Railway composition brake shoes laboratory performance tests: phase 1

Ringer, T. R.

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DIVISION OF MECHANICAL ENGINEERING

LABORATORY TECHNICAL REPORT

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RAILWAY COMPOSITION BRAKE SHOES
LABORATORY PERFORMANCE TESTS
PHASE I

T.R. RINGER

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DIVISION DE GÉNIE MÉCANIQUE

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LABORATORY PERFORMANCE TESTS

PHASE I

SUBMITTED BY / PRÉSENTÉ PAR: T. R. Ringer
LABORATORY HEAD / CHEF DE LABORATOIRE

AUTHOR / AUTEUR: T. R. Ringer

APPROVED / APPROUVÉ: E. H. Dudgeon
DIRECTOR / DIRECTEUR

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SUMMARY

The performance of a number of different composition brake shoes was investigated on a dynamometer to establish the friction coefficient for three load conditions and a range of wheel speeds with dry conditions, wet conditions and snow. With dry conditions the results obtained showed the classical reduction in friction coefficient as a function of increasing speed and load. Four different methods of applying water to the wheel tread were investigated. Spraying water on the wheel tread from air atomizing nozzles was found to result in more reproducible results than using single or multiple water streams. Hydroplaning was experienced with all composition brake shoes tested. At the highest speed, 50 mph (80 km/h) insufficient water was supplied during some tests to sustain hydroplaning.

Tests were conducted on one brake shoe under blowing snow conditions in the cold chamber at temperatures from -18 to -21°C. Hydroplaning at these temperatures was experienced when the wheel surface was at 0°C or higher.

1.0 INTRODUCTION

CP Rail requested the assistance of the National Research Council to determine the effects of adverse weather conditions, wet and snow, on composition brake shoe performance under winter conditions. The Low Temperature Laboratory was asked to carry out the simulated tests on brake shoes under controlled laboratory tests in a cold chamber.

Discussions were held with CP Rail personnel on possible test methods, and subsequently visits were made to two brake shoe manufacturers to examine their dynamometers and to discuss composition brake shoe performance in dry and wet conditions. As a result of this series of discussions a decision was made to design a new simple dynamometer test fixture that could be mounted in the large cold chamber at the Low Temperature Laboratory. The dynamometer was to be based on using a cylindrical wheel surface on which to test the brake shoes as opposed to the conical flanged wheel employed in service. Initially the proposal to use a cylindrical test wheel was the subject of considerable discussion, and agreement was obtained only after it was established that the brake shoe manufacturers in North America used cylindrical wheels for some of their test work.

In discussions with one of the brake shoe manufacturer's personnel, they indicated that there was considerable difficulty in getting accurate test data on composition brake shoes even under dry conditions, and that as many as ten repetitions of a test were conducted to obtain a reasonable average result. They stressed the necessity of obtaining an initial contact area of 80% by wearing in the shoes prior to performance tests, and also recooling the wheel and brake shoe to standard conditions between subsequent tests. One manufacturer had only conducted wet tests with a crude method of applying water to the wheel and did not believe that the laboratory test results could be applied to the field with any expectation of similar performance.

In reviewing the literature on brake shoe performance under adverse weather conditions, it was noted that only limited work had been conducted in North America. The AAR Report R-469[1] provided details on a single car field test with wet and dry conditions on both composition and cast iron brake shoes. The wet test was carried out with water supplied to each wheel in a single stream at the 12 o'clock position at a rate of 1-1/2 gallons per minute. The authors considered that this flow rate may have been excessive. The European standard UIC 541-4 OR[2] for testing composition brake shoes under wet conditions calls for water to be applied in six streams to the wheel tread surface at a rate of 14 ℓ/h. The water flow rate used in the AAR test was approximately 24 times that specified for the European standard, and thus probably was excessive. Neither test method, i.e. the single stream used by the AAR or the six stream method used in Europe, appeared to be representative of how water might be applied to braking in actual field service due to either rain or snow.

It was postulated that the water conditions during a rain storm or with a very wet roadbed would result in a water dispersion approaching cloud droplet size or under snow conditions that the undercarriage of a train would encounter small particle snow picked up from the roadbed.

The maximum liquid water content (LWC) of a cumulus cloud(3) may be greater than 2 g/m^3. If the water concentration in the air approaching the wheel is of this order, then at 30 mph and for a six-inch wide thirty six-inch diameter wheel the swept volume would result in an equivalent spray of 13.5 ℓ/h (225 ml/min.). At a higher, or lower, speed the equivalent spray required to simulate a 2 g/m^3 cloud would vary proportionately, e.g. at 50 mph (80 km/h) the flow rate would have to be 375 ml/min. In terms of blowing or drifting snow, the equivalent liquid water content within one metre of the surface(4) can be much greater than the maximum cloud LWC given above. Snow or ice build-up on a composition brake shoe surface will result in a water interface layer when the brake is engaged with the wheel tread. No information was located on composition brake shoe tests with a dynamometer under simulated snow conditions.

2.0 TEST FIXTURE

As a result of the various discussions held, it was agreed that a new and comparatively simple dynamometer would be designed for this test program. A D.C. motor of 150 HP was available, together with a suitable speed controller and a primary transformer to allow operation from a 600-volt 3-phase AC supply adjacent to the large cold chamber. Since it had been agreed that a cylindrical wheel would be used for the brake shoe friction tests, this ultimately led to the decision to use a special machined freight car wheel and axle set complete with roller bearings as the dynamic component. A suitable mounting frame based on rectangular steel tube sections was designed to mount the wheel set and the D.C. driving motor. A multi-vee power belt was chosen as the driving element between the electrical motor and the non-braking wheel of the wheel set. The wheel set was machined so that the one wheel for braking was carefully machined with a concentric cylindrical surface having a roughness not more than 20 microinches, while the second wheel was machined with multiple vee grooves for the belt drive.

Adjacent to the cylindrical wheel a pedestal was provided on the frame from which the brake shoe carrier was suspended. In line with the cylindrical wheel a bracket was provided on the supporting frame to allow mounting of the brake loading cylinder.

The mounting frame was fastened in position by four short structural columns bolted through the insulating floor penetrations to bedrock. A protective cover was designed for the multi-vee belt in order to keep water and snow off the drive surfaces during the simulated wet and winter conditions.

In order to provide a brake shoe loading force, it was convenient to use available plant air at 90 psi as the primary source. This air is instrument quality and moisture is not a problem even at low temperature. A reservoir and a pressure reducing regulator were provided in addition to a solenoid flow shut-off valve and an exhaust solenoid valve. An air cylinder, normally used on a transport truck, was chosen as the air operated brake loading cylinder. The actuator from the air cylinder was connected through a suitable compression load cell to the horizontal centreline of the brake shoe carrier. This carrier was suspended in the vertical direction through a suitable tension load cell from the structural pedestal on the supporting frame.

Figure 1 shows the dynamometer test fixture. In the left foreground is a flexible duct supplying filtered air to the motor ventilation fan. In the left background the protective cover over the multi-vee belt drive is shown, while in the right background the cylindrical wheel and the brake carrier support pedestal are located. The wheel drive system is shown in detail without the protective cover in Figure 2. In Figure 3 the load cells and the brake shoe fixture are shown in the retracted position. The brake shoe loading cylinder is shown in Figure 4. In order to measure the wheel set speed a slotted steel disc was fastened to the end cap on the wheel set, and a magnetic pulse sensor was mounted in close proximity as shown in Figure 5.

The wheel set for this dynamometer and the structural steel frame were machined and fabricated by CP Rail. The design and the final assembly were carried out by laboratory staff members.

The suspension method of the brake shoe carrier allowed for adjustment to compensate for variations in brake shoe thickness to ensure that when the brake shoe was engaged the tension load cell centreline was tangent to the wheel surface in the vertical plane. At the same time the compression load cell was required to be level in a horizontal plane and radial to the wheel set.

3.0 PREPARATION OF BRAKE SHOES

In order to reduce the time required to condition brake shoes for the tests, it was decided to machine the shoes to the wheel radius and then wear them into condition. On the first trial machining of brake shoes it was found that the distortion between machining and when fitted in the brake shoe carrier was such that considerable wear-in was required. A second trial machining using the brake shoe carrier as a fixture reduced the wear-in period; however, a considerable amount of time and effort was required to prepare each brake shoe. In order to improve the fitting of brake shoes and to reduce the time required with the dynamometer to wear in brake shoes, a special grinding fixture was fabricated. In this a brake shoe could be mounted in a carrier of similar dimensions to that used on the dynamometer and then ground to the wheel radius. This fixture reduced the time required for wear-in on the dynamometer, although this task continued to be a time consuming and tedious job for which considerable patience was needed to obtain an 80% contact fit on the wheel. The area of contact was initially determined by carbon tracing onto graph paper, although eventually it was done by direct measurement on the brake shoe.

After machining the brake shoes to profile, thermocouples were installed in the composition material. Either two or three copper-constantan thermocouples were installed in each shoe at a depth of one quarter inch (6 mm) below the surface and on the longitudinal centreline of the brake shoe. Figure 7 shows a two-thermocouple installation.

During wear-in of the brake shoes and also after brake shoe tests it was found necessary to clean the wheel carefully in order to maintain a 15 to 20 microinch surface. For this purpose a wheel dressing block was fabricated from hardwood and mounted on a brake shoe backing plate so it could be retained by the brake shoe carrier. On the face of the hardwood block a thin layer of high density foam rubber was bonded to provide resilient backing for the polishing sheets. Figures 8 and 9 show the dressing block.

During the wear-in of brake shoes on the dynamometer it was noted that both the wheel and the brake shoe temperatures increased rapidly during brake application, and if thermal damage of the brake shoe was to be avoided it was necessary to use short periods of brake application followed by cooling periods. The time interval for wheel cooling ultimately dictated the rate at which a brake shoe could be conditioned for testing.

4.0 DRY FRICTION TESTS

During the work on brake shoe conditioning it was established that the wheel set could be safely operated at speeds up to 60 mph equivalent. The speeds that were of interest and that were agreed to for the test program included 10 to 50 mph in 10 mph increments. Brake shoe loads classified as light, medium and heavy were to be applied with the heavy load to be limited by the capability of the drive. The heavy load limitation was established to be 2000 pounds while 1300 pounds was selected as the medium load and 800 pounds as the light load.

During the dry friction tests the test chamber temperature was maintained at +15°C and the wheel was recooled to +22°C or lower. The brake shoe recooled more rapidly than the wheel and thus was usually between 15 and 22°C at the start of each test. A small fan was used to blow air over the wheel during the recooling period.

Initially five tests were conducted at each test condition until it was established that three tests at any test condition would give a sufficiently accurate result. Each brake application was made for a 36-second period in order to limit the heat input to the wheel and brake shoe. This period of brake application reduced the hazard of thermal damage to the brake shoe. At the higher load and speed conditions the thermal input to the wheel and brake shoe from a 36-second brake application was such that recooling the wheel required almost one hour.

The procedure used during the dry friction tests was as outlined below. The pressure regulating valve on the compressed air supply to the brake cylinder was adjusted to the required value for the load condition. The dynamometer motor was energized and the wheel speed was stabilized at the required speed. The brake was applied for a 36-second period during which time the output from the load cells and the thermocouples was recorded by analog type instruments. The friction coefficient was determined from the average value of the radial and tangential forces during the last 24 seconds of the test run.

All of the dry and wet friction tests conducted during phase 1 are listed in Table I, which provides data on the brake shoe tested, the type of test (i.e. either dry or wet conditions), if wet the water supply system used, the range of water supply investigated, load range and speed range.

For the various brake shoes supplied by CP Rail, only the composition brake shoes identified as C1, C2 and C4 were tested at all five speeds and three load conditions. All other brake shoes were tested under dry conditions for fewer tests and only at a limited number of test conditions.

Table II summarizes the results of the dry friction tests on the various brake shoes tested. The results obtained showed the classical reduction in friction coefficient as a function of increasing speed and brake shoe force. Of the North American manufactured brake shoes, the "C" category showed the largest change in friction coefficient as a function of speed. The one brake shoe not manufactured in North America, category X1, was consistently higher in friction coefficient than all other brake shoes except at the high speed, high load condition where the friction coefficient was similar in value.

5.0 WET FRICTION TESTS

The review of literature had disclosed that at least three methods of applying water to the wheel tread had been tried by different investigators. As noted previously, the AAR had employed a simple tube providing water in a single stream to the wheel surface at a flow rate of 1-1/2 gallons per minute. The UIC specification 541-4 OR requires the supply of water at 14 ℓ/h from a six-orifice bar mounted at the 12 o'clock position. A constant head (1.8 m) water tank is used so that the water issues from the 0.5 mm holes as a steady stream rather than as droplets. In order to simulate both of these methods a 5/16-inch internal diameter copper tube was mounted at the 11 o'clock position (see Figure 10), while a spray bar similar in design to that outlined in the UIC specification (see Figure 18) was mounted at the 12 o'clock position (see Figure 11).

While this equipment allowed for duplication of tests conducted elsewhere, there was considerable doubt that these test methods were comparable with the wet conditions that might exist at the undercarriage of railcars. It was decided to employ a water spray system of the same type used for cloud simulation in an icing wind tunnel in the Laboratory, of which a spare was available. The droplet spray from these nozzles had been well investigated and it was known that the spray produced was a reasonable simulation of the natural cloud droplet spectrum. For given water flow rates the required air pressure at the atomizing nozzle to produce 20 μm median volume diameter (MVD) droplets had been established (see Figure 17). This assembly had a maximum calibrated flow capacity of 400 ml/min. or 24 ℓ/h, which was considered adequate when compared with the flow rate for the UIC system. The icing spray bar (ISB) was mounted at the 6 o'clock position so that the wheel travelled 270° from the spray to the brake shoe. This position was chosen on the basis that water that did not impinge on the wheel and cling would be drained away by gravity or centrifugal force.

Subsequent to the decision to employ a spray method based on icing cloud simulation, a reference was located[5] showing that British Rail Research and Development Division had used a spray system on composition brakes at flow rates up to 1.6 ℓ/min. Following some of the initial tests with water sprays it was decided to add a fourth method. This system was composed of a single spray nozzle of similar design to those used in the icing spray bar with provision for mounting at the 12 o'clock position. This was designated S-1/4 J.

The three methods, used elsewhere, of applying water to the wheel tread for braking tests had used widely different rates of water flow, i.e. 1-1/2 gallons per minute (5,678 ml/min.) by the AAR, 1.6 ℓ/min. (1600 ml/min.) by British Rail, and 14 ℓ/h (233 ml/min.) with the UIC method. Accordingly, a large number of tests were conducted to establish what flow rate should be used with the ISB system for various speeds and loads. The first wet tests conducted were 36 seconds duration and the water flow rate was increased sequentially from 0 to 225 ml/min., during which the friction coefficient decreased as an inverse function of water supply.

Figure 19 is a plot of the test results for tests 50 to 68 inclusive, conducted at a wheel speed of 20 mph and a brake shoe load of 800 pounds. For tests 69 to 71 the speed was increased to 50 mph, the load to 2000 pounds, while the water flow was maintained at 225 ml/min. The friction coefficient derived for these tests ranged from a low of 0.16 to 0.27 showing that only partial hydroplaning was taking place at the high load and high speed condition. At the conclusion of test 71 the brake shoe was examined and thermal cracks were observed. These thermal cracks were photographed and are shown in Figures 15 and 16.

The previously conducted wet test was repeated to determine if the thermal cracks showed any significant change in performance. In addition, it was decided to conduct the wet tests first by increasing the water supply and then by decreasing the water supply sequentially. Tests 73 to 103 were conducted at 20 mph and at a brake shoe load of 800 pounds, the results of which are given in Figure 20.

Due to the thermal damage of C1, a second brake shoe of the same type was prepared by wearing in and by conducting a full dry friction test series in order to go ahead with the determination of the water supply to use with the ISB system. Tests 151 to 214 investigated the wet performance of brake shoe C4 over a range of 10 to 50 mph and the three brake shoe load conditions with increasing test time durations and increasing water supply. The water supply was finally increased to 400 ml/min. and the test duration to 4 minutes. Two of the tests in this series were conducted at above normal brake shoe loads. Test 209 was conducted at 50 mph with a 3000-pound brake shoe load for which the friction coefficient was 0.012, while test 210 was conducted at 50 mph with a 4800-pound brake shoe load resulting in an estimated friction coefficient of 0.002.

Following the establishment of the water flow requirements for the ISB system, the simple copper tube water supply system was evaluated using the 400 ml water supply rate previously established as being adequate to ensure hydroplaning over the speed and load range to be investigated. The performance of the dynamometer, the spray water supply system, the instrumentation, and the brake shoe was first verified by tests 217 to 226 with the ISB at 400 ml/min. Tests 227 to 257 were conducted with the copper tube except for nine dry check tests and three verification tests with the ISB. The results of these tests are given in Table III. A range of friction coefficient values are given for most of the speed and load conditions tested. The variation in friction coefficient during a given test was so great that this method of applying water was abandoned. During the last two tests of the copper tube system, steam was noted to be issuing from the brake shoe-wheel interface; however, on conducting two no-flow reference tests and two wet tests with the ISB system the brake shoe performance was normal.

Tests 258 to 272 investigated the wet performance of brake shoe C4 with the modified UIC water supply system. Three load conditions and five speed conditions were used with a flow rate of 233 ml/min. The results of this test series are given in the wet test summary, Table IV.

Wet tests were subsequently carried out with three water application methods on the C2, C4, C6, C3, A2, and the T1 brake shoes, the results of which are summarized in Table IV. The X1 brake shoe was tested under wet conditions with only the ISB system and the results are given in Table IV.

The wet tests showed that all of the composition brake shoes will hydroplane if sufficient water is supplied to the wheel and brake shoe. Of the various methods employed, the icing spray bar (ISB) at a flow rate of 400 ml/min. mounted at the 6 o'clock position produced the most consistent results. With the UIC system there is a question of whether sufficient water is supplied at the higher speeds or whether the manner of supplying it is satisfactory for a cylindrical wheel.

During test 317 at a 2000-pound brake shoe force and at 40 mph, the coefficient of friction varied between 0.1 and 0.28. On completion of this test the test equipment and the wheel was examined. A number of circumferential heat streaks were found on the wheel (see Figure 14) that were centered between the individual water jets. The water on the surface of the revolving wheel had a wave pattern with the wave crests in line with the water jets and the wave valleys in line with the heat streaks. It should be noted that this test was conducted at 40 mph, and subsequently this speed was abandoned as a test condition because of vibration of the test fixture and wheel set. The vibration at this speed may have been a contributing factor to the results obtained. The wave pattern observed on the cylindrical wheel should not exist on a conical wheel due to the transverse accelerating force resulting with the water film.

The single nozzle at the 12 o'clock position was not evaluated to the same extent as the ISB, and on some of the tests conducted with this nozzle a question exists whether sufficient water was supplied to ensure hydroplaning.

The question exists as to whether the quantity of water applied to the wheel and brake shoe is realistic and relevant to possible field conditions. Ultimately this will only be resolved by a series of measurements under field conditions. The results obtained with the ISB at flow rates up to 400 ml/min. are encouraging from the aspect of simulation, and when compared with other test methods used in the UK and Europe the quantity of water is in the same order of magnitude.

6.0 SIMULATED SNOW TESTS

Snow has been manufactured in the large cold chamber as required for test work by the use of compressed air-water atomizing nozzles of a type similar to those used for icing tunnel work. Droplets in the approximate range of 20 to 50 μm are ejected into a cold air stream using external mixing nozzles. In order to project the drops further than would result from the momentum imparted by the nozzle, the spray nozzle arrays are mounted on the front surface of variable speed wind chill fans. At 20 mph (32 km/h) the droplets can be projected the length of the cold chamber, 50 feet (15 m). The wetness of the snow can be varied somewhat by changing the air-water ratio or the temperature of the cold chamber. In order to make a dry snow a high air-water ratio is used at a low ambient temperature. The manufactured snow is essentially only a frozen water drop that remains spherical if small in diameter, but may be distorted if larger in diameter due to pressure causing extrusion of water from the interior through cracks in the ice shell. Two of the snow making nozzle arrays are shown mounted on the wind chill fans in Figure 13.

For the brake shoe test only one snow making array and fan was employed. The first snow making test carried out was of an exploratory nature. It was proposed to heat the wheel and brake shoe by successive brake applications in a cold ambient temperature before blowing snow at the test fixture. Since the brake shoe cools at a faster rate than the wheel, it was anticipated that some of the snow striking the warm wheel would melt and a mixture of snow and water would be deposited on the brake shoe in the retracted position by centrifugal force, thereby forming a frozen deposit on the colder shoe.

The dynamometer was cooled to -22°C during an overnight period. The wheel and brake shoe were warmed to above freezing by four brake applications at an 800-pound force at a speed of 20 mph. Snow making was then started at an initial flow rate of 0.4 gpm during which two brake applications were made, resulting in a reduction in the friction coefficient of approximately 20%. Inspection of the brake shoe did not disclose any ice or snow build-up. The flow rate to the snow making nozzles was increased to 0.8 gpm and with successive brake applications the friction coefficient decreased until a value of 0.036 was obtained at a brake shoe force of 1475 pounds and a value of 0.031 at a bsf of 2115 pounds. The snow making continued for 36 minutes while the dynamometer speed was maintained at 20 mph.

Although the test was not a success in showing the deposit of snow and ice on the brake shoe and the development of a frozen mass at that location, it disclosed an unanticipated mode of failure by the development of a water film from impacting snow on a warm wheel of sufficient thickness to result in hydroplaning at a below freezing ambient temperature. The surface temperature of the wheel was above freezing at the completion of the 36-minute snow test, although the brake shoe was below freezing. The estimated rate of snowfall near the wheel was 0.5 inch (12.5 mm) per hour. The amount of snow that impacted the wheel during this test is of interest and can only be estimated from an approximation based on the area of the projected jet from the fan and the frontal area of the wheel. At the distance between the wind chill fan and the wheel axle it is estimated that the jet from the fan had expanded to a diameter of approximately six feet; thus, based on area ratios, the maximum rate of impingement would have been 160 g/m at the 0.8 gpm water flow rate.

The brake test with snow was repeated a second time with the ambient temperature at -18°C, the wheel speed at 20 mph (32 km/h) and a brake shoe load of 800 pounds. Five dry brake applications were made to heat the wheel to an above freezing temperature prior to starting the snow simulation. Two minutes after the snow was started the next brake application showed a reduction in the braking force of more than 30%. By eight minutes after snow making started, the friction coefficient had dropped to 0.04 and the brake was held engaged. At 19 minutes from the start of the test the coefficient of friction increased to 0.34, falling to 0.2 at 20 minutes and back to 0.04 at 21 minutes.

It was noted that the wheel temperature had dropped below freezing at approximately 19 minutes and after the higher friction for two minutes had increased to above freezing. Low friction persisted until the 31-minute mark, at which time the wheel dropped below freezing and the friction increased and stayed high for eight minutes during which the wheel temperature increased to above freezing, and at the 40-minute mark the friction coefficient decreased to 0.06. The test was terminated at this time.

This test had demonstrated that hydroplaning at low temperatures was a repeatable test condition and in addition, if the wheel temperature fell to below freezing and the water film from impacting snow disappeared, that dry friction would develop at normal friction coefficients, the heat from which would raise the wheel temperature and ultimately restore hydroplaning from the impacting snow. This second test was carried out at the 0.8 gpm water flow rate to the snow nozzles, and while hydroplaning had been demonstrated, the question existed of whether the quantity of snow was adequate.

A third snow test was scheduled with the initial ambient temperature at -21°C and the water flow rate to the nozzles increased to 1.2 gpm. The brake shoe force was maintained at 800 pounds while the wheel speed was increased to 30 MPH (48 km/h). Five dry brake shoe applications were made to increase the wheel temperature to above freezing prior to starting the water flow for snow making. At the 25-minute mark, 7 minutes after snowfall started the friction coefficient decreased to 0.041 and remained low until the wheel temperature dropped below freezing at 46-1/2 minutes. The friction coefficient increased for approximately 1-1/2 minutes before the wheel temperature resulted in the restoration of hydroplaning at the 48-minute mark. Hydroplaning continued until the test was terminated at the 74-minute interval.

The rate of snow impacting the wheel in snow test three would have been 240 g/m. As noted for the wet tests, this value is only slightly greater than that required to simulate a 2 g/m^3 cloud, whereas much higher concentrations can be experienced with drifting snow. The provision of snow during this test appeared to be adequate in that hydroplaning was established within seven minutes from starting. The hydroplaning continued for 39-1/2 minutes out of a 41-minute test. It was restored within 1-1/2 minutes when the wheel temperature decreased below freezing.

7.0 CONCLUSIONS AND RECOMMENDATIONS

It has been demonstrated that composition brake shoes will hydroplane in wet conditions if the water is supplied to the wheel at an adequate rate and in a dispersed mode. Of four methods of applying water the system based on a cloud simulating spray bar mounted at the 6 o'clock position was investigated most extensively and was found to be the most suitable for simulation of the hydroplaning mode of faiure.

All of the composition brake shoes tested showed hydroplaning performance. There is a question of whether the rates of water application to the dynamometer wheel are realistic or relevant to field conditions. It has been postulated that the quantities of water sprayed relate to cloud liquid water contents. This question should be resolved by field measurements of water concentrations and droplet size under trains.

During snow simulation tests at temperatures of approximately -20°C when the wheel had been heated by previous brake applications, hydroplaning was experienced at snow application rates well within that which snould exist under natural conditions from train drag or blowing snow. This mode of failure may be expected to exist with a ground cover of snow and speeds high enough to result in train drag snow conditions.

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TABLE I

DRY AND WET FRICTION TESTS

Test No.	Brake Shoe (Code)	Condition	Speed Range (mph)	Load Range	Spray Type (ml/m)
1- 50	C1	Dry	10-50	L M H	-
51- 65	C1	Wet	20	L	ISB 45/225
66- 68	C1	Wet	20	H	ISB 225
69- 71	C1	Wet	50	H	ISB 225
72	C1	Dry	20	H	
73- 75	C1	Dry	20	L	
76-102	C1	Wet	20	L	ISB 30/225
103	C1	Dry	20	L	
104-150	C4	Dry	10-50	L M H	
151-214	C4	Wet	10-50	L M H	ISB 45/400
215-216	C4	Dry	20	L	
217-226	C4	Wet	10-40	L M H	ISB 400
227-228	C4	Wet	10-20	L	Tube 400
229	C4	Dry	20	L	
230	C4	Wet	20	L	Tube 400
231	C4	Dry	20	L	
232	C4	Wet	20	L	ISB 400
233	C4	Dry	20	L	
234	C4	Wet	20	L	Tube 400
235-240	C4	Wet	10-50	L	Tube 400
241-243	C4	Dry	10-20	L M	
244-247	C4	Wet	20-50	M	Tube 400
248	C4	Dry	50	M	
249-253	C4	Wet	10-50	H	Tube 400
254	C4	Dry	20	H	
255	C4	Wet	20	H	ISB 400
256	C4	Dry	20	H	
257	C4	Wet	40	L	ISB 400
258-272	C4	Wet	10-50	L M H	UIC 233

TABLE I (cont'd)

DRY AND WET FRICTION TESTS

Test No.	Brake Shoe (Code)	Condition	Speed Range (mph)	Load Range	Spray Type (ml/m)
273-315	C2	Dry	10-50	L M H	
316-331	C2	Wet	10-50	L M H	UIC 233
332-346	C2	Wet	10-50	L M H	ISB 400
347-349	C4	Dry	20	L	
350-364	C4	Wet	10-50	L M H	S 1/4 J 45
365	C4	Dry	10	L	
366	C4	Wet	10	Aborted	
367-381	C4	Wet	10-50	L M H	S 1/4 J 90
382	C4	Wet	50	H	S 1/4 J 45
383	C6	Dry	10	L	
384-398	C6	Wet	10-50	L M H	S 1/4 J 90
399-405	C3	Dry	10-50	L M H	
406-412	C3	Wet	10-50	L M H	S 1/4 J 90
413-419	A2	Dry	10-50	L M H	
420-427	A2	Wet	10-50	L M H	S 1/4 J 90
428-435	T1	Dry	10-50	L M H	S 1/4 J 90
436-444	T1	Wet	10-50	L M H	S1/4J 90-280
445-461	C2	Wet	10-50 *	L M H	S1/4J 90-280
462-473	C2	Wet	10-50 *	L M H	ISB 400
474-485	T1	Wet	10-50 *	L M H	ISB 400
486-497	A2	Wet	10-50 *	L M H	ISB 400
498-509	A2	Wet	10-50 *	L M H	UIC 233
510-521	T1	Wet	10-50 *	L M H	UIC 233
522-524	A2	Wet	10-30-50	L	UIC 233
525-560	X1	Dry	10-50 *	L M H	
561-572	X1	Wet	10-50 *	L M H	ISB 400

* Tests were not conducted at 40 mph due to vibration at that speed.

TABLE II

SUMMARY OF DRY FRICTION TESTS

BSF	Brake Shoe	Speed (mph) 10	20	30	40	50
800	C1	–	.397	.345	.342	.338
800	C2	.451	.438	.351	.318	.290
800	C3	.455	–	.37	–	.34
800	C4	.439	.417	.373	.349	.342
800	A2	.395	–	.391	–	.382
800	T1	.365	–	.34	–	.331
800	X1	.56	.44	.39	–	.37
1300	C1	–	.376	.332	.314	.312
1300	C2	.437	.424	.340	.311	.306
1300	C3	–	–	.334	–	–
1300	C4	.439	.399	.345	.324	.315
1300	A2	–	–	.382	–	–
1300	T1	.38	–	.328	–	–
1300	X1	.53	.40	.41	–	.355
2000	C1	.37	.33	.30	.30	.30
2000	C2	.444	.437	.340	.307	.305
2000	C3	.440	–	.320	–	.309
2000	C4	.48	.387	.331	.303	.301
2000	A2	.396	–	.358	–	.268
2000	T1	.371	–	.317	–	.310
2000	X1	.48	.41	.39	–	.32

TABLE III

SUMMARY OF WET FRICTION TESTS - COPPER TUBE
BRAKE SHOE C4

	Speed (mph)				
BSF	10	20	30	40	50
800	.068	.340	.420	.357	.324
	.054	.210	.130	.261	.042
		.033	.063	.054	
1300		.293	.051	.102	.076
		.051	.280	.331	.293
			.083	.015	.140
2000	.360	.144	.161	.281	.294
	.037	.091	.049		.213

TABLE IV

SUMMARY OF WET TESTS

BSF	Brake Shoe	Water System	Speed (mph) 10	20	30	40	50
800	C4	ISB 400	.078	.076	.047	.053	.038
	C4	UIC/233	.129	.086	.06	.043	.043
	C4	S 1/4 J 90	.105	.053	.044	.036	.036
	C2	ISB 400	.118	.050	.042	.046	.154
			(.073)	(.034)	(.030)		(.030)
	C2	UIC 233	.043	.03	.026	.064/ .009	.013
	C2	S1/4J 90/280	.119	.060	.038	.034	.060
	A2	ISB 400	.034	.013	.013	-	.013
	A2	UIC 233	.037	.008	.012	-	.008
	A2	S 1/4 J 90	.064	-	.013	-	.017
	T1	ISB 400	.047	.034	.030	-	.030
	T1	UIC 233	.017	.017	.021	-	.026
	T1	S1/4J 90/90	.093	.054	.054	-	.218*
	X1	ISB 400	.225	.047	.038	-	.038
1300	C4	ISB 400	.071	.033	.028	.025	.028
	C4	UIC 233	.112	.052	.047	.035	.030
	C4	S 1/4 J 90	.076	.033	.020	.018	.018
	C2	ISB 400	.140	.076	.046	-	.036
	C2	UIC 233	.064	.051	.033	.041	.031
	C2	S1/4J 90/280	.172	.091	.071	-	.056
	A2	ISB 400	.022	.007	.007	-	.007
	A2	UIC 233	.035	.008	.005	-	.008
	A2	S 1/4 J	-	-	.013	-	-
	T1	ISB 400	.033	.025	.025	-	.025
	T1	UIC 233	.025	.018	.017	-	.020
	T1	S 1/4 J 90	-	-	.127*	-	-
	X1	ISB 400	.062	.029	.026	-	.034/ .195*

TABLE IV (cont'd)

SUMMARY OF WET TESTS

BSF	Brake Shoe	Water System	Speed (mph) 10	20	30	40	50
2000	C4	ISB 400	.041	.022	.018	.018	.018
	C4	UIC 233	.062	.034	.029	.026	.026
	C4	S 1/4 J 90	.043	.015	.012	.012	.012
	C2	ISB 400	.177	.049	.029	–	.023
	C2	UIC 233	.17	.08	.07	.166/ .1/.283#	.20
	C2	S 1/4 J 280	.15	.045	.037	–	.023
	A2	ISB 400	.022	.005	.005	–	.007
	A2	UIC 233	.023	.006	.005	–	.008
	A2	S1/4J 90/180	.032	–	.015	–	.268/ .020§
	T1	ISB 400	.033	.022	.025	–	.032
	T1	UIC 233	.025	.018	.020	–	.027
	T1	S1/4J 90/280	.066	–	.048/ .075	–	.125*
	X1	ISB 400	.101	.034	.030	–	.161*

\# Critical speed of rig ?

§ Higher value at 90 ml/min. & lower at 180 ml/min.

* Critical water amount ?

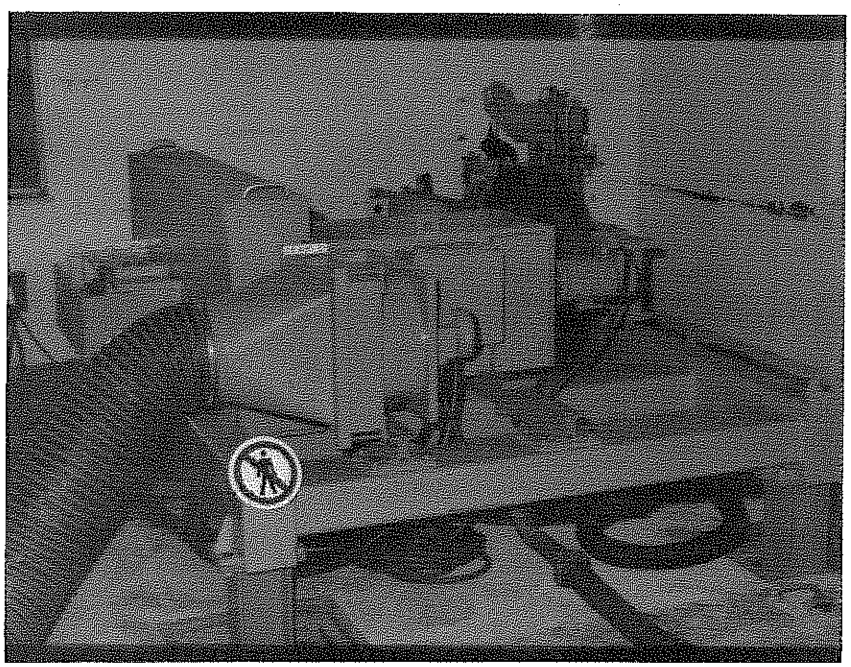

FIG. 1 DYNAMOMETER TEST FIXTURE

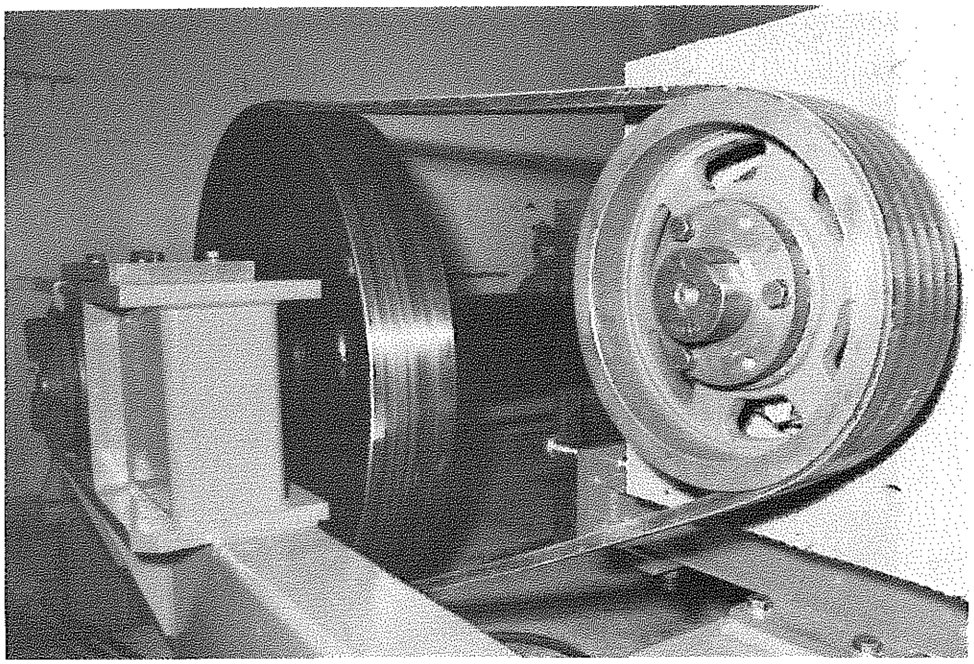

FIG. 2 WHEEL DRIVE SYSTEM

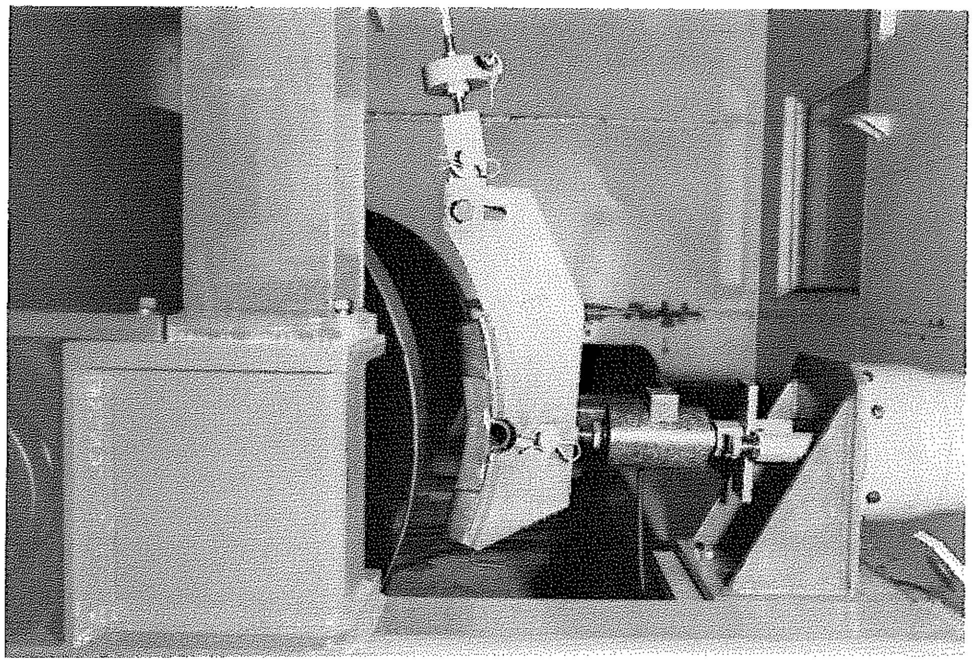

FIG. 3 LOAD CELLS AND BRAKE SHOE FIXTURE

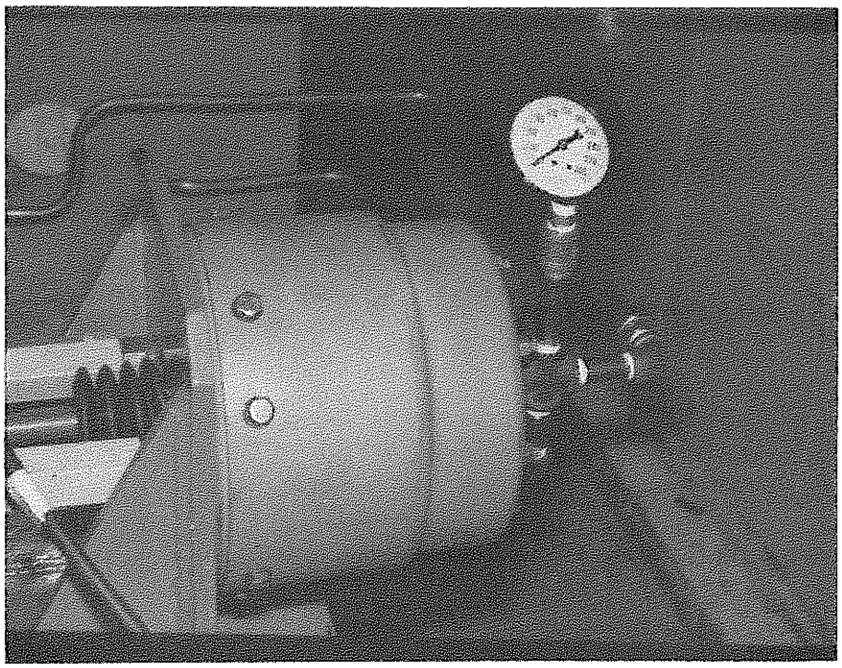

FIG. 4 BRAKE SHOE LOADING CYLINDER

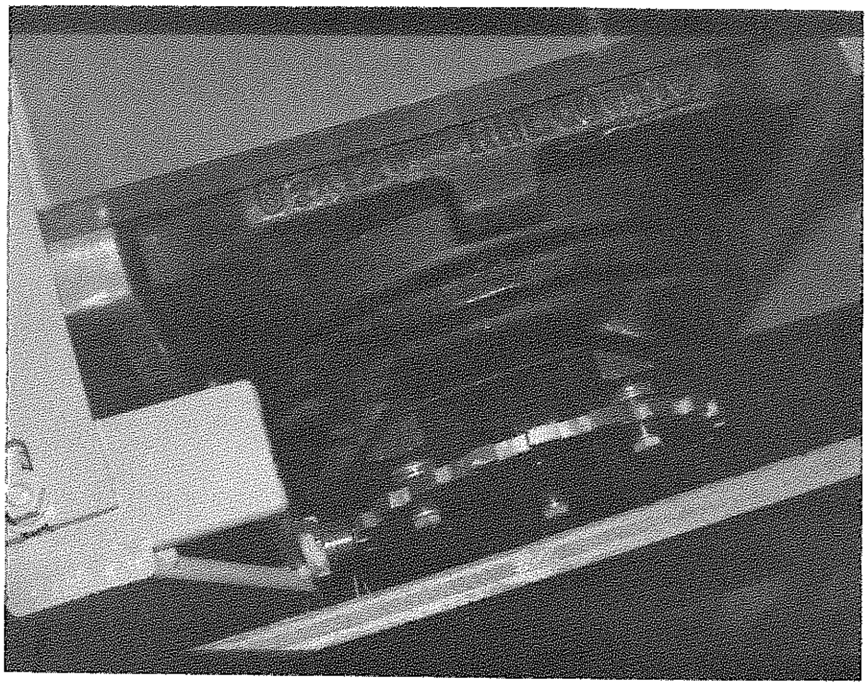

FIG. 5 SPEED GEAR AND SENSOR

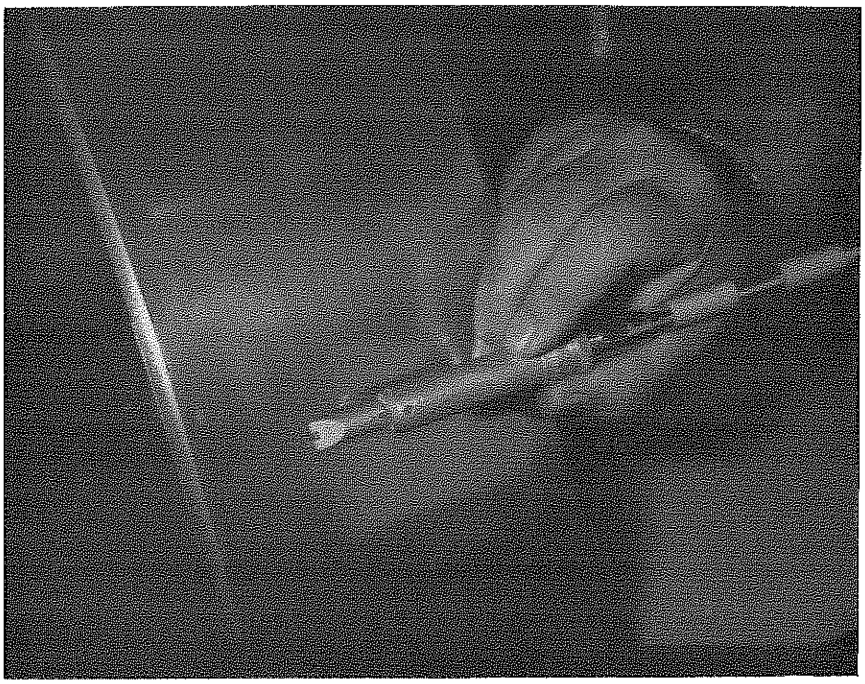

FIG. 6 MEASURING WHEEL SURFACE ROUGHNESS

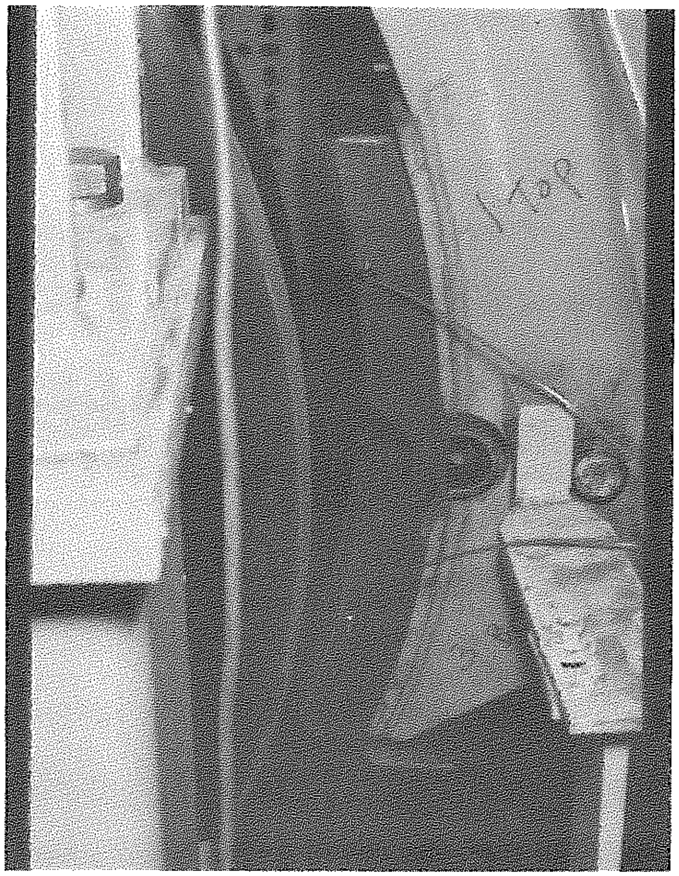

FIG. 7 BRAKE SHOE WITH THERMOCOUPLES

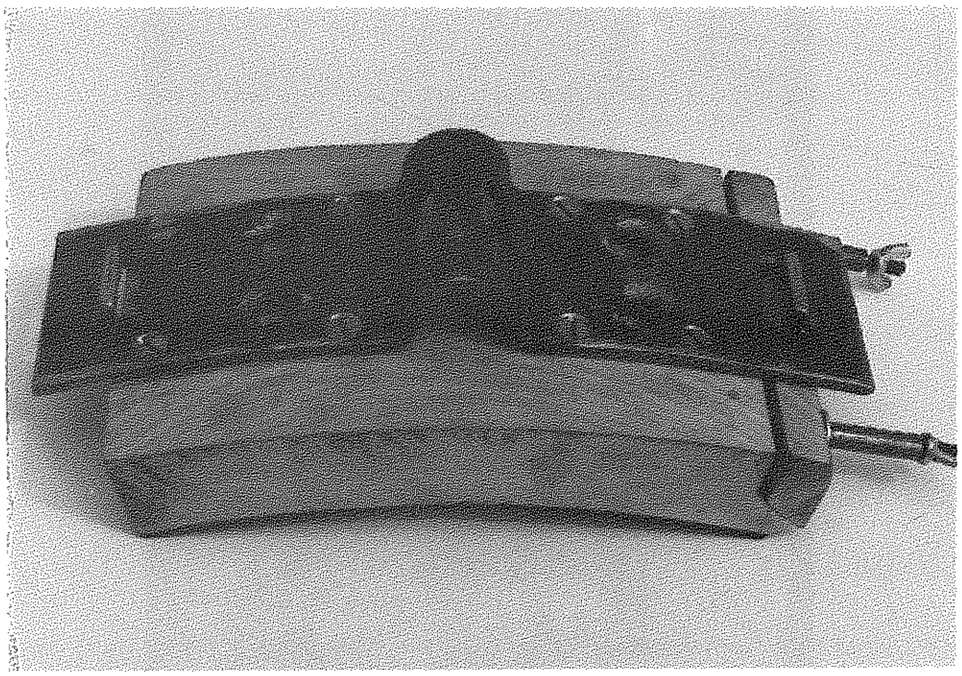

FIG. 8 WHEEL DRESSING BLOCK

FIG. 9 DRESSING BLOCK IN USE

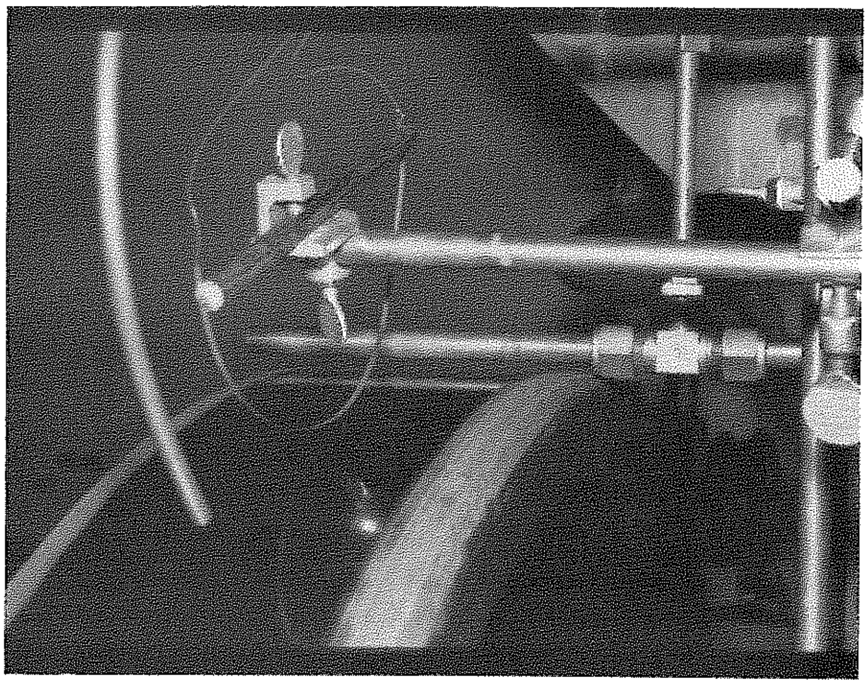

FIG. 10 COPPER WATER TUBE AND
WHEEL SURFACE THERMOCOUPLE

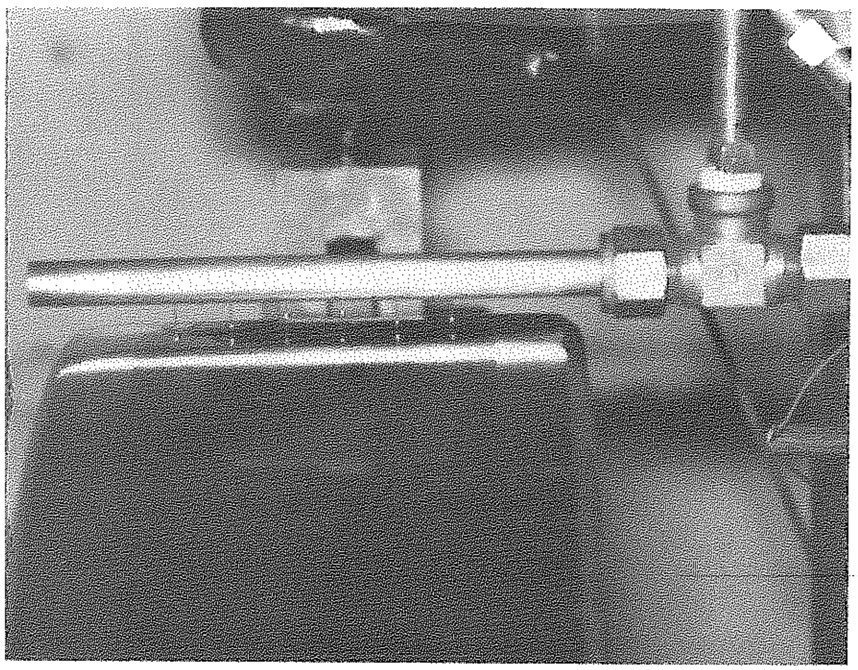

FIG. 11 MODIFIED UIC SPRAY BAR

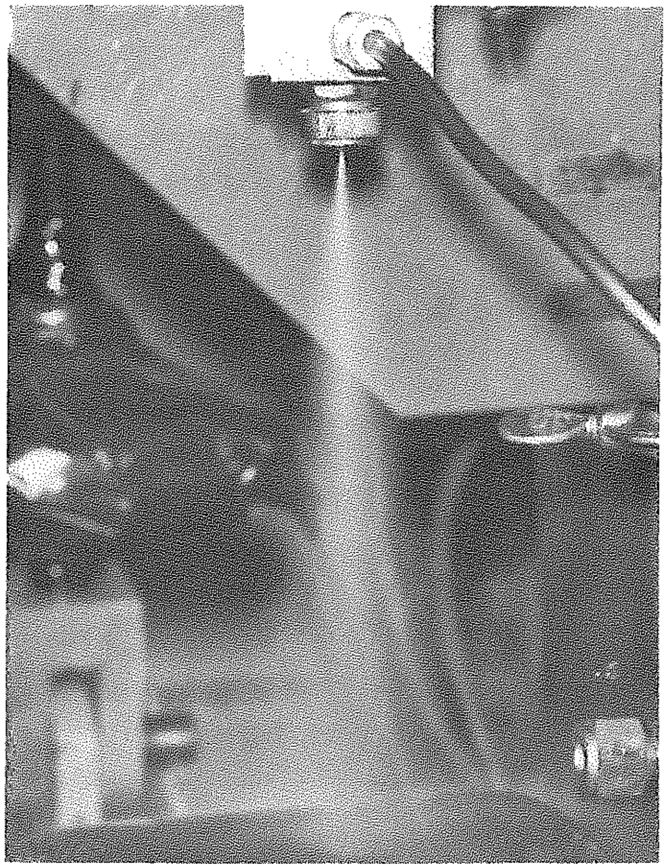

FIG. 12 SINGLE S 1/4 J NOZZLE

FIG. 13 SNOW MAKING NOZZLE ARRAYS ON WIND CHILL FANS

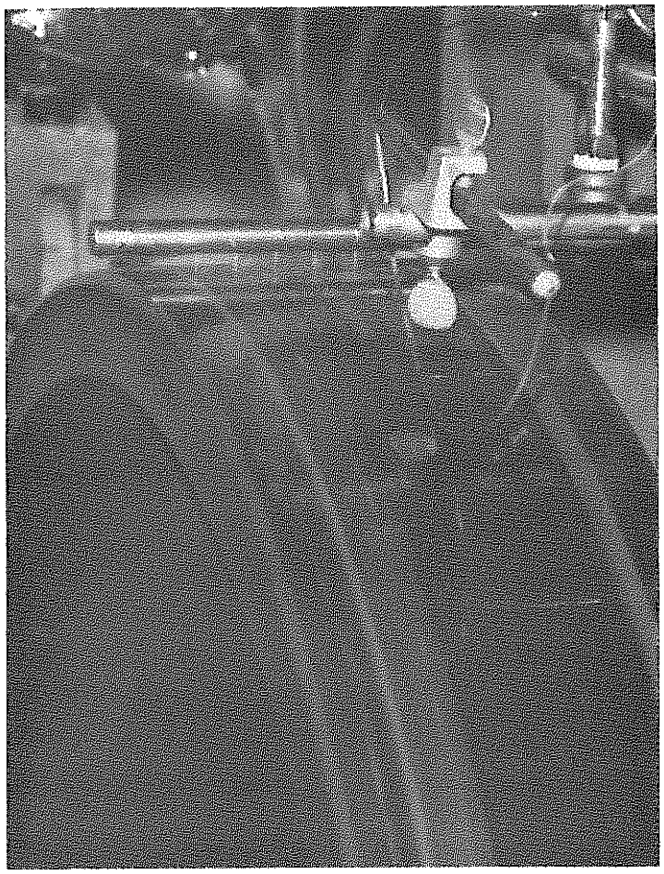

FIG. 14 HEAT STREAKS ON WHEEL SURFACE

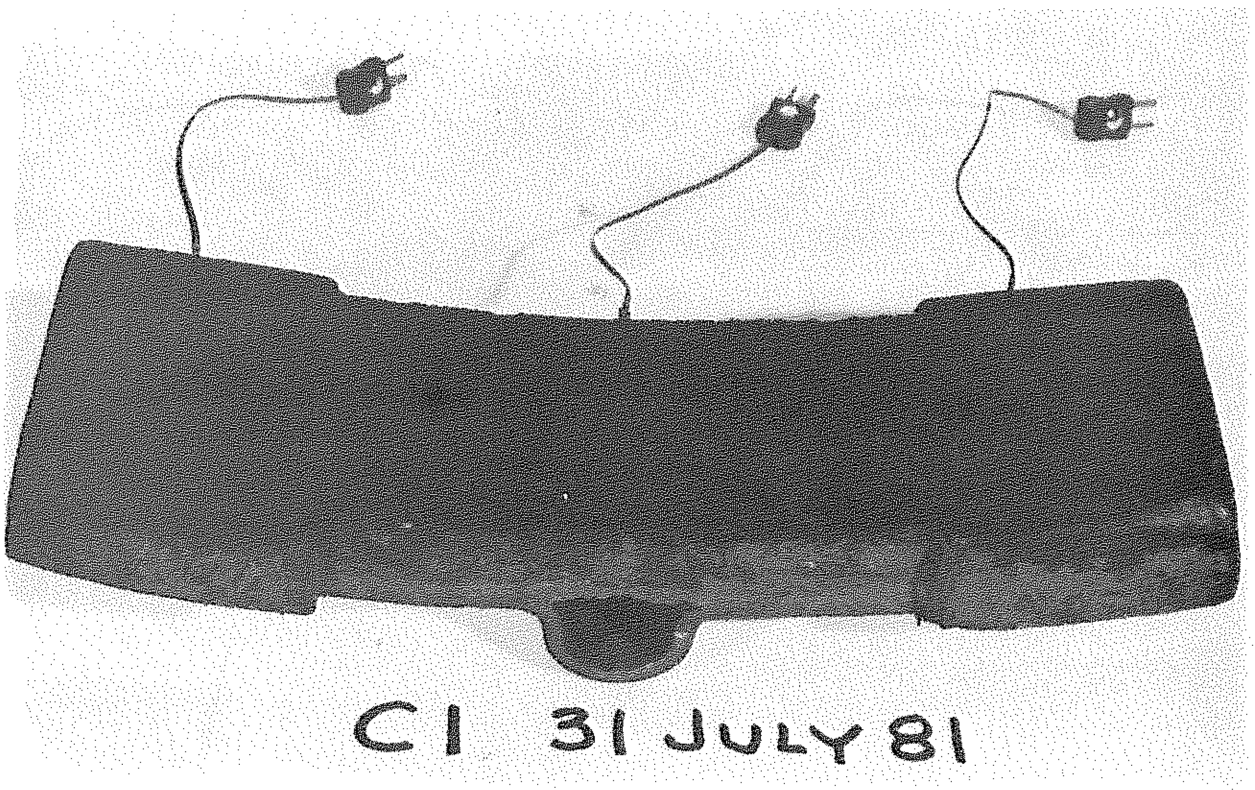

FIG. 15 THERMAL CRACKS ON C1 BRAKE SHOE

FIG. 16 CLOSE-UP OF THERMAL CRACKS

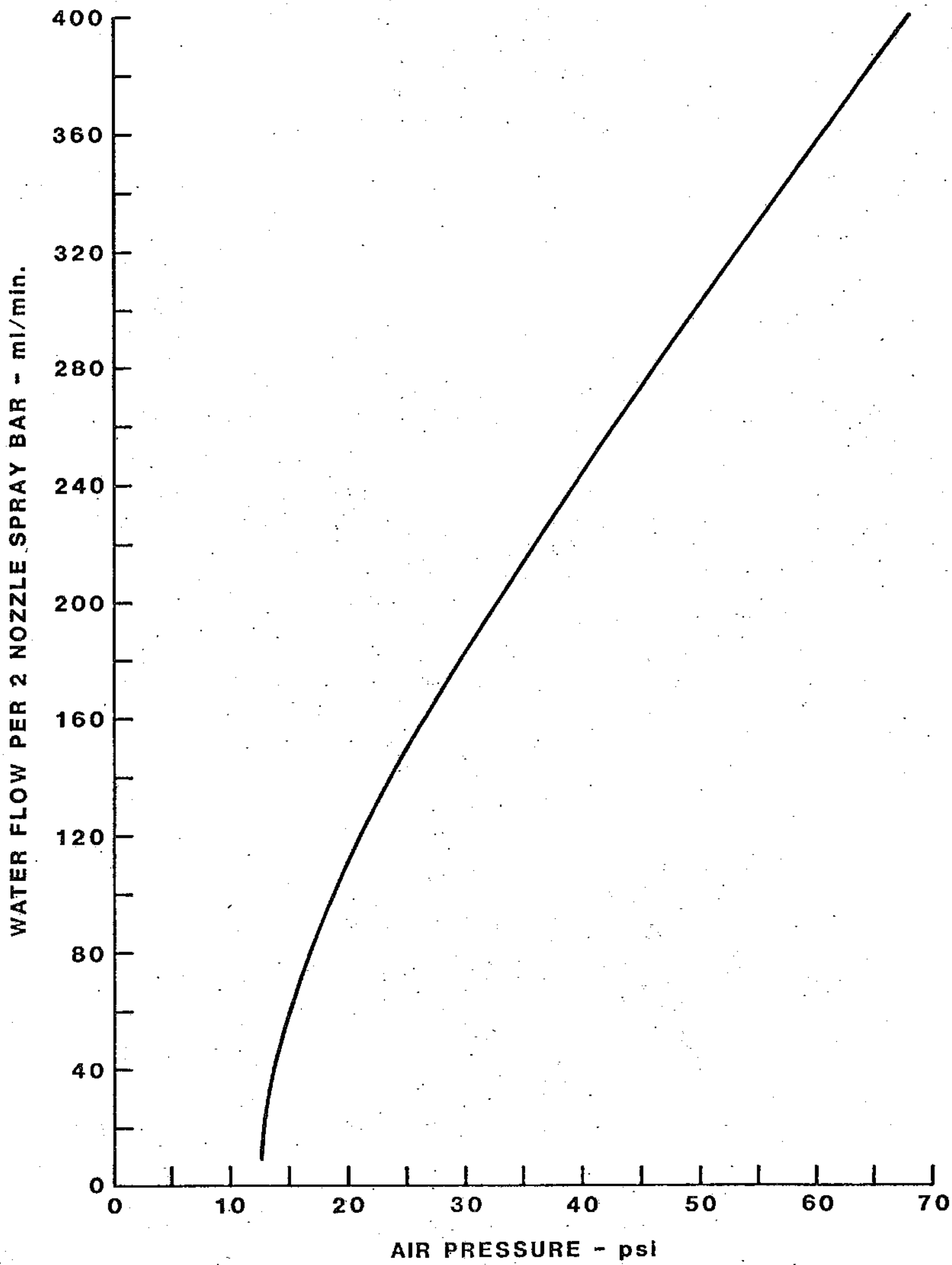

FIG. 17 WATER FLOW AND REQUIRED AIR PRESSURE FOR 20 μm MVD DROPS

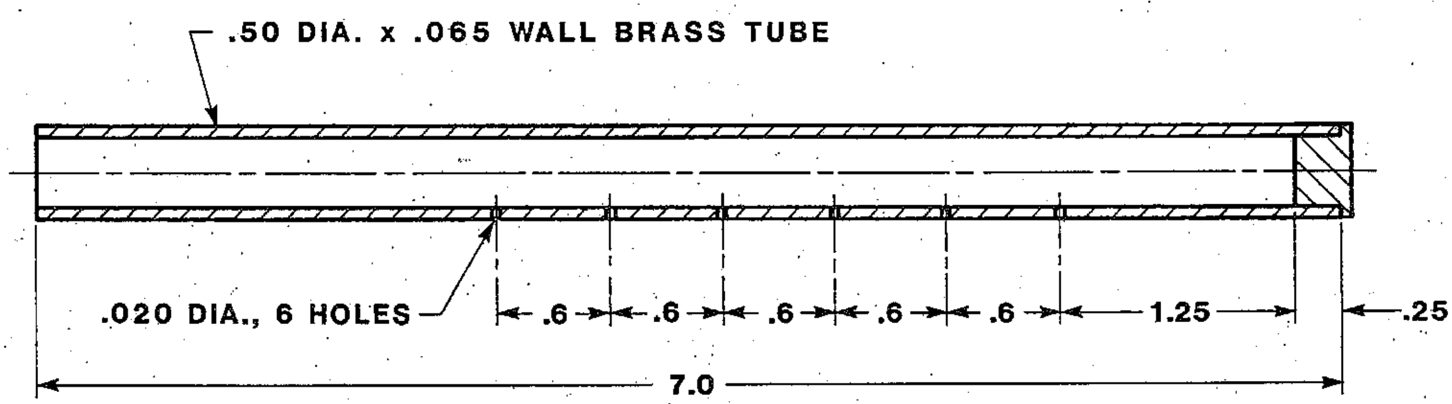

FIG. 18   MODIFIED UIC SPRAY BAR DESIGN

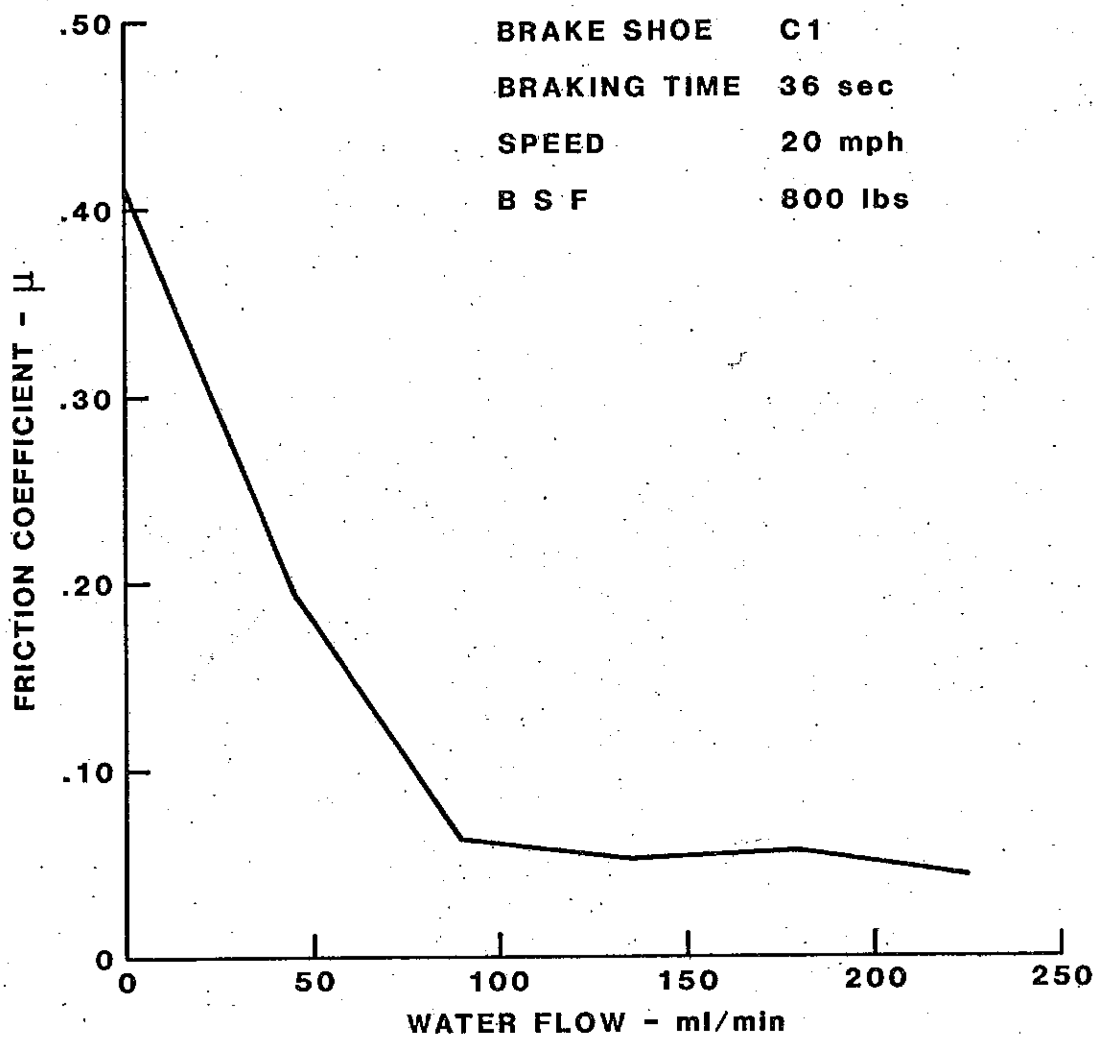

FIG. 19 FRICTION COEFFICIENT AS A FUNCTION OF WATER FLOW

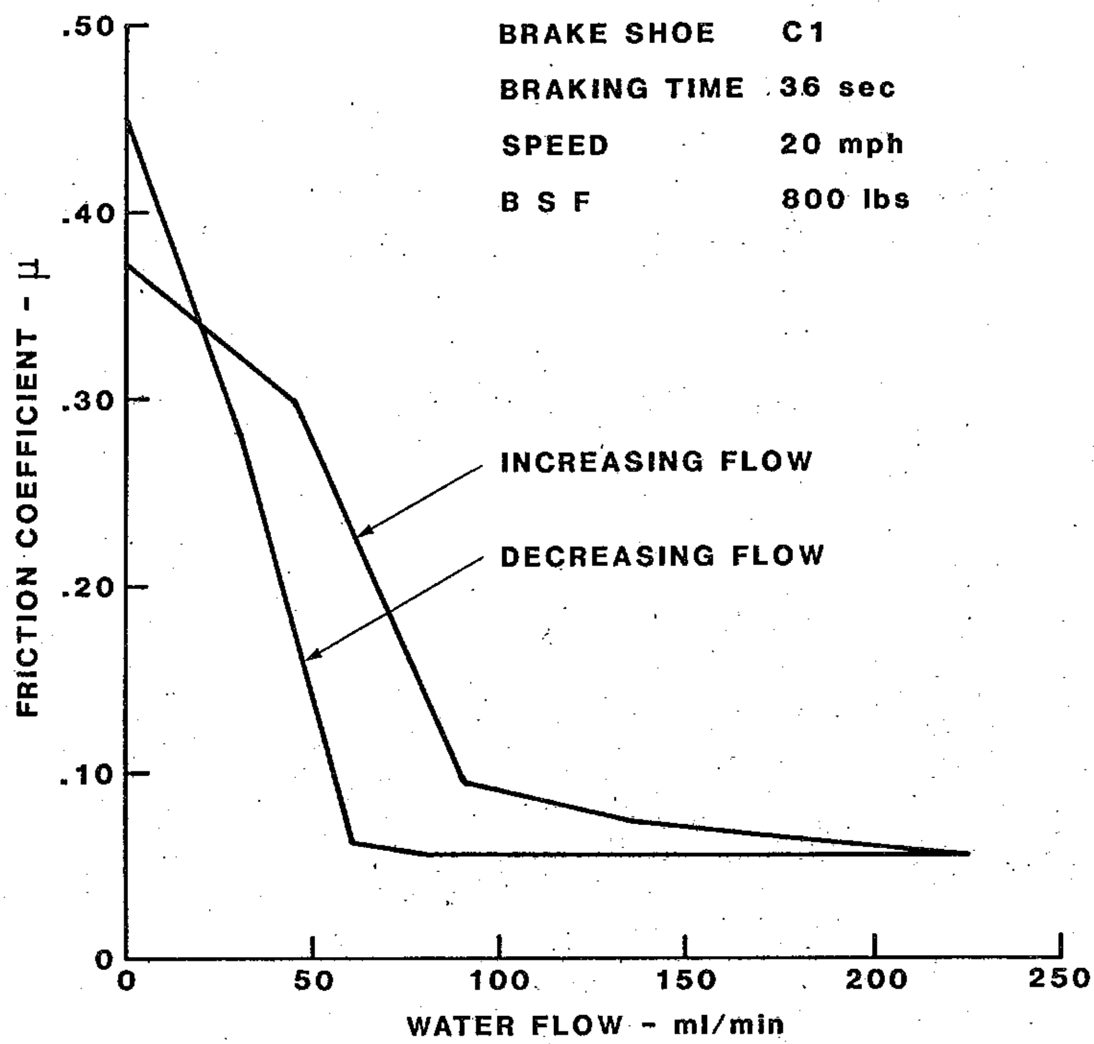

FIG. 20 FRICTION COEFFICIENT AS A FUNCTION OF INCREASING AND DECREASING WATER FLOW

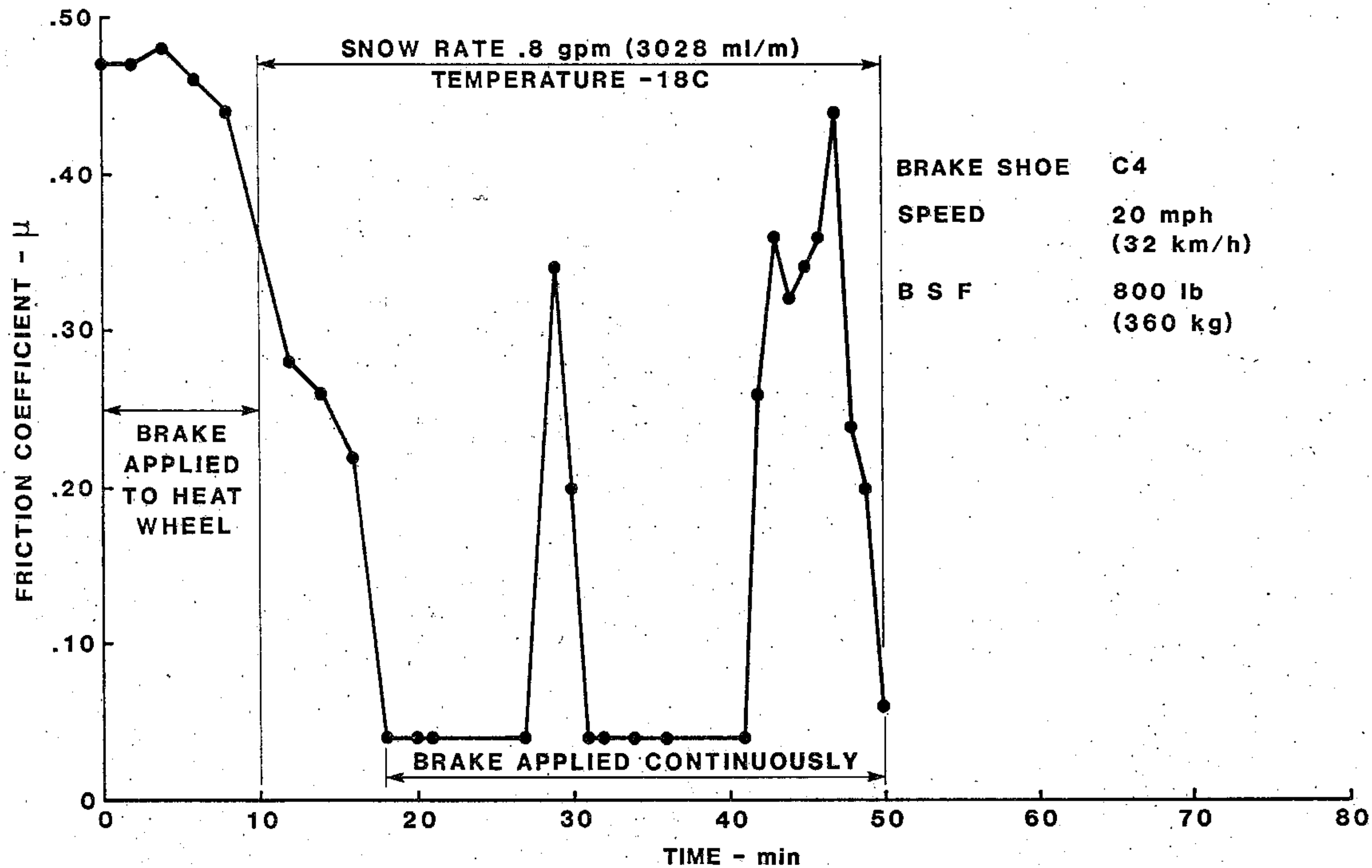

FIG. 21 SNOW TEST 2

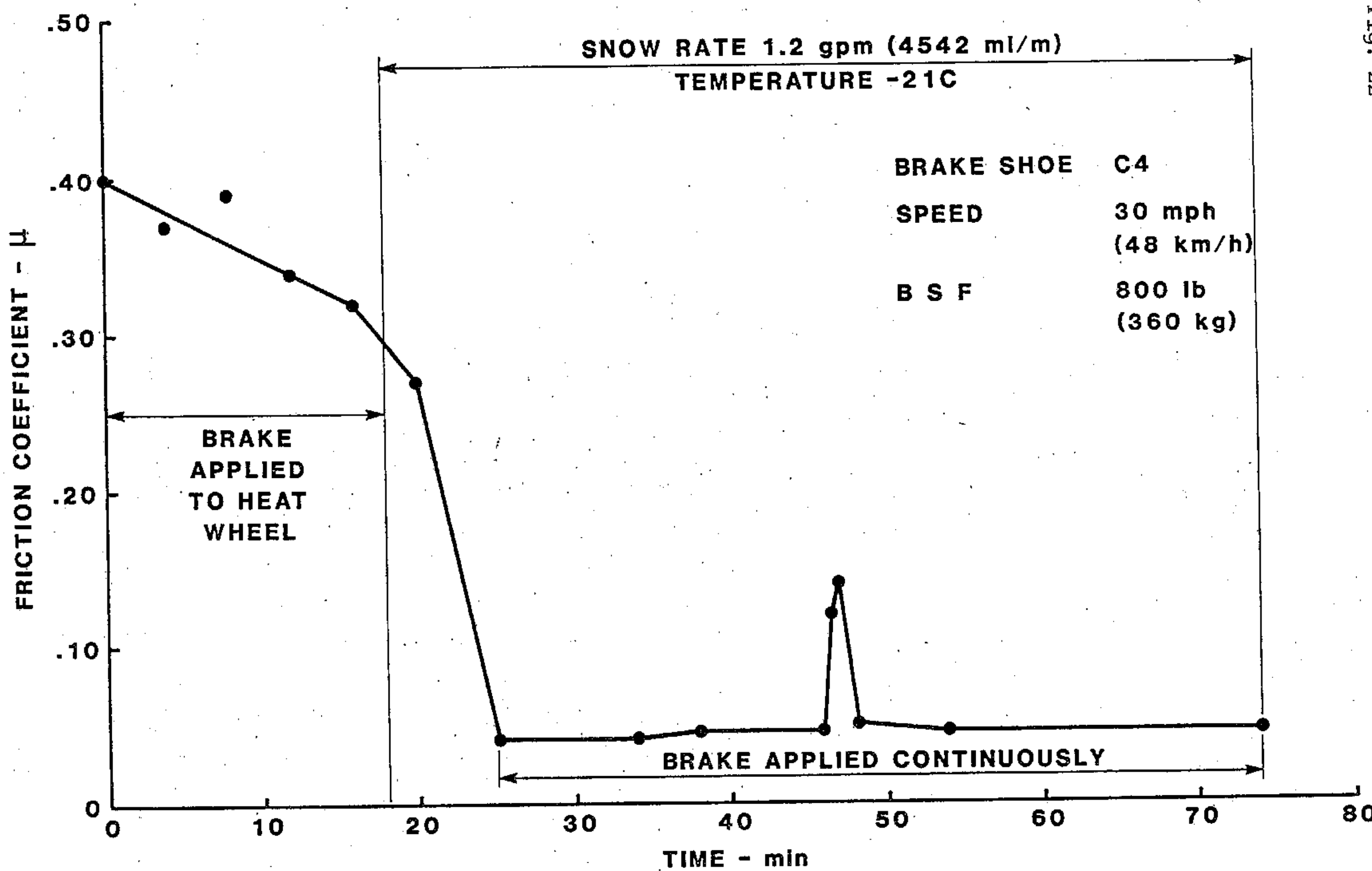

FIG. 22 SNOW TEST 3

APPENDIX A

EQUIPMENT

1. MOTOR -	ASEA Type LAB 250 DC 150 HP, 1600 rpm Forced Air Cooled
2. MOTOR CONTROL -	BEEL Controls Ltd. SCR Adjustable Drive
3. BRAKE CYLINDER	GRANNING Truck Suspension Ltd. #10-1080 Type 50
4. COMPRESSION LOAD CELL	BLH Corp. SR-4 Load Cell Type CXX 5000-pound capacity
5. TENSION LOAD CELL	LEBOW Model 3132 2000-pound capacity
6. SPEED SENSOR	AIRPAX Electronics Magnetic Speed Sensor A 07355 Part No. 087-304-0002
7. SPEED INDICATOR	HEWLETT-PACKARD Model 5308A Timer Counter
8. D.C. EXCITATION SOURCE	ANATEK Model 50-1.00 Dual Channel DC Power Supply
9. ANALOG RECORDERS	HEWLETT-PACKARD Moseley Dual Channel 17501 & 17502 Amplifiers