Brake Stops, a 4-Minute Parked Period, and Thermal Deviation of Right Front Inner Brake Lining While Driving without Braking (Temperature Reached 1,262°F)**

**Figure 27 – The Second Test on MH1 Showing the Right Front Rotor was Red Hot and Shooting Sparks (at Bottom of Rotor) from a Dragging Brake**

**Table 2 – Tests Conducted on MH1**

[redacted]

| | | | | |
|---|---|---|---|---|
| 41 | 0 | Skid Pad | LR Fire | |
| 15 | 0 | VDA | RF Red Rotor | Installed AXL1 |
| 42 | 0 | HSTT | no event | |
| 77 | 21 | Skid Pad | no event | |
| 18 | 32 | Skid Pad | no event | |
| 23 | 26 | HSTT+VDA | no event | ABS repaired |
| 19 | 18 | Skid Pad | no event | |

# Table 3 – Inspection Data from Post-Test Removal of Calipers

| Items Inspected (all components at ambient temperature) | | AML1 – Left Front (Reported Fire) | AML2 – Right Front (Red Hot Rotor – Test #2) | MH1 – Left Rear (Fire – Test #1) | MH1 – Right Rear (Reported Fire) |
|---|---|---|---|---|---|
| Rotor Appearance: | | good used rotor - no grooves, no deposited material, or rust | slight grooves with rust and deposited material | slight grooves with rust and deposited material | slight grooves with rust and deposited material |
| Hub Turning Torque: | | 10 ft-lb static breakaway<br>5 ft-lb continuously running | 6 ft-lb static breakaway *A<br>6 ft-lb continuously running | 31 ft-lb static breakaway<br>25 ft-lb continuously running | 52 ft-lb static breakaway<br>41 ft-lb continuously running |
| Brake Linings: (attempt to rattle brake linings with Vise-Grips on backing plates) | | inner and outer pads free<br>caliper not binding on brake pads | inner and outer pads free<br>caliper not binding on brake pads | inner and outer pads free<br>caliper not binding on brake pads | inner and outer pads free<br>caliper not binding on brake pads |
| Attempt to move caliper: | Radially: | little to no movement | 0.005" | little to no movement | little to no movement |
| | Tangentially: | little to no movement | 0.013" | little t[illegible]vement | little to no movement |
| Inspect Pin Boots: | | both boots intact | both boots intact | upper [illegible] pad and lower boot intact | both boots intact |
| Inspect Pin Bolts: | | good condition | good condition | good [illegible]n | good condition |
| Inspect Pin Flange Position: | | upon initial inspection neither was cammed, now both are cammed and leading pin flange "driven" into caliper casting, initial paint index marks moved | initial and final inspection found neither pin flange was cammed, no change on paint index marks | initial [illegible]d inspection found top pin flange barely cammed and bottom not cammed, no change on paint index marks | neither pin flange cammed, no change seen from initial inspection paint index marks |
| Pin Bolt Breakaway Torque: | Leading: | 82 ft-lb (torque wrench) | not measured - but light | 80 ft-lb (torque wrench) | 80 ft-lb (torque wrench) |
| | Trailing: | 92 ft-lb (torque wrench) | not measured - but light | 90 ft-lb (Chatillon pull on 1-ft wrench) | 60 ft-lb (Chatillon pull on 1-ft wrench) |
| Inspect Pin Bolts: | Leading: | green "patch" material | not performed | not noted | not noted |
| | Trailing: | not performed | not performed | removed lower bolt, remove brake pads, reinstall lower bolt - caliper binds as torque is applied | removed bolt and found white & blue "lock" material |
| Check Caliper Slide Force: (then set caliper aside) | Inboard: | 12 lb | 25 lb | 100 lb (13 lb after rotating pin 180°) *B | not performed |
| | Outboard: | 10 lb | 20 l[illegible] | 35 lb (12 lb after rotating pin 180°) | not performed |
| Twist and Insert Pins in Anchor Plate: | | free sliding | free [illegible] | free sliding | free sliding |
| Hub Turning Torque (w/o linings/calipers): | | 10/5 ft-lb breakaway/running | not [illegible] | 31/25 ft-lb breakaway/running | 31/25 ft-lb breakaway/running |
| Measure Pin Free Play: (in Anchor Plate Bore) *C Pin was Pushed to Compress Boot, then Released, Pin Moved to Neutral Position, then Free Play was Measured | Leading x = | 0.014" | not [illegible] | 0.006" | 0.008" |
| | y = | 0.030" | not [illegible] | 0.009" | 0.009" |
| | r = | 0.015" | not [illegible] | 0.008" | 0.009" |
| | t = | 0.016" | not [illegible] | 0.009" | 0.009" |
| | Trailing: x = | 0.038" | not [illegible] | 0.024" | 0.021" |
| | y = | 0.038" | not [illegible] | 0.024" | 0.023" |
| | r = | 0.037" | not [illegible] | 0.016" | 0.023" |
| | t = | 0.029" | not [illegible] | 0.020" | 0.024" |
| Insert 2-1/2 inch Wooden Block and Hand Apply Brake Pedal to Extend the Pistons: | | not performed (axle was removed from vehicle at time of inspection) | five brake applications to drive the pistons to the wooden block, fairly even deployment, upon release the wooden block was easily removed *D | five brake applications to drive the pistons to the wooden block, both pistons even after first two applies, lead piston behind trailing piston, then both even at block, upon release the wooden block was easily removed | five brake applications to drive the pistons to the wooden block, lead piston was 1/2 in behind trail piston, then both even at block, upon release the wooden block was easily removed |
| Metal Bar and C-clamp Retract Piston: | | not performed (axle was removed from vehicle at time of inspection) | normal piston return into bore *E | normal piston return into bore | normal piston return into bore |
| Condition of Caliper | | used, but apparently good condition | piston environment boot very thin and ripped toward center of caliper | piston environment boots burnt, 100% of each boot | piston environment boots burnt, 25% of each boot in middle of caliper |
| Condition of Brake Linings | | appears used, some glazing, evidence that pads had been installed in both orientations, was backwards as found | appears used, some glazing, sort of "dried" out, some white smoke stain along edges | appears used, some glazing, sort of "dried" out, white smoke stain along edges, corners of pad breaking off | appears used, some glazing, sort of "dried" out, some white smoke stain along edges |

notes:
*A = 140 ft-lb rotational torque was measured on the test track ten minutes after the stopping with a red-hot rotor, during teardown the next day, the torque had dropped to 6 ft-lb
*B = 50-lb slide force maximum allowed by Bosch updates
*C = Pin Free Play Measurement => x = horizontal, y = vertical, r = radially, t = tangentially
*D = the lead piston was immobile when brake pedal was actuated by hand immediately after the event
*E = piston could not be pushed back into the bore on the test track immediately after the event

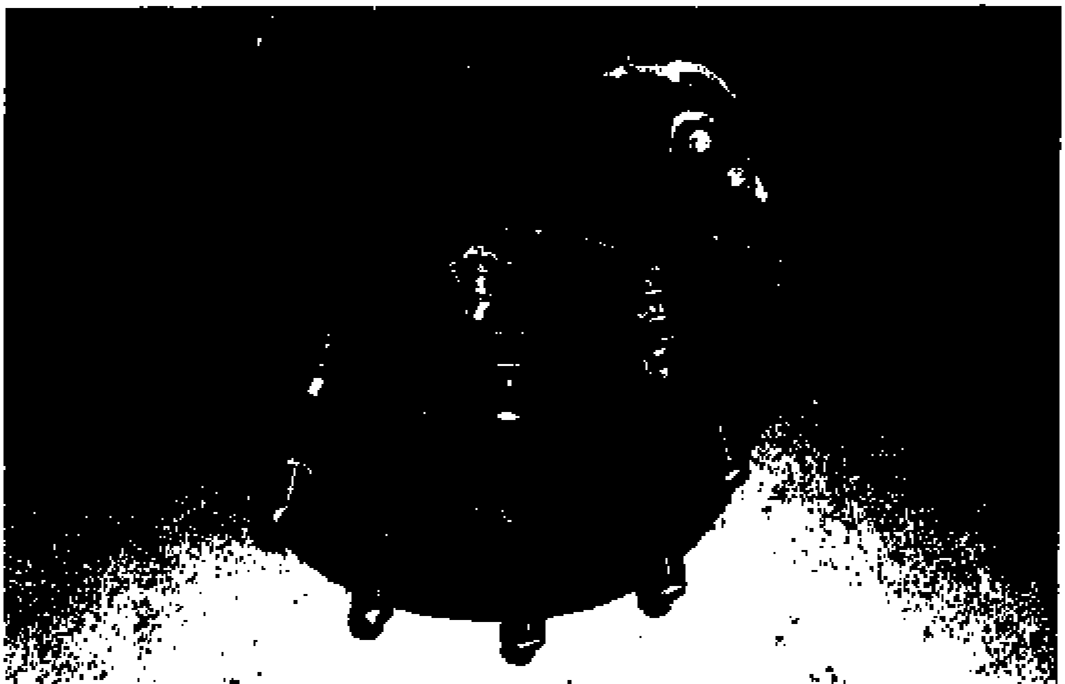

**Figure 28 – Post-Test Inspection of the Left Front Wheel-end of AXL1 Showed the Rotor Brake Surface Became Polished**

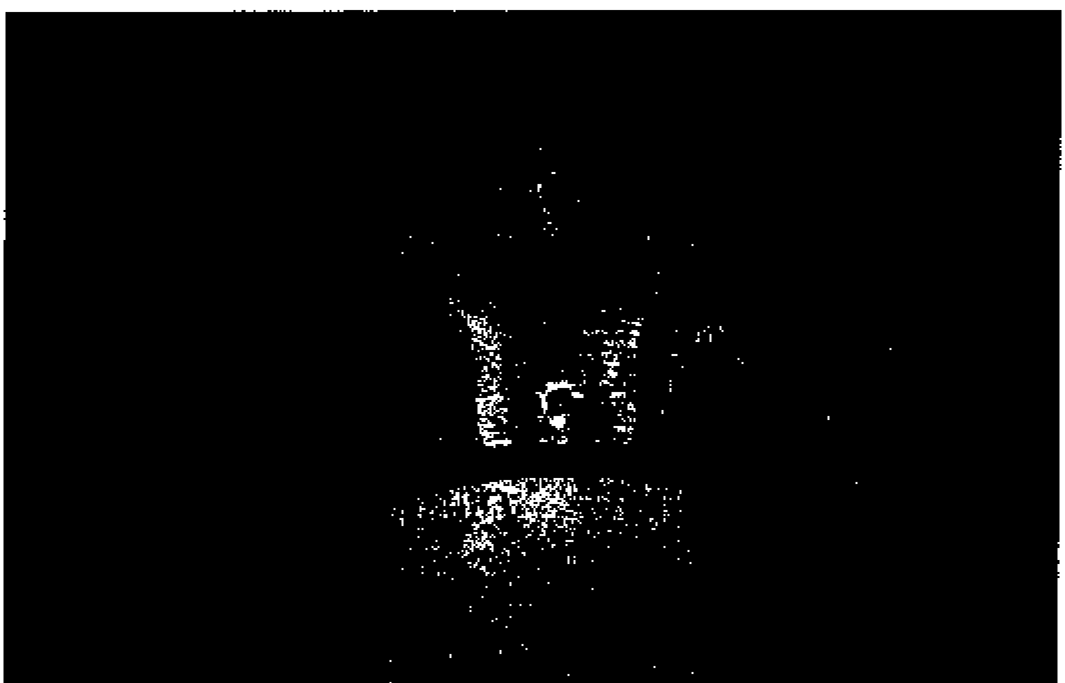

**Figure 29 – Post-Test Inspection of the Left Front Wheel-end of AXL1 Showed the Outer Brake Pad Had Evidence of Being Previously Installed as the Inner Brake Pad of the Caliper**

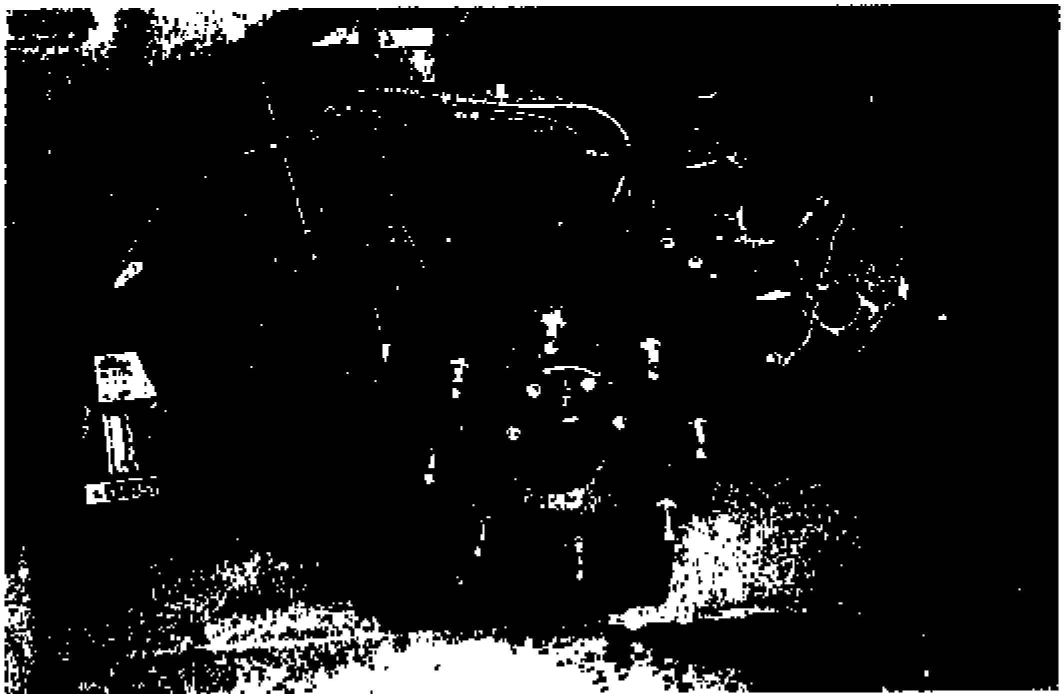

**Figure 30 – Post-Test Inspection of the Right Front Wheel-end Showing the Overall Appearance of the Rotor**

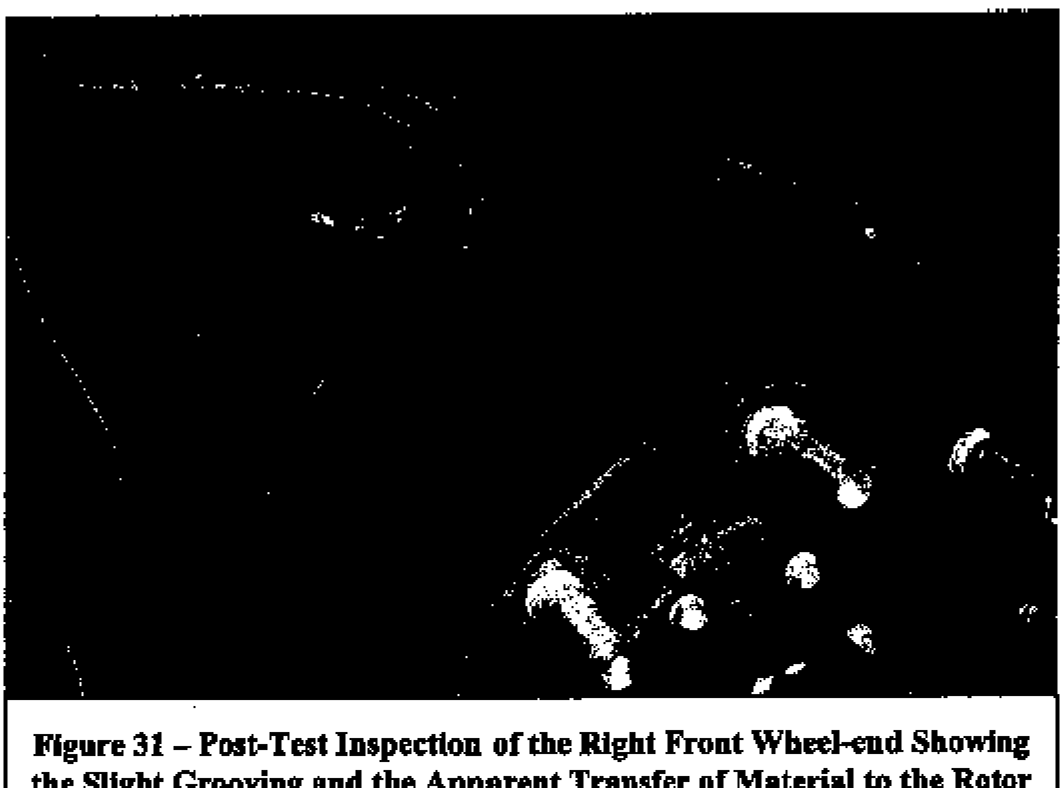

**Figure 31 – Post-Test Inspection of the Right Front Wheel-end Showing the Slight Grooving and the Apparent Transfer of Material to the Rotor**

**Figure 32 – Post-Test Inspection of the Right Front Wheel-end Caliper Showed the Leading Piston Now Has a Torn Boot**

**Figure 33 – Post-Test Inspection of the Right Rear Wheel-end Showed Slight Grooving and Apparent Transfer of Material onto the Rotor**

**Figure 34 – Post-Test Inspection of the Right Rear Wheel-end Showed Evidence of a Fire Event Reported by the Previous Owner**

**Figure 35 – Post-Test Inspection of the Left Rear Wheel-end Showed Slight Grooves and Apparent Material Transfer**
(Note that this wheel was on fire during the tests at VRTC)

**Figure 36 – Post-Test Inspection of the Left Rear Wheel-end Showing the Determination of the Caliper Slide Force**

**Figure 37 –Post-Test Inspection of the Left Rear Wheel-end Showed the Condition of the Caliper after the Fire during the First Test**

US Department
Of Transportation

National Highway
Traffic Safety
Administration

# Memorandum

Vehicle Research and Test Center P.O. Box B37
East Liberty, Ohio 43319
(937) 666-4511

Subject: INTERIM REPORT: VRTC-DCD2037 "Inspections and Bench Tests of Brake Calipers from a 2002 National RV Dolphin LX Motorhome (EA02-034)"

Date: JUL 1 2 2004

From: Michael W. Monk, Director

Reply to Attn. Of: NVS-310

To: Kathleen C. DeMeter, Director
Office of Defects Investigation

NVS-210

Attached are four copies of the subject report. This interim report covers the bench tests, conducted during the Bosch ZOPS test program, on calipers from a vehicle designated as NRV1.

#

Attachment: Reports (4)

# INTERIM REPORT 3 – VRTC-DCD2037 (EA02-034)

## Inspections and Bench Tests of Brake Calipers from a 2002 National RV Dolphin LX Motorhome

### 1.0 INTRODUCTION

This test program was performed at the Vehicle Research and Test Center (VRTC) in response to a request by the Office of Defects Investigation (ODI), National Highway Traffic Safety Administration (NHTSA). The ODI has received complaints alleging brake overheating on the Bosch "Zero-Offset Pin Slide" (ZOPS, aka International Diamondlife) caliper brake system on various vehicles. Many complainants have alleged that these brakes apply normally, and then fail to fully release, resulting in overheated wheel-ends and fires on various vehicles, including school buses. A previous report, titled ***"INTERIM REPORT 2 – VRTC-DCD2037 (EA02-035) Bench Tests of the Bosch Brake Calipers (ZOPS),"*** was sent to the ODI on 03/29/03 and describes the component testing that was the basis for a portion of this bench testing.

### 2.0 BACKGROUND DISCUSSION

Four Bosch 66-mm ZOPS calipers were received by VRTC on January 30, 2004 and are shown in Figure 1 in the Appendix, where all the figures are shown. The calipers were reportedly from a 36-foot 2002 National RV Dolphin LX on a Workhorse (Model W22) Chassis. The completed vehicle VIN was 5B4MP67G323340222. It was purchased in December 2001 and had an odometer reading of 15,157 miles at the time of the incident in December 2003. A repair facility provided the calipers to the VRTC within two months of the event.

The owner's e-mail report stated, *"On Tuesday, December 2nd we were north bound on the Florida Turnpike just north of the I-4 interchange traveling about 65 mph when we felt a vibration similar to the rough road feeling when a Caterpillar Bulldozer has been on the highway. We pulled into the rest area for a normal pit stop and to check the tires etc. Every thing seemed OK except we could smell a hot brake type of smell. It seemed to be all right when we pulled back out onto the Turnpike but the "vibration" was back within a mile or so. We pulled over onto the shoulder and, at that time, it was quite obvious that we had at least one brake locked up. The coach would not drift forward at all when I gave it a bit of gas."*

## 3.0 INSPECTIONS AND TESTING

The calipers were inspected at VRTC and labeled NRV1-1, NRV1-2, NRV1-3, and NRV1-4. The relative locations of these calipers on the vehicle were not reported by the repair facility and the brake linings were not included with the calipers. Visual inspections of the calipers showed that all four of the calipers had ruptured environmental boots with varying amounts of white ash on and around the boots. This ash indicated a significant thermal event had occurred. The fact that all four calipers had experienced a thermal event could be explained by a number of foundation brake, antilock brake control unit, or caliper defects. Since the vehicle was not available, the inspections and tests were conducted only on the calipers and a full troubleshooting evaluation could not be performed.

The calipers were first tested for piston knockback and retraction using the fixture developed by VRTC. These tests were conducted as closely as possible to the procedures listed in Section 5 of the Bosch Engineering Instruction No. UI-198[1]. The results of these tests were compared to the results of a newer generation Bosch Zero-Offset Harmonized Truck (ZOHT) 66-mm caliper (previously designated NEW-OEM3). Then the caliper piston operation was observed during a bench-top test with the caliper at elevated temperatures. This testing was similar to that described in the previous interim report noted in Section 1.0. Next, the calipers were disassembled, inspected, and measurements were taken of the piston diameter and the caliper bore diameter at room temperatures. The diameter of each piston was remeasured after heat soaking for 3 hours in an industrial oven at 257°F. This elevated temperature was previously determined during thermal penetration tests (Interim Report 2) in the piston at the depth of the critical seal land position in the bore. This piston temperature was determined for an inner brake lining center-of-pad temperature of 550°F, typical of previous driving tests that simulated stop-and-go driving on the test track by VRTC. The piston-to-caliper-bore clearance was then calculated for the components at ambient temperature and compared to calculations for a heated piston and ambient caliper housing.

## 4.0 RESULTS OF INSPECTIONS AND TESTING

The results are discussed below for each caliper from NRV1 in the order of testing.

### 4.1 Caliper NRV1-2

This caliper had ruptured environmental boots and some ash on the boots and caliper housing, as shown in Figure 2. Piston A (the left piston in Figure 2) had ash on the ruptured

---

[1] A soft pine block was substituted for a compressive block.

environmental boot as shown in Figure 3. Note that Piston/Bore A and B will hereafter refer to the left and right pistons/ bores respectively when the caliper is oriented with the pistons facing upward and the three bridge fingers are pointed toward the observer.

The caliper was first tested for knockback and retraction. This caliper performed worse for Piston A than the NEW-OEM3 (ZOHT) 66-mm caliper. However, Piston B of this caliper performed similarly to the new ZOHT caliper.

Three thermally elevated bench tests were conducted on Caliper NRV1-2 using brake linings from a previous test caliper (NMR1-LF) since no brake linings were sent by the repair facility that sent the calipers. It had been found in previous testing that the brake linings are an important factor in the transmission of heat to the caliper piston. Therefore, the results from these tests may not be the same as tests with the original brake linings from the National RV motorhome. The first test consisted of inserting a rotor segment heated to 1,132°F into this caliper and applying a hydraulic pressure of 447 psi, as shown in the data plot in Figure 4. The inner brake lining center-of-pad temperature (the green trace) increased after the release of the initial hydraulic-pressure application and the next application. This rise in temperature after the initial hydraulic release had not been observed during the previous testing. The rotor segment was moved with the channel-lock pliers and determined to be free; however, the temperature rose about 35°F between the 1- and 2-min points, as shown in the close-up view in Figure 5. To determine if the piston was seized in the current position, the brake was reapplied briefly at the 2-min point (even though it was above the target range of 550°F +/-10°F). The short duration application (~15 sec) caused the center-of-pad temperature to increase about 40°F but the rotor segment could still be moved with the channel-lock pliers after this pressure application was released. Using a new operating target range of 610°F +/-20°F, the brake rotor segment could still be moved freely with the channel-lock pliers after each hydraulic pressure apply and release cycle. The pistons did not stick in the extended position and seize on the brake rotor in the caliper during this test or the following two thermally elevated temperature tests of this caliper.

The caliper was further inspected, disassembled, and photographed. The environmental boot on Bore A separated during removal and part of the boot remained around the piston groove, as shown in Figure 6. After removal of the environmental boots, corrosion was evident on the hydraulic seal lands of both piston bores, as shown in Figure 7. After the pistons were removed from the bores, the inspection showed that the hydraulic seals of both pistons were twisted, or rolled, as shown in Figure 8. Rolled hydraulic seals have been identified by Bosch as a cause for thermal events. This could have contributed to the poor knockback and retraction performance and the increasing temperature of the inner brake lining center-of-pad temperature after the initial caliper apply-pressure was released.

The NRV1-2 caliper bore and piston diameters were measured at ambient temperatures. The piston diameters for this caliper were within specifications, as shown in Table 1. However, the caliper bores at the seal land area (at the top of bore) were undersized because of the growth of the corrosion. The seal land is the thin section of the bore between the top of the bore and the hydraulic seal receiver groove (the ring-shaped area above the rolled seal in Figure 8). The calculated piston clearance for this caliper was still within specification since the pistons were at the middle-to-small size of their allowable diameter. The piston-to-bore clearance was recalculated after heating the phenolic pistons at 257°F, the temperature previously found at the depth of the caliper housing critical seal land. The piston in Bore A was found to have a zero clearance fit and Bore B was found to have a 0.0015 in interference fit. This lack of piston-to-sidewall clearance in Bore B at operating temperatures could have contributed to the abnormal operation of this caliper when installed on the vehicle; however, it did not seem to cause abnormal operation during these bench tests. The rolled hydraulic seals also could have contributed to the abnormal operation when this caliper was installed on the vehicle.

## 4.2 Caliper NRV1-4

The inspection of Caliper NRV1-4 showed that both environmental boots were ruptured and had a significant amount of ash on the boots and on the caliper housing, as shown in Figure 9. This caliper appeared to have had the most severe thermal event of the set of four calipers.

This caliper was tested for knockback and retraction at ambient temperatures on the VRTC test stand. On both pistons, this caliper performed similarly to the new ZOHT 66-mm caliper.

Two elevated thermal tests were conducted on Caliper NRV1-4 using NMR1-LF brake linings, since the original linings were not available. During the first test, the rotor segment was heated, with some difficulty, to 1,123°F. The heating time took longer and was not the continuous slope that had been used in previous tests, probably because of a different heating technique by the torch operator. He was concerned with burning the wire to the rotor-segment thermocouple and restricted his heating of the inner friction surface (or backside) of the rotor segment. The hydraulic pressure used to apply the caliper was 448 psi. A short preliminary application was made first to seat the piston against the brake lining. Then the initial pressure was briefly applied and released and the inner brake lining center-of-pad temperature slowly drifted about 10°F higher, as shown in Figure 10. The caliper was re-clamped on the heated rotor segment and the temperature rose again into the new range around 610°F. The rotor segment was free to move (released) after every brake pressure application during this test and the following test.

The caliper was then inspected, disassembled, and photographed. The environmental boot on Bore B separated during removal and part of the boot remained around the piston groove. Removal of the boots showed corrosion on the top of the seal land areas of both bores, as shown in Figure 11. After the pistons were removed from the bores, the inspection showed that the bore face of the seal land areas were also corroded and that both caliper bores had normal (not rolled) hydraulic seals.

The NRV1-4 caliper bores and piston diameters were measured at ambient temperatures. The piston diameters were within specifications, as shown in Table 1. However, the caliper bores at the seal land area (top of bores) were undersized because of the growth of the corrosion. The calculated piston clearance for this caliper was 0.001 in below the specified clearance on Bore B due to the corrosion at the seal land area. After heating the pistons from this caliper and remeasuring their diameters, the pistons had interference fits of 0.0010 in and 0.0015 in for Bores A and B respectively. This caliper had more ash on the environmental boots and caliper housing than the other three calipers from Vehicle NRV1.

## 4.3 Caliper NRV1-1

The inspection of this caliper showed that both environmental boots were ruptured and had visible ash, as shown in Figure 12. This caliper was then tested for knock-back and retraction and found to perform similarly to the new ZOHT 66-mm caliper on both pistons.

Two elevated thermal tests were conducted on Caliper NRV1-1 using the NMR1-LF brake linings. On the first test, the rotor segment was heated to 1,130°F in a more normal manner, as shown in the data plot in Figure 13. The hydraulic pressure of 454 psi, used to actuate the caliper, was released when the brake lining center-of-pad temperature reached the 550°F point. Note that a quick brake application was used prior to the initial test application in order to seat the brake components. After releasing the initial brake pressure application, the temperature initially stayed fairly level for about 7 sec, and then gradually started to rise as it did for the other calipers. After rising about 16°F over this 15-sec release interval, as shown in Figure 14, the pressure was applied again, driving the inner brake lining center-of-pad temperature to the 620°F +/- 20°F range. In this test, and the next one, the rotor segment was free to move after every brake pressure application.

The caliper was then inspected, disassembled, and photographed. The environmental boot on Bore B separated during removal and part of the boot remained around the piston groove. Removal of the boots showed corrosion on the seal land areas of both bores, as shown in Figure 15. After the pistons were removed from the bores, the inspection showed that both caliper bores had normal (not rolled) hydraulic seals.

The NRV1-1 caliper bores and piston diameters were measured at ambient temperatures. The diameter of Piston B was 0.0010 in below Bosch specification, as shown in Table 1. Both of the caliper bores at the seal land area (top of bores) were undersized (A= 0.0015 in; B = 0.0030 in) due to the growth of corrosion. The calculated piston clearance was 0.0005 in below the specified clearance on Bore A. After heating the pistons to 257°F, and remeasuring the diameters, the piston clearances were calculated and found to be interference fits on both bores (0.0010 in on Bore A and 0.0015 in on Bore B).

## 4.4 Caliper NRV1-3

The inspection of the environmental boots showed that both were ruptured and covered with ash, as shown in Figure 16. This caliper was tested for knockback and retraction at ambient temperatures on the VRTC test stand. On both pistons, this caliper performed similar to the new ZOHT 66-mm caliper.

Four elevated thermal tests were conducted on Caliper NRV1-3 using the NMR1-LF brake linings. On the first test, the rotor segment was heated to 1,026°F in a normal manner, as shown in the data plot in Figure 17. The hydraulic pressure applied to actuate the caliper was 432 psi, which was released upon reaching the 573°F point. The temperature continued to rise about 64°F over the next 74 sec before the caliper was activated briefly to check for piston sticking. In this test, and the next one, the rotor segment was free to move after every brake pressure application.

The third elevated thermal test was conducted with the original target of 550°F for the inner brake lining center-of-pad temperature. The initial rotor temperature was 1,026°F and the hydraulic pressure applied to the caliper was 440 psi, as shown in the data plot in Figure 18. After 21 sec of the initial clamping on the heated rotor, the center-of-pad temperature reached 560°F. This temperature gradually rose an additional 15°F about 3 min after the initial brake pressure release; about 7 min was required after the initial pressure release for the temperature to drop to 546°F. The brake was then briefly reapplied several times and the rotor segment was free to move after each application.

This temperature rise, following the release of the initial brake pressure application, had not been seen in the previous testing of calipers from other vehicles. It was found previously that brake linings with different usage histories could transmit heat to a piston at different rates. The brake linings NMR1-LF had been bench tested at elevated temperatures in the previous testing. However, these brake linings had not been though a thermal event on a vehicle so they were thought to be fairly representative of a "normal in-use" brake lining.

To study the observed temperature rise after releasing the caliper clamping force, the NMR1-LF brake linings were replaced with the MH1-LR brake linings (which had been subjected to a brake fire when on vehicle MH1, but not bench tested) for the fourth elevated thermal test of this caliper. The initial rotor temperature was 1,058°F, the clamping pressure was 440 psi, and the center-of-pad temperature initially rose to 565°F, as shown in the green traces in Figure 19. For comparison, Figure 19 also shows the data plot (red trace) for the third test run with the NMR1-LF brake linings. The initial center-of-pad temperature rise for the MH1-LR linings took 84 sec compared to 42 sec on the previous test with the NMR1-LF brake linings. The center-of-pad temperature started dropping as expected after the release of the initial brake pressure application, as shown in the close-up of the test run (near the 1.5-min point) with the MH1-LR brake linings in Figure 20. However, after the third application, the temperature again stayed uncharacteristically level; no further hydraulic applications were needed to hold 550°F for almost 6 min, as shown in Figure 19.

Since the condition of the brake linings appears to greatly affect the thermal loading of the caliper system, test results may be more consistent if brake linings with specific break-in conditioning are utilized for comparison on bench tests of complaint vehicle calipers. For example testing could be conducted with brake linings removed from an exemplar vehicle just after a standard burnish or after more extended mileage that may simulate more typical use.

This caliper was not disassembled and no inspection photographs or measurements of the bores are available. This testing was terminated when Workhorse agreed to recall the ZOPS brake calipers.

## 5.0 CONCLUSIONS

Based upon the inspections and tests of the four ZOPS calipers, reportedly from a 36-foot 2002 National RV Dolphin LX on a Workhorse W22 Chassis, the following conclusions are noted:

1) All four calipers showed signs of thermal events, including ruptured environmental boots and white ash on the boots and caliper housing. This damage may be explained by other foundation brake, antilock brake control unit, or caliper defects, but the vehicle was not available. Therefore, the inspection and tests were conducted on the calipers alone and a full troubleshooting evaluation of the brake system could not be performed.

2) The four calipers (8 bores) were tested for knockback and retraction. Only one bore of one caliper (Bore A of NRV1-2) had results different from a new 66-mm ZOHT caliper. The results from Bore B and the other three calipers were normal.

3) Without the original brake linings installed at the correct positions in each caliper, elevated thermal testing may not subject the caliper pistons to the same thermal loading as when the calipers were on the vehicle. Since the condition of the brake linings appears to affect the thermal loading of the caliper system, test results may be more consistent if brake linings with specific break-in conditioning, like a standard burnish, be utilized for comparison on bench tests of complaint vehicle calipers.

4) During some of these tests at elevated temperatures, the inner brake lining center of brake pad temperature continued to rise after the initial hydraulic pressure actuation had been released. Although the reason for this rise is not clearly understood, it seemed to be related to the brake linings (NMR1-LF) tested initially.

5) Testing was conducted at elevated temperatures (610°F +/-20°F) that exceeded the intended range of 550°F +/- 10°F. Although it would have been preferable to have conducted testing of the complaint calipers in this intended range, and then elevated the temperature further if the calipers were still operating normally, the result would probably have been the same. There were no instances observed during the bench tests where a piston seized in the bore of the four calipers tested.

6) Post-test disassembly of three of the calipers showed corrosion in the critical seal-land bore area. Measurements of the pistons at ambient temperatures indicated none were over the specified diameter. Measurement of the caliper bores, below the seal-land area, showed all were within specifications. However, all three disassembled calipers showed that the top of each caliper bore, at the seal-land area, was below the specified bore diameter. When the pistons were heated in an oven to about 257°F, a temperature found during previous testing to have penetrated to the level of the seal-land area, the piston-to-

bore clearance was found to have become an interference fit for five of the six pistons/bores measured.

# APPENDIX

## List of Items in the Appendix in Order of Appearance

**Figure 1 – National RV Calipers**

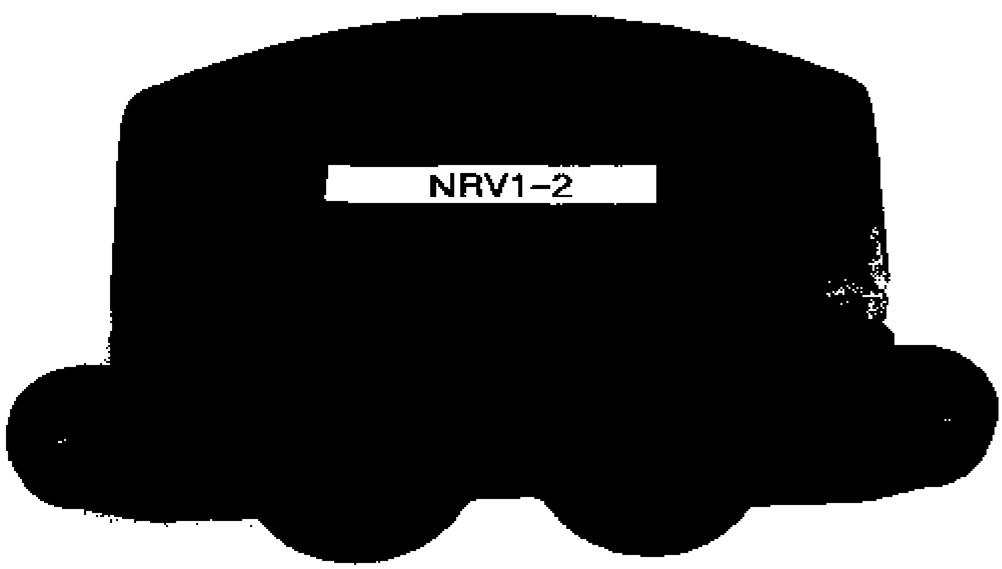


**Figure 2 – Some Ash on the Environmental Boots and Caliper Housing of Caliper NRV1-2**

**Figure 3 – Ruptured Environmental Boot and Ash on Caliper NRV1-2**

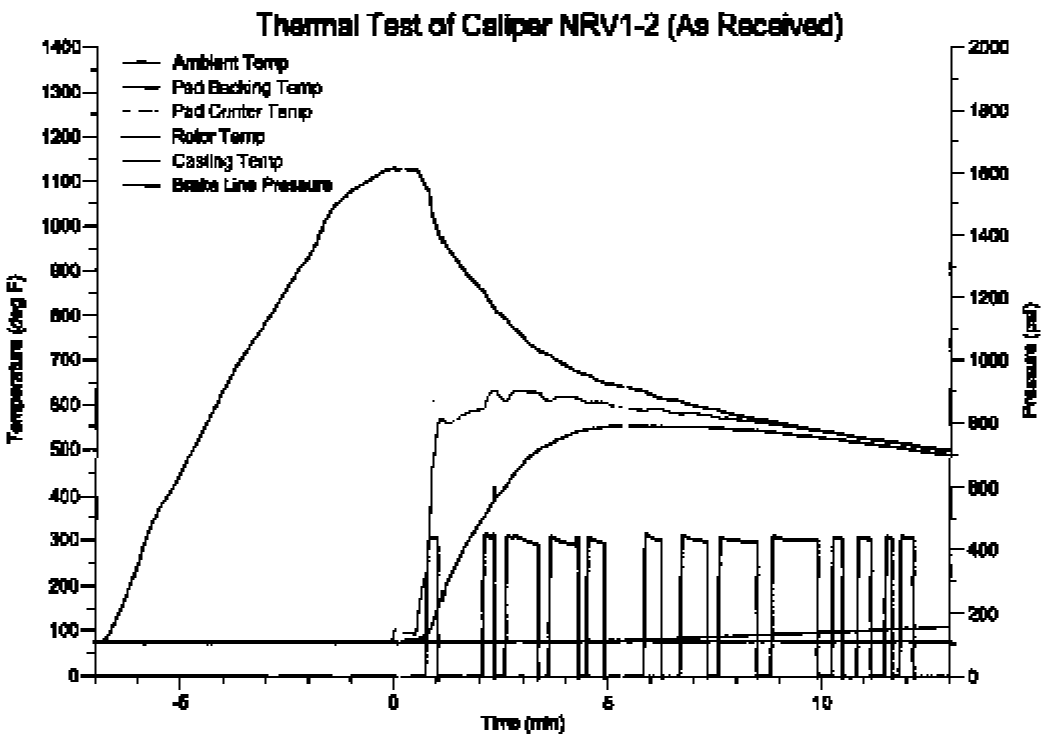


**Figure 4 - Results of the First Elevated Thermal Test of Caliper NRV1-2**

Note: Temperature continued to rise after releasing the initial hydraulic pressure application

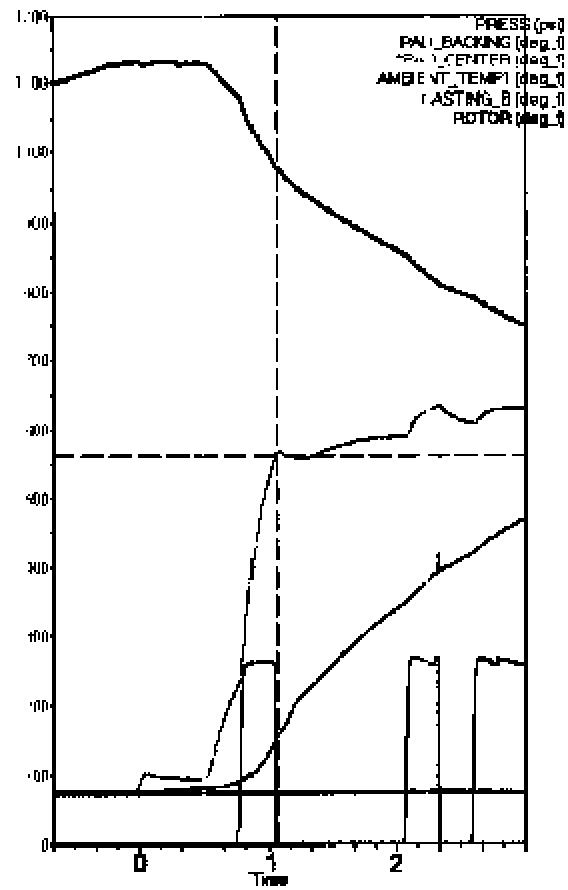


**Figure 5 – Close-up of Center-of-Pad Temperature (Green Trace) for Caliper NRV1-2**

Note: Temperature continued to rise after releasing the initial hydraulic pressure application

**Figure 6 –Part of Environmental Boot Attached to Piston A of Caliper NRV1-2**

Note: Sidewall Scoring from Bore A

**Figure 7 – Significant Corrosion on Seal Land Top Surface and Bore Face of Bore A of Caliper NRV1-2**

**Figure 8 – Rolled Hydraulic Seal on Bore B of Caliper NRV1-2**

**Table 1 – Calculated Piston Clearances in Caliper Bore**

| Measured Calipers | Measurements of Caliper Pistons and Bores at Ambient Temperature | | | | | | | | | | Measurements of Heated Pistons | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Piston Diameter | | Caliper Bore Diameter | | | | Calculated Piston Clearance | | | | Diameter of Piston Heat Soaked in Oven ([illegible]) | | Calculated Clearance of Heated Piston at Seal-Land Area | |
| | at Position of Bore Seal-Land | | Seal-Land Area (Top of Bore) | | Lower Bore | | Seal-Land Area (Top of Bore) | | Lower Bore | | | | | |
| | Piston A (in) | Piston B (in) | Bore A (in) | Bore B (in) | Bore A (in) | Bore B (in) | Bore A (in) | Bore B (in) | Bore A (in) | Bore B (in) | Piston A (in) | Piston B (in) | Bore A (in) | Bore B (in) |
| NRV1-1 | 2.5950 | 2.5930 | 2.5985 | 2.5970 | 2.6000 | 2.6000 | 0.0035 | 0.0040 | 0.0050 | 0.0070 | 2.5995 | 2.5985 | | |
| NRV1-2 | 2.5950 | 2.5940 | 2.5985 | 2.5980 | 2.6015 | 2.6010 | 0.0035 | 0.0040 | 0.0065 | 0.0070 | 2.5985 | 2.5995 | 0.0000 | [illegible] |
| NRV1-3 | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a |
| NRV1-4 | 2.5940 | 2.5950 | 2.5985 | 2.5980 | 2.6000 | 2.6000 | 0.0045 | 0.0030 | 0.0060 | 0.0050 | 2.5995 | 2.5985 | | |
| Bosch Specification | 2.5940 min to 2.5960 max | | 2.6000 min to 2.6020 max | | | | 0.0040 min to 0.0080 max | | | | n/a | | n/a | |

= value out of specification

= zero or negative clearance of a hot piston in an ambient temperature caliper

**Figure 9 – Ash on the Ruptured Environmental Boots and Caliper Housing of Caliper NRV1-4**

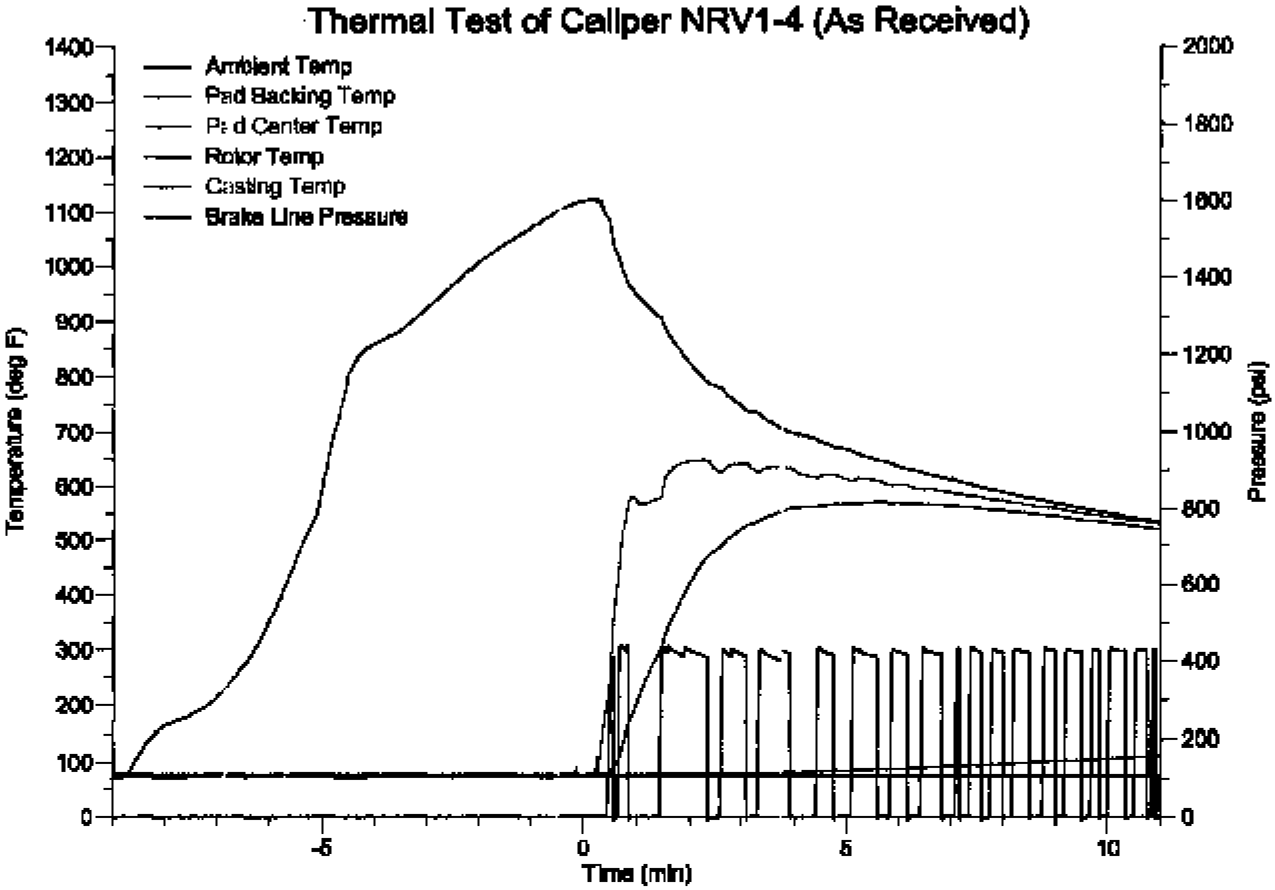


**Figure 10 - Results of the First Elevated Thermal Test of Caliper NRV1-4**

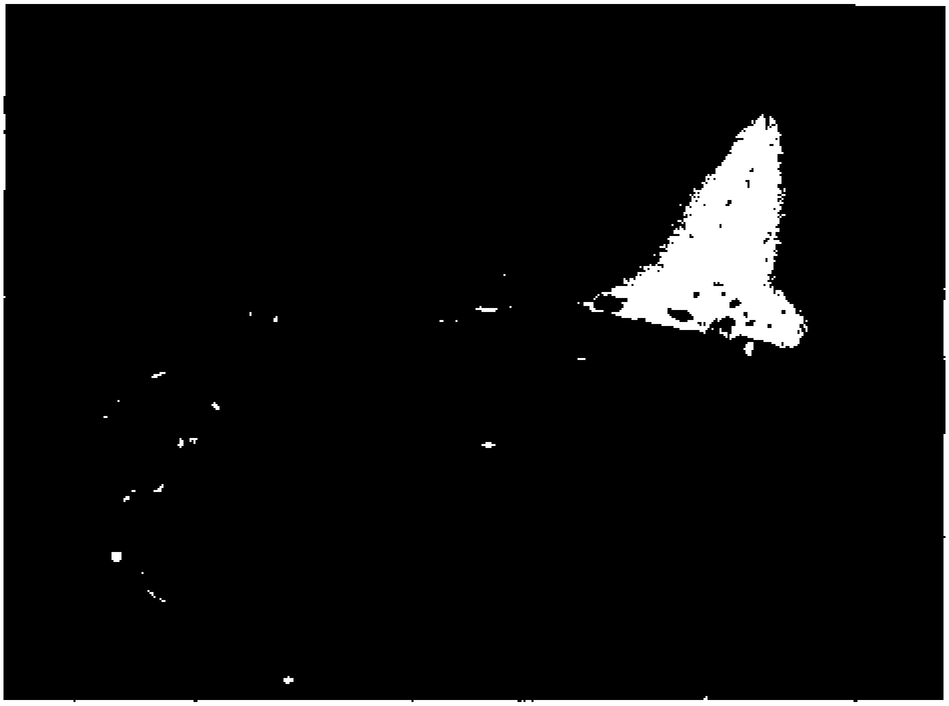

**Figure 11 – Corrosion on the Critical Seal Land Area of the Bore of Caliper NRV1-4**

**Figure 12 – Ash on the Ruptured Environmental Boots of Caliper NRV1-1**

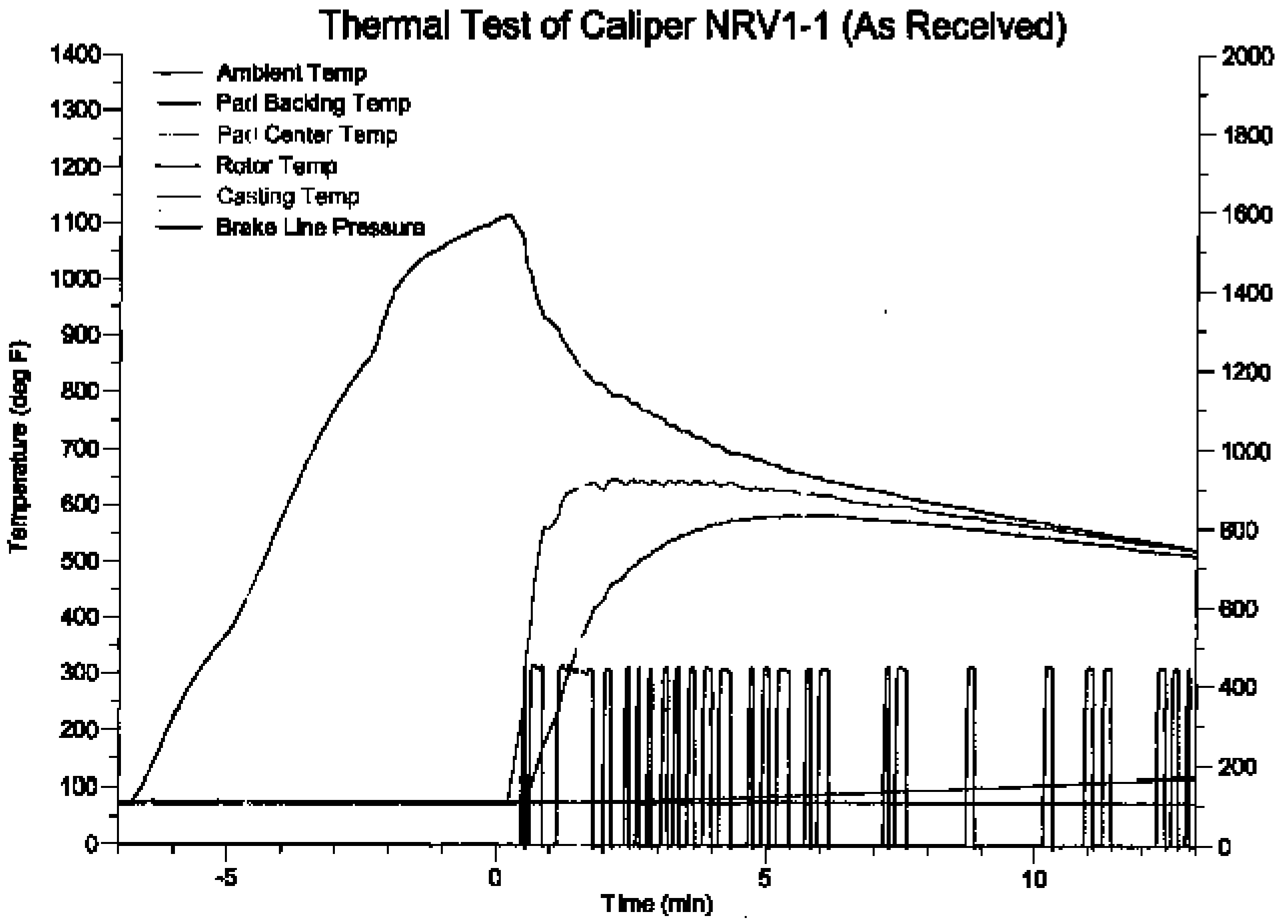


**Figure 13 – Results of the First Elevated Thermal Test of Caliper NRV1-1 – View 1**

Overall view of data plot

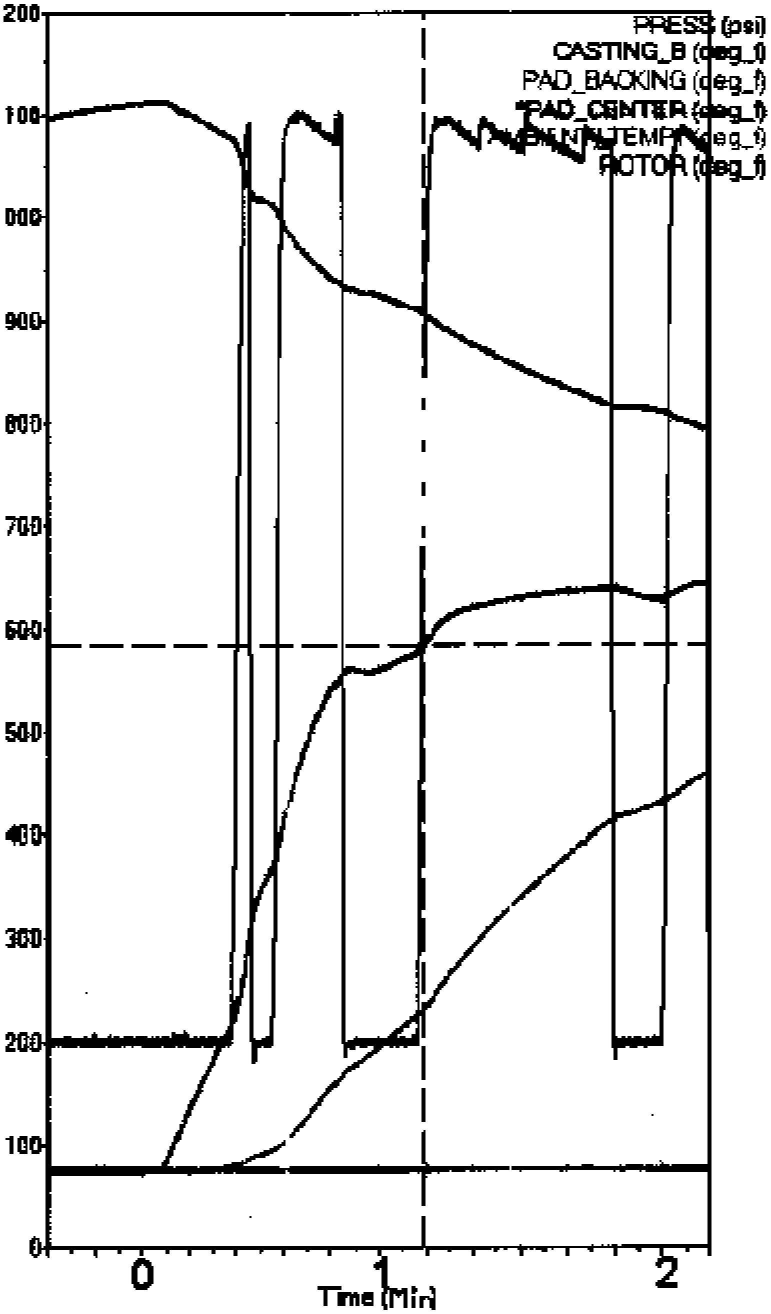


**Figure 14 – Results of the First Elevated Thermal Test of Caliper NRV1-1 - View 2**

Expanded view of data plot for initial pressure application

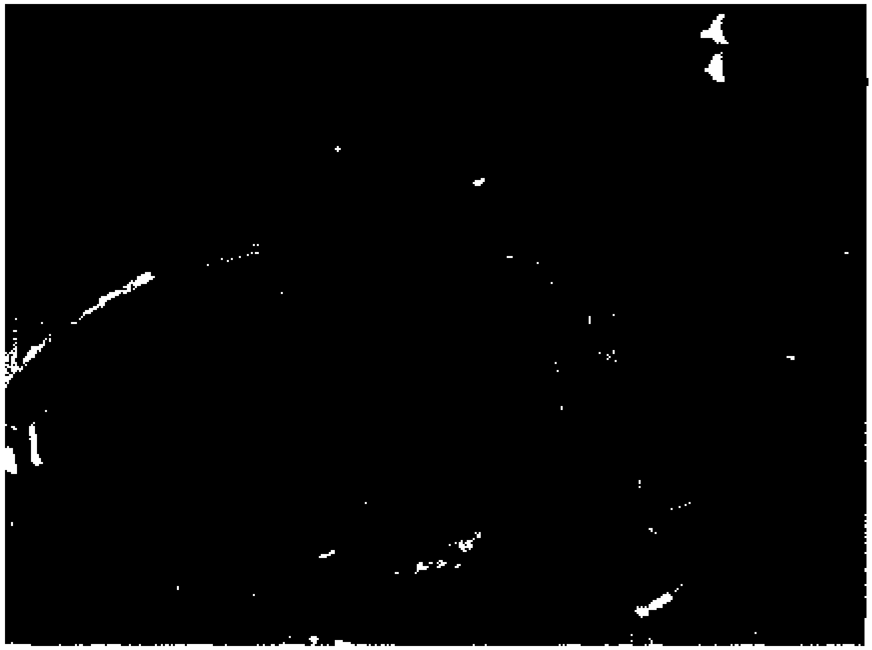

**Figure 15 – Corrosion on the Critical Seal Land Area of the Bore of Caliper NRV1-1**

**Figure 16 – Ash on the Ruptured Environmental Boots and Caliper Housing of Caliper NRV1-3**

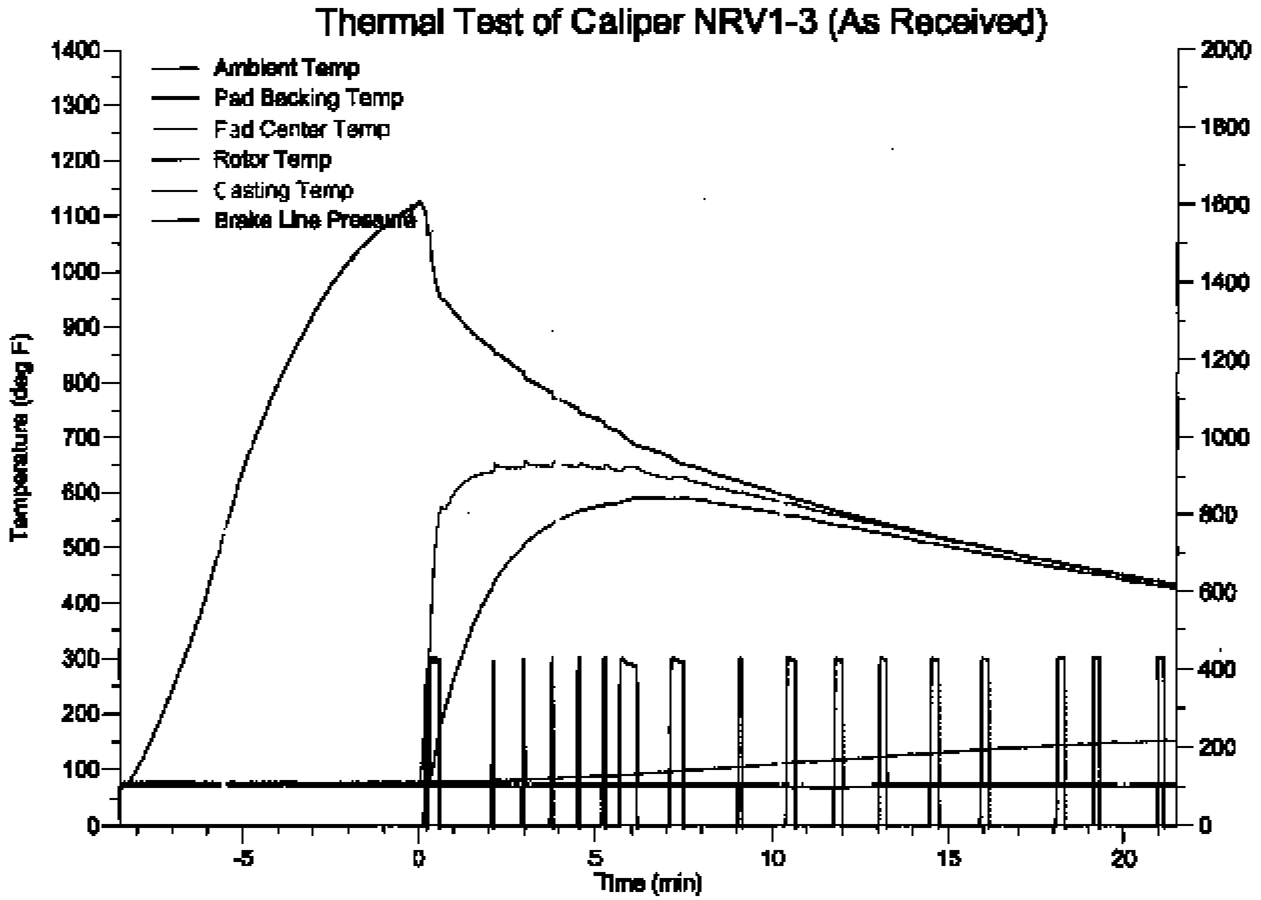


**Figure 17 – Results of the First Elevated Thermal Test of Caliper NRV1-1**

Note: Temperature continued to rise after releasing the initial hydraulic pressure application

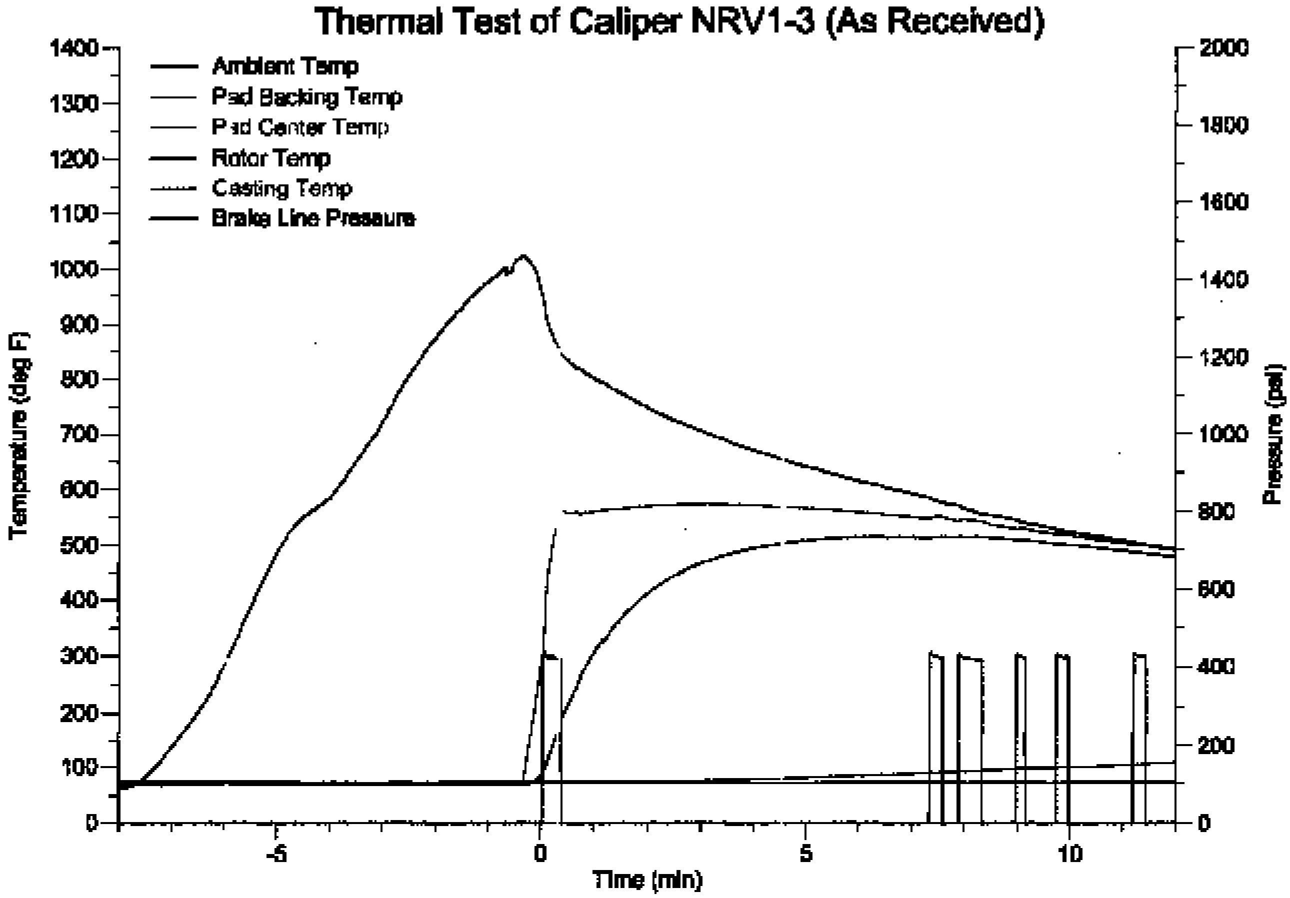


**Figure 18 – Results of the Third Elevated Thermal Test of Caliper NRV1-1**

Note: Target temperature of brake lining center-of-pad was 550°F +/- 10°F; The center-of-pad temperature remained at the target for almost 7 min before the second application of brake pressure

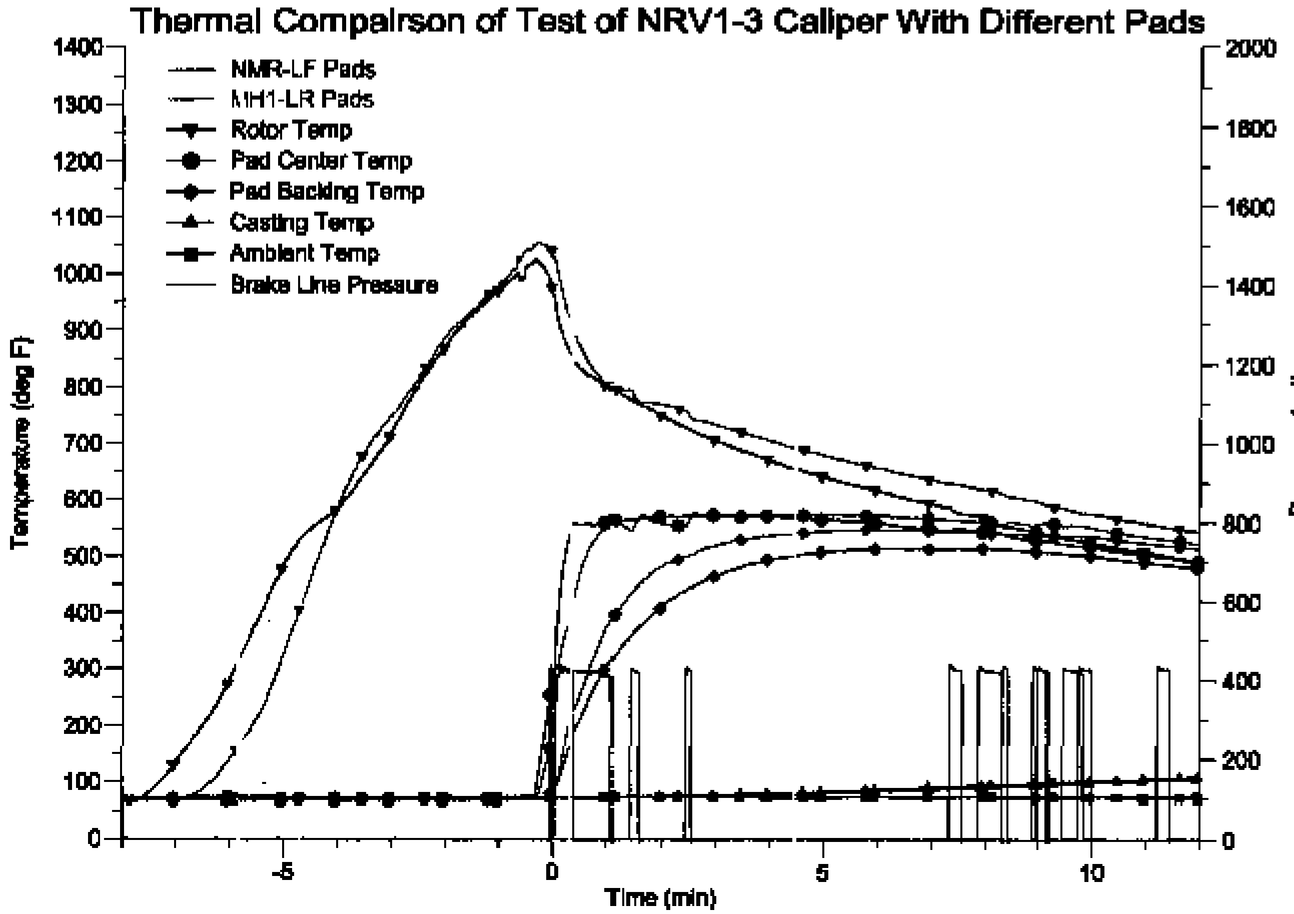


**Figure 19 – Superimposed Results from the Third and Fourth Tests on Caliper NRV1-3 Using Different Brake Linings**

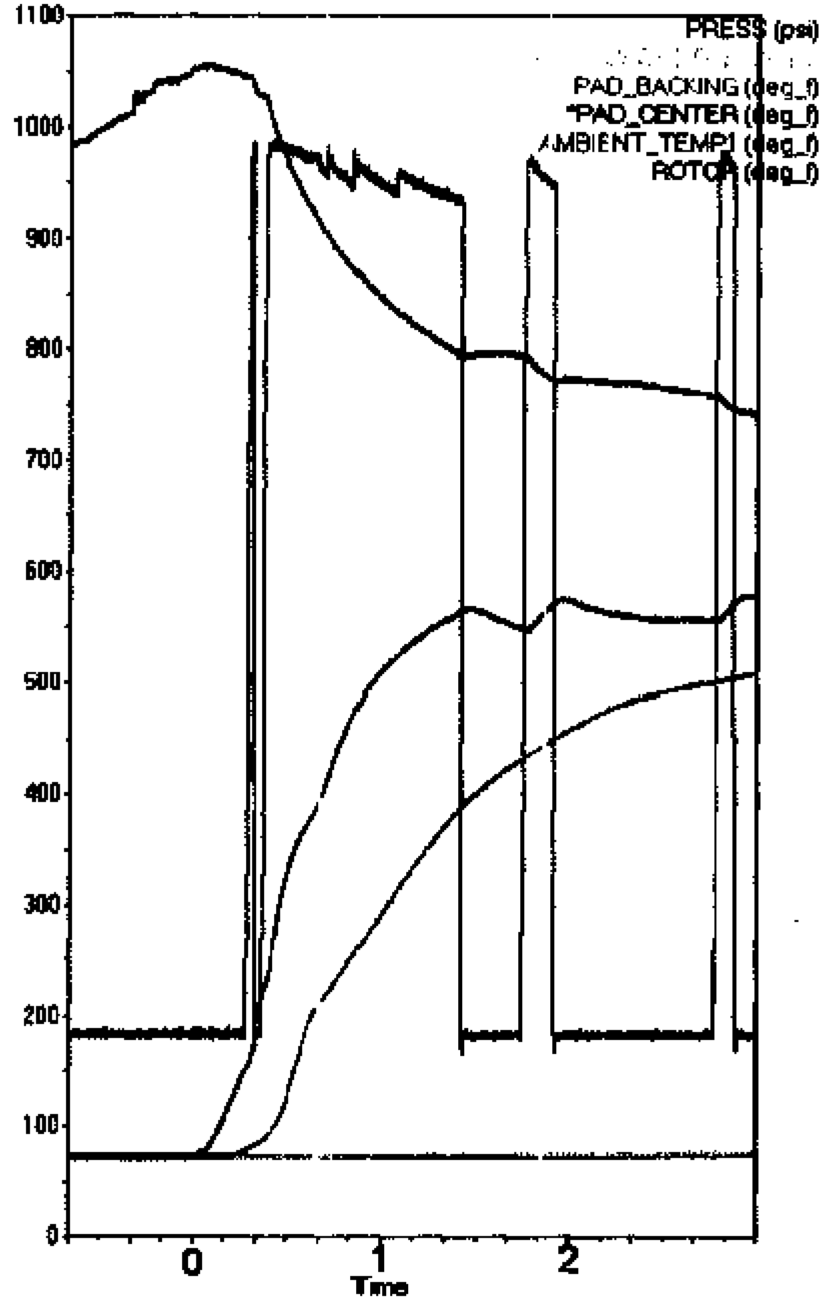


**Figure 20 – Close-up of the Initial Temperature Rise During the First Three Brake Pressure Applications for Tests with the MH1-LR Linings**

Note: Maximum pressure was about 440 psi (scale not shown); all temperatures on the same scale