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Texture Modification of the Shuttle Landing Facility Runway at Kennedy Space Center

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Abbreviations:

ALDF	Aircraft Landing Dynamics Facility
ATD	average texture depth
BPT	British Pendulum Tester
CAT	Computerized Axial Tomography
ITTV	Instrumented Tire-Test Vehicle
KSC	Kennedy Space Center
LG	longitudinally grooved
LSRA	Landing-Systems Research Aircraft
RTLS	return-to-launch site
SLF	Shuttle Landing Facility
STS	Space Transportation System
TG	transversely grooved

Summary

This paper describes the test procedures and the criteria used in selecting an effective runway-surface-texture modification at the Kennedy Space Center (KSC) Shuttle Landing Facility (SLF) to reduce Orbiter tire wear. The new runway surface may ultimately result in an increase of allowable crosswinds for launch and landing operations. The modification allows launch and landing operations in 20-knot crosswinds, if desired. This 5-knot increase over the previous 15-knot limit drastically increases landing safety and the ability to make on-time launches to support missions in which Space Station rendezvous are planned. The paper presents the results of an initial (1988) texture modification to reduce tire spin-up wear and then describes a series of tests that use an instrumented ground-test vehicle to compare tire friction and wear characteristics, at small scale, of proposed texture modifications placed into the SLF runway surface itself. Based on these tests, three candidate surfaces were chosen to be tested at full-scale by using a highly modified and instrumented transport aircraft capable of duplicating full Orbiter landing profiles. The full-scale Orbiter tire testing revealed that tire wear could be reduced approximately by half with either of two candidates. The texture-modification technique using a Humble Equipment Company Skidabrader™ shotpeening machine proved to be highly effective, and the entire SLF runway surface was modified in September 1994. The extensive testing and evaluation effort that preceded the selection of this particular surface-texture-modification technique is described herein.

Introduction

Since the beginning of the Space Transportation System (STS) program, the need has existed for a landing facility near the Space Shuttle launch site. This need stems from the possibility of having to make a return-to-launch-site (RTLS) abort landing and from a desire to make the Kennedy Space Center (KSC) Shuttle Landing Facility (SLF) a prime landing site for normal end-of-mission operations to reduce program cost, time, and ferry risk factors. Because of extreme conditions imposed on Orbiter tires (especially on the main gear tires) during landing, tire wear has been a long-standing issue for landings at KSC. The SLF runway was designed with extremely rough texture and transverse grooving to provide exceptional friction performance during heavy rainfall conditions. These factors, combined with landing in the presence of crosswinds, caused tire wear to be a limiting parameter for flight operations. Early landings of the Space Shuttle Orbiter were made on the lakebeds and smooth concrete runways at Edwards Air Force Base, California, to allow the greatest possible margin for errors in the final approach for landing or for anomalies during the landing rollout. The KSC SLF in Florida has a unique runway that was constructed in the mid-1970's that is approximately 5 mi from the Shuttle launch pads and provides the STS program with the capability to land safely in the event of an RTLS or poor weather conditions at other sites. Operationally, the prime landing site is the SLF, which minimizes program costs, reduces Orbiter processing time, and eliminates the hazards associated with ferry flights from the West Coast.

Early in the STS program, excessive wear on the Orbiter main gear tires was observed during landing operations at the KSC SLF. Almost every landing at the SLF had some tire-wear anomaly that could be traced to the roughness of the runway surface. The original specifications for flight operations included the capability to land in 20-knot crosswinds, but tire-wear concerns at the KSC SLF reduced the allowable landing crosswind limit to 10 knots. The 20-knot crosswind specification was to provide the STS program with the flexibility to launch and land without frequent weather delays. The unique Orbiter gear geometry, landing conditions, tire materials, and runway configuration all combined to produce tire wear that limited the Orbiter's crosswind landing capability. Numerous attempts to build operational capability to the 20-knot crosswind level have been made, including changing the SLF runway touchdown-zone texture and changing the tread material of the main gear tires.

In the mid-1980's, research was conducted to quantify the effect of various parameters such as speed, yaw angle, runway roughness, and load on the tire-wear phenomenon. Yaw angle is defined as the angle between the rotational plane of a tire and its velocity vector. The results of those tests showed that the spin-up process produced an unacceptable wear spot on the main gear tires and that the spot grew with subsequent cornering later in the rollout whether it was crosswind or pilot induced. At that time, work was begun to improve the tire-wear characteristics by changing the tread-rubber compounding. In addition, work was conducted at the Langley Aircraft Landing Dynamics Facility (ALDF) which showed that a large reduction in spin-up wear could be achieved by changing the texture in the spin-up regions of the runway (ref. 1). The original texture of the runway (fig. 1(a)) was an extremely rough, longitudinally brushed finish with transverse grooving that measured 1/4 in. wide by 1/4 in. deep, spaced on 1 1/8 in. centers. A 3500-ft-long section on each end of the 15 000-ft-long runway was modified to a texture which resembled corduroy material, its texture aligned with the landing direction (fig. 1(b)). The texture was modified by using a stack of diamond grinding wheels that cut into the original surface deeply enough to remove the original transverse grooves. This modification reduced the main gear tire spin-up wear levels to one-half the original values; therefore, the allowable crosswind value for landing and launching was increased from 10 knots to 12 knots but was still short of the original program requirement for 20-knot crosswind-landing capability.

In 1992 mission STS-50 landed with the first main gear tires using a new tread compound. This new compound produced less tread wear and allowed crosswinds for launch and landing to be as high as 15 knots. Numerous studies were conducted to see what effect the surface roughness had on rollout wear as opposed to spin-up wear (refs. 2 to 4). Results of those studies showed that while the transverse grooves had a great effect on spin-up wear, they had little or no effect on the magnitude of the rollout wear response of the tire (ref. 5). Conversely, the corduroy texture on the ends of the runway had a drastic effect on spin-up wear but caused the same amount of wear on the tire when rollout occurred on that surface. It was obvious that simply continuing the corduroy texture into the center 8000 ft of the runway would not produce the desired reduction in tire wear to allow for 20-knot crosswind operations.

The studies at Langley Research Center showed a relationship between tire wear and tire side energy. The relationship showed that to increase the tire-wear capability to a 20-knot crosswind level, the tire must be capable of absorbing twice the energy necessary for a 15-knot crosswind condition.

The purpose of the study described in this paper was to define a texture modification for the SLF which would reduce the Orbiter main gear tire rollout-wear rate by approximately one-half while retaining acceptable wet-friction performance. A plan was developed wherein a number of modification techniques were applied in small test strips directly onto the runway surface at the KSC SLF. An Instrumented Tire-Test Vehicle (ITTV) was used to rate 16 textures that were applied to the runway surface in addition to the two existing textures. Comparison testing with the ITTV involved loading a T-38 aircraft main gear tire and conducting yawed-rolling tests at low speeds by using a special instrumented fixture attached to the rear of the ITTV. Wear-rate information in the form of lost weight per foot of rollout distance was used to classify each surface-texture treatment. Wet-friction test results were also used in conjunction with the wear information to narrow the surface selection to three candidates. These three surface treatments were then applied to *full-scale* test sections that encompassed the full length of the runway (15 000 ft) and were about 10 to 12 ft wide. A specially modified Convair 990 transport aircraft was then used to conduct full-scale tests of Orbiter main gear tires on the candidate strips by simulating Orbiter landings under a variety of conditions and piloting techniques, including simulated 20-knot crosswind landings. The test results were used to select a modification technique to provide the necessary reduction in tire-wear rates to allow for 20-knot crosswind operations. This paper presents the modification techniques studied, documents the results of the ITTV testing used to narrow the full-scale candidates to a manageable number, and presents results of the Convair 990 aircraft full-scale tire tests which were used to select the modification technique that could provide a 20-knot crosswind-landing capability for the Orbiter.

Apparatus

Original Runway

The original runway surface, prior to any modification for these tests, consisted of an extremely rough, longitudinally brushed finish with transverse grooving measuring 1/4 in. wide by 1/4 in. deep, spaced on 1 1/8 in. centers (fig. 1(a)). A 3500-ft-long section on each end of the 15 000-ft-long runway was modified to a new texture that resembled corduroy material with its texture aligned with the landing direction (fig. 1(b)).

Test Vehicles

Instrumented Tire-Test Vehicle (ITTV). The ITTV is a highly modified 1976 truck (fig. 2). The 28 000-lb truck has a specially designed force measurement dynamometer attached to the rear that permits the mounting of a wide range of aircraft and passenger vehicle tires or other apparatus for various kinds of testing. Aircraft tires up to 26 in. in diameter can be accommodated in the fixture and can be vertically loaded by using a pneumatic system up to 5000 lb. The fixture can be yawed with respect to the direction of motion so that tire-cornering data can be acquired. Forces and moments associated with yawed or braked rolling conditions such as side load, drag load, aligning torque, and overturning torque can be measured and recorded by using an onboard electronic data acquisition system. Other pertinent data for tire testing, including vehicle speed and distance, are also measured. The ITTV can perform tests at any speed up to 65 mph. The vehicle operator and observer have numerous display devices to provide real-time feedback during testing in an attempt to maintain the desired test conditions throughout the test. Further information about the ITTV test capability can be found in references 6 and 7.

Landing Systems Research Aircraft (LSRA). In 1989 NASA designed a test facility capable of simulating full-scale Orbiter landing conditions. The facility consists of a modified Convair 990 aircraft and is known as the Landing Systems Research Aircraft (fig. 3). The LSRA program was funded by the NASA Shuttle Program Office at Johnson Space Center and provided the capability for full-scale testing of Orbiter main gear tires. Several other tire test facilities had various parameters such as vertical load that could be tested at full scale, but these facilities could not represent correctly other full-scale effects, such as a flat, concrete runway.

The development of the LSRA was undertaken at Dryden Flight Research Facility in Edwards, California. The aircraft was highly modified, and a large hole had to be cut in the aircraft belly at the center-of-gravity location between the main landing gear. A robust structural modification was designed to carry aircraft fuselage loads around the hole to ensure structural integrity throughout the aircraft. A hydraulic loading system was installed in the aircraft to apply vertical load to an articulating pallet to which the desired test article was attached (fig. 4). The system was capable of applying up to 250 000 lb of vertical load to the test article. For the present investigation, a steerable fixture with a single Orbiter main gear tire was attached to the pallet. The fixture was controlled by using a sophisticated feedback control system that permitted time histories of vertical load and yaw angle to be input into an onboard control computer prior to a test flight. A typical set of time histories used by the control computer during a simulated 20-knot crosswind Orbiter landing is shown in figure 5. A special rotary actuator, capable of yawing the fixture up to 35 deg/sec, hydraulically steered the fixture. The desired speed-time history was not incorporated into the feedback control system, but an indicator was mounted in the aircraft cockpit to give the test pilot a comparison of how fast or how slow the test article was when compared to the desired speed-time history. The steerable fixture was controlled in part by using a set of optical noncontact infrared translational speed devices. These devices measure translational speed by looking at interference patterns of the radiation reflected by the ground. Because the pilot must steer the aircraft in response to the side forces generated by the test tire or in response to the actual crosswinds on the test aircraft, a means of measuring the aircraft yaw angle (in this case, the angle between the aircraft body axis and its velocity vector) needed to be devised. Conventional inertial platform units do not have the accuracy or the response needed for this application; therefore, two optical units were mounted at ±45° from the body axis and at 90° to each other. The aircraft had zero yaw when both instruments agreed in their speed measurements. If one instrument reported a higher speed than its companion, the aircraft yaw angle could be computed in real time by the control computer, and the steer angle of the fixture relative to the body axis could be appropriately adjusted. This adjustment ensured that test-pilot inputs were isolated from the test-tire yaw angles.

The test aircraft was capable of landing at speeds up to 245 knots and of beginning a test at about 240 knots, if desired. The vertical load for the single-tire test fixture was structurally limited to 150 000 lb, which is slightly higher than the maximum desired test-tire load of 142 500 lb. The vertical load could be controlled to within approximately 2000 lb, the yaw angle accuracy was approximately 0.25°, and the aircraft speed was generally held within 2 to 5 knots of the desired speed-time histories.

Over 100 channels of data were recorded both onboard the aircraft and after telemetry to a ground control station. Some of the pertinent parameters recorded for this part of the investigation included aircraft speed, test-tire vertical, side, and drag loads, test-tire yaw angle, and tread temperature. Extensive video coverage of the test tire from three different locations also proved to be an invaluable measurement tool. The video signal was synchronized to the data stream and thus the exposure time of different Orbiter tire-carcass cord layers could be recorded in postprocessing playback. This visual measurement of tire wear was one of the most widely used pieces of information in this investigation. Numerous safety features were added to the aircraft for these tests, including low-oxygen sensors to detect the presence of a nitrogen gas accumulator leak, fault-detection hardware and software in the computer and control system, fire detection and suppression systems, triple-redundant mechanisms to ensure cessation of load application, if needed, and armor plating of certain areas of the aircraft. A more detailed description of this unique test facility can be found in reference 8.

Test Tires

ITTV tests. The test tires used on the test fixture of the ITTV were 20×4.4 bias-ply Type VII aircraft tires with a ply-rating of 14 and a 3-groove tread design; they are similar to those found on the main gear of a T-38 aircraft. A new and a worn ITTV test tire are shown in figure 6(a). The rated load and pressure of the tire are 6000 lb and 265 psi, respectively. Because it was desirable for wear testing to have the test tire inflated to the actual Orbiter tire pressure, the ITTV test tires were inflated to 350 psi. The tires were mounted on standard aircraft wheels according to accepted buildup procedures. A new tire was used for each surface tested.

LSRA tests. The test tires used on the LSRA steerable test fixture were of the same design as the Orbiter main gear flight tires. One of the 44.5 × 16.0 - 21 bias-ply aircraft tires with a 34-ply rating is shown in figure 6(b). The original rated load of the tire and the pressure were 60 900 lb and 315 psi, respectively. These test tires (and the flight tires) are generally inflated to higher values prior to flight because of some small expected leakage and the cold temperature expected during normal landing operations. Therefore, these test tires were inflated to 340 psi at ambient temperature. The peak certified tire load at the time of this writing is 142 500 lb. This load limit is intended to prevent excessive tire deflections which could damage the carcass structure during landing operations. The test tire is of the *modified* tire design, in which an additional 0.1 in. of undertread was added to the original design, and the entire tread material was changed from a natural rubber composition to a blend of natural and synthetic rubbers comparable to those used on commercial aircraft. These modified tires provide a much-improved wear behavior as compared to tires of the original design. The tread grooves themselves are 3/32 in. thick. A sketch of the tire cross section is shown in figure 7.

The only difference between the test tires and the actual flight tires is that the test tires failed certain government quality-control tests for cosmetic reasons. The manufacturer's certification of the tires for flight and for all-wear testing to date suggests that these *rejected* tires are fully as robust as those that make it to the flight vehicle. A new tire was used for each test run conducted on the full-scale test strips by using the LSRA. The Orbiter tires were mounted on standard Orbiter beryllium brake wheels according to accepted buildup procedures. The tire-wheel combination was mounted on a specially designed axle, along with a standard Orbiter beryllium brake assembly, to allow it to be attached to the test fixture on the aircraft.

Other Test Equipment

Mu-Meter. The Mu-meter (fig. 8(a)) is a friction-measuring device designed to be towed behind a vehicle on a test surface (ref. 9). The device consists of two test tires loaded vertically and *toed* out to include an angle of 15°, thus forcing each tire to operate in a yawed-rolling condition with side forces directed away from and canceling each other. The device measures the tensile force in the axle and gives a measure of the surface friction being developed by the yawed test tires. The device can conduct tests on dry surfaces and is capable of using an onboard water tank to wet the test surface just ahead of the test tires.

Skid trailer. The Florida Highway Department provided a test device which was used to help characterize the surface-friction capability of some test surfaces used in the ITTV testing. The skid trailer and the tow vehicle (fig. 8(b)) consist of an instrumented trailer equipped with a water supply and dispensing system and actuation controls in the tow vehicle cab for braking the trailer test wheel from a free-rolling condition to a momentary complete (100 percent slip) lockup (ref. 10). After the test apparatus is brought to the desired test speed, e.g., 40 mph, water is dispensed at a constant rate to produce 0.04 in. surface water depth (delivered ahead of the test tire), and the braking system is actuated to lock the test tire. The resulting friction drag force acting between the test tire and the pavement, together with the speed of the vehicle, is recorded with the aid of suitable instrumentation. This skid trailer also can be operated on dry or naturally contaminated, e.g., rain-wet, surfaces.

British Pendulum Tester (BPT). The British pendulum tester, a device designed to provide a measure of surface microtexture, was used in this investigation to help quantify the relative roughness of the texture for each surface tested. Microtexture is defined as a surface-roughness quality on the subvisible or microscopic level. The passenger tire industry uses such a parameter to help quantify long-term automobile and truck tire wear. Macrotexture, on the other hand, provides a measure of the surface roughness on a much larger scale and is comparable to the quality and scale one would perceive if one rubbed his hand on a surface.

The BPT uses a pendulum to which a rubber footpad (fig. 9) is attached. The device is used by placing the feet of the tester on the surface to be tested and by leveling the apparatus. The footpad is then raised to a predetermined height (angle) and released. The pendulum and the footpad swing freely, allowing the rubber footpad to *scrape* the surface when the pendulum traverses the vertical orientation. A certain amount of energy is then dissipated by friction and wear of the footpad. According to the theory of the device, the pendulum then swings upward to a height (angle) lower than the equivalent release point on the other side. This difference in height gives a measure of the dissipated energy and the relative surface microtexture. The height reading is in nondimensional units; larger units denote a *rougher* surface that prevents the pendulum from rising to as high a point as it would with a smoother surface. Thus, the higher a reading is, the rougher or higher a microtexture the surface has. Generally, on surfaces where one can feel an increased macrotexture, one would expect the BPT to indicate a higher microtexture as well. The BPT was used after wetting the surface to be tested. Some surfaces were not evaluated by using the BPT, but the ones that were tested were evaluated by using the pendulum swing direction both parallel and perpendicular to the long axis of the runway. More information regarding the BPT can be found in reference 10.

Outflow meter. The Outflow meter is a device intended to provide a measure of surface macrotexture (ref. 11). The meter consists of a rubber *doughnut* attached to the bottom of a tube that is open at its top end (fig. 10). The doughnut is placed on the surface being evaluated, and a standard quantity of water is poured into the top of the tube. Because the surface macrotexture does not allow the entire rubber doughnut to contact all the *valleys* in the surface texture, the water escapes through the contact patch, and the time for the entire volume of water to escape is measured. The time then becomes the relative measurement of surface texture when this device is used. Thus, the shorter the time for the water to escape, the rougher the surface texture is.

Grease sample texture-measurement kit. Another means of quantifying the macrotexture of a surface was included in this investigation. A grease sample texture-measurement kit (fig. 11) was used to find the average texture depth (ATD) of each surface tested in this study. The kit contains a supply of ordinary grease, a hard rubber squeegee, a plunger, and a short tube that is open on both ends and has a handle. The short tube is filled with grease and provides a calibrated, known volume of grease for the measurement. The plunger is used to extrude the grease onto the surface being evaluated. The grease is spread evenly with the rubber squeegee as far as possible between two strips of masking tape placed at a known distance apart on the surface. At this point, essentially all valleys created by local *hills* on the test surface have been filled with the grease. The initial volume of grease is then divided by the measured area on the surface and yields a measurement of the average depth of the surface texture. This parameter agrees well with the results one would feel while rubbing his hand on the surface. A more detailed discussion of the technique is given in references 9 through 12. One should note that there are other surface qualities that certainly must influence tire wear such as *sharpness* of surface disparities, but measurement techniques for these other qualities are not yet fully devised or understood.

Computed tomography. Computed tomography was used to provide an alternate means of defining tire rubber loss caused by wear. A device, similar to medical CAT (Computerized Axial Tomography) scanners, passes X rays through the cross section of the tire, and sensitive detectors are used to receive the attenuated signals on the opposite side of the tire. By placing a calibrated block of known size in the scan with the tire, a digital measurement program can be used to measure the tire width or thickness before and after wear testing. An example of the tire-profile dimensions before and after testing is shown in figure 12(a). In the figure, dimensions 1 through 40 represent scans that are parallel to the rotational plane of the tire, thus providing 40 data points from the left towards the right shoulder of the tire to characterize the tire-tread wear. Figure 12(b) provides a representation of the tire cross section before and after testing. The change in thickness can then be correlated with other tire-wear measurements. This kind of examination is advantageous because many more *individual* or discrete measurements can be performed automatically in a nondestructive manner. Reference 13 has more information about this technique.

Other measurement hardware. Several common measurement tools were also used in this investigation. To measure tire wear during the small aircraft tire testing by using the ITTV, a sensitive scale was used that gave weight readings that were accurate to about 1*g* or 0.002 lbf. The entire test tire and wheel were weighed on each candidate surface at various times during the tests so that a history of tire rubber loss could be recorded.

For both the ITTV and the LSRA tests, a tire-tread-measurement gauge was used to provide tire-wear measurements. The gauge is designed to sit flat across the tire-tread ribs and has an extendable probe which is pushed to the bottom of the tread grooves and measures the remaining tread depth. For cases in which Orbiter tire wear was expected to be between the bottom of the tread grooves and the first carcass cord layer, several small 1/4-in.-diameter holes were bored into the main gear tire tread by using a small rotary tool. These holes were bored 9/32 in. deep until the first carcass cord layer was just exposed. By measuring from the bottom of the hole to the outer surface of the tire, one could determine wear depth prior to exposure of the first carcass cord layer.

Texture-Modification Devices

Four methods of modifying the existing concrete runway at the KSC SLF were employed in a number of ways to provide 16 new textures in addition to the existing 2 textures on the runway. The four methods were diamond-blade grinding, Skidabrader™ shotpeening, rotopeening, and methacrylate coating. Table 1 presents a chart identifying the 18 texture test strips. Table 2 presents data for all 18 test surfaces, including the results of ATD measurements, BPT measurements, Outflow meter measurements, and limited Mu-meter and skid trailer testing. The Mu-meter and skid trailer results are presented as nondimensional values calculated by dividing the measured side loads by the vertical load on the test tires. Although some surfaces were not evaluated with the BPT and the Outflow meter as shown, these data can be used to quantitatively compare the different textures.

Figure 13 shows a sketch of the runway and the location of each test strip. Figure 13(a) shows an overall layout of each test area used in this investigation. Figure 13(b) shows eight test strips used during the ITTV testing which are located towards the north end of the runway and east of the runway centerline. Figure 13(c) shows eight test strips used during the ITTV testing which are located towards the north end of the runway and west of the runway centerline. Figure 13(d) shows a sketch of the full-length test strips applied to the runway for LSRA testing. Note that test strips 1 and 3 had a different texture on the touchdown zones, compared to the center part of the strips, and that test strip 2 had the same texture application for the entire strip.

The original surface type prior to modification is referred to either as TG, the transversely grooved 8000-ft-long section in the center of the runway, or as LG, the longitudinally grooved 3500-ft-long touchdown zones. These zones, often referred to as the corduroy touchdown zones, did not actually have grooving but rather had the texture that remained after the 1988 grinding operation gave the appearance that longitudinal grooves had been installed.

Diamond-blade grinding. The diamond-blade-grinding texture-modification technique uses a stack of diamond saw blades to cut into the existing texture. This technique has been used for many years to smooth sections of highways and recently has been used to alter the texture on some runways. Figure 14 shows one type of machine that is designed to grind concrete surfaces. The machine height can be controlled for depth of cut, and water is typically used as a cooling agent. The slurry produced during cutting is typically vacuumed and pumped into holding tanks for later removal. The device is designed to traverse the surface slowly, and forward speed is not normally varied. Figure 15 shows a close-up of a cutting head used on a smaller version of the machine shown in figure 16. The spacers between blades can be adjusted so that a range of blades/in. configurations can be selected. For these tests, an ITTV test strip was cut (all ITTV test sections were 2 to 6 ft wide and 400 ft long unless otherwise noted) by using a blade spacing of 5 blades/in. For the LSRA testing, a 7 blades/in. configuration was used in a test strip 12 ft wide and 11 500 ft long. This configuration is the practical limit for normal blade spacing and provides a fairly smooth surface. Another ITTV test section was created by using the same grinding machine but with a head that had interlocking diamond saw blades that produced an extremely smooth surface that is similar to a polished stone surface. This same equipment was used to produce the corduroy touchdown zones on the runway in 1988 by using a blade spacing of 4 1/2 blades/in. A photograph of this surface, which is typical of this technique, is shown in figure 17.

Skidabrader™ shotpeening. The Skidabrader™ machine was used extensively to produce a variety of textures. This device, shown in figure 18, uses pressurized air to propel small steel shot at the surface being traversed. The intention is to break many of the sharp peaks on the original rough surface to reduce the ATD of the surface. The machine is also used to roughen smooth surfaces such as the rubber-contaminated touchdown zones of commercial runways. The steel shot also impacts other areas of the surface texture, and one can imagine many possibilities of modification outcomes. The size and shape of the shot and the shot velocity can be varied. The forward or traverse velocity of the machine also can be varied to change dramatically the resultant texture. The shot is vacuumed up after impact, along with surface debris, and is separated and recycled to be used again. The machine produces a modified swath 6.5 ft wide. For the ITTV test strips, the Skidabrader™ was used with a single shot size and a single shot velocity, but with three forward velocities. Six test strips were produced by traversing both the corduroy touchdown zone and the original center section of the runway at machine velocities of 100, 150, and 220 ft/min. For the LSRA tests, one test strip 12 ft wide was produced by using the Skidabrader™ and by traversing the full 15 000-ft length at 150 ft/min in two swaths. Two other test strips were produced by using the Skidabrader™ machine at the same velocity, but only the 3500-ft-long corduroy touchdown zone on the end of the runway was modified as an entrance to a different texture strip in the center 8000 feet of the runway. For one case, the touchdown zone on each end of the runway was modified as an entrance for a texture that will be described in the next section; for the other case only one end of the runway was modified (the LSRA test strip that was produced by using the diamond-saw-grinding technique). During the creation of all Skidabrader™ surfaces, many ATD measurements were taken, and the equipment operators were required to produce a texture that varied in ATD by no more than 10 percent throughout the entire test section.

Rotopeening. The rotopeener shown in figure 19(a) is a device with tungsten buttons attached to leather-like belts or straps. A head loaded with these straps of buttons rotates, and as it does, the buttons *slap* the runway surface and cause the tops of the macrotexture peaks to be broken off in much the same way as they are with the Skidabrader™. The buttons were unable to penetrate the texture as deeply as the Skidabrader™ machine; thus, the rotopeener changed the texture on the very top surface of the runway and on the edges of the transverse grooves when applied in the center section of the runway (fig. 19(b)). For the ITTV test strips, the buttons wore out occasionally; consequently, the operators felt that different results would be obtained with old-versus-new belts. Therefore, on the corduroy touchdown zone of the runway, a test section using new belts was produced. This section could be compared with another path in the same zone by using old belts. The operators suggested that the machine would produce a different result if it were operated in the transverse direction on the runway; therefore, the machine was operated in a lateral direction and produced a longitudinal strip that was placed in the center or transversely grooved section of the runway. For the LSRA tests, a 10-ft-wide laterally rotopeened strip was placed in the center 8000-ft section of the runway with a 3500-ft-long Skidabrader™ strip as the entrance to this texture on each end of the runway. The machine modified only a 10-in.-wide swath at a time, so this process was very time-consuming. Once again, operators of the rotopeening equipment were required to produce test sections which varied no more than 10 percent, as measured by the ATD method.

Methacrylate coating. The fourth method used to produce modified textures at the SLF involved the use of a low-viscosity liquid known as methacrylate (fig. 20). This compound bonds to the concrete runway surface and dries extremely hard. The intention was to fill the low areas of the surface texture in hopes of reducing the ATD of the surface. In a photograph, the surface would appear simply to be wet; the compound gave the impression of dried polyurethane. This liquid was applied (fig. 20(a)) only on the corduroy touchdown zone texture because no efficient way could be devised to force it to stay on the *land* areas of the transversely grooved center section texture while it dried. One test strip was produced by using ordinary paint rollers to apply a single coat of the compound in a 2-ft-wide by 340-ft-long area. Another short test strip measuring 2 ft by 60 ft was produced by applying two coats of the compound. A close-up view of this coating after the liquid hardened is shown in figure 20(b). This strip showed that extra coats of this costly compound would continue to reduce the ATD, but the strip was not long enough for wear testing.

Test Procedures

ITTV Testing

The ITTV was used to measure and compare tire-wear rates on a variety of short test strips that were modified by using several techniques. A new 20×4.4 test tire was mounted on a standard aircraft wheel for each surface tested. The wheel was weighed without bearings prior to being installed on the test-fixture axle that was mounted at the rear of the ITTV. This initial wheel weight became the measurement standard for each test strip. To provide meaningful wear data for test-strip comparisons, it was decided to attempt to conduct tests totaling about 4000 ft on each strip. In the case of one of the smoother surfaces, a total distance of over 7000 ft was achieved. To reasonably accelerate the wear rate of the test tires, the tires were always set at a fixed yaw angle of 8°. To distribute the expected wear across the test-tire footprint evenly, the test tire was yawed towards the opposite direction after every test run.

The ITTV was then driven to the desired test strip and lined up in preparation for a test. The data-recording system onboard the ITTV was then activated, and the test tire was lowered to the test-strip surface and loaded to 4500 lb. The ITTV was then accelerated slowly to approximately 25 mph and driven in a straight line to ensure that the test tire remained on the test strip. The ITTV braked to a stop at the end of the test strip. The tire was raised, and the ITTV was then driven to the original starting point for setup to repeat the test and to accumulate distance on the test tire.

The tire and wheel were removed after every two or three individual test lengths and weighed to provide a tire weight loss-versus-distance history. The tire-tread depth gauge was used each time the tire was weighed, and tire-tread depth measurements were recorded at four places around the tire circumference in each of the three grooves. The tire-wheel combination was then returned to the test axle and more distance on the tire accumulated in the same fashion. After wearing through the tire-tread material, wear into the test-tire carcass commenced. This process changed the wear rate for those portions of the overall tests on each tire, but each tire was taken to a wear condition of approximately five cord layers, thus preserving the capability to make wear-rate comparisons between surfaces. Data were periodically reviewed to ensure that steady-state vertical and side loads were being maintained. The vertical load during each test reviewed was steady at the desired 4500 lb. All the ITTV wear testing was conducted on dry test surfaces, and as a result, all the recorded side loads, regardless of the test surface, were approximately 1700 lb throughout each test. The 168 individual tests were conducted on the ITTV test strips to provide wear-rate comparison data.

For wet-friction evaluation of the modified surfaces, the ITTV was used for 20 tire-cornering tests at yaw angles of 2°, 4°, and 8° under both wet and dry conditions at a 4500-lb vertical-load condition. The surfaces included in this testing were the single coating methacrylate strip (test strip 2), the Skidabrader™ 150 ft/min strips on both the corduroy touchdown zone and the center section (test strips 5 and 6), the solid-head-cutter diamond grinding on both the corduroy touchdown zone and the center section (test strips 14 and 15), and both the unmodified corduroy touchdown zone and the center section (test strips 17 and 18). Only these test strips were evaluated for wet friction because it became clear that the other textures would not be selected as full-scale test-strip candidates. The solid-head-cutter diamond-grinding test strips had excellent wear characteristics, as will be shown, but were unlikely to have satisfactory wet-friction performance.

For these tests, the ITTV was driven over the desired test strip both at walking speed and at 60 mph. For the high-speed tests, the test tire was lowered just as the ITTV was entering the test section, which consisted typically of a 40-ft length dry surface of the desired type followed by a 40-ft length of the same surface texture which a KSC fire truck had wet down just prior to the test. The water condition simulated the conditions shortly after a typical rain shower, with a water depth of approximately 0.02 to 0.04 in. The same data were recorded as for the wear testing except for the tire weight-loss data, which were not considered relevant to these friction tests.

LSRA Testing

The 23 flight tests were conducted by using the LSRA to impose full-scale landing conditions on Orbiter main gear tires. The flight tests covered a wide range of conditions that might be experienced during actual flight operations and included simulating a variety of piloting techniques which might affect tire wear. Because the tests were intended to expand the crosswind-landing envelope to 20 knots, all tests were conducted by simulating a 20-knot crosswind from either the right or the left. The previously tested aircraft was considered a reliable and repeatable facility on which to perform the full-scale testing; high confidence in the system to perform the test programmed into the control computer had been achieved. The challenge for the test team was to program the correct types of tests to make the decision-making process as clear as possible. To simulate 20-knot crosswind landings, time histories of tire vertical load, tire yaw angle, and speed are needed. A tire-cornering model based upon tire vertical load and yaw angle (by far the two most important parameters which influence tire cornering) had been developed previously by using ALDF and LSRA test results. This tire-cornering model produces tire side force as its output, and this force was used as one of the inputs into a Shuttle Orbiter landing and rollout simulator program. Other important parameters such as vehicle-control surface dynamics and vehicle aerodynamics were also modeled in the simulator. Based on aerodynamic inputs modeling a 20-knot crosswind on the vehicle during landing, the simulator output included main gear tire yaw-angle time histories. These time histories were checked by conducting tests with the LSRA that used the same time histories and by measuring tire side forces. The side forces closely matched the side forces predicted by the simulator and thus provided a check of the modeling process. This check provided confidence that the LSRA could actually simulate crosswind landings on the test tires.

Test conditions. A number of 20-knot crosswind-landing profiles were developed to define a range of possible conditions that the Orbiter tires might be subjected to in actual flight experience (table 3). Yaw angle was the most important parameter relative to Orbiter main gear tire wear. The yaw time history for the tires has a nominal value for each crosswind and Orbiter speed during the rollout, but other flight disturbances add to or subtract from that baseline. For example, if the Orbiter lands with a lateral drift rate at touchdown, the touchdown yaw angle could go up or down, depending on the direction of drift. If the pilot allows the crosswind to push the vehicle downwind prior to derotation, then a steering maneuver to bring the vehicle back to the centerline will cause increased yaw angle and therefore increased wear on the tires. Derotation speed and rate also affect main gear tire vertical loads that ultimately will manifest themselves as changes in tire-wear behavior. Although there are many possible flight conditions, three types of 20-knot crosswind profiles were generated, and they are referred to as *case 9*, *case 10*, or *case 11* in table 3. All three cases assumed a touchdown-speed dispersion of 20 knots, which forced a 225-knot touchdown speed for the tires. Note that figure 5 is a graphical representation of case 9. The main difference between case 9 and case 10 is the addition of the triangular steering pulse just after peak tire load. Peak tire load on the main gear tires occurs just as the nose tires touch down after the derotation maneuver for the Orbiter. The steering pulse is intended to model a 20-ft *S* maneuver that an aggressive pilot would perform after having been pushed downwind by a strong crosswind. This maneuver had been performed several times in actual Orbiter flight experience, even though such a maneuver was discussed and discouraged during pilot training.

Case 11 is similar to case 10 except that the crosswind is modeled as coming from the left as opposed to the right (as in cases 9 and 10). The yaw-angle time histories for cases 10 and 11 are different; the Orbiter main gear tire has a phenomenon known as ply-steer that produces an uncommanded side force to the left as it rolls, even at zero yaw. To achieve the same side force to combat identical aerodynamic side forces, the vehicle assumes a slightly lower yaw angle during rollout with crosswinds from the left because of the *free* forces developed by the four main gear tires. This phenomenon cannot be mitigated by mounting tires backwards on the wheels or by rolling the tires backwards. Because of the unavoidable asymmetric nature of the composite structure of the bias-ply tire design, the ply-steer force always acts in a single direction. The rollout simulation program had a small anomaly that resulted in a 0.2° increase in anticipated yaw angle at the time of peak load that was simply accepted in these flight tests.

These three cases therefore include a number of dispersions from the expected norms for a crosswind landing but represent the types of events that could be encountered in actual flight. These dispersions could be added together in a root-sum-squared (RSS) manner that would result in a more benign set of speed, load, and yaw-angle time histories, but it was decided that these dispersions were independent, and the problems were likely to cascade under high-crosswind conditions. Therefore, the dispersions were linearly combined to define a worst-case landing profile. The test tire would thus have to survive the worst of these profiles to verify a 20-knot crosswind capability.

LSRA procedures. For each flight using the LSRA, a new test tire was installed on the aircraft test fixture and inflated to 340 psi at ambient conditions. The aircraft normally conducted a *preroll* on the test tire in which the tire was loaded to about 60 000 lb and rolled 10 000 ft with zero yaw. This preroll was designed to heat up and work the nylon carcass cords to precondition the carcass in case the tire's first landing (in Orbiter use) was an RTLS abort. The technique helps to ensure tire survivability under those conditions. Although a first-landing RTLS abort was not a concern during the LSRA testing, it was desirable to treat each test tire as if it were a flight tire on the Orbiter. After the preroll, the aircraft was either parked overnight to allow the test tire to cool down to ambient temperatures (the test-tire temperature would normally climb over 140° F during the preroll), or the tire was sprayed with cool water for approximately 45 min to reduce the temperature to about 90° to 95° F.

For a typical test run, the pilot made a normal takeoff with the test tire retracted, flew a closed loop around the SLF, and set up for a test landing by aligning the aircraft with the desired 10- to 12-ft-wide test strip. Most tests required a test-tire touchdown speed of 225 knots that required the LSRA test pilot to land the vehicle 5 knots faster. After LSRA touchdown, the pilot derotated the aircraft and at the proper speed gave a *start test* command. The test conductor onboard the aircraft then enabled the test-control computer to perform the test as programmed. The pilot steered the aircraft to keep the test tire on the test strip (for all tests, the test pilot never once strayed out of the 10- to 12-ft-wide test strips) and decelerated the LSRA to match the desired speed profile, thus simulating the rollout and stop of the Orbiter. The test conductor monitored the test to ensure that the control computer was following the desired profiles. A video operator was responsible for observing the LSRA landing gear and the test tire and for monitoring aircraft fire-suppression systems should they be needed.

Since these tests were known to be near the maximum wear capability of the tire, the crew was constantly aware of the test progress. If the test tire failed because of excessive wear (which it did several times), the crew executed procedures to retract the test tire, and depending on the speed and position of the LSRA, either performed a takeoff or brought the aircraft to an emergency stop.

The results of a test-tire failure with personnel near it would be catastrophic because of the tremendous potential energy stored in the tire. After a test, the test-tire wear condition was evaluated by using the onboard video coverage. If the tire remained inflated but had worn into 8 or more of its 16 cord layers (the tire would normally fail if wear progressed into layer 9 or 10), the aircraft was parked, and a robotic device was used to approach the test tire and drill a hole into the tire sidewall by using an ordinary cordless drill, thus deflating the tire. If wear was not severe, the tire-wheel assembly was allowed to cool for an hour and was then dismounted from the aircraft and removed from the test axle.

LSRA touchdown positions and the touchdown position of the test tire itself were marked and measured on the SLF runway surface by ground observers. Rollout lengths were measured and recorded. Comparisons of the desired-versus-actual time histories of the test parameters were produced almost in real time during the test so that decisions about the next scheduled test could be made quickly.

The LSRA was also used to conduct limited wet-runway tests. For these tests, the control computer was normally programmed to load the Orbiter test tire to 75, 100, 150, and 200 percent of its rated load and yaw the tire in a stair-step fashion at each load. The tire was yawed rapidly and then held at the desired yaw angle (normally ±1°, 2°, 4°, and 7°) for a short period to let the side force stabilize at each steady yaw angle. Such tests were conducted at speeds ranging from 50 to 200 knots. Because of limited resources and time during the LSRA testing, wet-friction tests were conducted on the *smoothest* version of the full-scale test strips. In the touchdown zones, the wet tests were conducted on the Skidabrader™ surface because it was assumed that it would display the highest friction loss of the two possible touchdown zone modifications. In the center section of the runway, wet tests were conducted on the rotopeened test strip because that strip had the smoothest feel and also was expected to lose more friction capability when wet, as compared to the other two textures in the runway center section. The purpose of the tests was to demonstrate satisfactory wet-friction characteristics even on the *worst* surfaces so that the friction loss on the rougher surfaces, caused by wetness (increased roughness almost always provides more protection against friction loss from wetness) could be ignored as a disqualifying factor for selection of those textures as potential solutions to the wear problem. For each test, a water-tank truck wet down the runway just prior to an LSRA landing. The tank truck was driven at approximately 30 mph next to the intended test strip and allowed water to drain from a 4-in. valve and wet the lateral half of the test strip closest to the runway centerline. The runway crown in that area (1 percent) caused the other lateral half of the strip to be wet prior to LSRA testing, which usually occurred within about 3 to 4 min. The wetness condition was approximately the same as for the ITTV wet-friction tests.

Data Reduction

ITTV Wear Tests

Data collected for the ITTV wear testing consisted of (1) recording the distance traveled during each test (normally 400 ft), (2) recording the weight loss caused by tire wear after approximately every second test, and (3) recording the various environmental data for later analysis, if necessary. The tire weight loss was measured in grams but will be presented in this report as lbm to provide easy-to-understand plotted data. Wear rates in lbm/ft will be presented as the slope of the last measured weight for each test tire.

ITTV Wet-Friction Tests

Data collected during the ITTV wet-friction testing consisted of test-tire yaw angle, vertical load, and side force. The side-force friction coefficient μ for each test was calculated by dividing the average steady side force (produced by the test tire) by the average vertical load on the test tire during each test. The μ values for the 2°, 4°, and 8° tests on each wet surface were compared to the μ values for a dry concrete surface at the same yaw angles. For each surface and yaw angle, the wet μ value was divided by the dry μ value to give a percentage of the average dry value. The three values of the percentage of average dry values for each surface were then averaged to give a single value for each wet surface. This averaging was done for both speed conditions.

LSRA Wear Tests

Data collected during the LSRA wear testing included test-tire yaw angle, vertical load, side load, tread temperature, vehicle speed, and video coverage of the tread area of the tire. These parameters were the most important in terms of quantifying Orbiter main gear tire wear; however, a wealth of other information was collected. Other instrumentation defined, controlled, and tracked many support functions on the aircraft and allowed the testing to be conducted. The side loads produced by the tire as a result of rolling under various combinations of vertical load and yaw angle are critically important in the wear phenomenon.

A parameter known as side energy was previously developed (ref. 4) in which tire wear can be expressed as a function of the work that the tire performs in the lateral direction during cornering. The side energy can be calculated as

$$E = \int_0^T F_s (\sin \psi) V dt \qquad (1)$$

where

E	side energy
F_s	side force
ψ	yaw angle
V	velocity
t	time
T	duration

The work term defined by the equation can be thought of as a force acting through a distance; the work is the integrated product of the side force and the lateral component of the longitudinal distance traveled. This work or energy term has been used with success in providing a tool for predicting tire wear under different combinations of speed, load, and yaw angle on a given surface. Note that it appears that the technique might allow prediction of wear caused by braking since that also can be thought of as a force acting through a distance. However, one must be careful when applying the phenomenon to braking because during braking, most of the energy is absorbed by the brake, whereas for cornering all the energy is absorbed by the tire.

Using the LSRA onboard recorded data, time histories of side force, yaw angle, and speed were used according to the above equation to provide a time history of the side energy for the test tire. The videotape of the test as seen from the front of the test tire was reviewed, and the time at which different carcass cord layers became visible was recorded to be correlated later with the side-energy time history. As the first and successive cord layers of the test-tire carcass become visible because of wear, a *bull's-eye* pattern is produced that makes the interpretation of tire wear reasonably easy. Figure 21 shows a photograph of a typical bull's-eye pattern. As stated earlier, other data were analyzed during these tests, but the wear data became the most important on which to base a runway modification decision.

LSRA Wet-Friction Tests

Data relied upon for these tests were the same as for the wet ITTV tests. A single yaw angle of 4° was used during these tests. The side forces obtained during these tests were compared to the side force obtained on dry concrete (which could be predicted accurately by the cornering model) at 4° and at the different vertical loads tested. The side forces for the wet tests were then divided by the dry side-force values to yield a wet behavior for the different surfaces tested. The wet behavior is expressed as a percentage of the dry-friction value to allow wet runways to be easily modeled in Orbiter rollout simulators. A wet runway usually can be modeled satisfactorily by multiplying dry friction by a percentage and dividing by a velocity term which reduces friction values even further as speed increases.

Results and Discussion

Note that certain testing was conducted by using both the Mu-meter and the skid trailer to help characterize the wet-friction performance of the ITTV test strips. Those data helped in understanding how different techniques for measuring surface friction relate to each other and also provided background information as to which kinds of tests can be conducted. Also note that texture measurements made by using the British Pendulum Tester and the Outflow Meter provide background information about the various methods developed to quantify surface texture. Data generated by these four devices, however, were not used in the decision-making process for selecting full-scale test strips on which LSRA tests were conducted and thus are not discussed in this section.

ITTV Wear Tests

Each modification applied to the KSC SLF runway used a technique which was sensitive to the original surface texture. For example, the Skidabrader™ machine was used to smooth each of the original textures on the runway, but the device was also used elsewhere to roughen the surface. Therefore, both original textures on the runway surface were treated as different runways, allowing for the possibility that the technique chosen to modify the touchdown zones might not be the same technique chosen for modifying the center section.

Average values of test-tire wear rate for each surface type are presented in table 4. Figure 22 presents a plot of test-tire wear as a function of distance (at a yaw angle of 8°) for the 20 × 4.4 test tires on modifications applied to the corduroy touchdown zone texture. The figure shows that the original corduroy surface produces the highest wear rate. These data suggest that any reasonable attempt at *smoothing* the surface would result in better tire-wear performance. The figure shows that the 5 blades/in. diamond-grinding technique improves the wear performance of the surface but not to the same degree as some of the other techniques do. This result was expected because the original surface was created by using exactly the same technique with a slightly wider (rougher) blade spacing of 4 1/2 blades/in. Two modification techniques provided extremely similar tire-wear behavior, including the Skidabrader™ machine at both 100 and 150 ft/min and the rotopeener (with a new belt). These two methods of modifying the surface produced a noticeably different *feel* to the touch but had extremely similar ATD's (0.0104 in. to 0.0115 in.). The similar ATD's suggest that there may be a strong link between surface-wear characteristics and ATD. The remaining data plotted in figure 22 show the wear behavior of the test tire on the original corduroy touchdown-zone surface treated with a single coat of methacrylate. The plot shows that the methacrylate-coated surface produced the least tire-wear rate of any modification tested on the touchdown-zone textures.

Figure 23 presents a plot that confirms this strong link and shows the wear rate for the test tires on both the transversely grooved center section and the corduroy touchdown zone with their respective modifications plotted as a function of ATD. The figure, however, does not completely explain the wear phenomenon. As seen in table 2, the ATD for the 5 blades/in. diamond grinding that is applied to the corduroy touchdown zone is 0.0108 in. This ATD is virtually identical to the values for the Skidabrader™ and rotopeening techniques, yet the wear on the 5 blades/in. diamond-grinding surface was worse and provides evidence that there must be other parameters such as sharpness qualities that the ATD technique does not measure but that are important nevertheless. The values in table 2 for the BPT of these surfaces also show that the BPT cannot discern a significant difference among these four surfaces. Table 2 shows that the surface with the single coating of methacrylate had an ATD of 0.0123 in. This apparently small change in the ATD, as compared to the Skidabrader™ and rotopeened surfaces (since it reflects an even rougher surface), is further evidence of the existence of other unmeasured parameters. Although equivalent side loads were produced on all these surfaces during tests, one could hear an unusual noise as the test tire traversed the methacrylate test strip. The low-pitched sound gave the impression that the tire was *slipping* on this test surface more than on the other test surfaces.

The similar wear behavior measured on the 100 and 150 ft/min Skidabrader™ test strips, combined with the data in table 2 that shows similar ATD values for them as well as for the 220 ft/min Skidabrader™ test strip, led the test team to decide that no advantage was likely to be gained by conducting time- and resource-consuming tests on the 220 ft/min Skidabrader™ test surfaces either on the original corduroy touchdown zone or on the original center section. Likewise, very little difference in the ATD was measured for the various techniques of using the rotopeener (new-versus-old belts or longitudinal-versus-lateral installation); therefore, only the one application for the rotopeener that applied to the corduroy touchdown zone was tested. The number of available test tires was such that some narrowing-down of possibilities was necessary in real time during the testing.

The test strip produced by the solid-head-cutter diamond grinding was exceedingly smooth (table 2); the test team was convinced that the wear tests on that surface would have shown the lowest tire-wear values of any of the test surfaces. Since this surface was smoother than other ungrooved runway surfaces that are known to have unacceptable wet-friction characteristics, it was felt that the surface would not meet the wet-friction criteria later in the testing; thus, wear tests were not performed on this surface. The results of this testing phase indicated that the anticipated reduction of tire wear to one-half the original value was possible on the corduroy touchdown zone and that at least three of the proposed methods could accomplish that goal: using the Skidabrader™ machine, rotopeening, and applying a single coating of methacrylate.

The results of the 20×4.4 tire-wear testing on the original or transversely grooved center section are plotted in figure 24, which shows test-tire wear as a function of distance. Again, tests on the original surface were conducted to define the baseline wear behavior that was to be improved upon. Data were collected on the test strips in the original center section, which had been modified by the Skidabrader™ at both 100 and 150 ft/min. The results showed that the forward speed of that device did not have a significant effect on ATD or tire wear (figs. 22 and 24); therefore, the decision was made to refrain from further testing on the strip produced by the Skidabrader™ machine at 220 ft/min.

Data collected on the test strip modified by using the rotopeener longitudinally showed results similar to those experienced on the corduroy touchdown zone wherein the longitudinally rotopeened surface produced the same wear as the Skidabrader™ surfaces. The laterally rotopeened test strip in the original center section produced significantly lower tire wear than the Skidabrader™ surfaces (fig. 24). Even though the data in table 4 show nearly identical ATD's for the laterally versus the longitudinally rotopeened surface, the tire wear was significantly lower for the lateral case. The laterally rotopeened surface did have a noticeably smoother *feel* as compared to the longitudinally rotopeened surface. This result again implied that there are other unmeasured qualities which influence tire wear.

In figure 24, the lowest wear surface shown is the one produced by using the solid-head-cutter diamond-grinding technique. Although this surface surely would have been too slick (when wet) for the corduroy touchdown zone tests, it had some merit as a modification technique in the original center section because transverse grooves remain after the technique has been applied, and it is known that providing an escape path for water in the tire footprint reduces the severity of the friction-versus-speed penalty for wet surfaces. Tests on that surface showed a 2/3 reduction in tire-wear rate for the original center section that exceeded the 50-percent reduction deemed necessary to achieve a 20-knot crosswind Orbiter landing capability. Thus it appeared that two techniques had the capability to reduce tire wear in the original center section to acceptable levels: solid-head-cutter-diamond grinding and lateral rotopeening.

Note in table 4 that the wear rate for the original center section and the corduroy touchdown zone are nearly identical, as are their ATD's. This result suggests that for rollout conditions (countering crosswinds and steering as opposed to spinup), the transverse grooves in the center section do not cause increased tire wear. However, the grooves are shown to be one of the primary tire-wear factors during the spin-up process (ref. 2).

ITTV Wet-Friction Tests

As mentioned earlier, the wet-friction performance of a surface usually decreases with increasing speed and with reductions in surface roughness. The Orbiter rollout simulator has shown that a 50-percent decrease in wet-friction performance of a runway can be accepted since vehicle control is achieved not only by using tire forces but also by using aerodynamic forces generated by control surfaces. Figure 25 presents the result of extremely limited testing (by using the ITTV) of some of the candidate strips. The figure shows the percentage of dry-cornering values obtained on the wet test strips as a function of speed.

Although the ITTV test speed of 50 knots does not adequately permit the prediction of surface performance at 200 knots, the data were used to provide some insight into general friction trends. The data show that the original two-surface textures (the original center section and the corduroy touchdown zone) retain the highest level of wet performance at slow speed. The 150 ft/min Skidabrader™ surface on both the original surfaces showed good retention of friction at low speed. The solid-head-cutter diamond-grinding test strip and the single-coat methacrylate test strips displayed more performance loss at slow speed than the other surfaces, as was expected because of their smooth nature. The methacrylate strip was not tested at the maximum ITTV speed because it was assumed that it would lose too much performance at high speed. The solid-head-cutter diamond-grinding technique applied to the original center section was tested at about 50 knots and showed what appeared to be a gain in performance as compared to its slow-speed value. Based on what is known about wet-surface friction behavior, such gains are not likely to occur consistently; thus, these data provide an indication of the accuracy level of this type of testing. The 150 ft/min Skidabrader™ surfaces on both original textures were tested at about 50 knots. The data show very little performance loss for the technique as applied in the center section, but a relatively large loss of about 15 percent of the dry performance for the technique as applied on the corduroy touchdown zone. This trend, if it continued linearly up to 200 knots, would suggest that too much performance loss would occur for a Skidabrader™ modification of the corduroy touchdown zone. However, since the Orbiter has a wealth of aerodynamic control in the early phase of landing (because of speed) when it is traversing the touchdown zone, the need for high friction in that zone is somewhat diminished.

LSRA Wear Tests

Time and cost were two important considerations in determining what modification techniques should be applied in full-scale test strips for LSRA testing. The methacrylate treatment is a very costly one, and concerns arose regarding its uniqueness. No other runway experience had been gained by using that treatment, and there was a reluctance to have the KSC SLF be the test case for the technology. The application cost for the Skidabrader™ device was about $1.00/yd^2 and the cost for rotopeening was about $1.20/yd^2, making both treatments very economical. The application rate and therefore the time for the treatments are quite different. The Skidabrader™ machine travels at 150 ft/min, modifies a swath 78 in. wide, and provides an application rate of about 108 yd^2/min. The rotopeener device is controlled manually, travels at 50 ft/min, modifies a swath just over 10 in. wide, and provides an application rate of about 5 yd^2/min.

Based on the wear behavior of the test surfaces measured by using the ITTV, the limited wet-friction performance measurements, and the cost and schedule requirements, a recommendation was offered and accepted to initially apply two full-scale test strips near the KSC SLF runway centerline for LSRA full-scale Orbiter tire testing. Sketches of these test strips are shown in figure 13(d) and are denoted as test strips 1 and 2. As described previously, test strip 1 (west strip) consisted of an 8000-ft center section modified with the rotopeener used in a lateral direction with a 3500-ft entrance on each end that was produced with the Skidabrader™ machine at 150 ft/min. Test strip 2 (east strip) was produced with the Skidabrader™ machine at 150 ft/min.

Figure 26 shows a wear-performance plot of the Orbiter tires on the original surface prior to any modification. The plot shows tire wear as a function of side energy (eq. (1)). Tire wear is shown both in cord layers and inches, with the first cord layer the closest to the tire tread. As shown in figure 7, about 9/32 in. of wear is required to expose the first cord layer. The Orbiter tire has been extensively tested, and a wear limit of 6 cords (of the available 16) has been established as a safe wear condition for the tires at the end of a rollout. The band denoting the existing KSC runway represents the range of experience of tire wear on that surface, as tire wear variability can be as high as several cord layers at equivalent energies. The two vertical bands represent the energy the tire may be required to absorb for both a 15- and a 20-knot crosswind landing. The bandwidth represents the reasonable range of energy that may be experienced in each crosswind condition, depending on pilot performance and atmospheric uncertainties. The lower energy level of each band shows the energy required during a *perfect* landing in which no anomalies are experienced and no steering (other than that necessary just to counter the steady crosswind) is performed. The 20-knot crosswind band shows that approximately twice as much energy is required to be absorbed by the tire than for the 15-knot crosswind case.

Figure 27 shows a bar chart of various dispersions shown in table 3 that increase the energy requirement of the tires. The right edge of the bands in figure 26 represent the energy requirements when all dispersions are present (at 20-knot crosswind). Note that these studies were conducted assuming that steady crosswinds and actual flight rules use maximum winds, including gusts, so that a 20-knot steady-crosswind capability (as measured during these tests) includes some margin in capability, as compared to a real flight where steady winds are almost never encountered.

The data in figure 26 indicate that the unmodified surface is unable to support even a 15-knot crosswind if significant dispersions are present. To verify this observation, note that a vertical line at the right edge of the 15 knot band will intersect the lower curve at about 3 cords of wear and will intersect the upper curve at about 9 cords of wear. Prudent judgment leads to the conclusion that it is likely that the defined safe limit of 6 cords will be exceeded. Testing has also shown that the tire usually fails in the 9- to 10-cord region of wear. Thus, a tire failure under 15-knot crosswind conditions is a possibility that must be considered. Figure 26 also shows a band denoting the side energy associated with the runway as modified by the Skidabrader™ machine. The improvement resulting from this technique is quite evident. A 15-knot crosswind landing can be accommodated easily. A 20-knot crosswind-landing capability is feasible except for the most severe conditions, and even then the likelihood of actual tire failure is low. These results were encouraging and suggested that further studies of the Skidabrader™ modification technique would be beneficial.

Figure 28 shows the result of a number of tests conducted on two full-scale test strips shown in figure 13(d) (test strips 1 and 2). The figure shows tire wear as a function of side energy, with tire wear scaled in both inches and cord layers. The upper shaded region shows tire-wear behavior on the original surface under high landing speed and high crosswind conditions. The lower shaded region shows tire-wear behavior at more benign landing conditions, including touchdown speeds up to 200 knots and crosswinds lower than 15 knots. The legend shows each run as having been conducted under either case 9, case 10, or case 11 conditions from table 3. An LSRA *calibration* run is shown as the open square data symbols in figure 28. This run was used to verify that the LSRA could produce repeatable wear results before examining the modified surfaces. The data points represent the energy levels retrieved from the flight data at the point when each cord layer became visible on the time-correlated flight videotape. Connecting the data points shows the progression of tire wear as side energy was accumulated by the tire. The data for both test strips show that a significant reduction in tire wear is achieved by smoothing the original textures. The data indicate that the tire wear on test strip 2 was slightly less than for test strip 1. This result seems contrary to the idea that less wear would be observed on the smoother surface, which in this case was test strip 1 (the strip with the rotopeened center section). The ATD for test strip 1 was 0.008 in., while the ATD for test strip 2 was 0.010 in. In addition, test strip 1 was noticeably smoother to the touch than test strip 2.

When observing the tire damage after each test, it appeared that more discoloration and tread delamination occurred during the testing on test strip 1 than occurred during the testing on test strip 2. These findings are indicative of higher tread temperatures on the test strip 1 tires. Subsequent analysis of the tread temperature data for those flights confirmed that slightly higher average tread temperatures were present. The higher temperature causes parts of the tread rubber to revert nearly to their uncured state and to lose adhesion to the textile carcass. These delaminations cannot support the high shear loads during cornering and rip off and expose the carcass to the runway and cause more overall damage to the tire. It was surmised that the higher temperatures were caused by the increased smoothness of test strip 1 itself. By causing less initial tire wear because of the surface smoothness, the tire must retain more of the hysteretical heat created by yawed rolling and deflection caused by vertical load. The rubber that would have carried away some of the heat (as it is worn away on a rougher runway surface) is now retained and causes the heat damage described above.

To evaluate this theory, test strip 3 (the far west strip shown in fig. 13(d)) was installed on the runway. This test strip used the Skidabrader™ texture in the corduroy touchdown zone as an entrance to the new center section texture created by using a diamond-blade-grinding technique with a 7 blades/in. spacing. Test strip 3 had an ATD of 0.003 in. and was intended to represent the smoothest test strip that could be installed quickly and inexpensively. Since the ATD was so low, it was hoped a clear change in the wear behavior of the tire would be observed. Figure 29 shows the wear results for test strip 3. Results from figure 28 are repeated in figure 29, but in a lighter shade so that the results of the testing on test strip 3 can be discerned easily. The energy bands associated with 15- and 20-knot crosswinds are also shown. Figure 29 shows that the texture in test strip 3 did not result in a clear decrease of tire wear as compared to the results on test strips 1 or 2. Instead, test strip 3 sometimes showed more wear and sometimes less wear than test strip 2. Subsequent testing that used the LSRA on the smooth, ungrooved runway at Edwards Air Force Base, California, confirmed these results. Nevertheless, the results of the LSRA wear testing at the KSC SLF showed that using the Skidabrader™ machine at a nominal 150 ft/min rate on both the corduroy touchdown zone and on the original center section produced a surface that appeared capable of increasing the Orbiter tire crosswind-landing capability to 20 knots (fig. 26).

LSRA Wet-Friction Tests

The LSRA was used to conduct tests on the full-scale test strips to provide assurance that sufficient wet-friction capability would be retained for Orbiter directional control and braking. Because of limited time and test resources, only two sets of tests were conducted. The first tests were conducted on the rotopeened center section of test strip 1 prior to the conclusion of the wear studies and before it was known that the modification recommendation would be to use the Skidabrader™ machine. The results of these tests are presented in figure 30. The plots show the percentage of dry friction retained when the aircraft is operating at different speeds on the test surfaces. The data in the upper curve show that the rotopeened center section retains virtually all its dry capability even when wet. This result is largely because of the retention of the transverse grooves in the test strip. This result provides confidence that the rougher test strip 2, produced by using the Skidabrader™, would also have satisfactory wet-friction performance under full-scale conditions. The middle curve for tests conducted on the corduroy touchdown zone that was modified with the Skidabrader™ machine shows the same trend identified by the ITTV test on that surface in which a decrease in friction level (as speed is increased) is observed. The tests using the LSRA at low speed corroborate the results obtained by the ITTV at its maximum speed. The data show that the friction on the Skidabrader™ surface that is applied to the touchdown zone decreases to about 40 percent of the dry value at approximately 200 knots. This decrease was deemed acceptable and was significantly better than the wet Edwards runway surface behavior, as shown in the lower curve. For the wet Edwards runway, the friction level drops to only 25 percent of the dry value when aircraft are operating at 200 knots. This severe reduction in friction levels was reported to be unacceptable, and any runway modification would have to perform better than the Edwards wet runway.

Final Recommendation

Based on the ITTV wear testing, the ITTV wet-friction testing, the LSRA wear testing, and the LSRA wet-friction testing, a recommendation was made to and accepted by the Shuttle Program Office to modify the entire KSC SLF runway by using the Skidabrader™ machine operated at 150 ft/min. The runway modification was performed in September 1994 (see aerial view in fig. 31), and numerous Orbiter landings have been performed on it at crosswinds as high as 12 knots to date, with wear results as predicted by the curves shown in figure 26. The STS program will continue to monitor tire wear as a function of side energy as opportunities to land in higher crosswinds arise. Providing the tire-wear capability for 20-knot crosswind landings will permit the program to realize an increase in the statistical probability of meeting short launch-window opportunities and also will provide an increased safety margin for normal end-of-mission landings under crosswind conditions.

Concluding Remarks

An experimental investigation was performed to define a texture modification for the existing Kennedy Space Center (KSC) Shuttle Landing Facility (SLF) runway which would provide an increase in Orbiter main gear tire-wear capability that is sufficient to support Orbiter landings in crosswinds as high as 20 knots. Tests were conducted by using an instrumented vehicle to compare the friction and wear characteristics, at small scale, of a number of proposed texture modifications placed into the SLF runway surface itself. A strong link between surface average texture depth (ATD) and tire wear was observed. Based on these tests, three candidate surfaces were chosen to be tested at full-scale by using a highly modified and instrumented transport aircraft capable of duplicating full Orbiter landing profiles. Test strips for the three candidates were prepared for the entire length of the 15 000-ft runway.

The full-scale Orbiter tire testing revealed that tire wear could be reduced approximately by half by using either of two treatments. Full-scale testing also revealed a phenomenon which caused increased tire damage when aircraft are operating on a runway smooth enough to prevent sufficient wear to carry away excess tire heat. For the Orbiter tire, it appears that a balance between surface texture and tread heating can be achieved to minimize tire wear or damage. A device known as the Skidabrader™ was shown to be effective at reducing the texture of the existing KSC SLF runway while retaining adequate wet-friction performance. The reduced texture approximately doubled the capability of the tire to absorb side energy, thus enabling the tire to withstand 20-knot crosswind landings while retaining some wear margin to allow for various landing dispersions. The Skidabrader™ shotpeening machine was used to modify the entire KSC SLF runway. Since completion of the modification in September 1994, numerous landings have been conducted to date with no tire-wear anomalies. The runway surface texture will continue to be monitored as will Orbiter tire-wear behavior, as opportunities to land in higher crosswinds arise.

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Hampton, VA 23681-0001
December 15, 1996

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Table 1. Description of Test Surfaces

Test surface	Original surface	Texture modification
1	[a]LG	Methacrylate: double coating
2	LG	Methacrylate: single coating
3	LG	[c]Skidabrader™: 100 ft/min
4	[b]TG	Skidabrader™: 100 ft/min
5	LG	Skidabrader™: 150 ft/min
6	TG	Skidabrader™: 150 ft/min
7	LG	Skidabrader™: 220 ft/min
8	TG	Skidabrader™: 220 ft/min
9	LG	Rotopeening: longitudinal
10	TG	Rotopeening: lateral
11	LG	Rotopeening: longitudinal, new belt
12	LG	Rotopeening: longitudinal
13	TG	Rotopeening: longitudinal
14	LG	Solid head-cutter diamond grinding
15	TG	Solid head-cutter diamond grinding
16	LG	Diamond-saw grinding: 5 blades/in.
17	LG	Original corduroy TD zone
18	TG	Original center section

[a]Longitudinal grinding (corduroy touchdown zones)
[b]Transverse grooving (center section)
[c]Skidabrader™ shotpeening machine (Humble Equipment Company)

Table 2. Texture Characterization Measurements for Test Surfaces

Test surface	Original surface	Description of texture modification	ATD, in.	[a]BPT	BPT	Outflow meter, sec	Mu-meter, 40 mph	Mu-meter, 60 mph	Skid trailer, 40 mph	Skid trailer, 60 mph
1	[b]LG	Methacrylate: double coating	.0056	41	37					
2	LG	Methacrylate: single coating	.0123	75	48					
3	LG	[d]Skidabrader™: 100 ft/min	.0104	83	73	5.11		.41		
4	[c]TG	Skidabrader™: 100 ft/min	.0130	86	76	.85		.7		
5	LG	Skidabrader™: 150 ft/min	.0115	76	73			.39	.55	.38
6	TG	Skidabrader™: 150 ft/min	.0159	86	83	.77		.7	.64	.57
7	LG	Skidabrader™: 220 ft/min	.0119			4.63	.69	.44		
8	TG	Skidabrader™: 220 ft/min	.0136			.90	.79	.7		
9	LG	Rotopeening: longitudinal	.0083							
10	TG	Rotopeening: lateral	.0108	76	86	1.30	.8	.72	.58	.47
11	LG	Rotopeening: longitudinal, new belt	.0104	75	65					
12	LG	Rotopeening: longitudinal	.0088			5.52				
13	TG	Rotopeening: longitudinal	.0119			.85				
14	LG	Solid head-cutter diamond grinding	.0046							
15	TG	Solid head-cutter diamond grinding	.0062	56	76	3.20				
16	LG	Diamond-saw grinding: 5 blades/in.	.0108	83	64					
17	LG	Original corduroy TD zone	.0210	84	73	3.08	.91	.83	.55	.38
18	TG	Original center section	.0192	88	84	.91	.82	.73	.71	.63

[a]British pendulum tester
[b]Longitudinal grinding (corduroy touchdown zones)
[c]Transverse grooving (center section)
[d]Skidabrader™ shotpeening machine (Humble Equipment Company)

Table 3. LSRA Test Conditions

(a) Nominal conditions

Crosswind, knots	20
Target touchdown speed, knots	205
Start of derotation, knots	≈175
Tire peak load, lb	120 000
Centerline tracking	No steering

(b) Types of dispersions

Type	Dispersions
A	225-knot touchdown speed
B	Additional 0.4° touchdown yaw to model drift
C	Simulator error of 0.2° additional slip near peak load time
D	Aggressive steering; 3° additional yaw triangular pulse 4.5 sec long immediately after peak load
E	High-rate derotation increases tire vertical load to 142 000 lb
F	Right crosswind forces vehicle to assume yaw to counter tire ply-steer (extra 0.6° at wheelstop)

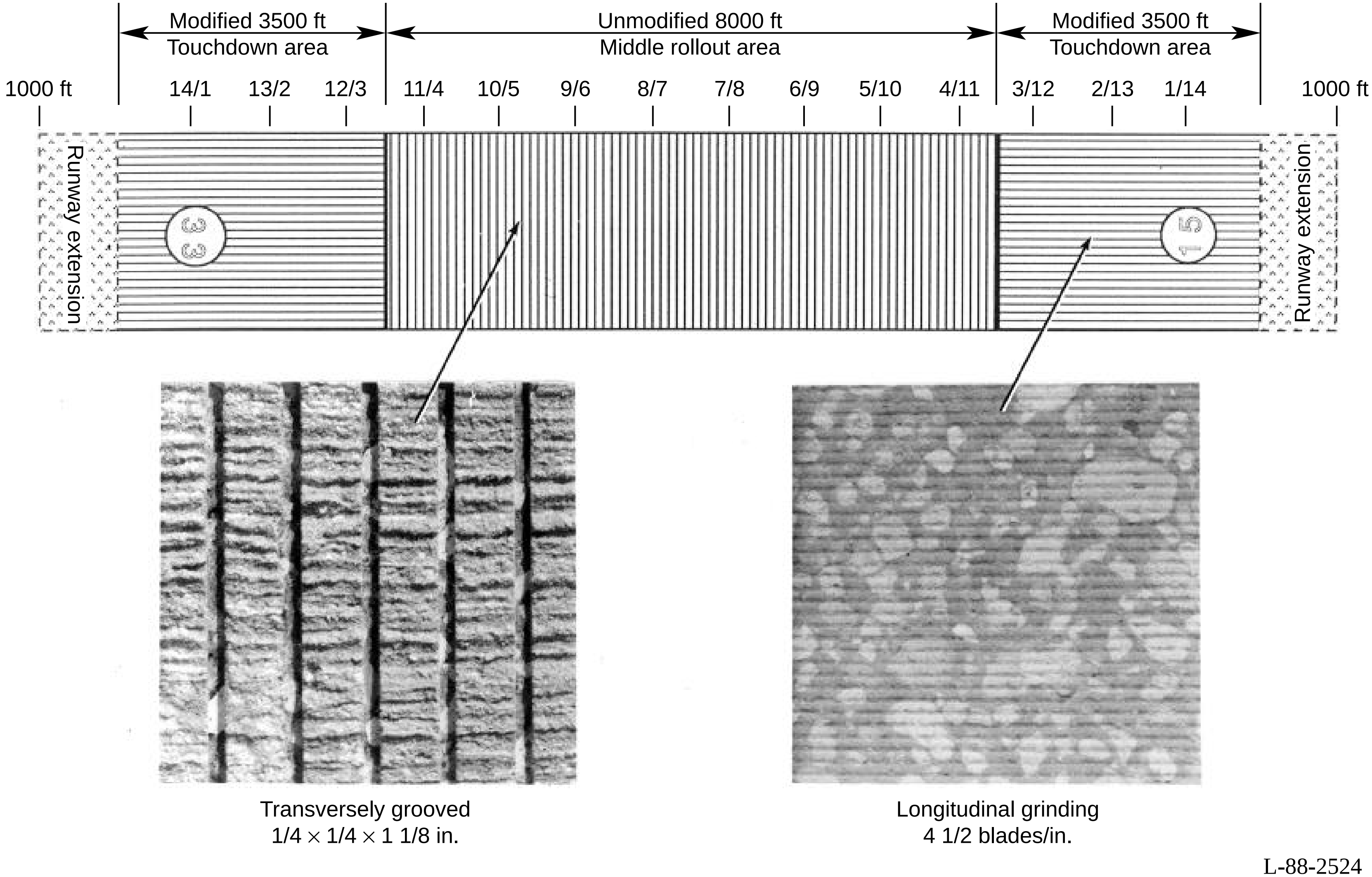
(c) Case definitions

Case	Nominal landing plus types of dispersions included
9	A, B, C, E, F
10	A, B, C, D, E, F
11	A, B, C, D, E

Table 4. Instrumented Tire-Test Vehicle (ITTV) Test-Surface Wear Summary

Test surface	Description of texture modification	Wear rate, lbm/ft	ATD, in.
1	Methacrylate: double coating		.0056
2	Methacrylate: single coating	308.4E-6	.0123
3	[a]Skidabrader™: 100 ft/min	330.4E-6	.0104
4	Skidabrader™: 100 ft/min	418.5E-6	.0130
5	Skidabrader™: 150 ft/min	330.4E-6	.0115
6	Skidabrader™: 150 ft/min	506.6E-6	.0159
7	Skidabrader™: 220 ft/min		.0119
8	Skidabrader™: 220 ft/min		.0136
9	Rotopeening: longitudinal		.0083
10	Rotopeening: lateral	242.3E-6	.0108
11	Rotopeening: longitudinal, new belt	330.4E-6	.0104
12	Rotopeening: longitudinal		.0088
13	Rotopeening: longitudinal	440.5E-6	.0119
14	Solid head-cutter diamond grinding		.0046
15	Solid head-cutter diamond grinding	198.2E-6	.0062
16	Diamond saw grinding, 5 blades/in.	418.5E-6	.0108
17	None, original corduroy TD zone	616.7E-6	.0210
18	None, original center section	594.7E-6	.0192

[a]Skidabrader™ shotpeening machine (Humble Equipment Company)



(a) Original texture.

(b) Corduroy texture.

Figure 1. Kennedy Space Center Shuttle Landing Facility (SLF) runway surface layout prior to testing.

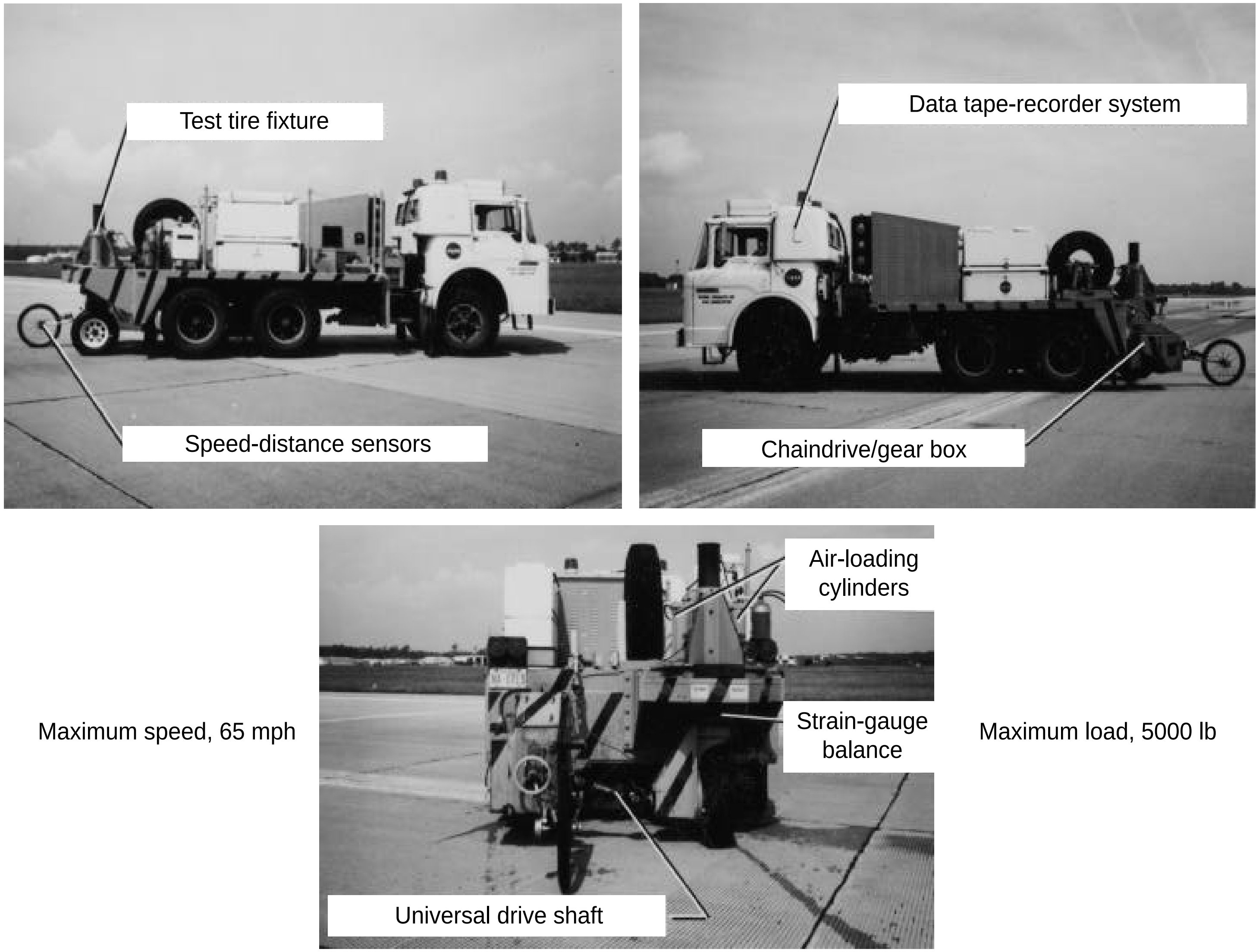


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Figure 2. Instrumented Tire-Test Vehicle (ITTV).

Figure 3. Landing Systems Research Aircraft (LSRA).

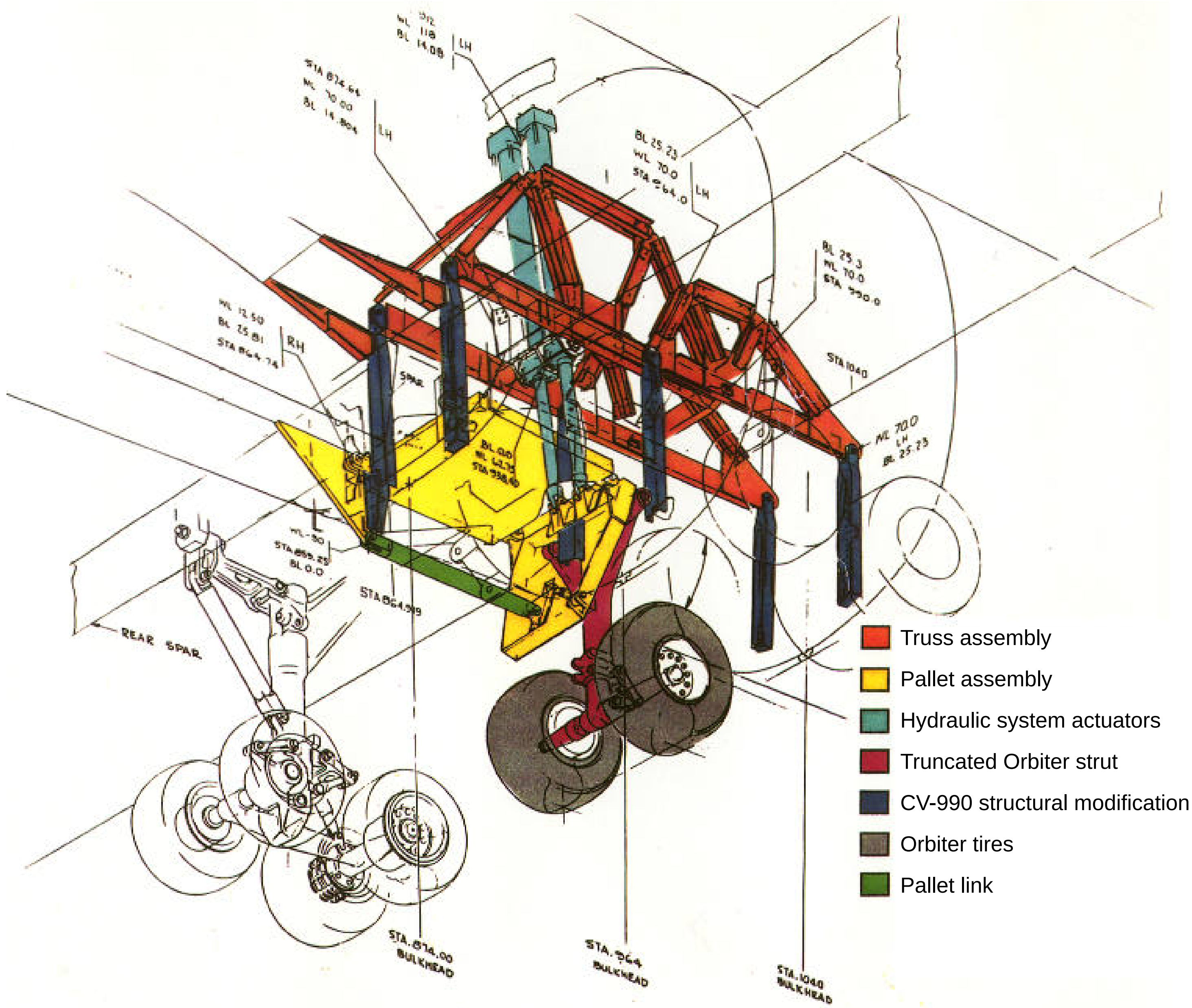

Figure 4. Schematic of LSRA test gear modification.

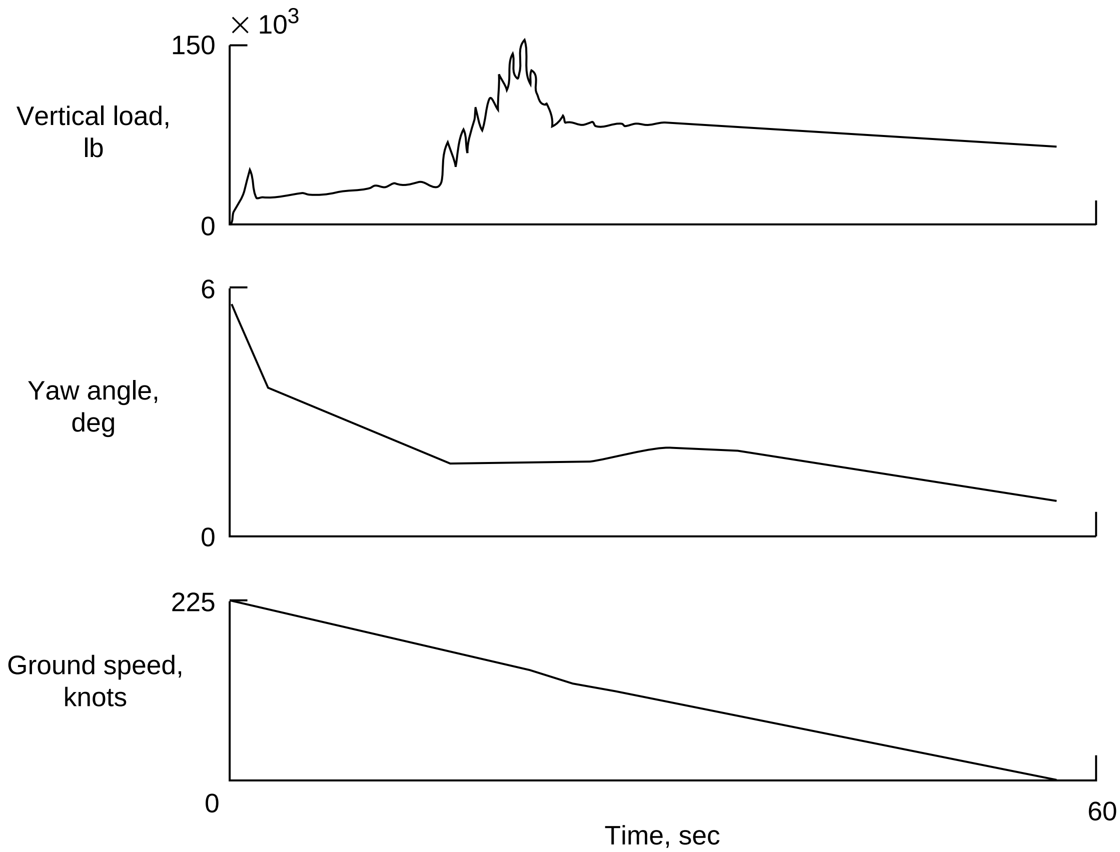

Figure 5. Typical time histories of inputs for LSRA test fixture.

(a) ITTV test tires.

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(b) Orbiter main gear tire used during LSRA testing.

Figure 6. Test tires.

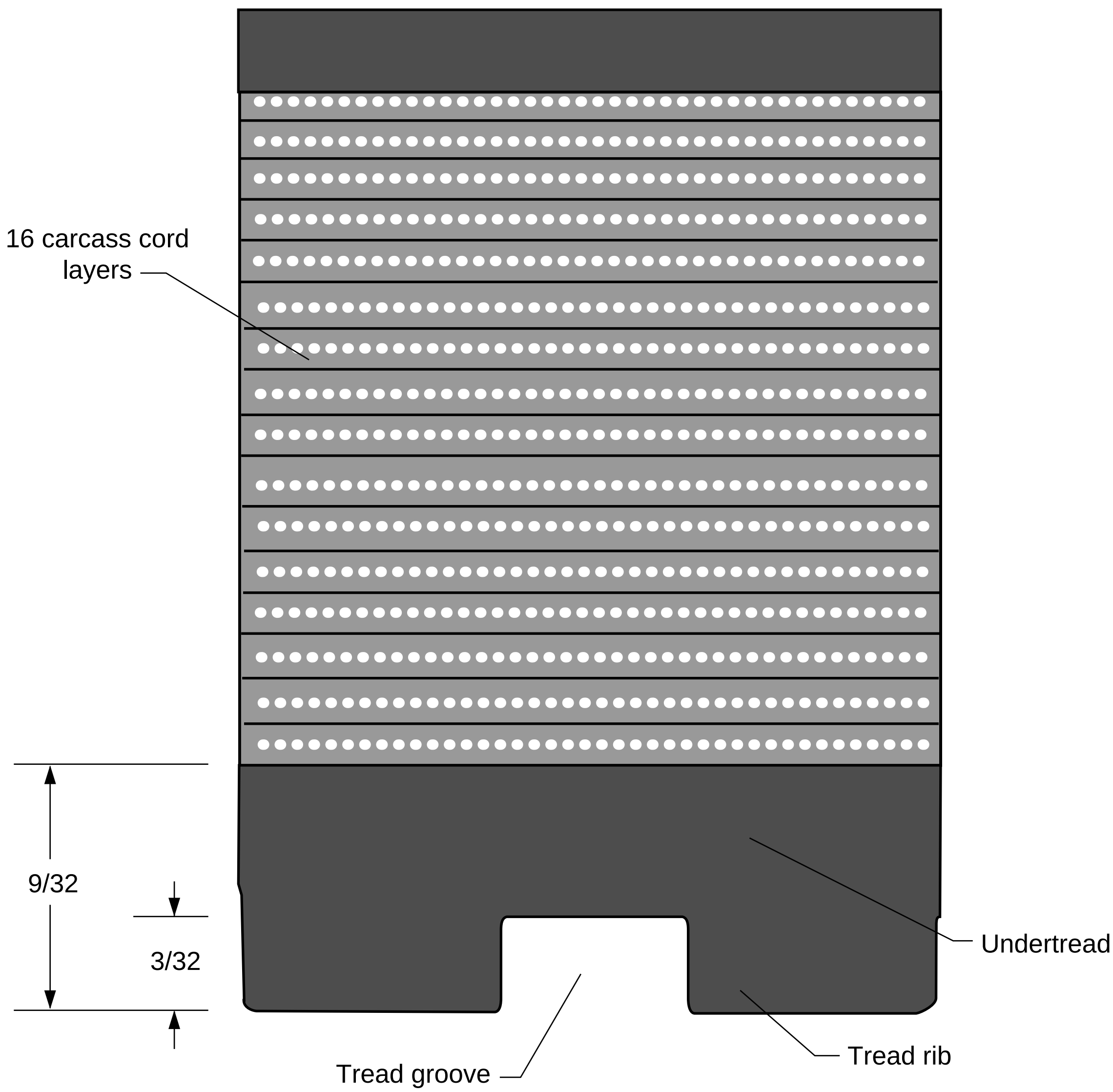


Figure 7. Cross section of modified Orbiter main gear tire. Dimensions are in inches.

(a) Mu-meter and tow vehicle.

(b) Skid trailer and tow vehicle.

Figure 8. Other test vehicles.

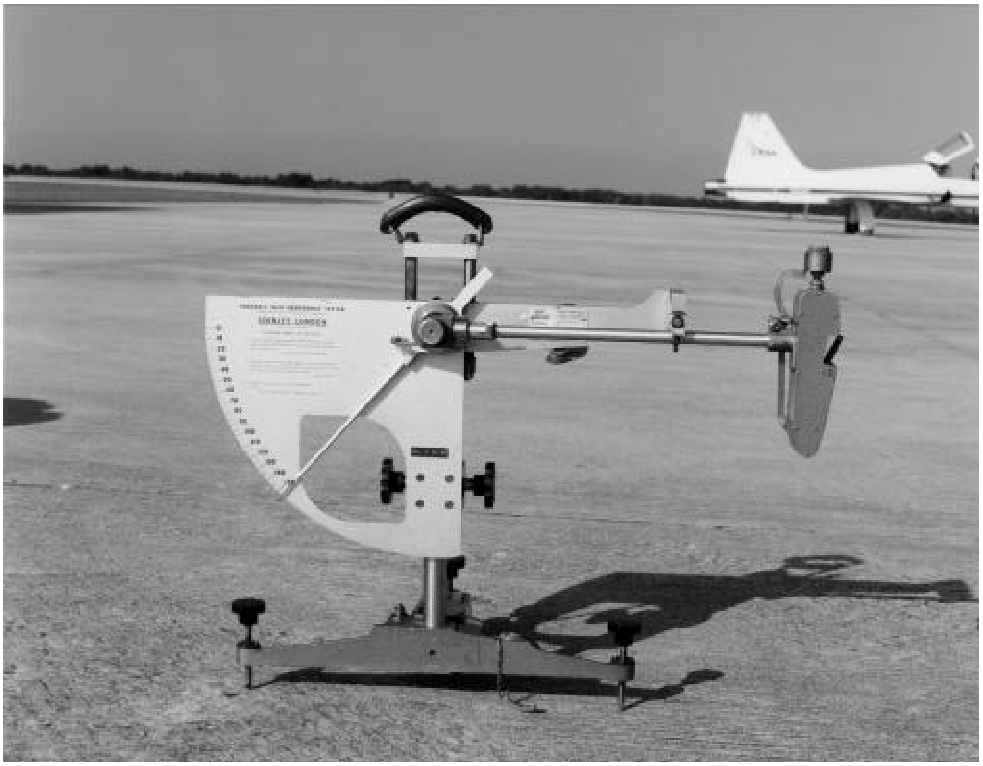


Figure 9. British pendulum tester (BPT).

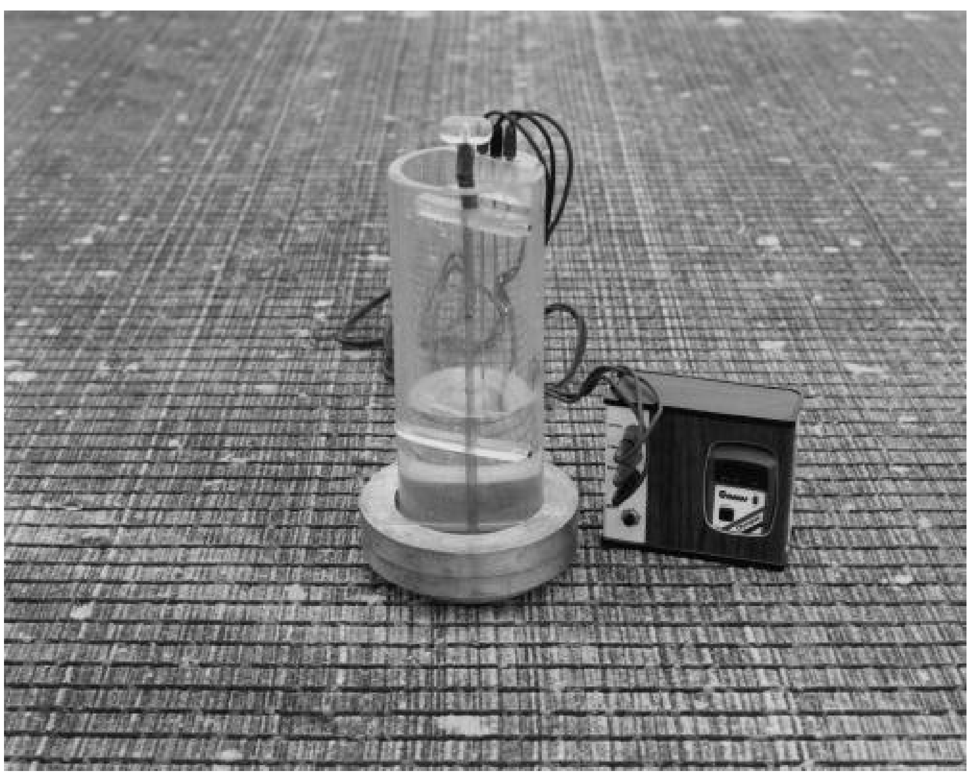
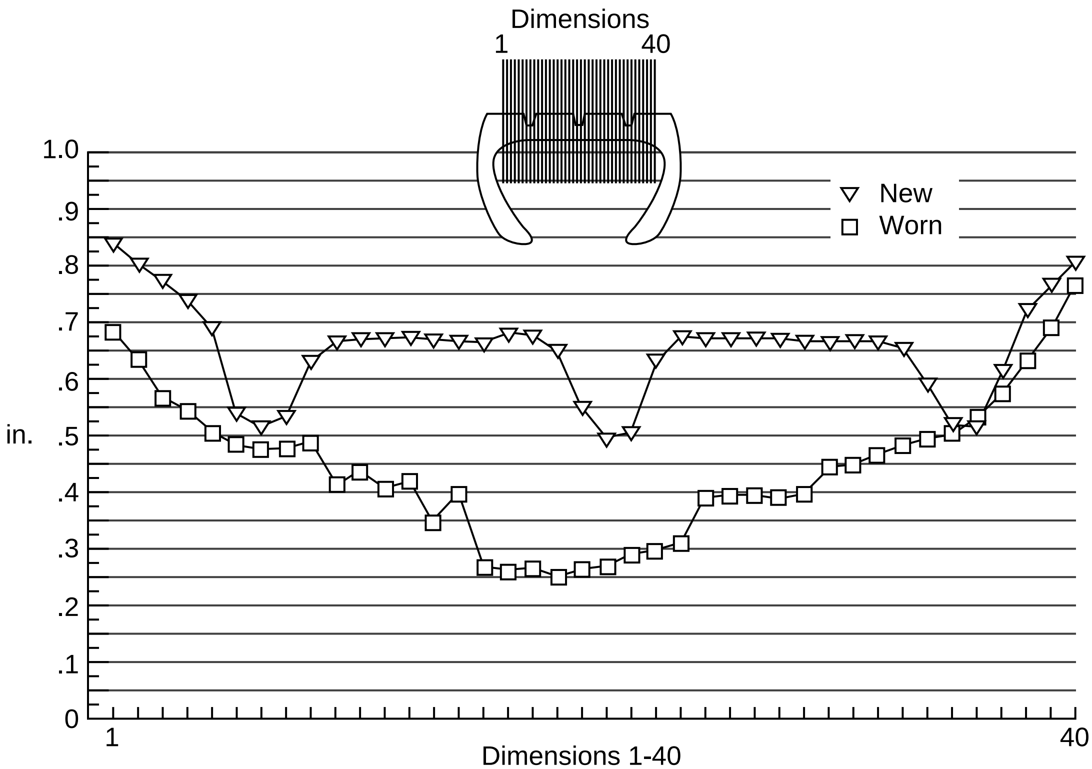
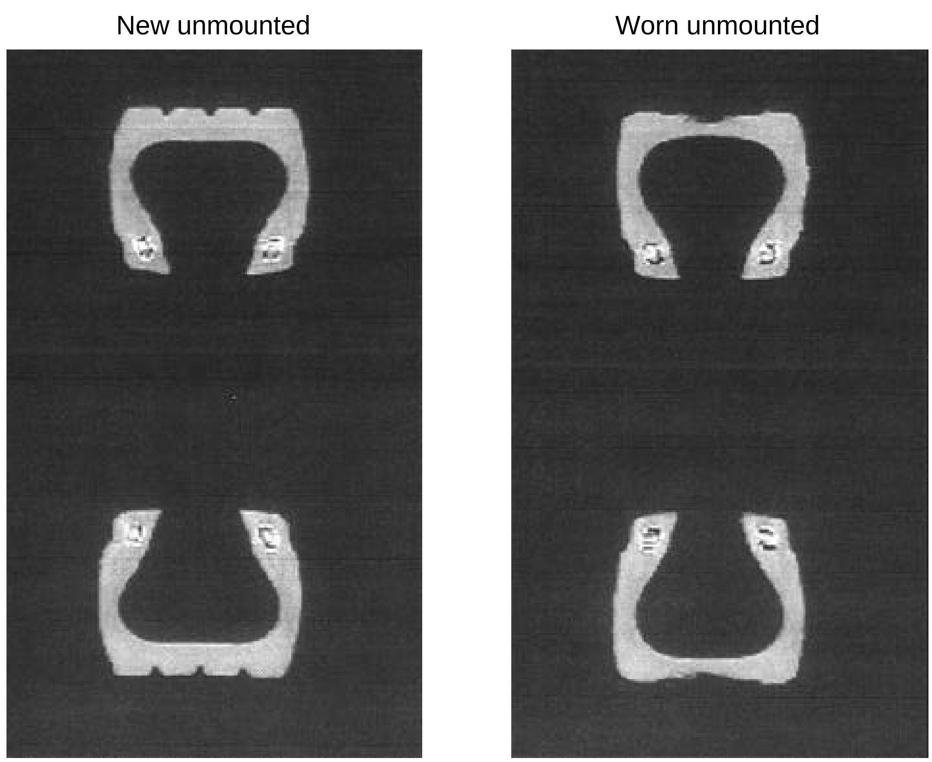


Figure 10. Outflow meter.

Figure 11. Grease sample texture-measurement kit.

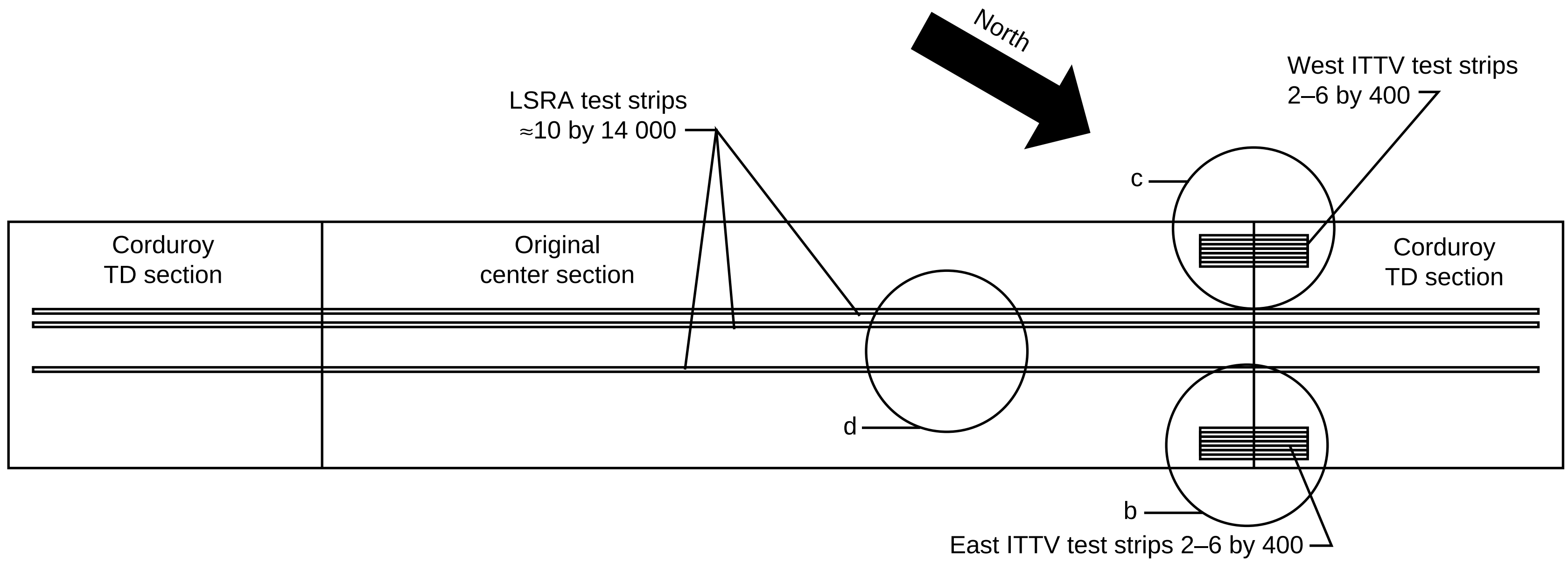


(a) New versus worn tire-profile comparison.



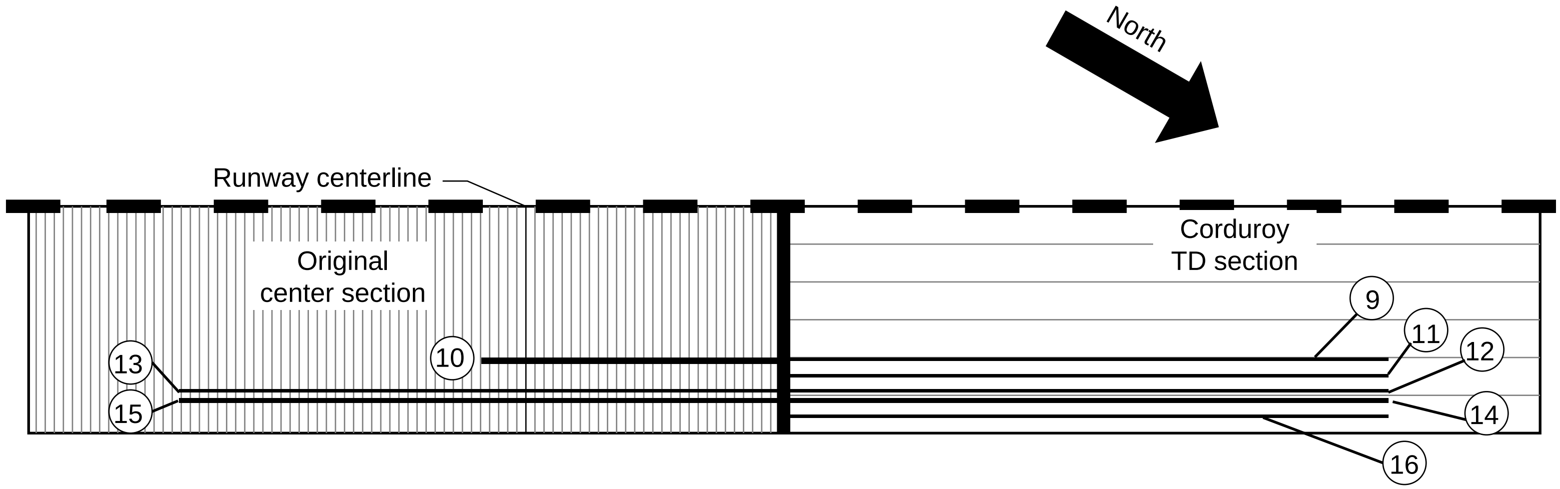
(b) Tire scan images.

Figure 12. Computer tomography examples.

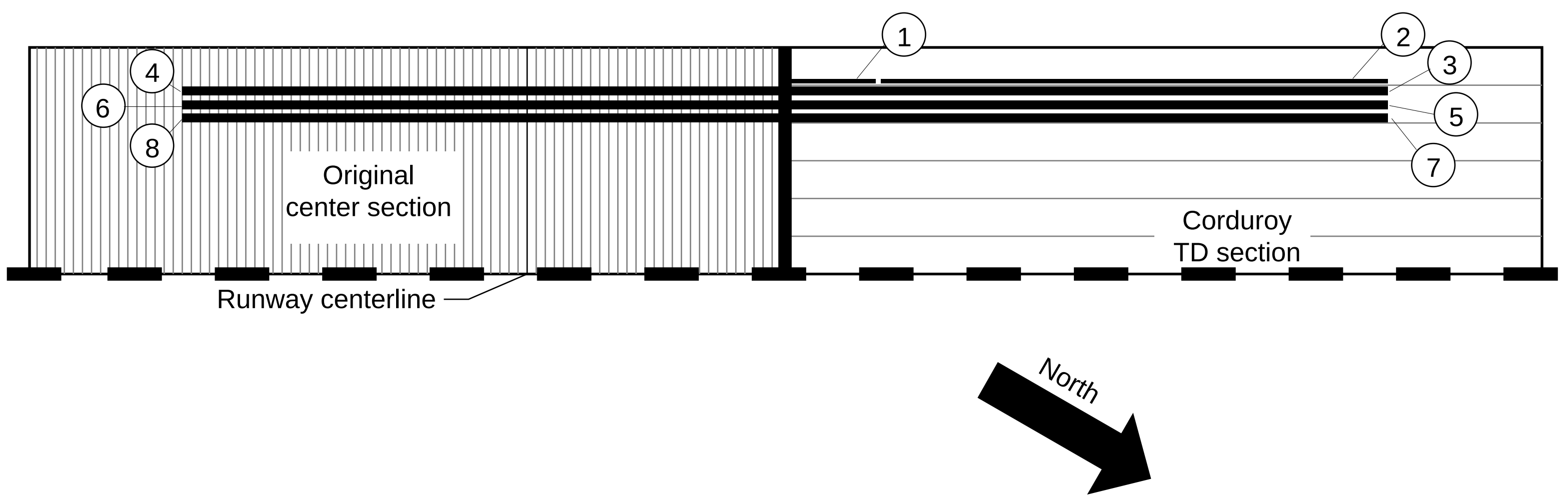


(a) Overall layout.

Figure 13. KSC SLF test-setup layout. Dimensions are in feet.

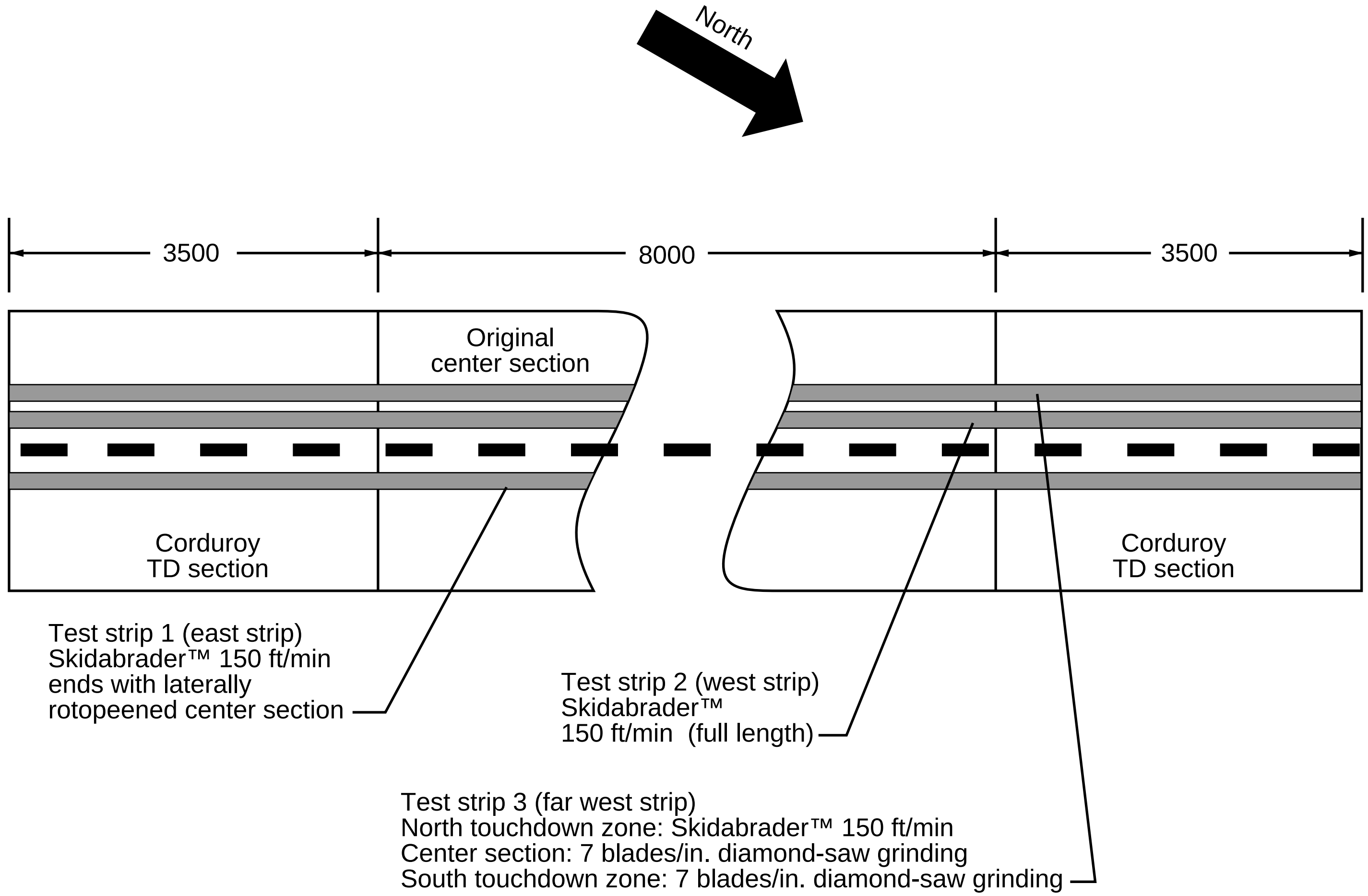


(b) East ITTV test strips. Circled numbers denote test-surface numbers.



(c) West ITTV test strips. Circled numbers denote test-surface numbers.

Figure 13. Continued.



(d) LSRA test strips. Dimensions are in feet.

Figure 13. Concluded.

Figure 14. Diamond-blade-grinding machine.

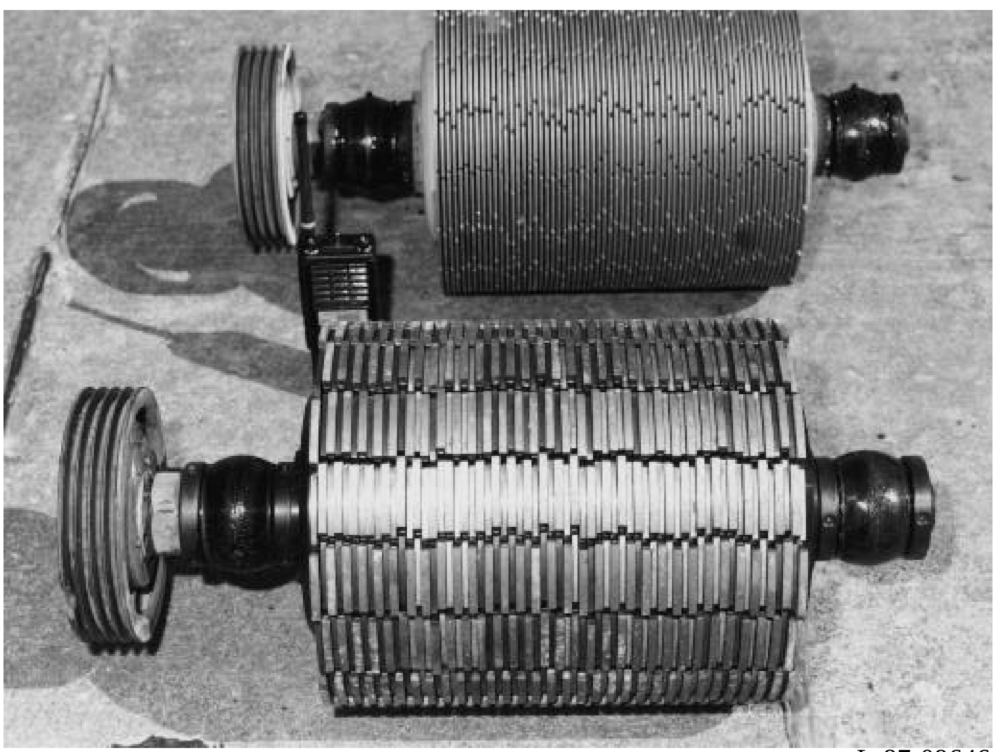


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Figure 15. Diamond-blade-grinding machine cutting heads.

Figure 16. Large diamond-blade-grinding machine.

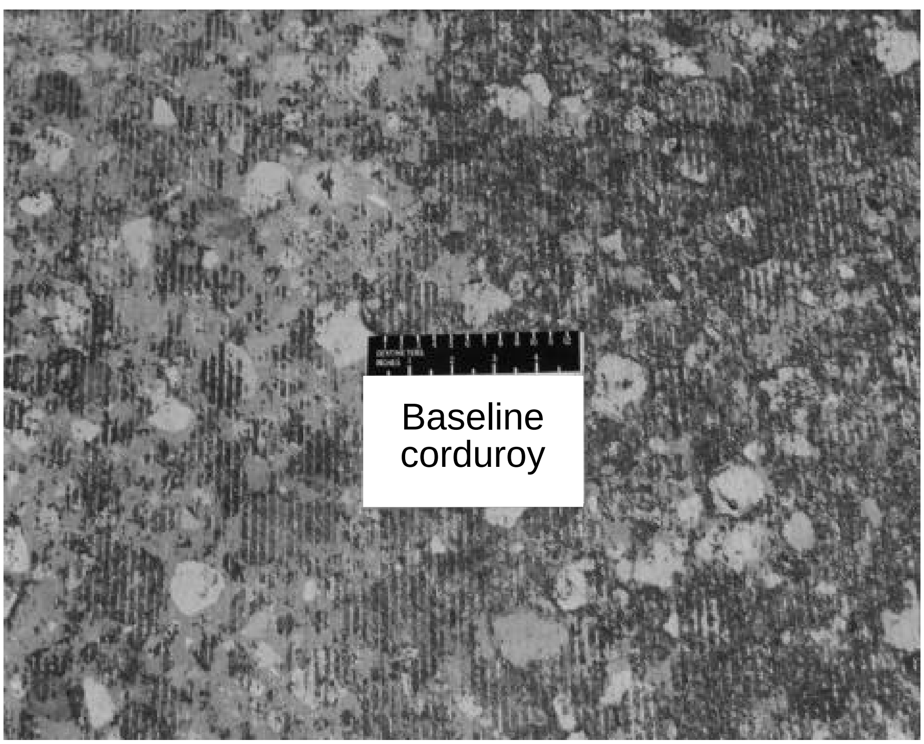
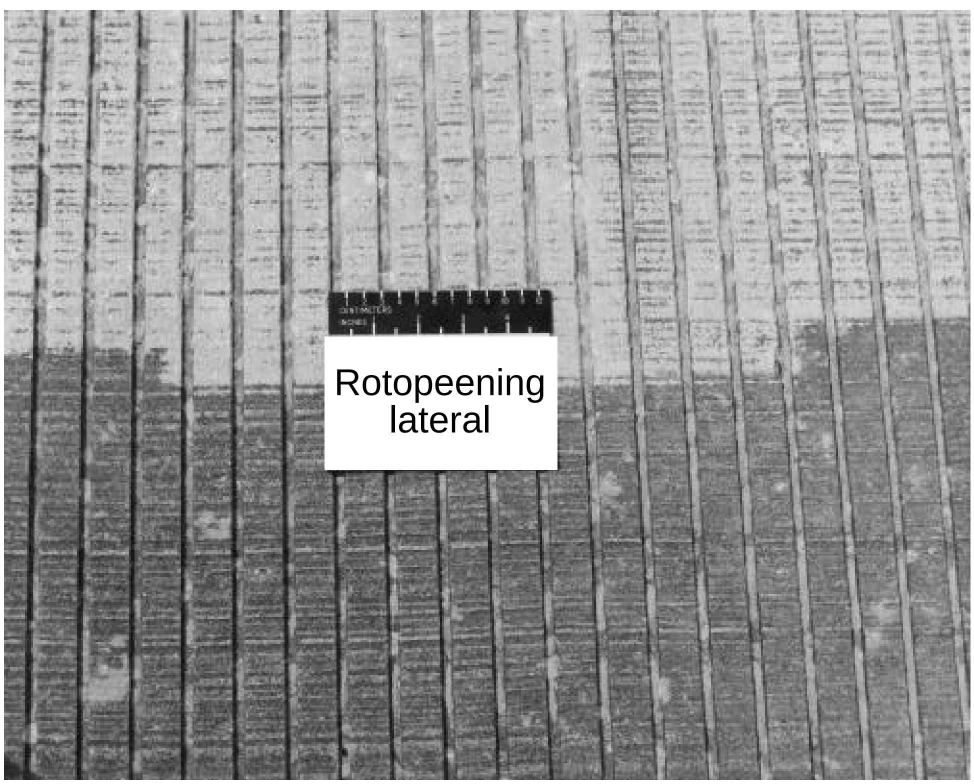


Figure 17. Typical appearance of corduroy texture.

Figure 18. Skidabrader™ machine in operation.

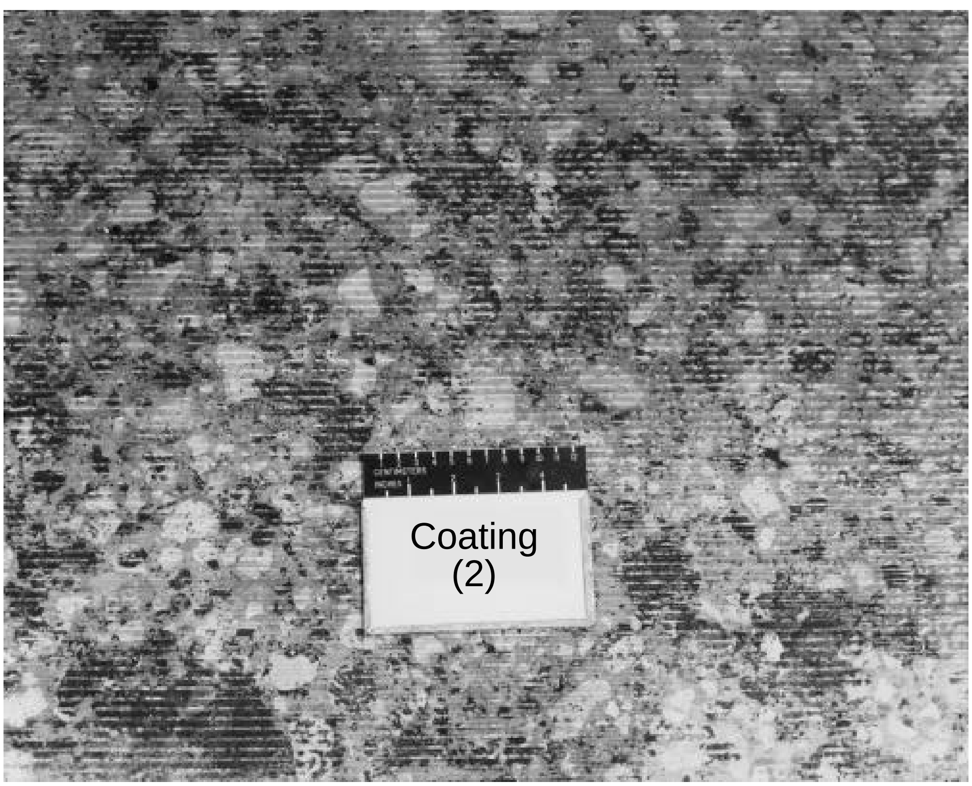
(a) Lateral application.



(b) Surface after rotopeening.

Figure 19. Rotopeener machine.

(a) Application to corduroy surface.



(b) Appearance of methacrylate after drying on surface.

Figure 20. Methacrylate coating.

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Figure 21. Typical *bull's-eye* appearance of spin-up wear spot after cornering.

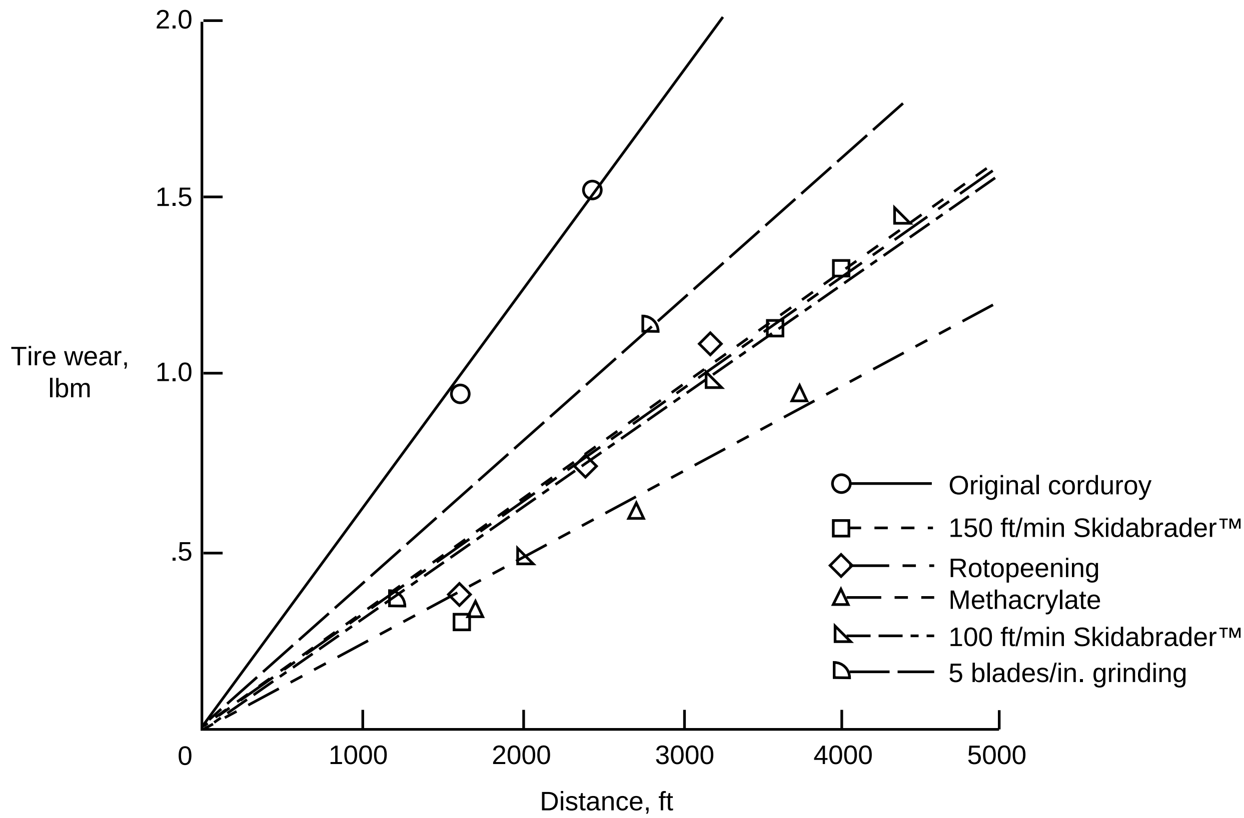

Figure 22. Tire-wear behavior on modifications to touchdown zone surface.

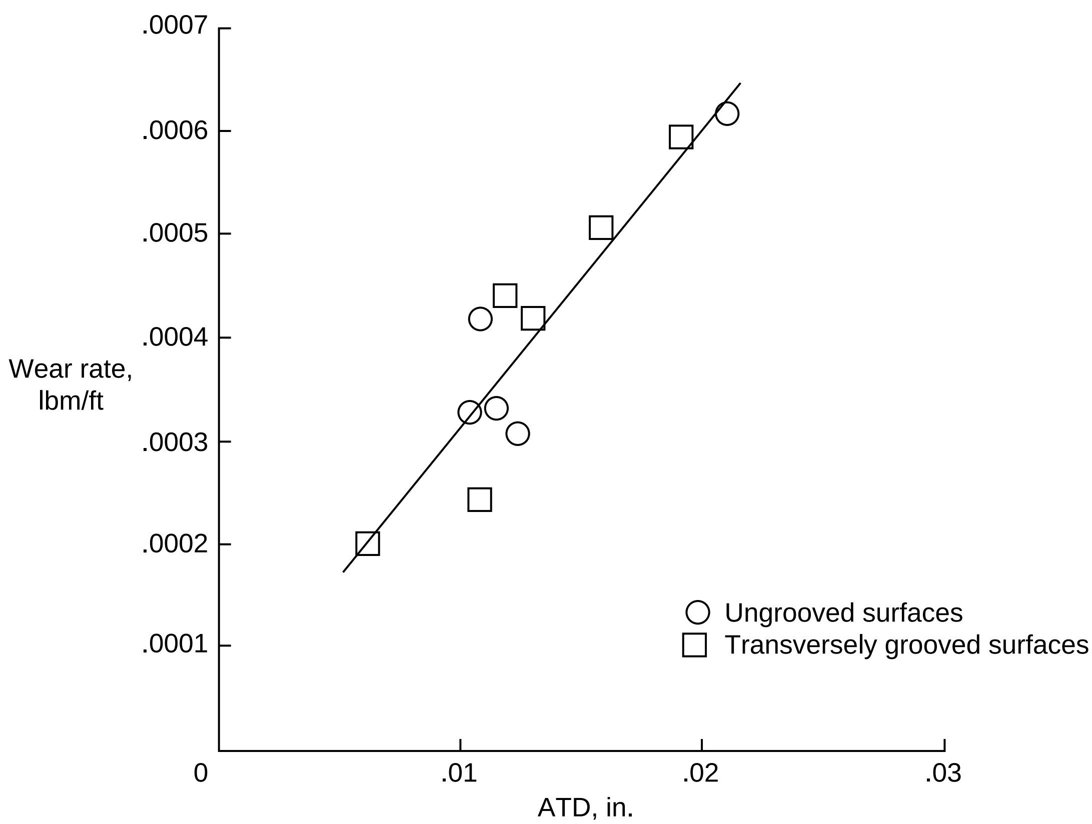

Figure 23. Relationship between wear rate and average texture depth (ATD).

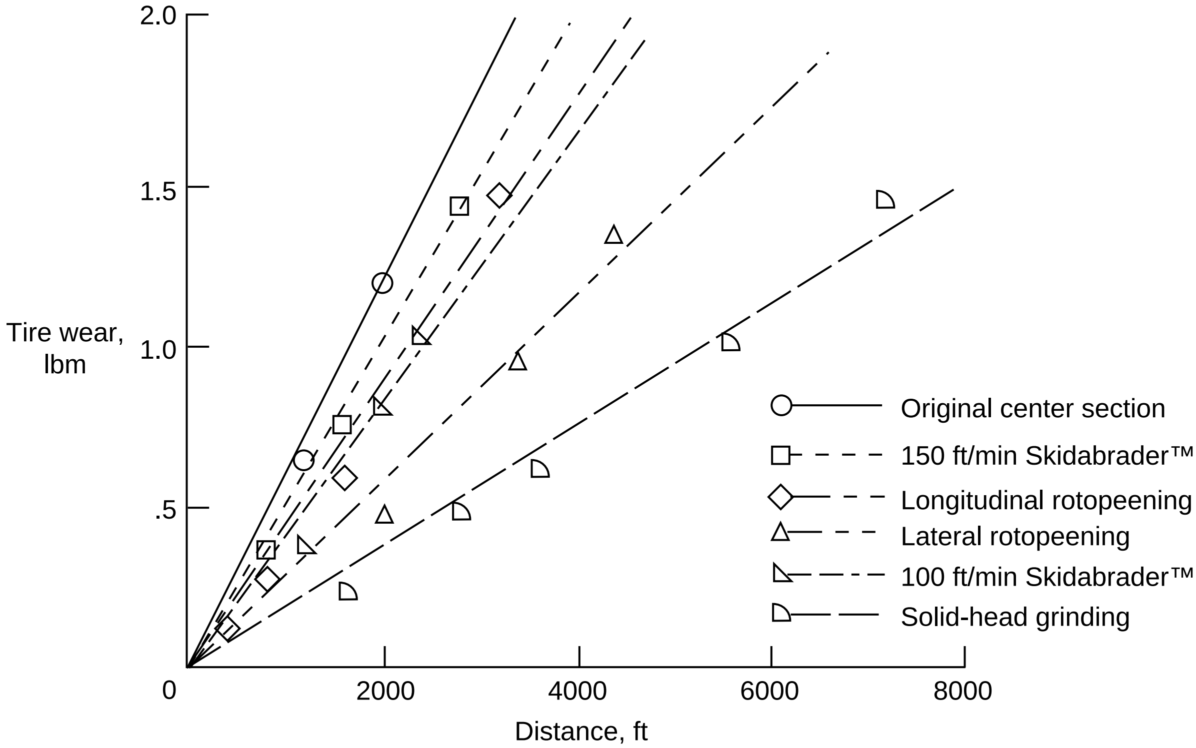

Figure 24. Tire-wear behavior on modifications to original center-section surface.

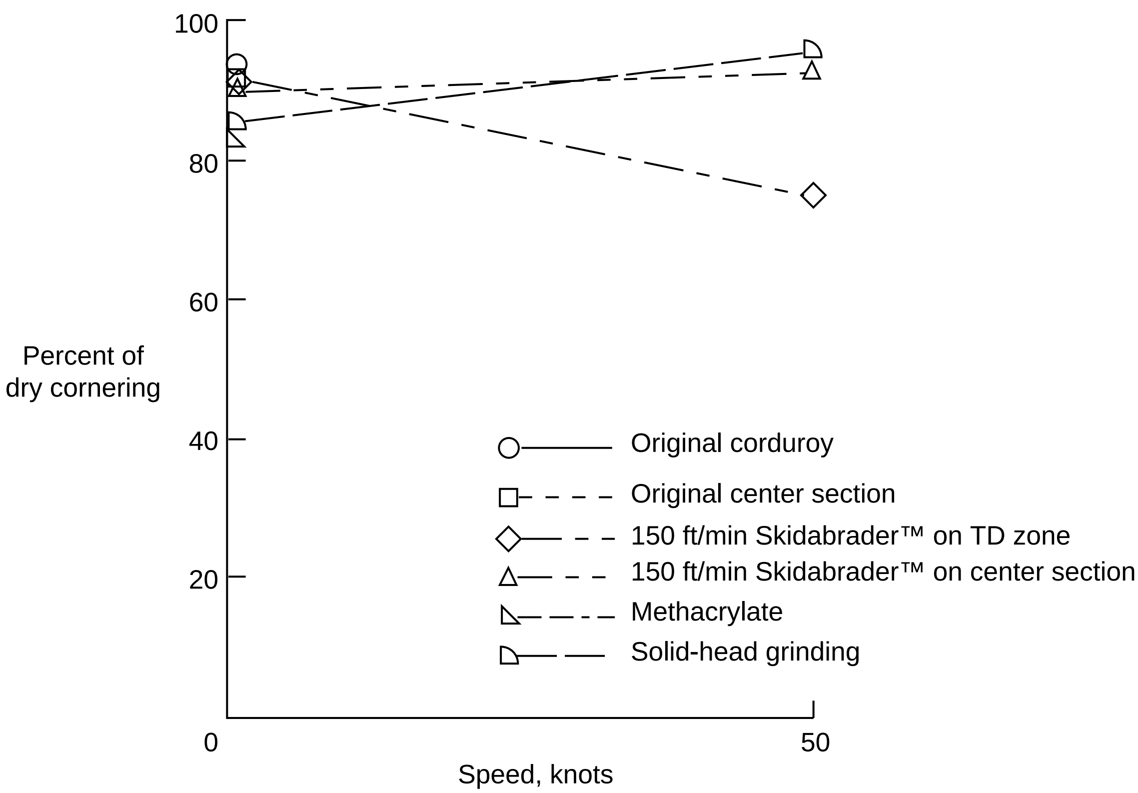

Figure 25. Effect of speed on wet-cornering performance for various textures.

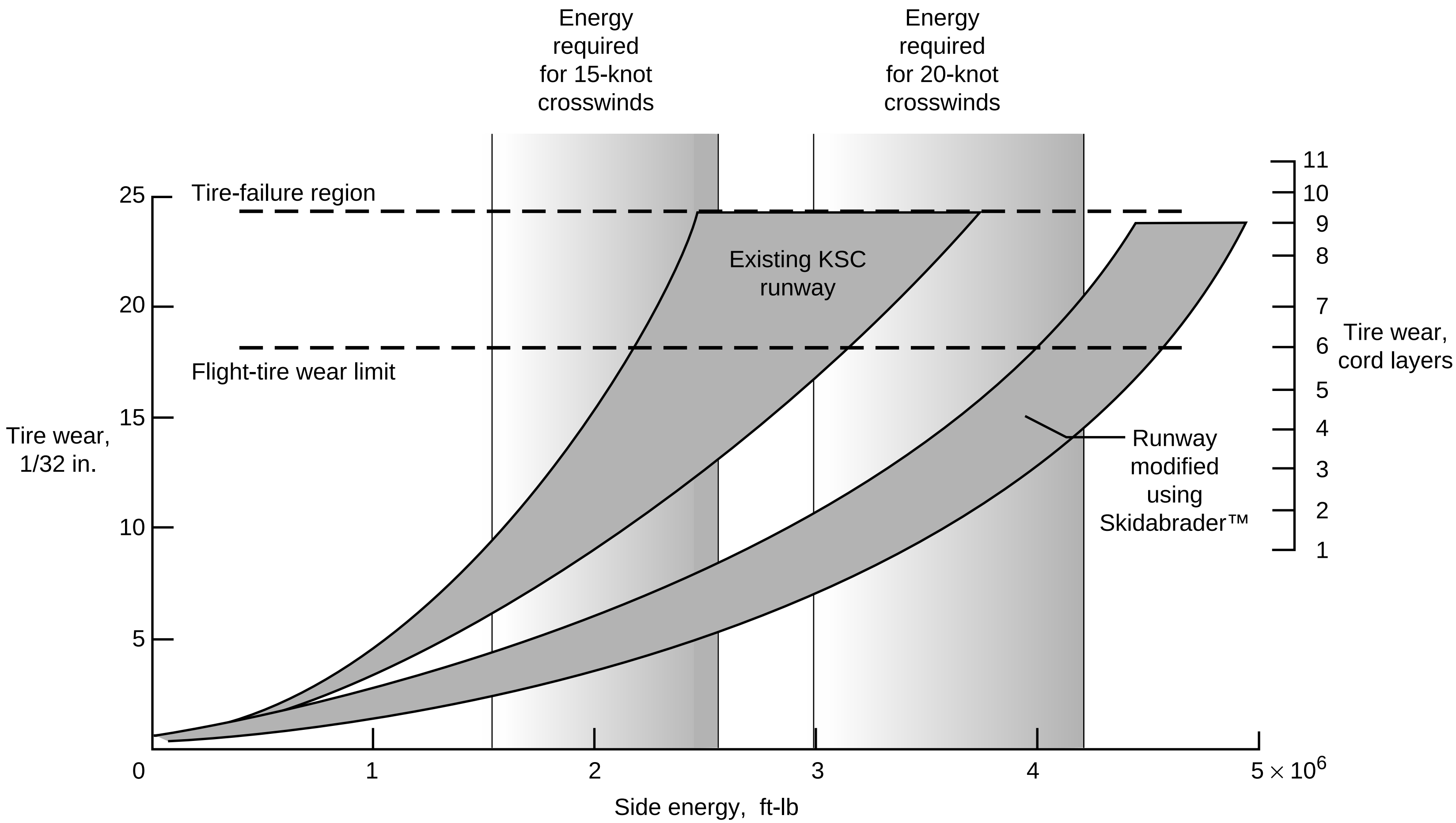

Figure 26. Tire-wear behavior on existing KSC runway and runway modified by using the Skidabrader™ machine.

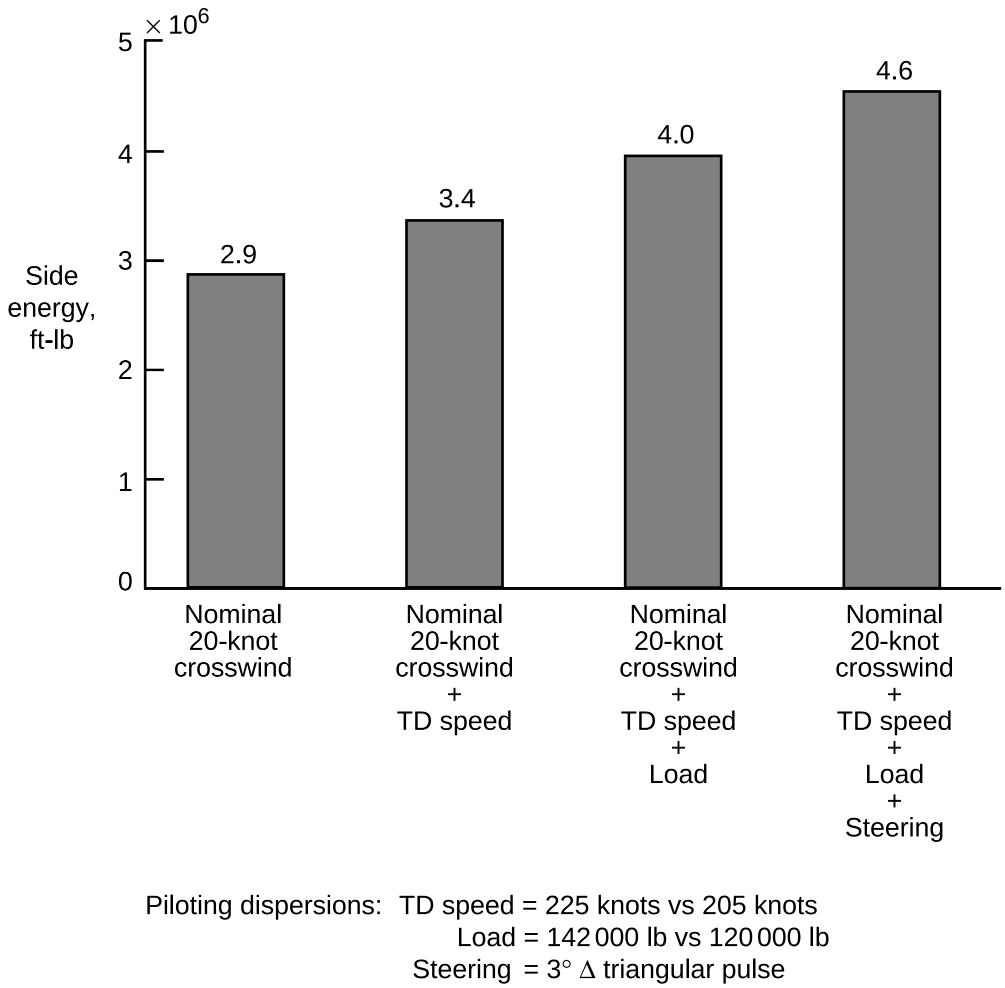

Figure 27. Tire side energy required for nominal 20-knot crosswind landing with and without piloting dispersions.

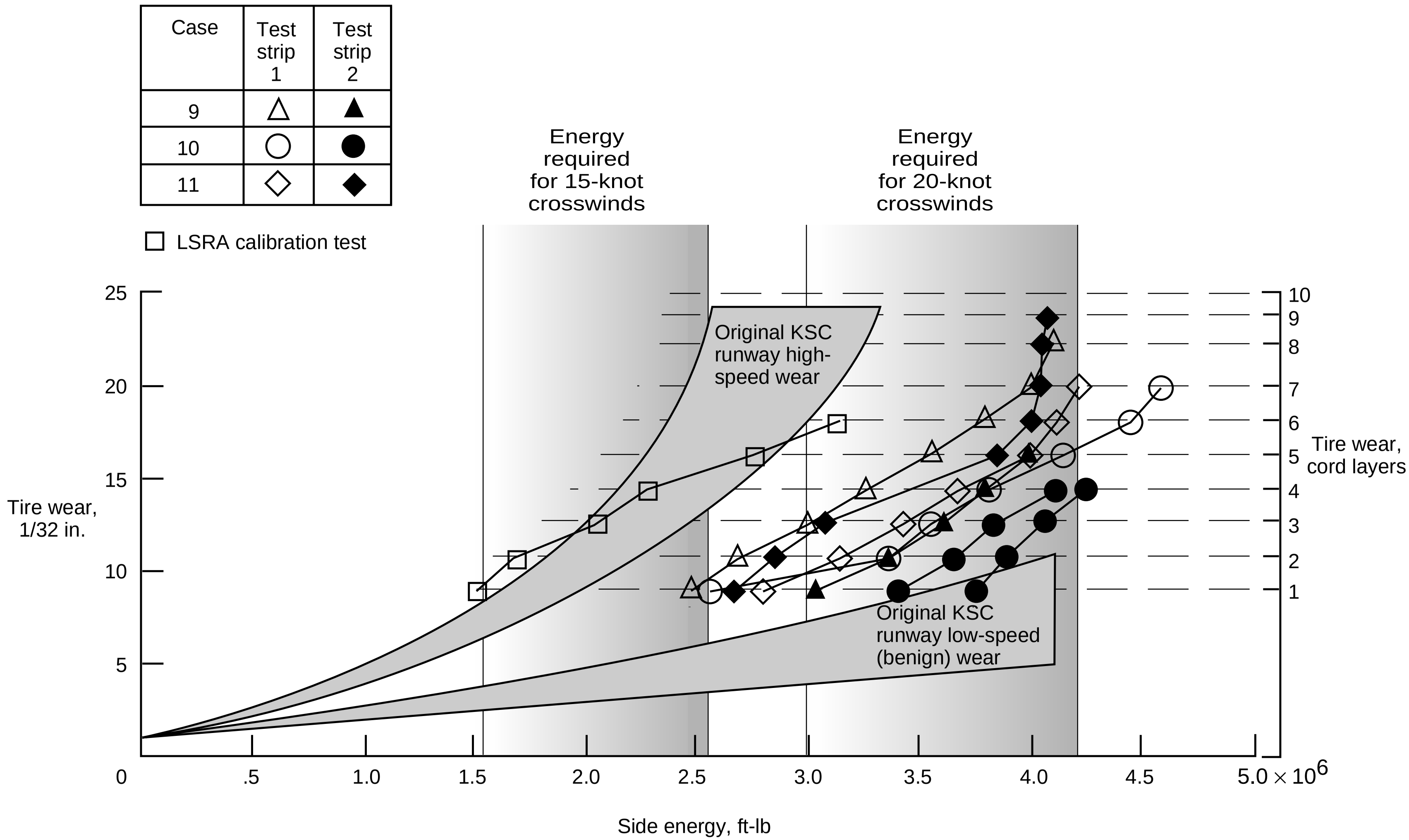

Figure 28. LSRA wear results on test strips 1 and 2.

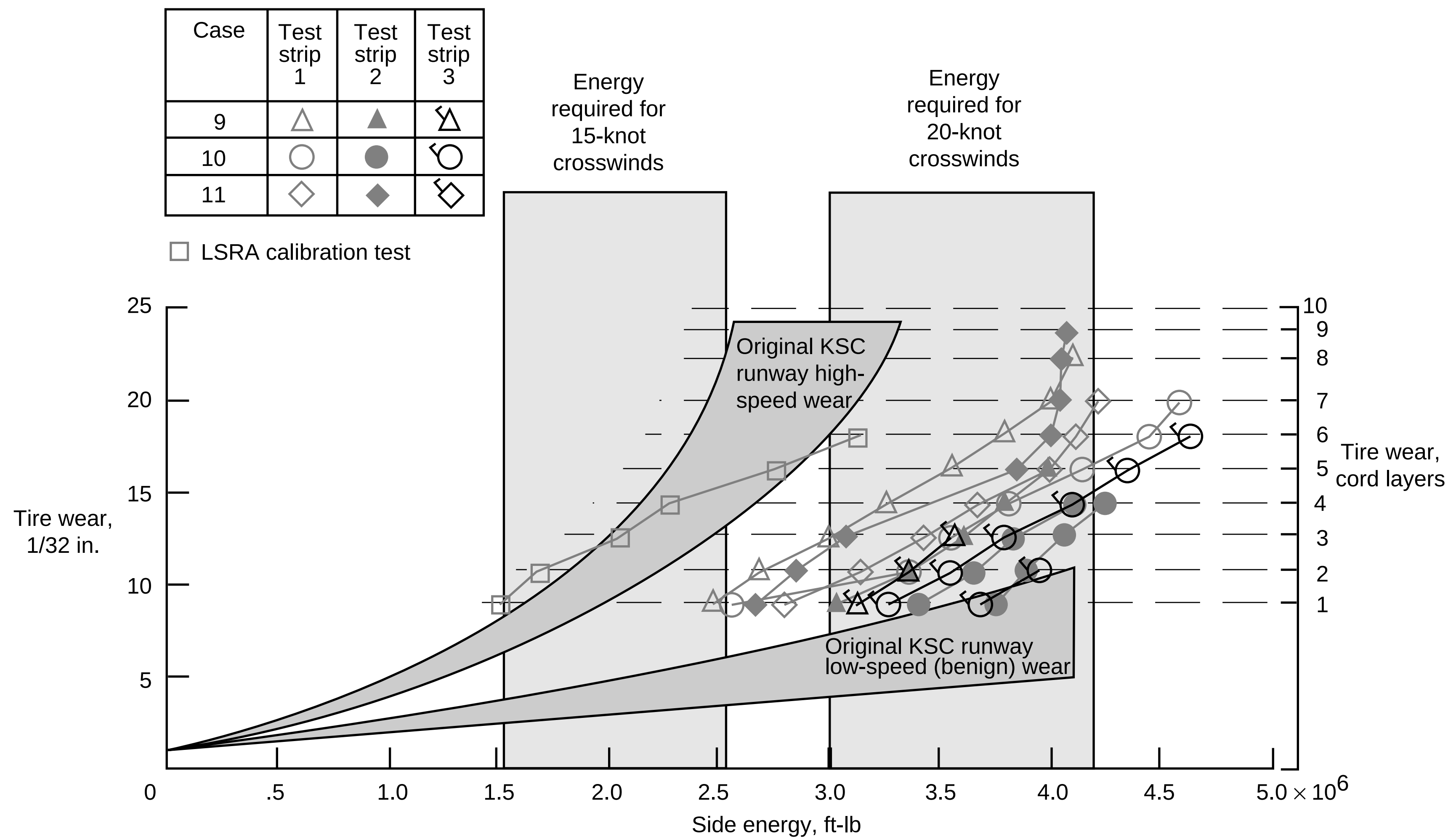

Figure 29. LSRA wear results on test strips 1, 2, and 3.

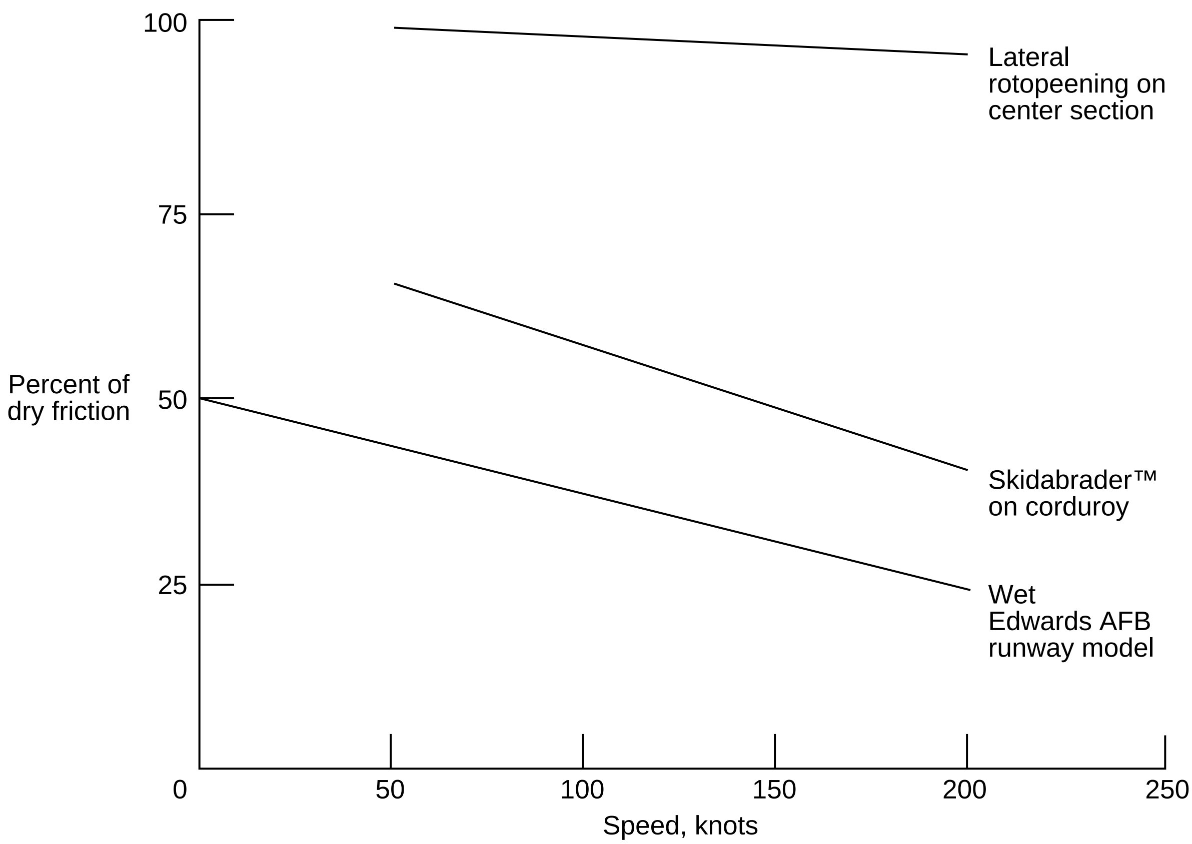

Figure 30. Effect of speed on wet-friction behavior on modified surfaces.

Figure 31. View of Skidabrader™ machines modifying entire SLF runway.

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13. ABSTRACT *(Maximum 200 words)*

This paper describes the test procedures and the criteria used in selecting an effective runway-surface-texture modification at the Kennedy Space Center (KSC) Shuttle Landing Facility (SLF) to reduce Orbiter tire wear. The new runway surface may ultimately result in an increase of allowable crosswinds for launch and landing operations. The modification allows launch and landing operations in 20-knot crosswinds, if desired. This 5-knot increase over the previous 15-knot limit drastically increases landing safety and the ability to make on-time launches to support missions in which Space Station rendezvous are planned. The paper presents the results of an initial (1988) texture modification to reduce tire spin-up wear and then describes a series of tests that use an instrumented ground-test vehicle to compare tire friction and wear characteristics, at small scale, of proposed texture modifications placed into the SLF runway surface itself. Based on these tests, three candidate surfaces were chosen to be tested at full-scale by using a highly modified and instrumented transport aircraft capable of duplicating full Orbiter landing profiles. The full-scale Orbiter tire testing revealed that tire wear could be reduced approximately by half with either of two candidates. The texture-modification technique using a Humble Equipment Company Skidabrader™ shot-peening machine proved to be highly effective, and the entire SLF runway surface was modified in September 1994. The extensive testing and evaluation effort that preceded the selection of this particular surface-texture-modification technique is described herein.

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