STANDARDIZATION OF FRICTION TESTING OF INDUSTRIAL WORKING SURFACES

NIOSH Research Report

STANDARDIZATION OF FRICTION TESTING
OF INDUSTRIAL WORKING SURFACES

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Project Officer
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PREFACE

This report describes the historical and technical bases for the development of a friction testing device designed for monitoring the safety of industrial walkway surfaces. The device called the Universal Friction Testing Machine (UFTM) is also intended for laboratory use to measure coefficients of friction of footwear materials.

Readers of the report will be appraised of the state-of-the-art of friction testing of shoe materials, floor polishes, and walkway surfaces and will be informed of the desirability of standardizing procedures and devices for the measurement of coefficients of friction.

Comstock & Wescott, Inc. carried out the year-long assignment for the National Institute for Occupational Safety and Health under the direction of Project Officer, Jeff I. Kamin, Engineering Branch, Division of Laboratories and Criteria Development.

ACKNOWLEDGMENTS

We are indebted to Angus P. Wilson and Patrick J. Mahoney of the U. S. Army Natick Laboratories for their cooperation in providing previously unpublished data obtained from their British Portable Tester and to Wilson for his cooperation in testing the hardness and resiliency of the rubber material used for tests with the UFTM and for the testing of several comparative footwear materials.

John H. Merscher, then of S. C. Johnson and Son, Inc., provided the multilaboratory James machine test data obtained through the efforts of an ASTM task force. Merscher was Chairman of the ASTM Committee D21.06 on slip resistance.

Charles H. Irvine of the Liberty Mutual Insurance Company Research Center provided previously unpublished data obtained with his Horizontal Pull Slipmeter.

B. Everett Gray, Chairman of Committee Z-41 of the American National Standards Institute, provided several samples of typical footwear materials for physical testing as well as information concerning national usage of the materials.

To all of these contributors and to the many other helpful people who gave generously of their valuable time to provide the Principal Investigator with background information, we express our sincere appreication.

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ABSTRACT

TITLE: Standardization of Friction Testing of Industrial Working Surfaces

AUTHOR: Reed, M. E.

TEXT - (KEYWORDS) Friction, Working-Surfaces, Floors, Testing-Machine, Instrumentation, Safety-Standards, Shoes, Walking-Surfaces, Skid-Resistance, Footwear-Materials.

(BODY) The design and construction of a portable friction measuring device for use on industrial working surfaces are described. Historical background obtained from the literature, reports of interviews with current friction testing device users, and study of the theoretical aspects of the measurement of the coefficient of friction of footwear on walkway surfaces provided the basis for the concept development for the device named the Universal Friction Testing Machine (UFTM).

The operational characteristics of the presently available friction testing devices are described and compared with those of the UFTM. The results of a number of measurements made with the UFTM using rubber, leather, vinyl, and oak samples are reported.

Conclusions are drawn from the tests with recommendations made to study further the frictional transition region between static and dynamic values of friction between footwear and walkway materials.

INTRODUCTION

The Purpose and Scope of the Project

Although various devices for measuring coefficients of friction have existed since the 1940's or earlier, there is still no universally accepted standard method or device for determining such values as related to footwear and the surfaces people walk on. This report will discuss the most common methods and devices now used for determining values of coefficient of friction (COF) as well as the reasons why these methods and devices are not universally accepted by the interested parties. It will also describe work done under this contract to study this problem and to develop procedures and a test device intended to fill this need.

Those groups interested in the friction properties of footwear and working surfaces include insurance companies, floor polish manufacturers, flooring materials producers, shoe manufacturers and distributors, and the managers of enterprises at which employees walk about in performing their prescribed duties. Although they may be unaware of the technical aspects of the problem, a very large number of workers are a part of the problem of safety as it relates to the friction characteristics of footwear and floors.

The National Institute for Occupational Safety and Health (NIOSH) is authorized under Section 22c of the Occupational Safety and Health Act of 1970 to develop and establish recommended occupational safety and health standards. By Section 22d of the Act, the Director of NIOSH is empowered to conduct research and experimental programs for the development of criteria pertaining to improved safety and health standards.

This contract resulted from the recognition by NIOSH of the need to be able to measure the coefficient of friction of footwear materials on the various types of industrial working surfaces. The measurement must be made with a device which will give reproducible results from place to place and from operator to operator. It must follow a standardized procedure which can be universally accepted as being able to produce a valid measurement of the coefficient of friction of the materials involved. Sufficient study of the history and theory of friction testing must have been completed to produce a sound basis for the design of a universal friction testing machine (UFTM). This report will elaborate on all of these matters.

The Need for a UFTM

The need for standard equipment and methods for determining the coefficients of friction of footwear on floors and walkway surfaces has been recognized for quite a long time. In 1948 Sigler et al.[1] described the need for the establishment of a safety code for walkway surfaces and for an adequate method for measuring slipperiness. In 1961 Task Group T-41 reporting in a National Academy of Sciences publication[2] outlined the need for determining the relative slip-resistance of various materials and for methods of measuring slip-resistance.

In 1970 the National Commission on Product Safety issued its final report[3] to the President and Congress of the United States in which statistics of injuries related to floors, floor materials, and footwear were included. The product categories of floors, floor materials, and footwear were near the top of the lists showing the frequency and severity of injuries by category.

Thus, it may be said that the need for standardization of methods of friction testing of working surfaces has been recognized since at least as early as the mid-1940's. Action to improve the situation has now been initiated by NIOSH in the issuing of this contract.

Outline of the Project

In the development of standard test methods, the first step was to study and to evaluate the various methods presently in use in determining the friction coefficients, both static and dynamic, of various surfaces and materials. To accomplish this, the Principal Investigator visited several laboratories where friction measuring devices were commonly used and discussed the methods used with the experimenters.

In addition, a literature search was made to determine what information has been recorded in periodicals, books, government publications, and other monographs.

Based on the results of this study, conceptual work was begun to arrive at a suitable design for a universal friction testing machine (UFTM). The device was designed, detailed, and constructed. This was followed by a period of experimentation with

The UFTM in which the device was calibrated and used to obtain data with a small variety of materials with various sample velocities. The data are reported and analyzed later in this report.

An operating manual for the UFTM, a maintenance manual, and design drawings of the UFTM are provided separately from this report.

THEORETICAL TREATMENT OF FRICTION COEFFICIENT

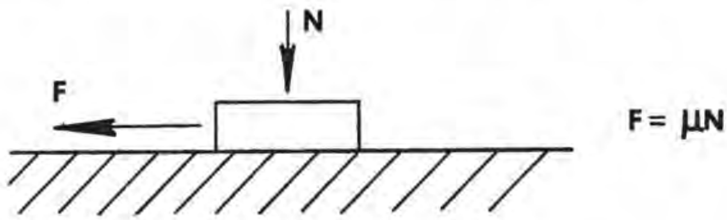
Boundary Layers

It should be helpful to review some of the fundamentals relating to the concept of friction before becoming involved with the details of particular types of test machines.

Friction is the force of resistance occurring when one surface in physical contact with another is caused to move relative to it. The magnitude of the sliding force is a function of the amount of normal force being exerted between the surfaces. Traditionally the coefficient of friction (COF) is defined by the ratio

$$\mu = COF = F/N \tag{1}$$

where F is the sliding force exerted parallel to the surfaces and N is the normal force between the surfaces as illustrated below:



The COF is affected by the nature of each of the surfaces. The characteristics of the roughness; i.e., the average height of the asperities above and below the mean plane and the physical-chemical properties of the material of the surface affect the frictional properties of the surface.

Very significant changes in the frictional characteristics of a surface are caused by extremely thin layers of film deposited on the basic substrate material. Even one or two molecular monolayers of a material such as water vapor cause significant differences. Boundary layers cause friction changes especially if the film is strongly attracted to the substrate by physiochemical bonds and the film consists of material which has polar properties. Fatty acids, such as stearic acid, have polar properties and tend to form molecular layers or films on surfaces. The oils of human skin (sweat) contain organic materials with polar properties.

The subject of friction involves a large body of knowledge in the literature. Some of the early classical studies were done by Bowden and Tabor.[4,5] More recently Rabinowicz[6] has written some broad ranging discussion of the factors affecting friction. A comprehensive review of boundary lubrication was prepared for the American Society of Mechanical Engineers by Ling et al.[7]

Velocity and Pressure Effects

Two of the variables which are of particular importance in this contract because they relate to footwear are the velocity and the unit pressure of friction surfaces. Traditionally the literature of mechanics has mentioned static and sliding coefficients of friction in reference to the common construction materials such as steel, wood, and brass.

In the broader field of friction, papers have been published by Bartenev et al.,[8] Conant and Liksa,[9] Grosch,[10] and Schallamach.[11] These papers report on the effects of certain variables on the friction of rubber-like materials. For these materials the COF varies with velocity and pressure on the sample.

Conant and Liska[9] show a plot of frictional force vs. sliding velocity of rubber on clean, dry surfaces. The curve goes through a maximum at a sliding velocity of approximately 5 in/min (0.2 cm/sec). This maximum is labeled "max. 'static' friction," to indicate the division between "creep" velocities and sliding velocities. At 0.5 in/min the friction force is approximately 29% less and at 50 in/min, the friction force is from 0 to approximately 12% less depending on whether the surface is rough or smooth.

Grosch[10] reported on experiments from which he constructed plots of COF vs. velocity of various rubber samples. He used a scale factor dependent on the glass transition temperatures of the rubbers to produce a common curve for the four non-crystallizing rubbers he studied. On his master curve for rubber on a "wavy glass" surface, the maximum COF occurred at a velocity of approximately 1.0 in/min (0.044 cm/sec). At each side of the peak at velocities ten times greater and ten times slower, the values of COF varied by approximately 2% and 6%, respectively.

These two investigations show that the COF for rubber does vary with velocity but that for small changes in velocity of a few per cent, the change in the COF is relatively small and not particularly significant.

[This fact is pointed out at this time because one of the concepts considered for the design of the UFTM (and actually later was selected for the design) used a rotating arm to slide the sample around in a circular path. The portion of the sample on the inside of the circle in this case has a sliding velocity of 13% less than does the center of the sample. Thus, using Conant and Liska's[9] data, we can estimate that any error due to non-uniform velocity across the surface of the sample would be much less than 1%.]

The frictional effects of rubber occur on a molecular level. Grosch[10] describes the releasing of adhesional bonds between the rubber and the track with the rubber jumping locally a distance of molecular dimensions, approximately 6×10^{-7} cm. From this it can be assumed that movement of rubber over a track in short jumps of molecular dimensions will not be affected measurably by a slightly rotary motion of the sample moving along an arc with a radius of 3 in. (± 13%).

On the other hand, a test device which has a wide range of speeds may be used to study the effects of velocity on friction. Grosch's[10] master curve shows changes in the COF by factors of approximately 3 to 6 with changes in velocity of ± 4 decades (± 10,000 to 1). Variations of COF of this magnitude are worthy of study and evaluation in relation to the physical phenomena of walking.

The effect of pressure (lb/in^2) on the frictional surfaces may also be of interest in the overall study of friction (see Schallamach[11]). However, the pressure to be imposed on the samples has been specified in this contract to be 9 ± 1 lb/in^2. It is important that the pressure be known and constant so that results are reproducible and consistent for any given pair of materials. The value of 9 ± 1 lb/in^2 is approximately the same pressure as that exerted by the James machine in obtaining static values of COF and by the Horizontal Pull Slipmeter in obtaining static or dynamic values of COF.

With the UFTM, the weight of the motor on the samples of fixed size will remain unchanged so that the pressure on any sample will always be the constant value of 9 ± 1 lb/in^2.

Thus, in review, we emphasize the importance of sample handling and preparation and the importance of knowing and controlling all the variables inherent in the measurement of friction. These variables include velocity and sample pressure on the substrate.

Static versus Dynamic Friction

It is commonly known that to start a heavy object sliding on a horizontal surface takes more force than is required to keep it moving once it has started to slide. The COF associated with the initial push is called the static coefficient of friction. For many materials, static COF values are readily measurable.

However, the velocity dependence of rubber presents a difficulty when attempting to measure its static COF. As reported by Schallamach,[11] "It is almost impossible to determine the exact value of the tangential stress under which the sample begins to move." Wilson and Mahoney[12] expressed the same problem in the words, "As lateral force is applied to a rubber specimen, continuous sidewise deformation occurs and then total movement begins, but the demarcation between the two is not clear."

Therefore, the velocity must be known and stated along with the value of COF even though the velocity may be difficult to measure at extremely low values. Truly "static" values of COF for rubber-like materials may not be practical to measure.

For non-rubber materials, such as leather, we have not found similar references to difficulties in measuring static values of COF. However, we recommend standardization of start-up velocities even with non-rubber materials when undertaking material measuring programs.

Dynamic friction implies the measurement of a COF with the sample moving at any continuous, constant velocity. The velocity dependence of materials again enters the picture since almost any sample and test apparatus has some built-in elasticity or springiness which may cause a "stick-slip" phenomenon whenever the sliding COF is less than the static COF. The driving force builds up forces in the sample and test apparatus until the sample slides, at which point the forces in the system decrease to that corresponding to the sliding COF. At high enough velocities, the intermittent stick-slip oscillations tend to disappear into an average velocity with a constant COF since the response of the test apparatus is unable to follow the rapid cyclic changes. See Rabinowicz[6] for a mathematical treatment of the stick-slip phenomenon.

Further discussion concerning the factors involved in the dynamic friction of rubber-like materials will be included in the section which reviews the published literature.

CURRENT ACTIVITIES WITH FRICTION TESTING DEVICES

Introduction

One of the objectives of this contract is to investigate the methods of measuring the coefficients of friction presently in use and to evaluate these methods with respect to their suitability for accurately and reproducibly measuring coefficients of friction between footwear materials and actual industrial working surfaces (floors). The investigation included interviewing several users of friction testing devices in their laboratories and talking with numerous experts in the field of friction testing. These users included people working in the areas of footwear, flooring, floor coatings or polishes, and an insurance company.

In the text which follows, we will list some of the locations where friction testing of floors and/or footwear is actively underway with some description of that activity and with some explanation of the purpose of the work. The description of the activities represents a sampling of the state-of-the-art of friction testing of shoe materials on working surfaces.

U. S. Army Natick Laboratories

The laboratories at Natick have been established for technical support of the procurement process for materials, clothing, and equipment used by the U. S. Army. Contact was made with Messrs. Angus P. Wilson and Patrick J. Mahoney, who have been involved in many aspects of rubber technology in the Clothing, Equipment and Materials Engineering Laboratory (CEMEL) there. The laboratory has many types of equipment including several friction testing devices.

These include a British Portable Tester, an inclined plane and carriage device developed by the Natick Laboratories, and a hydraulically operated traction testing device designed and built for the Natick Laboratories by Comstock & Wescott, Inc. This latter device was designed to simulate the action of the lower leg and foot and to measure and record the conditions relating to slippage between actual combat boots and selected walkway surfaces.

The hydraulic traction testing device is part of a system consisting of the boot loading device itself, a hydraulic power unit, the instrumentation with its enclosure, and an electrical power distribution enclosure. The hydraulic traction testing device is a stationary, non-portable mechanism equipped with force transducers for measuring both the downward force on the boot and the horizontal traction force on the test surface. It is also provided with a potentiometer which measures the position of "the lower leg" and enables recording of the frame angle at which the boot begins to slip. Since the two forces and the angle between them are simultaneously recorded, the slippage characteristics of a particular boot and test surface can be derived from analysis of the recorder chart. The device may be used for making measurements from which values of either static or dynamic COF may be calculated.

The inner frame which carries the simulated leg and foot is pivoted freely in one direction at the top so that as soon as the angle of the lower leg reaches the point where the boot slips, it is free to continue to slip for a number of degrees as the hydraulic cylinder continues to exert a constant downward force.

The traction device thus is a research tool for the study of slippage and normally requires the use of an actual shoe or boot on a specially prepared sample of walkway surface.

The British Portable Tester is a pendulum type of apparatus available commercially. It is illustrated and described in the American Society for Testing and Materials (ASTM) Standard Method of Test E303-74[13] and in a 1965 paper by Giles et al.[14]

The inclined plane and carriage apparatus was developed to comparatively and dynamically test various rubber and plastic footwear materials. Wilson and Mahoney[12] designed the apparatus to approximate the velocities and pressures developed by the heel of a shoe as it contacts the ground in walking. They made tests with many of the same materials using the British Portable Tester, got results that correlated with those of the carriage test device, and concluded that the British Portable Tester was therefore a device suitable for specification testing. They also concluded that no rubber or commercially available polymer which they had tested possessed "outstandingly superior skid resistance."

Thus, the Natick Laboratories, whose work is directed toward the development of better clothing and protective wear, including shoes for arctic and for tropical environments, depends primarily on the dynamic measurements of the energy absorption type such as are produced with the British Portable Tester. They have the capability of making tests with their hydraulic traction tester which would simulate the initial contact and break-away forces of a heel contacting a walkway surface. The capability to make this type of measurement, however, at this time is limited to the Natick Laboratories where the rather elaborate equipment is available.

Although Wilson and Mahoney have tested an impressive variety of rubbers and plastics[12,15] with their inclined plane and carriage device, none of their results are expressed in terms of coefficient of friction. They were expressed in terms of the length of the skid. This makes it difficult to compare the results of their work with those of other experimenters.

None of their friction testing has been done in temperature and humidity controlled environments. The laboratory, however, does have a cold box for use with the hydraulic traction testing device and is reported to have available a room which has temperature and humidity control.

No commonly accepted test procedures, such as those which might be promulgated by the ASTM, are currently in use at the Natick Laboratory. They follow in a general way the manufacturer's instructions in using the British Portable Tester and are familiar with the applicable ASTM specifications for test method E303-74.[13]

This represents the state-of-the-art of friction testing of footwear materials at the Natick Laboratories, one of the more advanced testing facilities.

U. S. National Bureau of Standards

Information relating to the activities of the NBS was obtained by phone conversations with Sam Toner[16] and earlier with Ryan Pierson.[17] In 1973 they were doing some work for the Consumer Products Safety Commission to study the traction characteristics of materials used in children's shoes. Most of the work was reported to have been done on vinyl asbestos tile, smooth stainless steel, and sanded oak. They had reported testing 22 pairs of shoes and 10 or 12 repair materials, wet and dry, and with room temperatures and cold temperatures down to -10 to -15°F.

Their testing apparatus consisted of a floor model Instron tensile testing machine adapted for horizontal track testing in a manner somewhat similar to that shown in ASTM test method D1894-73.[18] However, the sample was held 30 degrees from the horizontal and was moved horizontally at a speed of approximately 1 in/min.

A report further describing the work was in draft form in mid-1975. Toner indicated that he did not expect to do further testing of footwear materials in the near future.[16]

Without having the detailed report of the work done, it is difficult to evaluate the significance of the experiments. Perhaps the greatest significance lies in the type of apparatus and the low velocity used for their testing which makes the work unique.

In addition to the NBS - Consumer Products Safety Commission study, some other studies and development work have recently been undertaken by Robert J. Brungrabber,[19] working on intergovernmental agency loan under the Building Safety Section at the Center for Building Technology. The emphasis of his work was reported to be on floor standards.[19] In late 1974 he was developing a portable hand-operated rotary friction tester and a small portable static friction testing device[19] similar in principle to the James machine (ASTM test method D2047-72[20]).

Used with the proper operating procedures, each of these devices may find use in the making of static COF measurements.

Underwriters' Laboratories, Inc.

In contrast to the previous two sections which dealt with governmental agencies involved with friction studies, this section will describe the test work being done by an independent commercial testing laboratory. Some of the early work in this field was done by Dr. Sydney V. James of the Underwriters' Laboratory. In the mid-1940's, he designed and built the machine which later came to be known as the James machine.

The device measures the static value of COF between a 3 x 3 in. leather shoe and samples of flooring material. Underwriters' Laboratory used the machine to test the coatings of "wax" or resin polishes sent to them by their customers, manufacturers of the polishes. U. L. provided the testing service and the prestige and authority of an independent testing laboratory to determine that minimum frictional properties had been met by the customers' products.

Apparently Dr. James and the U. L. established the value of 0.5 as the minimum acceptable COF shortly after development of the James machine.[21] Although Sigler et al.[1] considered 0.4 to be the dividing point between slippery and non-slippery surfaces, the U. L. point of view seems to have predominated. The Chemical Specialties Manufacturers Association in 1970 approved the value of 0.5 as determined by the ASTM test method D2047-69.

The Underwriters' Laboratory at the Northbrook (Chicago area) facility is still providing testing service to manufacturers of polishes. The friction testing room was air conditioned with temperature and humidity control when the Principal Investigator visited the facility in July, 1974. William R. Hooper showed him the motorized and the hand-operated James machines which they used for commercial testing. Hooper said they used the manually operated machine in preference to the motorized version because it gave them more consistent results.

Hooper indicated that they try to follow ASTM specifications in their test work. He later sent us a copy of "Subject 410"[22] which provided additional details of U. L.'s test methods. In some respects "Subject 410" provides more specific instructions than does ASTM procedure D2047. For instance, the U. L. procedure specifies that the normal force on the sample should be 80 lb and the ASTM procedure does not specify the value. It specifies the size of the sample shoe (though erroneously "3 square inches" instead of a 3 in. square) whereas the ASTM procedure does not.

U. L. describes in some detail the type of leather to be used for the shoe and specifies that, "If a new shoe is to be used, its glaze shall be completely removed by the sanding." Hooper mentioned that when they used a shoe with a new piece of leather on it, they got lower coefficients than they would get with one which had been worn and sanded for a period of time.

The U. L. procedure requires preconditioning of the tiles for 24 hours in a 73.4°F room at 50 per cent relative humidity before using them for test, whereas the ASTM procedure merely specifies that the emulsion on the tile be dried in 73 ± 3.6°F and 50 ± 5 per cent relative humidity air for a period of time.

There was no mention at U. L. of any preparation of the test panel itself as described in Paragraph 4 of ASTM procedure D2047 except for the temperature and humidity preconditioning mentioned above. U. L. used a flooding of the liquid coating material over the tile rather than an immersion technique as described in D2047.

In actual practice U. L. used commercially available tiles rather than the "Official Test Asphalt Tiles" (OTAT) except for those cases in which the results were borderline.

The 9 x 9 in. official test tiles which were available from the Chemical Specialties Manufacturers Association (CSMA) were no longer available according to Copenhaver of CSMA in March, 1975.[23]

Tiles 12 x 12 in. have become the manufacturers' standard size and the tiles are only available with coatings. Probably U. L., ASTM, and CSMA will have to revise their specifications and standards.

Underwriters' Laboratory did not have nor use any other types of friction testing apparatus.

In summary, the Underwriters' Laboratory at Northbrook appeared to represent one of the most advanced centers available for the determination of values of COF with the James machine.

Sears Roebuck and Company

Sears had a motorized James machine at their Chicago facility when the Principal Investigator visited there in July, 1974. Richard H. Koehrmann, Group Manager - Materials, was responsible for the selection of materials used in Sears' footwear and flooring products. Koehrmann discussed the various types of friction testing devices available. Highlights of the interview follow.

Although Sears had a tensile tester available, it had not been set up for friction testing. Sears did not have a British Portable Tester as Koehrmann indicated that no one in the shoe nor floor industry had such a machine in use. He said that when he visited the office of the Shoe and Allied Trades Research Association (SATRA) in England, he discussed the British Portable Tester with them and they did not recommend its use for the evaluation of coatings on floor materials.

Thus, Sears depended entirely on the static COF readings made with their James machine for internal evaluations of their footwear and flooring materials. In making tests, they followed what they called a "UL" procedure, using a value of

COF = 0.5 as a go, no-go type of evaluation. For wet versus dry tests, they applied water to the shoe sample rather than to the floor itself.

Koehrmann indicated that they supplemented their laboratory tests with field tests and subjective wearer evaluations.

Although the quantity of testing may have been considerable at Sears, the procedures and equipment used did not produce quantitative values of COF by which various footwear and flooring materials could be evaluated relative to each other.

S. C. Johnson and Son, Inc.

S. C. Johnson is in the business of making chemical specialties. They make floor polishes although this is reported to be a small portion of their production. They use the James machine to evaluate their floor finishing materials.

Merscher had related the history of the ASTM method D2047 for use of the James machine in a 1972 paper.[24] He expressed the opinion that the alignment and leveling of the James machine was important to the obtaining of "reliable, duplicable" results. Merscher felt that Johnson's machine was a good one and that the Candy Company in Chicago also had a good machine. At that time he reported approximately 25 James machines in use in the polish manufacturing industry.

This gives some perspective to the amount of interest which existed in the floor polish industry in the testing of COF values for their products. The polish industry appears to comprise one of the largest groups using a type of friction testing machine for the obtainment of values of COF for flooring materials. They appear to use the ASTM method D2047[20] exclusively whenever any carefully documented tests are conducted.

Liberty Mutual Research Center

For many years Liberty Mutual has been involved in research activities in the field of accident prevention and in the checking of the coefficients of friction of floors. In 1958 Willem S. Frederik presented a paper[25] describing his 12 lb portable slip testing machine which worked on a principle similar to that of the James machine. In 1967 Charles H. Irvine, also with the Liberty Mutual Research Center, described his new Horizontal Pull Slipmeter[26] which he concluded was "an adequate replacement for the more fragile and expensive Portable Slip Testing Machine designed by Frederik."

Irvine's Horizontal Pull Slipmeter (HPS) weighs 6 lb and consists of a mechanical spring force scale, a steel block, three small leather disks used as feet, and a battery operated winch to pull the slipmeter over a horizontal surface. According to Irvine, Liberty Mutual Insurance Company has many of the HPS in use by their agents throughout the country.

The HPS is a simple device capable of measuring both static and dynamic values of COF. Its speed is limited, however, to one value, approximately 3.9 in/min. The device was not designed for frequent replacement of the sample feet.

We were unable to determine the degree of acceptance of the HPS outside of the Liberty Mutual organization. As will be discussed later, the literature we found reporting on tests made with the HPS[27] consisted almost entirely of work done by Irvine. His work covered a considerable number of shoe materials on structural steel[27] and several types of flooring materials.[26]

Irvine himself noted[26] the inconsistencies resulting from the use of leather for the test feet. This fact, plus the inability to vary the velocity of sliding, perhaps accounts for what appears to be a lack of acceptance of the HPS by insurance and accident prevention experts and by friction testers in general.

SATRA

We corresponded with Dr. R. E. Whittaker[28] of the Shoe and Allied Trades Research Association in England to learn more about the state-of-the-art of friction testing there. SATRA does not manufacture any equipment for slip testing but has shown interest in new equipment for slip testing in the past.

Whittaker sent two monographs to describe some work done by SATRA. A paper by Kellet[29] described slip testing done with a variable angle walkway ramp. There was no data nor discussion given in terms of coefficient of friction which made it difficult to relate to other work.

Bunten[30] preferred the British Portable Tester to the inclined ramp. He provided a number of COF values for plastics and rubbers on clay tiles, wet and dry, as well as one value for leather.

In the absence of more recent information, it is difficult to judge the status of friction testing procedures in England.

American Society for Testing and Materials

The F-13 Safety and Traction for Footwear Committee of the ASTM formed a subcommittee called F-13.10 Subcommittee on Traction whose Chairman is Claude Robb. They have been active for more than a year making tests with the British Portable Tester, the James Machine, and the Instron Tester. They have tested approximately 20 footwear materials.[31] Their intention was to obtain some degree of correlation of results from among the machines in order to arrive at some standard method(s) for measuring the coefficient of friction of footwear materials.

Among the various tests was a method using the British Portable Tester in which the slider, normally rubber, was made of stainless steel and the fixed surface was the rubber being tested. According to Robb[31] the method didn't work out too well. The ASTM subcommittee notes[32] indicated that the British Portable Tester did not correlate with the Instron or the James machine.

American National Standards Institute

The ASTM is a cooperating organization with the ANSI and submits their recommendations for standards to ANSI for official national recognition. According to De Turnowsky[33] the ASTM is the only group he is aware of which is active in the area of testing of friction of footwear and walkway materials.

Chemical Specialties Manufacturers Association

The CSMA has been interested for several years in test methods for floor polishes.[24] The CSMA Wax Division Subcommittee "N" on Slip Resistance has been considering the use of the Topaka machine for evaluation of polishes.[19] The Topaka machine is used to pull a weight resting on a piece of onion-skin paper over a floor and to measure the force required to pull the weight by means of a spring scale.[34]

REVIEW OF THE LITERATURE

Introduction

Most of the literature relating to the measurement of coefficients of friction for footwear materials on walkway surfaces was found in short monographs. Many of them either described a particular device for the determination of COF or reported the results of a test program with some particular device.

A review of the characteristics of the test devices showed that each of them could be classified into one of three categories as follows:

Preload and initial slip; e.g., the James machine
Energy absorption; e.g., the British Portable Tester
Horizontal sliding; e.g., the Horizontal Pull Slipmeter

Another group of references described studies of the various aspects of walkway safety and the measurement of the friction of footwear and footwear materials on walkway surfaces.

A third grouping consisted of a number of papers which described investigations of the frictional properties of rubber and rubber-like materials against numerous types of flat surfaces. Most of these papers did not refer directly to footwear or to walkway surfaces. However, the theoretical principles involved apply to rubber footwear as well as they do to rubber tires.

Methods of Measurement of Friction

Preload and Initial Slip

This grouping of test devices is characterized by the application of a vertical force on a flat sample through a pivoting linkage so that as the angle of the vertical force is moved away from the vertical, the horizontal component causes the shoe to slide. The angle at which the sample slides is determined and related to the coefficient of friction.

The most widely used machine of this type, the James machine, was developed in the mid-1940's[21,24] by Dr. Sydney V. James working for the Underwriters' Laboratories, Inc. This machine is similar in operating principle to the Hunter machine described in a 1930 paper written by R. B. Hunter.[35]

Other machines such as the Dura Slip Resistance Tester, a smaller version of the James machine,[2] and the Frederik machine, a 12 lb portable device,[25] have been built, but the James machine appears to have survived and becomes the most commonly used machine in this grouping.

We found no references describing in detail the features and operation of the James machine. However, two papers discussed certain aspects of the James machine. Ekkebus and Killey[21] described the principle of the James machine and related it to the geometry of the human body as it walks in order to evaluate what is a safe value of the COF. Gavan and Vanaman[36] discussed the significant variables which affect the results obtained with the James machine.

The American Society of Testing and Materials has issued a series of Standard Methods of Test for the James machine, the latest of which is designated D2047-72.[20]

Further description of Frederik's machine is available in his paper.[25]

Energy Absorption

In this category the British Portable Tester appears to have become the most widely used device. Other devices included the inclined plane and carriage developed by Wilson and Mahoney.[12] Task Group T-41[2] briefly mentioned several other types which measured friction by a pendulum device, a bicycle wheel, and a sliding puck.

Giles et al.[14] described the "Development and Performance of the Portable Skid Resistance Tester" in 1962 and acknowledged that their machine was copied from the "slipperiness tester" developed by Sigler[1] at the U. S. National Bureau of Standards. Giles et al. used the British Portable Tester for the evaluation of the friction of rubber on roadway surfaces. Sigler's work was directed towards the measurement of slipperiness of footwear materials on walkway surfaces and therefore is more directly useful for the study of friction testing of walkway surfaces.

The ASTM has issued a Standard Method of Test for use with the British Portable Tester. The latest designation is E303-74.[13]

Wilson and Mahoney[12] concluded in their paper that the inclined plane and carriage device was a suitable device for testing heel and sole materials and that the British Portable Tester gave results which correlated with their rolling carriage device. They evaluated a considerable number of rubber and plastic materials and flooring materials in their 1970 paper.[12]

Mahoney[15] extended the list of materials evaluated in 1971. He included the results of tests on shoe tread design, composites and coarse additive materials, siping of flat specimens, and temperature effects on the rubber samples used. A summary of Wilson and Mahoney's work[37] was published in 1972.

Horizontal Sliding

Some of the earlier references to the measurement of friction using horizontal sliding were of interest because of the description of the devices although materials other than footwear materials were sometimes used in the measurements of COF. D. I. James[38] (not to be confused with S. V. James of the James machine) measured the COF of a rubber-like polymer (PVC) on steel with a lathe-bed type of device at very low speeds, 0.0014 cm/sec to 1.4 cm/sec. His measuring system included an electric force measuring device and a chart recorder which enabled the recording of stick-slip oscillations of the sample.

Sponsellar and Gavan[39] also used a horizontal lathe-bed device to measure the COF of hard maple on stainless steel with various surface roughness conditions. No results with footwear materials were given.

Irvine[26] described his Horizontal Pull Slipmeter (HPS) in a 1967 article. The initial article gave results of tests on six different floor surfaces and two different sliding materials, leather and stainless steel. The work also served to compare the Frederik machine with the HPS.

In a later (1970) paper Irvine[27] reported the results of additional tests he had made with the HPS. These involved changing the leather feet normally used on the HPS to one of 12 different footwear materials and sliding these on unpainted structural steel. Each material was tested wet and dry. Tests were also made on painted structural steel and on cold structural steel.

Robinson and Kopf[40] evaluated the HPS by comparing the results of tests made with the HPS to those made with an Instron testing machine and with those made with a James machine. Mathematical averages and standard deviations of the data were presented. They concluded that the results from the James machine were higher than those obtained from the HPS. They also concluded that data from the HPS were not significantly different from that obtained from the Instron at the 95% confidence level.

Robinson and Kopf[40] used an Instron tensile testing apparatus similar in principle to that shown in the ASTM test method D1894-73[18] Procedure B.

The literature to date yielded very little information relating to other horizontal sliding-friction testing methods other than specialized research facilities which will be described later.

Studies of Friction of Footwear Materials on Walkway Surfaces

One of the earliest comprehensive studies of the traction of footwear was published in 1948 by Sigler et al.[1] Sigler developed and used a pendulum type of apparatus to evaluate leather and one type of rubber, wet and dry, against 23 different types of walkway surfaces. Sigler recognized the need for establishing a safety code for walkway surfaces and for the development of an adequate method of measuring the COF of such surfaces. His paper discusses the mechanics of human locomotion, his test machine, his procedures, the effects of certain "constants" such as pressure on the sample, and the results of approximately 800 measurements made with his test machine.

Some of the variables Sigler discussed were the effect of normal daily usage on the COF of coated floors, the effect of increasing wetness of the surface of floors, and the effect of repeated contacts of the same pendulum slider.

Another overall look at the causes of walkway slipperiness was published in 1961 by Task Group T-41[2] for the Federal Construction Council. It provided a comprehensive review of the state-of-the-art, including description of the many types of test devices which had been developed to that time. Among them was a rotary "Polisher-Ammeter" friction testing device.

They described the importance of boundary films and prevailing contaminants on the floor at the surface of contact and described the problem of obtaining meaningful data when there are so many variables affecting results. The variables mentioned included the type of test machine and the technique of the operator.

The Task Group recommended that a range of standard roughness for flooring be determined and that a simple, portable, economical test device similar to the rotary polisher-ammeter be developed for periodically measuring the COF of walkway surfaces. They recommended that a program be initiated to carry out a research and development program to establish the many criteria necessary to insure safety from slips.

Santos[41] discussed COF tests in relation to floor safety in a 1966 article on floor slipperiness. Discussion centered on the types of flooring and their characteristics although the Horizontal Pull Slipmeter was described. In a companion article by Hopkins[42] the design of shoe soles and the selection of shoe materials were discussed. Shoe materials were recommended for various working conditions. Hopkins described some work done in France which was directed towards the design of an anti-slip sole pattern. The cube-like pattern was claimed to be "better than any of 24 soles that were on the market when it was developed." The French institute used an apparatus similar to that described in ASTM test method D1894-73,[18] Procedure B. The method utilized a tensile test machine with horizontal sliding of the sample.

Some work has been done by the Shoe and Allied Trades Research Association (SATRA) located near London, England. Bunten[30] in 1967 used an inclined ramp test in which a wearer walked up a ramp whose angle was increased until the shoes just slipped. He evaluated 12 hard plastics and rubbers, leather, and steel, dry and wet, and compared the results with tests made on a British Portable Tester and on a horizontal pull test device. Nearly all combinations produced unsafe coefficients of friction if 0.5 is used as a criterion.

In 1969 Kellett[29] of SATRA used the inclined ramp to evaluate rubber and plastic on clay and vinyl tiles, wet and dry. He recommended that for PVC a hardness of 55-75 International Rubber Hardness Degrees (IRHD) be used to avoid excessive complaints of slip. His results were not given in terms of coefficient of friction.

A recent state-of-the-art paper was presented by Wolfe[43] and published by the National Bureau of Standards in 1972. He noted that since the 1961 NAS review[2] was published, "The most noteworthy contribution to slip resistance testing has been the Horizontal Pull Slipmeter."

Another recent article by Doering[34] concentrated on defining a safe walking surface. Although the emphasis was placed on the legal and political aspects of maintaining walkway surfaces, it did refer to the work of Sigler et al.[1] and made comparisons between and evaluations of several types of friction testing devices. Doering suggested some management techniques for arriving at the proper walkway material selections and discussed maintaining walkway surfaces in safe condition after installation.

Studies of Friction of Rubber on Solid Surfaces

Schallamach[11] described "The Load Dependence of Rubber Friction" in a 1952 article. He determined that the coefficient of friction of rubber on glass decreases with increasing normal load, and that the "load dependence of rubber friction can be satisfactorily explained by the assumption that the frictional force is proportional to the true area of contact between rubber and the track." He presented an equation from which the coefficient could be calculated from the pressure on the rubber. All of his work was done at low speed, 0.05 in/min (0.0022 cm/sec) and did not study the effects of velocity.

In 1960 Conant and Liska[9] published a comprehensive study of the state-of-the-art of "Friction Studies on Rubberlike Materials." They reported that friction is independent of surface roughness except for the plowing component. For tires (and soles?) sliding on wet road surfaces, the coefficient is independent of load. On clean dry surfaces, the friction force is proportional to the true area of contact. The coefficient of rubber-like materials on smooth, dry surfaces increases with increased velocity up to a maximum value and thereafter decreases with speed.

Heavy "bloom" on rubber can reduce the coefficient to one-tenth of its original value. On extremely low coefficient road surfaces the effect of wiping action of edges made with molded slits can improve skid resistance up to 100%.

This paper for the most part simply reported on work done by other authors. It had 165 references.

A 1964 paper by Grosch[10] discussed work done on "The Relation Between the Friction and Viscoelastic Properties of Rubber." His apparatus was a temperature controlled horizontal pull type. He determined also that the coefficient increases with velocity up to a maximum, then falls at higher velocity. In his study he used four non-crystallizing rubbers with widely varying viscoelastic properties. All velocities were under 71 in/min (3 cm/sec). He found that the coefficient peaked at approximately 1 in/min (.044 cm/sec) and that "stick-slip" always began at the peak value of friction. Grosch also confirmed that rubber friction is made of two parts: interfacial adhesion and the plowing effect.

Bevilacqua and Percarpio[44] derived an empirical equation for the coefficient of rubber on a roadway surface. It involved measured constants, the modulus (or hardness) of the rubber, and the resilience (or hysteresis) of the rubber. Thus the modulus (hardness) and the resilience (hysteresis) of a type of rubber determine its friction properties. They also determined that "high friction without abrasive damage can occur on dry surfaces, but not on wet."

In a 1972 paper by Bartenev et al.[8] they described a laboratory friction testing device using an optical method of determining actual contact area of rubber under test. They studied the coefficient of butadiene acrylonitrile rubbers on steel, glass, and polymer at pressures between 14 and 2800 lb/in^2 (1 to 200 kgf/cm^2) and at velocities up to 79 in/min (3.3 cm/sec). They determined that the friction force is the product of a constant and the actual contact area between the rubber and the opposing surface. The so-called constant increases with increasing velocity whereas the area of real contact decreases with increasing velocity. (Note that this is consistent with the findings of Conant and Liska.[9]) At constant load, the friction force decreases with increasing temperature.

CHARACTERISTICS OF EXISTING FRICTION TESTING DEVICES

Discussion of the Characteristics

The following paragraphs will describe the physical characteristics of the several types of friction testing devices. Their strong points and their limitations will be discussed in terms of their suitability for making standardized measurements of COF of footwear materials on walkway surfaces.

Table I summarizes the physical parameters and characteristics of the friction measuring devices currently in use. The values of the parameters shown are taken from the references given.

Preload and Initial Slip

The James machine is widely accepted as the laboratory test device to be used for the evaluation of floor polishes and "waxes." It is a floor mounted device about 4 ft tall which exerts through a linkage a force of 80 lb on a 3 x 3 in. sample of leather. The operator manually cranks the floor sample horizontally (or a motor drives it) until the horizontal component of the weight causes the leather to slide over the floor tile. The point of slippage is recorded and determines the coefficient of friction.

The James machine is capable of making static readings only. In operation the loading of the sample is done before the tile is moved. The length of time the sample shoe rests on the sample tile is a significant variable according to Gavan and Vanaman.[36] The rate of application of the load was found by them to be a significant variable also. Any variations of the James machine will suffer from the same uncertainties as the same physical principles will be involved.

Energy Absorption

For the testing of automobile tire materials, the British Portable Tester (BPT) has been widely used. This pendulum type of device has also been used for the general evaluation of other rubber, plastic, and some leather materials (Wilson,[12] Mahoney,[15] Sigler,[1] and Bunten[30]) against various floor and tile materials.

TABLE I

CHARACTERISTICS OF FRICTION TESTERS

Device	Reference	Sample Velocity		Unit Pressure		Contact Area		Type of Reading	Portable	Operator Skill Required
		in/min	cm/sec	lb/in^2	kgf/cm^2	in^2	cm^2			
James Machine	20 21	0 to high		8.9	0.63	9.0	58.1	Static only	No	High
Frederik Machine	25	0 to high		10.2	0.72	0.59	3.8	Static only	Yes	High
Br. Portable Tester	13 14	6480.	274.	30.0	2.1	0.17	1.1	Dynamic only	Yes	High
Inclined Plane and Carriage	12	4224.	179.	88.0	6.2	0.18	1.2	Dynamic only	No	High
Horizontal Pull Slipmeter	26	3.9	0.17	10.5	0.74	0.59	3.8	Static or Dynamic	Yes	Low
Instron	18	6.0	0.25	0.071	0.0050	6.25	40.3	Static or Dynamic	No	High
Topaka	34	Unknown		Unknown		Unknown		Static or Dynamic	Yes	Low
Hydraulic Traction Tester	45	720. (towards surface)	---	to 200 lb. on sample		Variable		Static or Dynamic	No	High
UFTM		0.72 to 3600.	0.03 to 152.	9.0	0.63	0.95	6.1	Static or Dynamic	Yes	Medium

The Sigler machine, upon which the BPT machine was based, was very similar in its design and operation.

These machines only provide a dynamic value of friction based upon a calculated scale originally intended to correspond with coefficients of friction. The principle does not lend itself to controlled values of normal force on the sample nor on a well defined area of contact on the sample. Variations of the energy absorption principle, such as the inclined plane used by Wilson, suffer from the same difficulties.

It is recognized that the "slowing down" type of sliding does simulate certain real conditions like stopping a car, but it does not accurately simulate the condition of heel contact in which the heel is momentarily almost stationary on the walkway surface before slipping occurs.

Horizontal Sliding

One of the most widely known devices now using the horizontal sliding principle is the Horizontal Pull Slipmeter. As described by Irvine[26] it operates by moving a six lb assembly over the floor at a velocity of approximately 3.9 in/min (0.17 cm/sec). It is drawn by a small battery operated motor winding up a string. It is capable of both static and dynamic readings although the instructions for use describe a method which yields static values only.

The instructions direct that the samples should be resurfaced once for each set of ten readings. There is a high probability of contamination of the leather samples from the use of a paint brush for removing the sandings and similar high probability of contamination of the floor area to be tested from the dusting with a cloth. There is also some question that after the first sample reading, contaminants on the floor may change the sample surfaces and cause differences in the COF readings.

The literature to date shows very little information relating to other horizontal sliding, friction testing methods. The Instron tensile testing device modified as shown in ASTM Standard Method D1894-73[18] Procedure B has been used by some for friction testing.

Robinson and Kopf[40] described their use of the Instron for this purpose. The crosshead speed used for obtaining static readings was 2 and 5 in/min. Normally the Instron is not capable of attaining more than 50 in/min (2.12 cm/sec).

Other Methods

The inclined plane and sliding sample is a traditional classroom method used for demonstrating the measurement of COF. It provides a means of measuring static values and even dynamic values, but not with any degree of control of velocity. It does not lend itself to the design of a portable device for use on horizontal floors.

There have been many types of devices built and used to measure friction through the years but, to the best of our knowledge, they have all been variations on the three categories described above.

Evaluation of the Performance of Existing Devices

The attainment of a representative value of a COF for any given set of materials involves the use of statistical evaluation to some degree. As a minimum perhaps three or four measurements might be averaged requiring a simple statistical calculation. For more advanced studies, some measure of the amount of spread or scatter of the individual measurements comprising the mean or average is desirable. The indicator which will be used here is the standard deviation from the mean, a mathematical expression which can be found in any text book on statistics.

The appraisal of a particular type of test device also depends on statistical evaluation. The goal is to determine how reproducible the results of the device are notwithstanding differences between operators and different machines of the same type and design. Ideally the effect of real differences in COF values would be separable from differences caused by the test device and the operator. Actually the only rigorously valid way of separating these effects is to design an experiment and analyze the data obtained from a number of operators and a number of machines of the same type.

Data from the Literature

Statistical information is not generally available in the literature. Few authors report values of standard deviation of the means of their measurements of COF. Fortunately some have. In Table II are shown some representative values of COF for different types of test devices as taken from published references.

TABLE II

REPRESENTATIVE VALUES OF COEFFICIENT OF FRICTION AND STANDARD DEVIATION

Device	Reference	Type of Reading	Moving Sample Material	Fixed Sample Material	Number of Measurements in mean	Measured COF	Standard Deviation
James Machine	40	Static	Leather	ASTM OTAT Asphalt Tile			
				Wax No. I	4	.688	.015
				Wax No. II	4	.573	.026
				Wax No. III	4	.680	.028
				Wax No. IV	4	.690	.041
				Wax No. V	4	.555	.060
Sigler (Similar to British Portable Tester)	1	Dynamic	Leather	23 different materials	3 to 5	.19 to .64	.01 to .03 with .02 avg.
			Rubber	23 different materials	3 to 5	.47 to .82	
Horizontal Pull Slipmeter	26	Static	Leather	Asphalt	50	0.60	.03
	40	Static	Leather	ASTM OTAT Asphalt Tile			
				Wax No. I	10	.460	.013
				Wax No. II	10	.421	.014
				Wax No. III	10	.406	.012
				Wax No. IV	10	.608	.035
				Wax No. V	10	.429	.022

TABLE II (Continued)

REPRESENTATIVE VALUES OF COEFFICIENT OF FRICTION AND STANDARD DEVIATION

Device	Reference	Type of Reading	Moving Sample Material	Fixed Sample Material	Number of Measurements in mean	Measured COF	Standard Deviation
Instron	40	Static	Leather	ASTM OTAT Asphalt Tile			
				Wax No. I	10	.426	.020
				Wax No. II	10	.405	.020
				Wax No. III	10	.447	.054
				Wax No. IV	10	.644	.056
				Wax No. V	10	.407	.014

The conditions under which the measurements were made with the Instron by Robinson and Kopf[40] were different from the values shown in Table I. The values used were as follows:

Velocity:	2.0 in/min	(0.085 cm/sec)
Unit pressure:	10.5 lb/in^2	(0.74 kgf/cm^2)
Contact area:	0.59 in^2	(3.8 cm^2)

Data from Unpublished Tests

The ASTM D21 Committee on Polishes ran a series of experiments in 1970 which involved James machines in five different laboratories. The purpose of the experiments was to determine the degree of agreement which could be obtained using several James machines measuring the coefficients of friction between the same materials. If the assumption is made that there are no significant differences in the materials, then any resulting significant differences in the results would be caused by differences in the machines and the operators. These measured differences should provide a valid measure of the consistency of the James machine and its several operators.

The results of the experiment are shown in Table III. It is interesting to note that Laboratory No. 3 obtained the highest standard deviation in both experiments but the lowest standard deviation occurred in different laboratories.

By calculation[46] from Table III the maximum allowable error from the mean was calculated for an uncertainty of less than 3 in 1000. The results are given in Table IV.

TABLE IV

James Machine Results

Lab. No.	Mean	Max. Error	Range
1	.68	± .032	.65 to .71
2	.71	± .011	.70 to .72
3	.77	± .056	.71 to .83
4	.70	± .026	.67 to .73
5	.68	± .027	.65 to .71

From this tabulation it appears that there was no significant difference between the results of any one of the laboratories and the overall mean. An average value of the COF of 0.71 is indicated from these calculations.

TABLE III

CHARACTERISTICS OF FRICTION TESTERS AS DETERMINED FROM PREVIOUSLY UNPUBLISHED DATA

Type	Source of Data	Materials moving/fixed	Number of Values in mean	Measured Value Mean	Measured Value Standard Deviation
James machine	ASTM (J. H. Merscher)	Leather/un-coated new official test asphalt tile			
		Lab. 1	6	0.68	0.026
		Lab. 2	6	0.71	0.009
		Lab. 3	6	0.77	0.046
		Lab. 4	6	0.70	0.021
		Lab. 5	6	0.68	0.022
		Leather/used official test asphalt tile			
		Lab. 1	6	0.64	0.012
		Lab. 2	6	0.63	0.025
		Lab. 3	6	0.76	0.050
		Lab. 4	6	0.65	0.023
		Lab. 5	6	0.61	0.034

Data from the British Portable Tester were obtained from Wilson and Mahoney at the U. S. Army Natick Laboratories and are shown in Table V. It should be remembered that values obtained from the BPT are approximately 100 times greater than values of the COF.

Irvine of Liberty Mutual Research Center provided data taken with his HPS. A selected portion of it is shown in Table V. For these tests the material of the feet of the HPS was varied. Three of the four combinations were run on asphalt tile. It is interesting to note that the standard deviation of PVC varied considerably between the two series of tests even though a sample size of 10 was used for each series. Values of "Slip Index" are approximately 100 times the value of the COF.

Conclusions

In order to determine the consistency of a type of test machine, it is necessary to carry out experiments involving several machines of the same design and/or several different operators making measurements with test materials which are the same for all tests. When this is done, it is possible to separate mathematically the differences between machines or operators.

The results from the James machine tests shown in Table IV indicate that the James machine yields values of COF which are consistent between operators and laboratories. The standard deviation of ± 0.05 from the mean of COF = 0.71 was not unacceptably high.

We do not have similar data from experiments done with other types of test machines. Examination of the data shown in Table V indicates values of standard deviation which are comparable if not less than those obtained from the James machine. Therefore, the scatter of the data about the mean appears to be comparable or less than that obtained from the James machine. This does not necessarily mean that the British Portable Tester nor the Horizontal Pull Slipmeter is comparable to or better than the James machine for making independent absolute measurements of the COF. It only means they have been used to get results which are consistent within themselves with one operator and one machine.

Examination of Table I shows the wide range of test variables which exist between the various test methods and test devices. In order to obtain reproducible values of COF, tests must be made with standard conditions of velocity, acceleration, pressure, geometry, etc. It is principally this wide range of variables which makes it impossible to obtain correlation of results between different types of machines.

TABLE V

CHARACTERISTICS OF FRICTION TESTERS FROM PREVIOUSLY UNPUBLISHED DATA

Type	Source of Data	Materials moving/fixed	Velocity Range		Unit Pressure		Contact Area		Number of Values in mean	Measured Value	
			in/min	cm/sec	lb/in^2	kgf/cm^2	in^2	cm^2		Mean	Std.Dev.
British Portable Tester	U. S. Army Natick Labs.	Rubber/vinyl asbestos tile	6480.	274.	90.	6.33	0.056	0.36	10	85.3	1.25
		Leather/VAT	6480.	274.	60.	4.22	0.083	0.54	10	17.1	0.32
		Rubber/wet VAT	6480.	274.	90.	6.33	0.056	0.36	10	10.0	2.11
		Leather/wet VAT	6480.	274.	60.	4.22	0.083	0.54	10	9.4	0.84
		Soaked Leather/ wet VAT	6480.	274.	60.	4.22	0.083	0.54	10	8.8	2.07
		Vulcanized rubber, Shore A 85/VAT	6480.	274.	60.	4.22	0.083	0.54	48	77.2	2.71
Horizontal Pull Slipmeter	Liberty Mutual Research Center	Leather/vinyl asbestos tile	∼3.7	∼0.16	10.5	0.74	0.59	3.8	11	50.2	1.33
		PVC No. 1/ Asphalt tile	∼3.7	∼0.16	10.5	0.74	0.59	3.8	10	69.3	5.36
		PVC No. 2/ Asphalt tile	∼3.7	∼0.16	10.5	0.74	0.59	3.8	10	63.4	1.96
		Solid neoprene/ asphalt tile	∼3.7	∼0.16	10.5	0.74	0.59	3.8	10	98.2	1.55

EXPLANATION OF THE C&W CONCEPTUAL DESIGN

Requirements of the Contract

Some of the variables for the UFTM are specified in the contract. The unit pressure on the sample surface is to be 9 ± 1 lb/in^2.

Similarly the velocity of the sample is to range from 0 to 5 ft/sec or 3600 in/min (152 cm/sec). We have interpreted "velocity" to mean the average velocity of the sample.

Control of Variables

Rotary motion lends itself well to good speed control since the use of a motor tachometer allows feedback to the control circuit. It also allows a wide range of speed to be attained by motor control alone. In addition, the range may be extended by mechanical means such as by gearing between the motor and the sample holder shaft. Attainment of a constant velocity is simplified by avoiding repeated starting and stopping accelerations as with the BPT although it is still convenient to use the UFTM for the measurement of static friction.

For elastomeric materials the actual contact area is a critical variable as further explained by Bartenev et al.[8] and Conant and Liska.[9] The true area of contact may differ from the apparent area in contact with the sample surface but it is important to start with a well-defined apparent sample area. In this way, at least an apparent pressure on the sample can be determined from the normal (vertical) load on the sample and the measured size of the contact surface. Therefore, we have chosen a disk-shaped sample which can easily be cut out with a rotating tool like a hole saw. This should help to keep the cost of sample preparation to a minimum and will provide a well-defined apparent area of contact.

Similar reasoning dictates the use of the disk flat on the walkway surface rather than edged as is done with the BPT and the carriage and inclined plane.

The normal force on the sample is kept constant by the force of gravity acting on a constant mass. Linear ball bearings minimize friction while allowing the constant mass to move vertically.

Description of the Design of the UFTM

Physical Features

The samples of footwear material slide on the walkway surface in a circular path. They are loaded with the dead weight of the driving and measuring assembly above them. As shown in Figure 1, the weight of the DC motor, the gearbox, the force transducer, the linear bearings, and the sample rotor arm all rest on the samples. These weights are constant and the friction in the linear bearings is negligible so that the normal force on the samples is accurately known. The samples measure 25/32 in. diameter so that the pressure on the samples is 9 ± 1 lb/in^2.

When the driving and measuring assembly is not resting on the samples, it is supported from the top plate by a cam lever, connecting rod, and lifter bar. The cam lever may be seen in the top view of the UFTM, Figure 2, and in the side view, Figure 3. The cam lever operated from the top of the UFTM raises and lowers the samples onto the walkway surface.

The driving and measuring assembly is supported by four flexure plates which allow rotary motion of the gearbox and motor assembly about the centerline of the rotor shaft but are rigid vertically. The force transducer is rigidly mounted at one end to the gearbox while the other end of it is connected through a thin tension rod to the linear bearing housing. In this way any torque tending to rotate the motor-gearbox assembly is reacted through the force transducer to the frame. By proper scaling of the force measuring system, the torque produced by the samples being driven over the walkway surface registers the COF directly on the UFTM digital voltmeter.

A bottom view of the UFTM, Figure 4, shows the samples (of leather in this case) attached to the rotor arm. Plastic collars unscrew from the rotor arm to release the samples. Samples are attached by double-sided adhesive tape to 1 in. diameter x 1/16 in. thick aluminum disks which are retained under the shoulder of the plastic collar. This makes the samples easy to fabricate and to attach and remove from the UFTM.

The electronics consist mainly of three principal circuits -- the force measuring system, the motor control system, and the static COF measuring circuit. The force measuring system consists of a commercially available circuit board, shown in Figure 5, which operates from 115 volts, 60 Hertz power, and the force transducer rated at 25 lb. It provides a dc output which, through a divider network of resistors, is applied to the digital voltmeter to read COF directly.

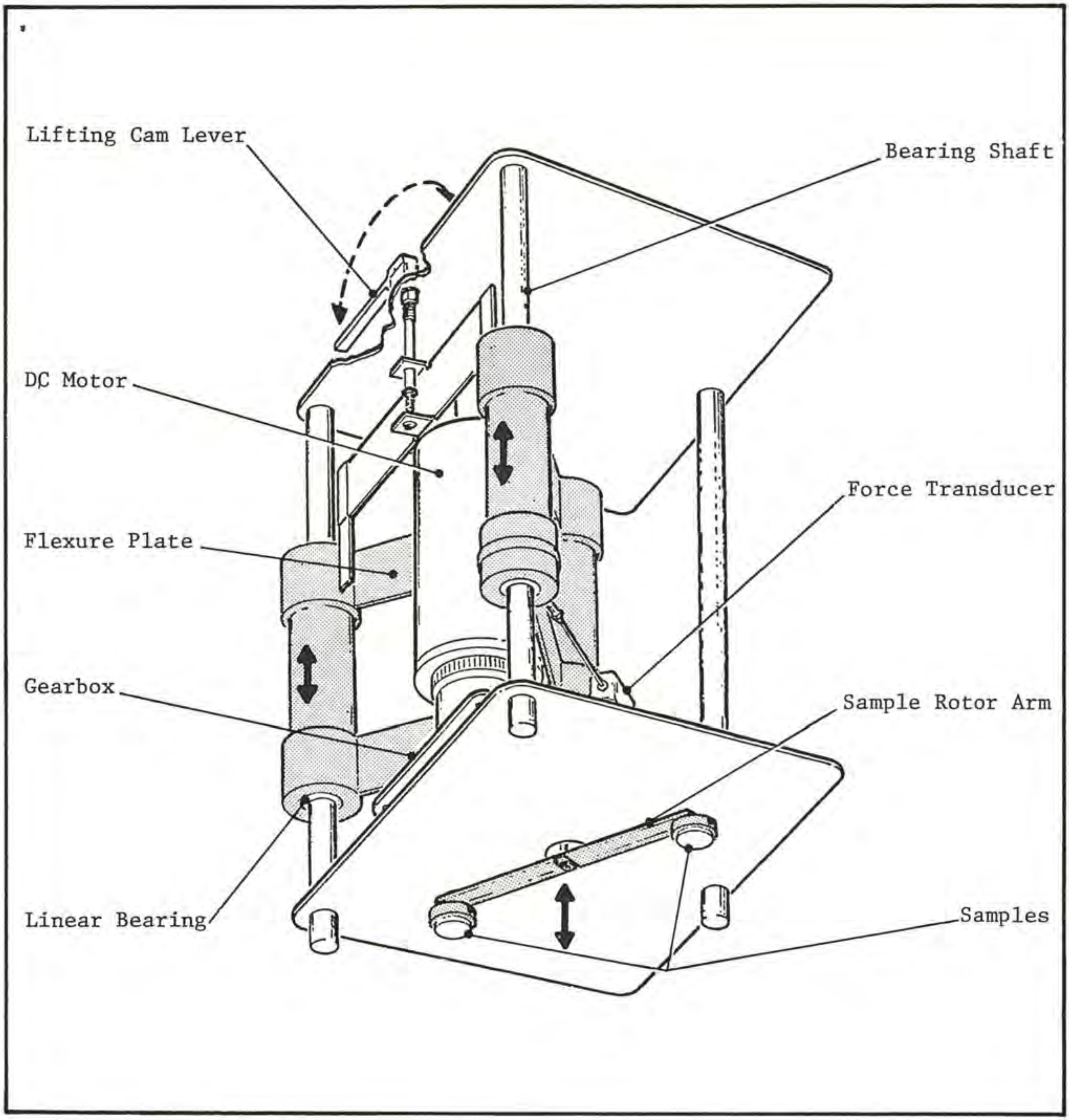


Figure 1. Concept of mechanical and measuring system of UFTM.

Figure 2. Top view of the UFTM as seen by the operator.

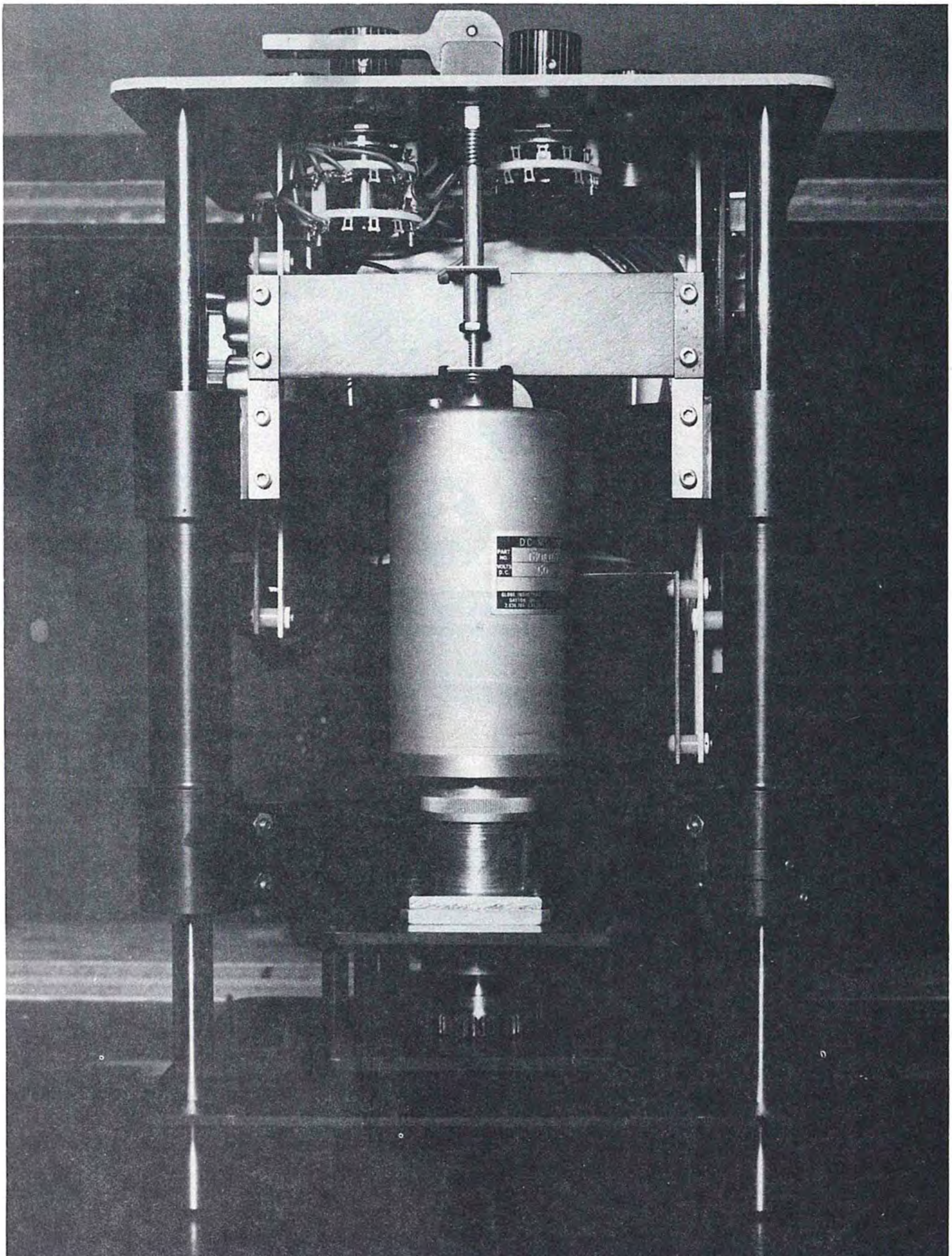


Figure 3. Side view showing lifting cam, cross bar, DC motor and gearbox.

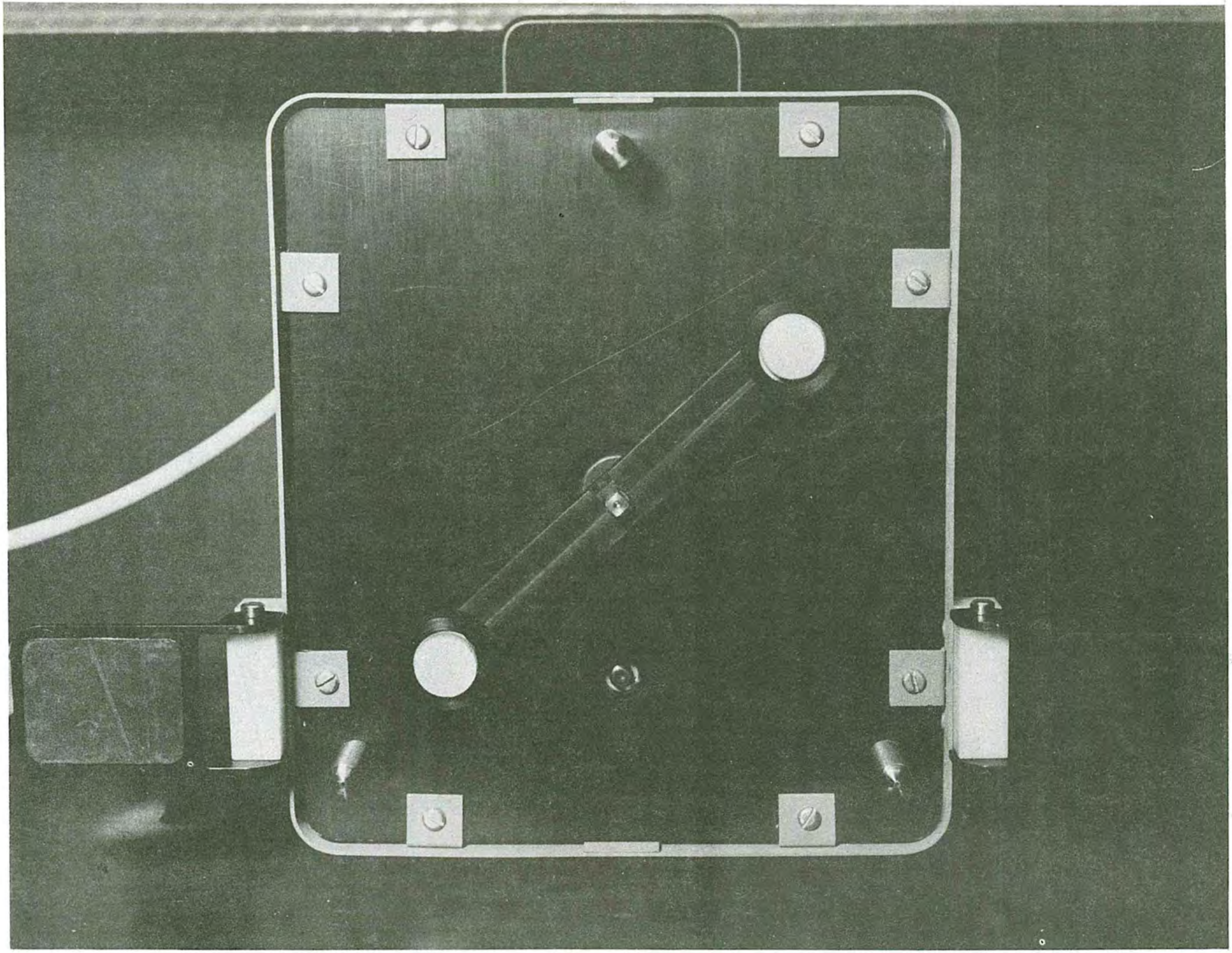


Figure 4. Bottom view of the UFTM showing the two samples and the foot pedals for holding the UFTM stationary.

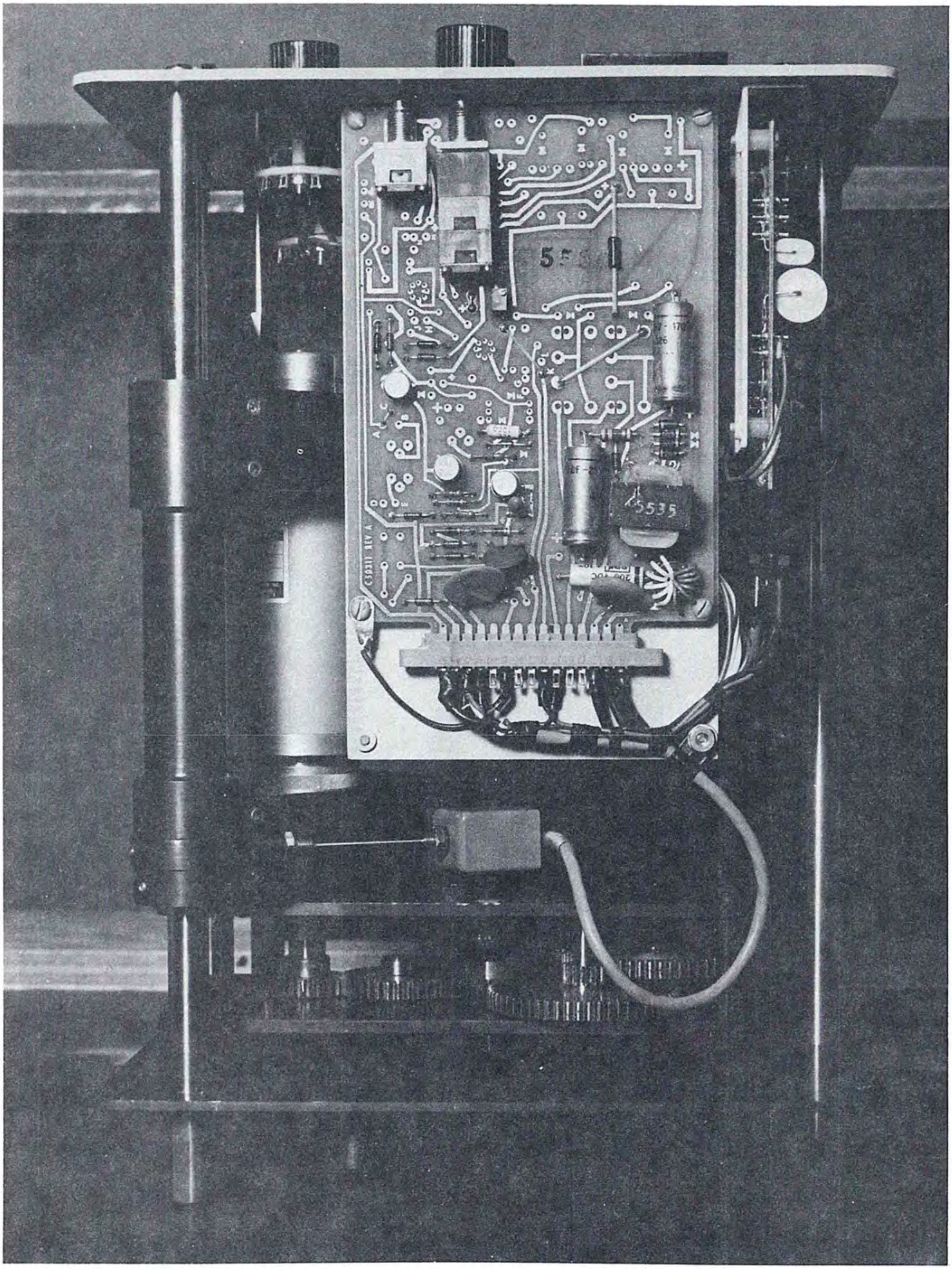


Figure 5. Force measuring circuit board, force transducer, and tension rod.

The motor control is a commercially available circuit board, shown in Figure 6, operated from 115 volt, 60 Hertz power also. It converts the power to dc for control of the armature voltage and thus speed of the permanent magnet motor. The motor speed control knob is shown in Figure 7. A speed range of 50 to 1 is attainable by motor control alone. The velocity range switch actually reverses the direction of rotation of the motor causing a change in the output speed of 100 to 1 to the sample rotor. This is accomplished by using two one-way clutches in the gear drive. The direction of the sample rotor does not change. This speed reduction in the gearbox plus the motor speed control provides an overall speed ratio of 5000 to 1. Thus, it is possible to attain speeds of the sample comparable to the speed of walking, approximately 3.4 miles/hr or 5 ft/sec (152 cm/sec) and also to attain low velocities approaching creep velocities, 0.71 in/min (.03 cm/sec).

The static COF measuring circuit, shown in Figure 8, was designed and built by Comstock & Wescott to register and maintain on the digital voltmeter the peak value attained instantaneously when the samples start to move from the stationary condition. Static friction generally produces a larger value of COF which is maintained only for a very brief time -- too short to observe on a voltmeter. Thus, the components mounted on the circuit board are switched into the measuring circuit by the "coefficient of friction" switch shown in Figure 7 when it is desired to measure static friction. The solid state circuit amplifies the signal from the force measuring circuit and charges a resistor capacitor network to accomplish this function.

The digital voltmeter with LED display is used to indicate velocity of the sample in cm/sec as well as the COF. This function is obtained by switching the voltage from a tachometer attached to the motor to the voltmeter. The "meter reading" switch is shown in Figure 7.

The "mode" switch is used to check that the gain of the force measuring circuit has not changed since the last calibration made with a "torque wrench." Zero adjust and gain adjust screwdriver adjustments from the front panel are available for use with the force measuring system.

Main power is obtained from the 115 volt line through the plug in the upper left of the top plate as shown in Figure 7. The power is operated with the on-off pushbutton switch.

When 115 volt line power is not available, the system may be operated from a battery power supply and inverter. The system is shown in an overall view in Figure 9.

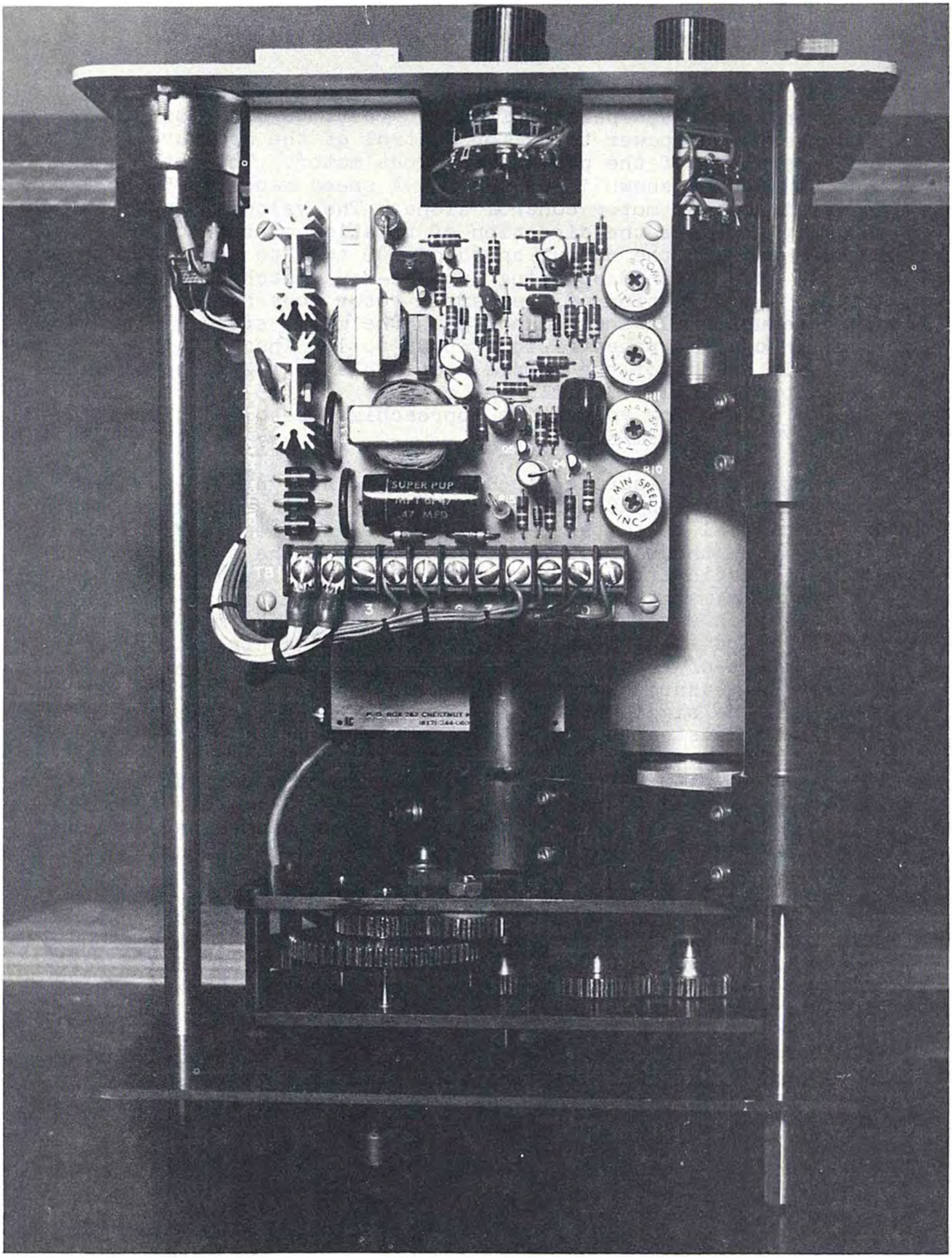


Figure 6. Motor control circuit board and gearbox.

Figure 7. Layout of operating controls on UFTM.

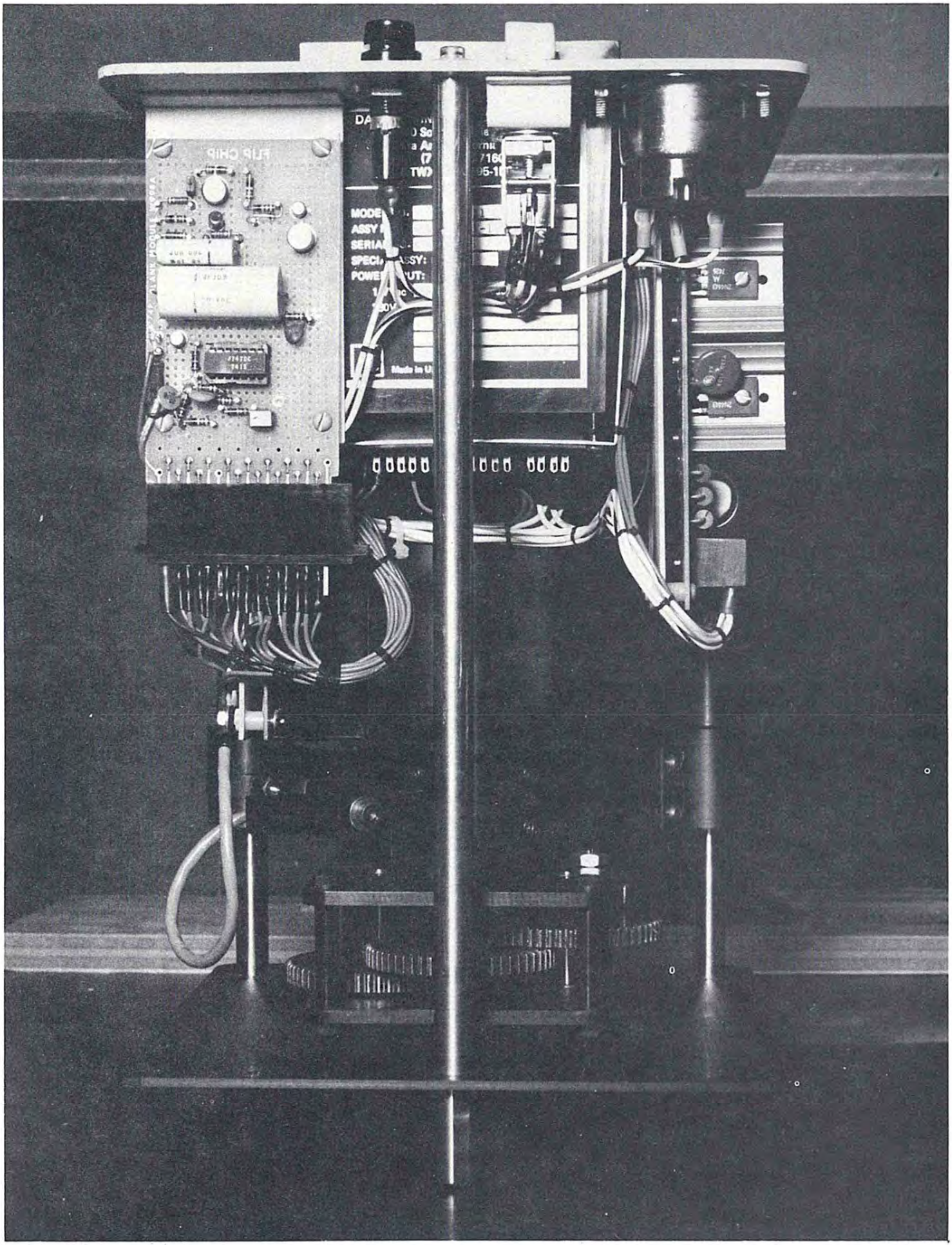


Figure 8. Static COF measuring circuit board
and 15 volt dc power supply.

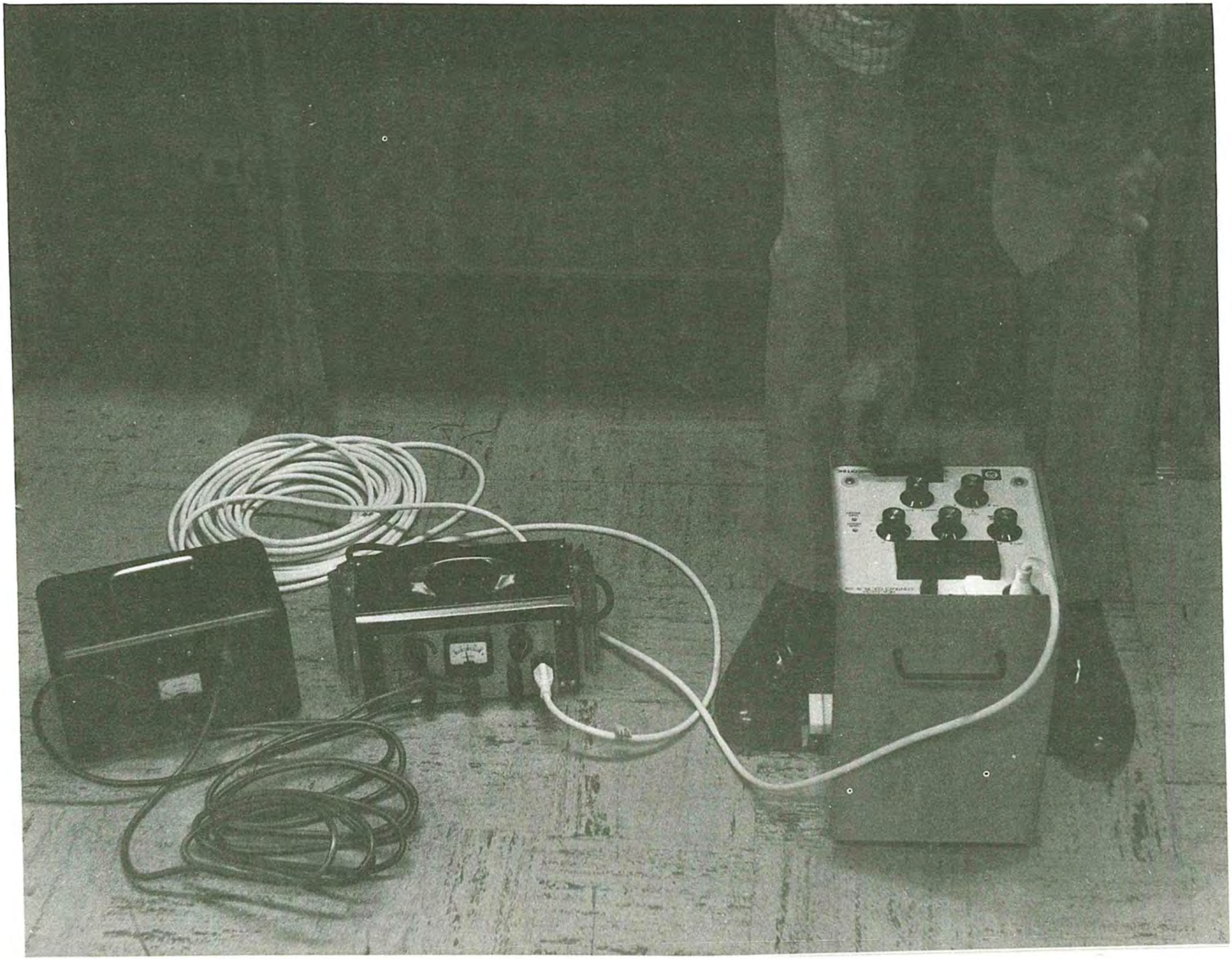


Figure 9. Overall view of UFTM, inverter, and battery power supply.

Calibration of the COF measuring system is accomplished by applying a known torque to the sample rotor arm as shown in Figure 10. The threaded rod has been turned to advance the rod against the torque wrench to develop the calculated torque required to correspond to a COF equal to 1.00.

Design Features

The general philosophy behind the design described above was to create a test device which would provide footwear material sample motion which can be accurately known and controlled over a wide range of speeds, with contact area of the sample well defined and with constant normal force on the sample. Friction coefficient was to be read directly on a digital meter. In order to facilitate the reading of static values of COF, a special circuit was incorporated to retain the peak value of COF developed the instant before a sample begins to slide on a walkway surface.

Portability is a major feature of the UFTM. It weighs 21 lb. Two 50-ft extension cords weight a total of 5.5 lb. The battery box weighs 18 lb, the inverter/charger 17.25 lb, making a total system weight of 61.75 lb. Although the great majority of readings are expected to be made with line power, approximately 25 to 50 readings may be made with a single battery charge. The UFTM measures 8 3/4 x 10 x 14 3/8 in. high.

Ease of operation is another principal design goal. All controls are located within easy reach at the top of the UFTM. It is easy to read the voltmeter. Adjustments and operations are all easily accomplished with a push of a button, turn of a knob, or movement of the cam lever.

Since there has been some question in the literature concerning the errors which are caused by the time the sample is in contact with the test tile used in a James machine test, the UFTM has been designed to minimize delay. The sample may consistently be lowered to the surface and the sample almost immediately started in motion by the lifting of the cam lever and the turning of the motor control knob.

One of the friction parameters which we believe should be further studied is the change in COF which accompanies the transition from static to dynamic friction. Intuition tells us that a footwear material which maintains or increases its traction when sliding starts would be a safer material. In order to study the transition, it is necessary to use a test device with

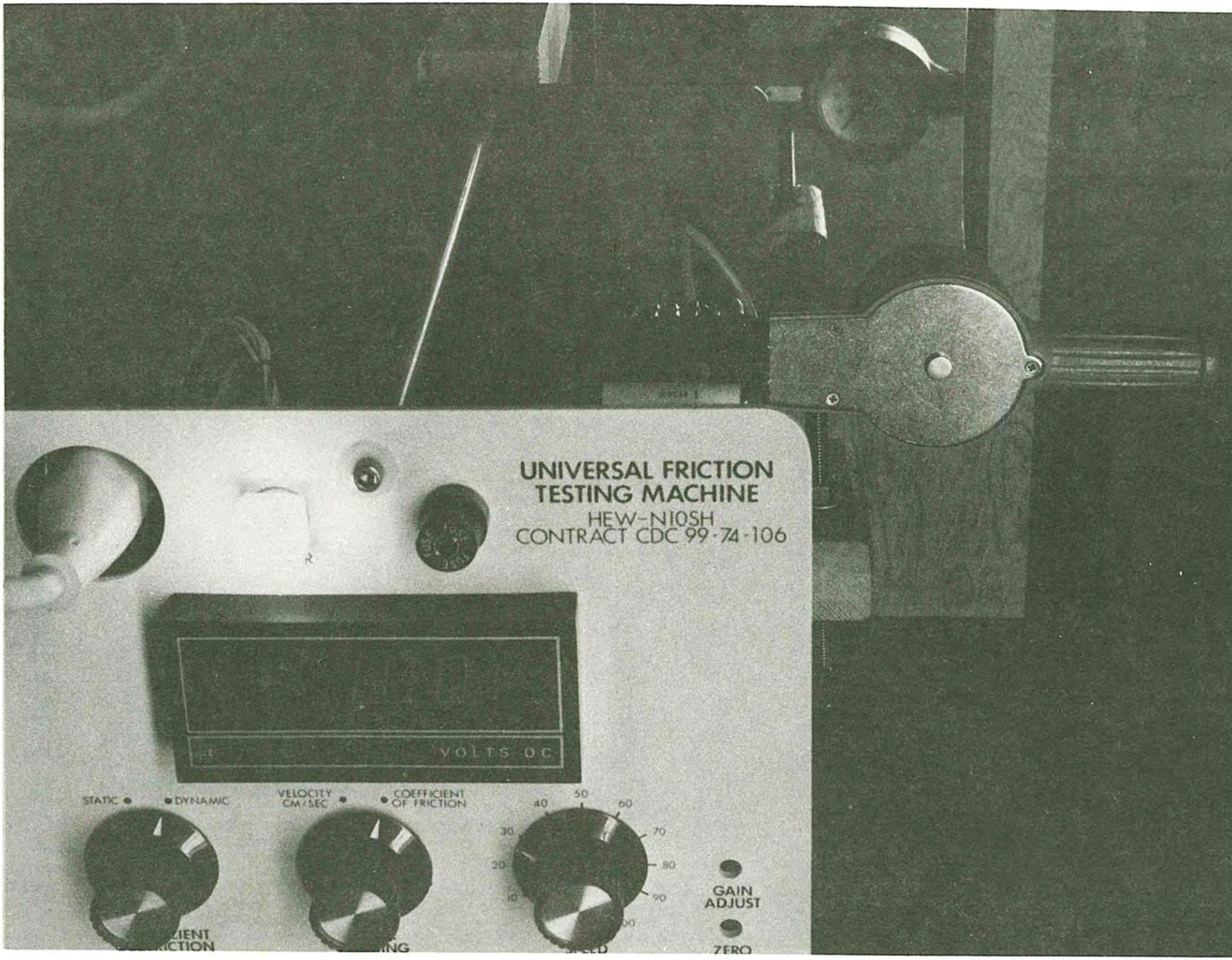


Figure 10. Calibration procedure showing face of torque wrench in the mirror.

which sliding velocity in the very low ranges can be achieved. The study would encompass a number of different constant velocities from very low values to a high value approaching walking velocity. We believe the UFTM is well suited for this type of study. Some preliminary measurements of this type made with the UFTM will be described in the next section.

SOME EXPERIMENTAL RESULTS OBTAINED WITH THE UFTM

Apparatus

The UFTM was calibrated using a calibration stand sketched in Figure 11. The stand consisted of a plywood base with three wooden posts extending up from it ten inches enabling the technician to attach a torque wrench underneath the UFTM on the square shaft end of the sample rotor. The threaded rod enabled the steady application of force to the handle of the torque wrench to enable concurrent readings of COF and torque to be made.

For laboratory measurements the test fixture shown in Figure 12 was constructed of heavy plywood. The retainers reacted the torque produced by the UFTM and kept it from rotating as the samples were driven around on the walkway material sample captured in the 12 x 12 in. opening.

Procedure

The weight of the motor gearbox assembly was first determined by placing a spring scale under the samples with the UFTM outer frame supported on the calibration stand. The torque required to develop a COF of 1.00 was calculated from the measured weight of the assembly and the radii to the samples, 3.0 in.

This calculated torque was applied to the rotor arm shaft with a torque wrench using the calibration stand to support the UFTM. The zero and gain adjustments of the measuring system were thus accomplished.

The velocity readings were calibrated using a hand tachometer pressed against the rotor shaft beneath the UFTM. Measured rpm was then compared with calculated surface speed in cm/sec at that rpm and the necessary potentiometer adjustment made to make the meter read correctly.

The calibration resistor used to check the gain of the measuring system was trimmed so that it read 1.00 on the meter when the mode switch is turned to "calibrate."

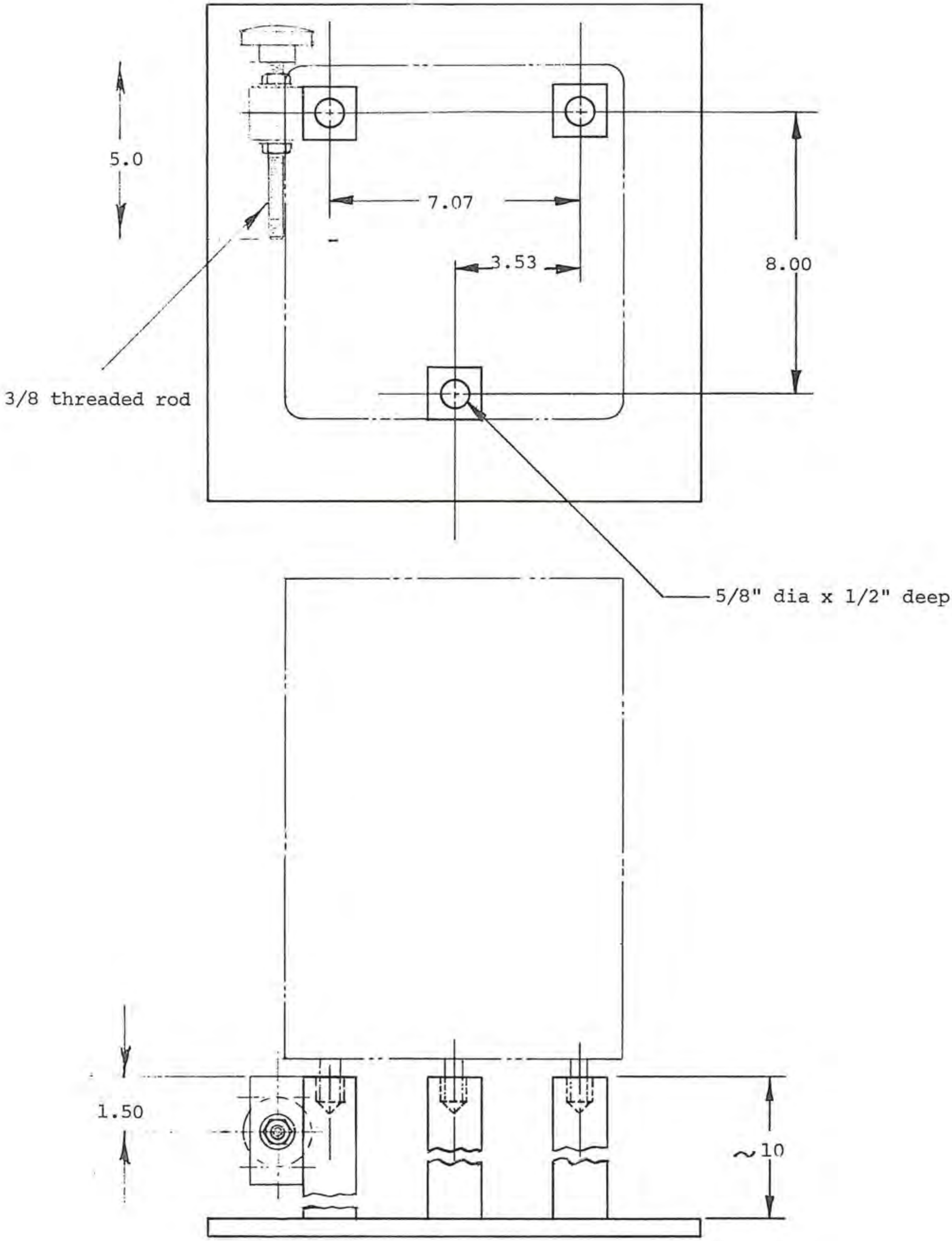


Figure 11. Calibration stand.

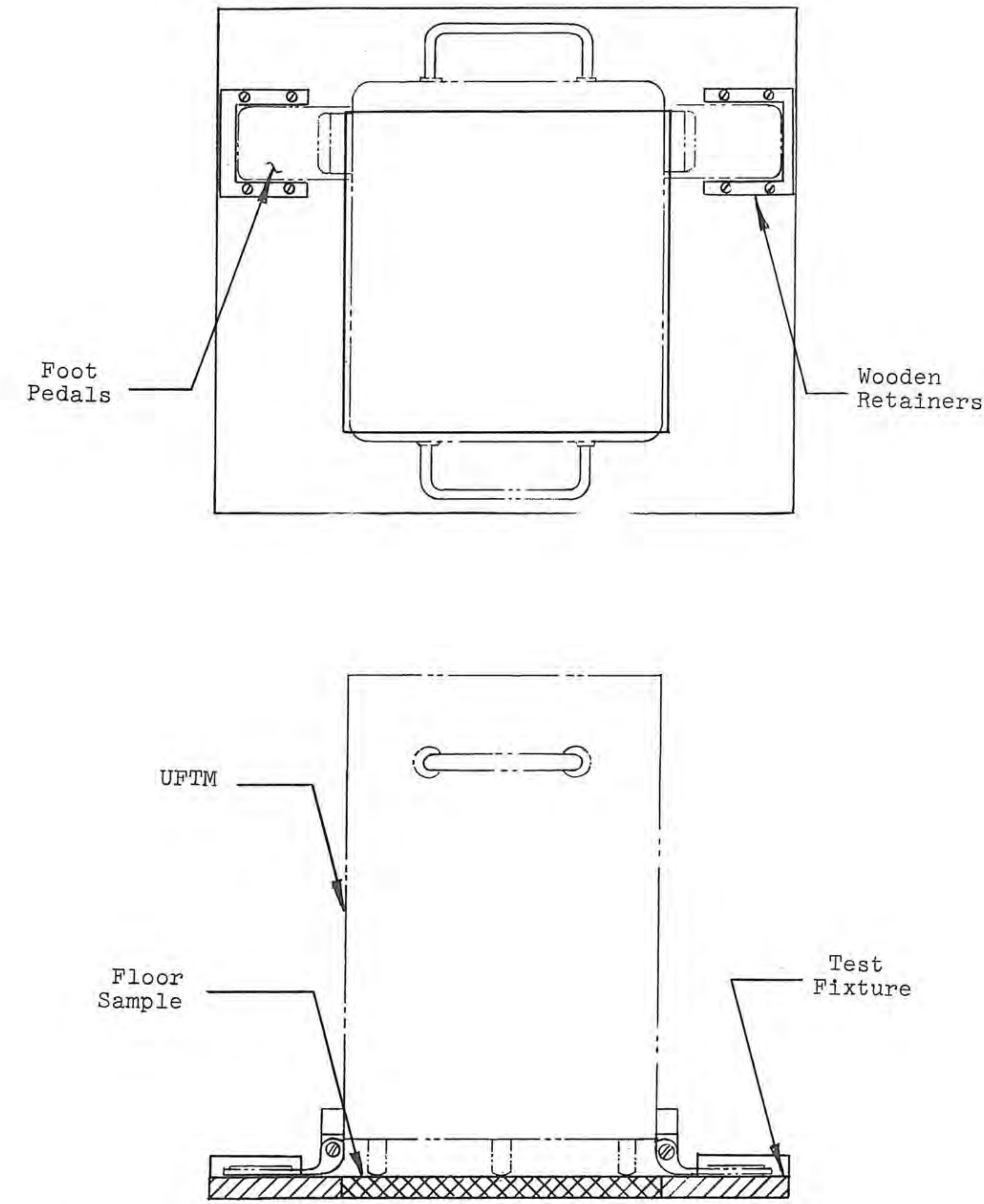


Figure 12. Suggested torque restraining test fixture for bench-top laboratory testing with UFTM.

Samples of leather were cut from 12 iron (1/4 in. thick), prime Grainflex vegetable leather obtained from Eberle Tanning Co. as specified in ASTM test method D2047-72.[20] Samples of rubber were cut from Rubber Manufacturers Association (RMA) reference compound obtained from Smithers Laboratories as specified in ASTM test method D1630-61 (reapproved 1968).[47] The samples were cut to the shape shown in Figure 13.

The UFTM was used in the test fixture, Figure 12, with the following walkway materials:

Vinyl, asbestos reinforced
Oak, across the grain
Oak, with the grain

Each walkway material was tested dry with leather and rubber at the following sample velocities:

Static to	1.52 cm/sec
	0.03 cm/sec
	1.52 cm/sec
	152.00 cm/sec

The vinyl, obtained from local suppliers, was washed with a bristle brush in floor detergent solution and allowed to dry at least overnight before use. The oak was sanded with 400A Wetordry silicon carbide paper to remove all visible traces of any previous track or wear materials. Oak dust was vacuumed off with a glass nozzle connected to a vacuum cleaner.

The rubber samples were wiped with acetone on wiping paper such as Kimwipe Type 900 or Scott Soft-Cote 05316 until no further contamination was visible on the clean wiper and until no lint was visible on the sample. At least three hours were allowed for the sample to dry.

Leather samples were sanded lightly on 400A silicon carbide paper per ASTM test method D2047-72[20] after which the dust was removed with a glass nozzle connected to a vacuum cleaner. The method specifies four 4 in. back-and-forth strokes with the process repeated at an angle of 90 degrees from the direction of the first strokes.

Temperatures and relative humidities were measured at the times of the test although no control was available for these variables. The coefficients of friction were recorded for each test.

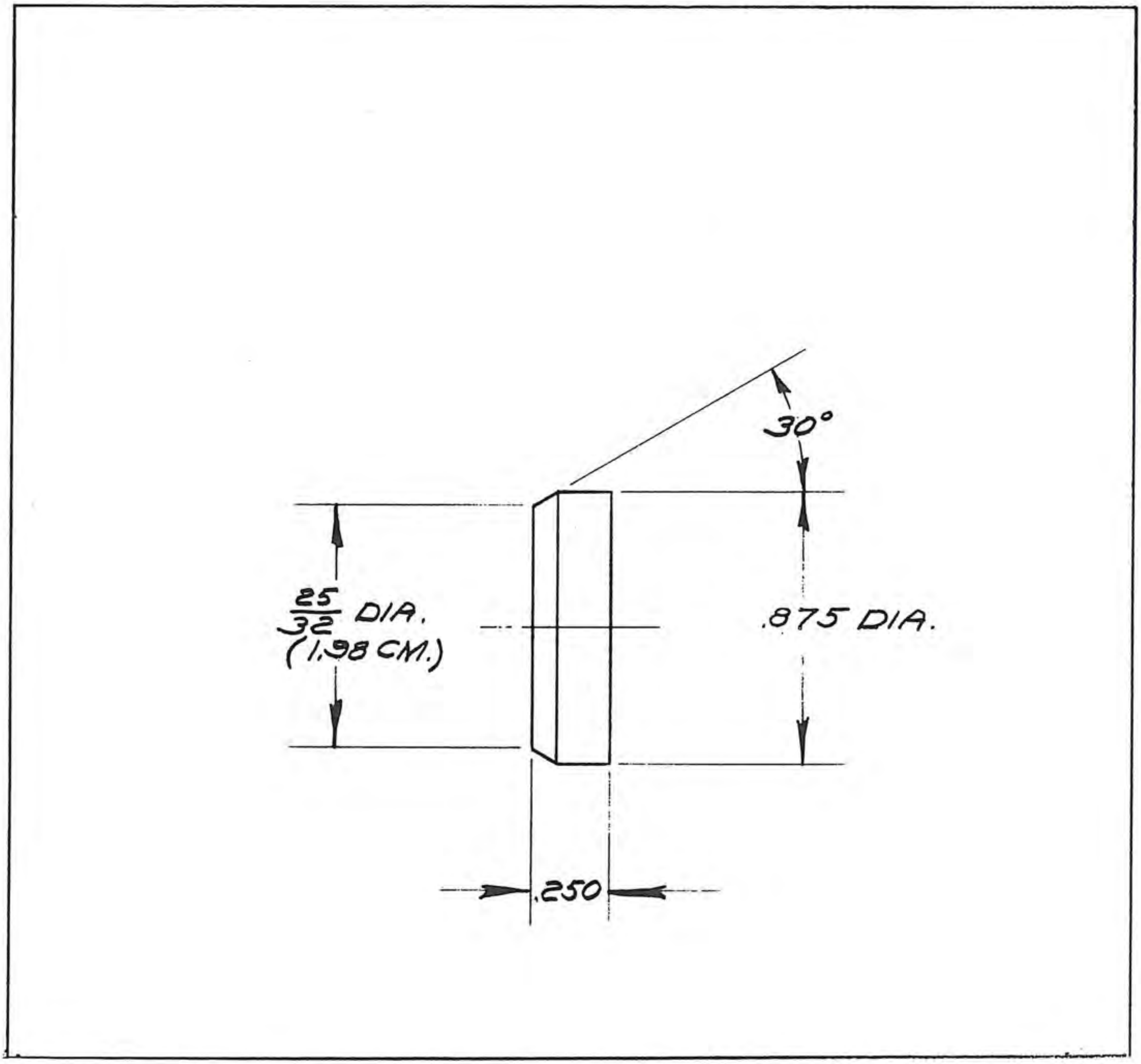


Figure 13. Footwear material sample detail.

Data and Results

The data and results are presented in Table VI. In the case of measurements involving stick-slip, the highest initial values were used. In all other dynamic tests, initial readings were used. For each footwear sample the static reading was made first, and the dynamic measurements were made successively at the three increasing velocities. Each value shown in a horizontal row represents five freshly prepared sets of samples.

The results shown in Table VI have been plotted in Figure 14 for rubber and Figure 15 for leather.

Conclusions

From the data and results given, we have concluded that values of COF for the RMA rubber are extremely sensitive to the velocity at which the COF is measured.

The COF of leather is also sensitive to velocity but is less sensitive than rubber on an absolute scale. Leather produces dynamic values of COF which would generally be considered unsafe for the use of leather as the heels of shoes.

The peak of dynamic COF values found with rubber and described in the literature appears to have shown up with the RMA rubber samples on oak, but not on vinyl asbestos tile.

TABLE VI

Summary of Coefficients of Friction and Calculated Error at 95% Confidence Level*

RMA Reference Compound

Temperature:	77°F
Shore A Portable Durometer hardness:[48]	66
Shore A2 Conveloader hardness:	65
Precision Scientific Bashore Resiliometer:[49]	51

Materials	Temperature Range **	Relative Humidity Range **	Velocity (cm/sec)			
	(°F)	(%)	152	1.52	0.03	Static
RMA rubber on vinyl	75-79	36-45	0.85 ± 0.10	1.24 ± 0.12	1.71 ± 0.03	1.94 ± 0.11
RMA rubber on oak across the grain	77-82	31-45	0.61 ± 0.03	0.76 ± 0.06	0.71 ± 0.05	1.52 ± 0.12
RMA rubber on oak with the grain	77-82	31-45	0.53 ± 0.08	0.75 ± 0.07	0.66 ± 0.05	1.42 ± 0.09
Leather on vinyl	76-84	31-45	0.61 ± 0.06	0.46 ± 0.07	0.44 ± 0.11	0.66 ± 0.10
Leather on oak across the grain	74-85	31-45	0.41 ± 0.01	0.41 ± 0.03	0.65 ± 0.03	0.88 ± 0.03
Leather on oak with the grain	74-85	31-45	0.42 ± 0.07	0.43 ± 0.06	0.66 ± 0.04	0.86 ± 0.06

* Maximum allowable error, E, as defined in ASTM Recommended Practice E122-72[46] for the 95% probability that the sample mean does not differ from the population mean by more than ± E.

** ASTM Standard Specification E171-63[50] specifies standard temperature as 73.4 ± 3.6°F and relative humidity as 50 ± 5%.

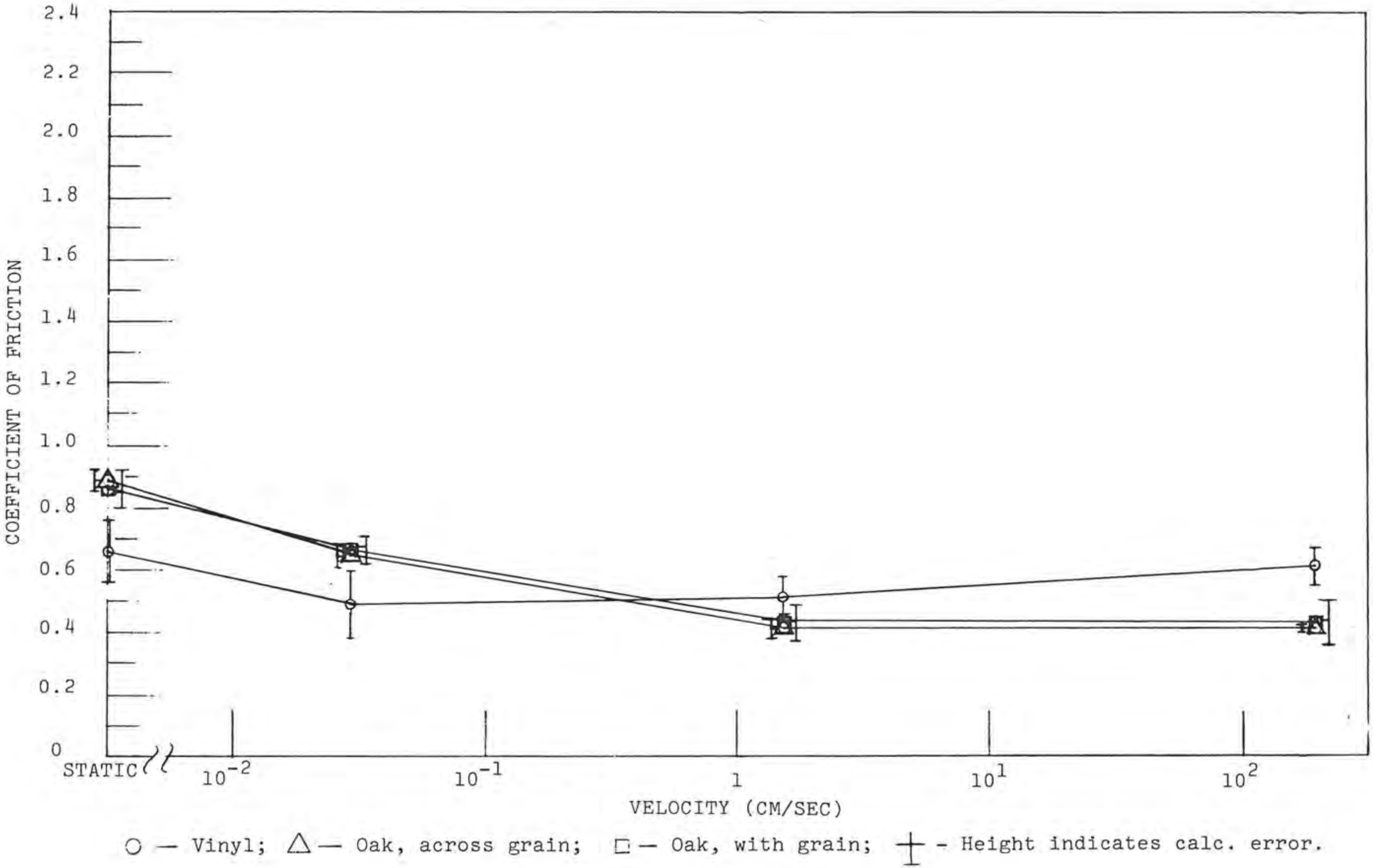
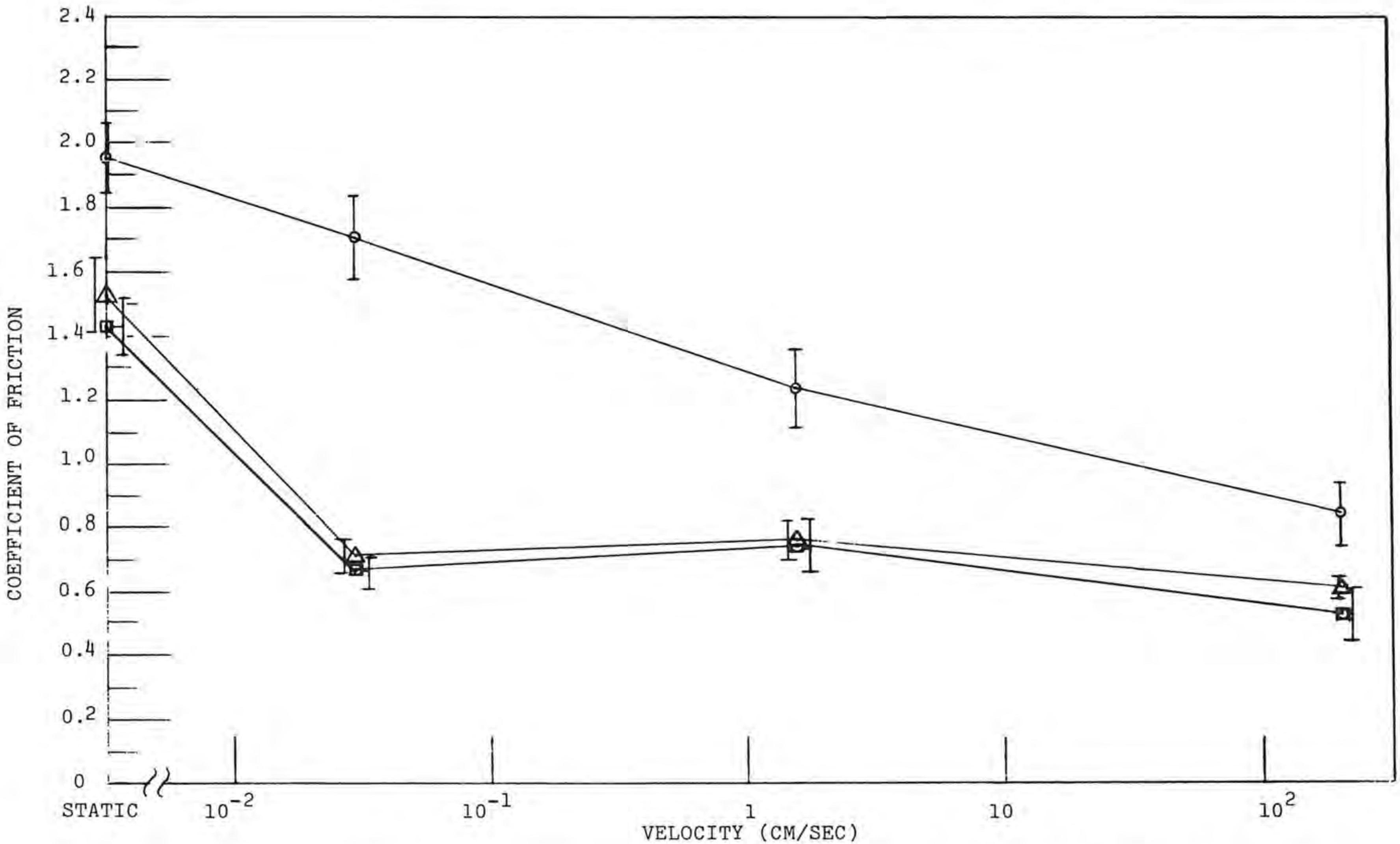


Figure 14. Coefficient of friction of RMA rubber vs. velocity.



○ — Vinyl; △ — Oak, across grain; □ — Oak, with grain; I - Height indicates calc. error.

Figure 15. Coefficient of friction of leather vs. velocity.

COMPARATIVE MATERIALS

The experimental results described above comprise a small sampling from among a large number of footwear and walkway materials. For purposes of comparison with RMA rubber, although COF measurements with these materials have not been made with the UFTM, we include in Table VII a listing of the hardness and resilience of several typical footwear materials. These several materials were obtained from industrial footwear manufacturers who produce shoes in the medium popular-priced ranges. These materials represent a total of 24 per cent of the total shoes produced. The other 76 per cent of soling materials is spread over a series of dress shoes as well as some service type footwear. The materials listed in Table VII should indicate typical properties for industrial work type footwear.

TABLE VII

PHYSICAL PROPERTIES OF SOME TYPICAL INDUSTRIAL SHOE SOLE MATERIALS

Description of Sole Material	Manufacturer	Per cent Usage of Total Shoes Produced	Thickness (irons)*	Temp. (^{o}F)	Hardness: Shore A[48]	Hardness: Shore A2 Conveloader	Resiliency Bashore[49]
Black, neoprene, nylon cord	Quabaug	5	17	78	78	--	21
Natural, chemigum oil proof	Goodyear Rubber Co.	5	14	78	73	71	16
Brown, cork	American Biltrite Co.	6	18	78	68	66	28
Black Hypalon	Quabaug	4	12	78	70	69	23
Black cush-n-crepe forward thrust	Avon Sole Co.	4	30	78	54	--	24

* An iron is 1/48 in.

CONCLUSIONS

The review of published literature relating to the traction of footwear materials on walkway surfaces and the personal interviews with people actively involved with friction measuring has led us to believe that the status of technology for the measurement of friction of footwear materials on walkway surfaces has been largely status quo since the 1940's. The James machine has offered attainment of static values of COF, but not with portable equipment. The Horizontal Pull Slipmeter offered portability but has not received wide acceptance probably because of its susceptibility to error caused by operator technique. The British Portable Tester gave results which were difficult to correlate with other methods and thus has not been accepted for footwear friction testing.

The proposed ASTM method using the James machine does not represent an advance in the state-of-the-art of friction testing of footwear materials.

The National Bureau of Standards portable James type of machine is strictly capable of static measurements only.

None of these previously existing test devices is capable of or is suitable for evaluating the transition conditions between static and dynamic friction of footwear material on walkway surfaces.

We believe the UFTM is capable of providing the following advantages:

1. It can obtain consistent and reproducible COF values independent of operator differences.

2. It is a portable unit suitable for shop and factory monitoring of walkway surfaces.

3. It is expected to have a reasonably low cost when built in quantity.

4. It may be used to study the transition friction effects between static and dynamic values of COF.

RECOMMENDATIONS

Use the prototype UFTM in the laboratory to study the transition region between static and dynamic friction of footwear and working surfaces for the purpose of selecting optimum footwear materials and walkway surfaces.

Use the UFTM to obtain a number of values of COF for combinations of materials and study ways to correlate these values with the safety of various industrial tasks such as walking, pushing hand trucks, or sliding goods over the floor.

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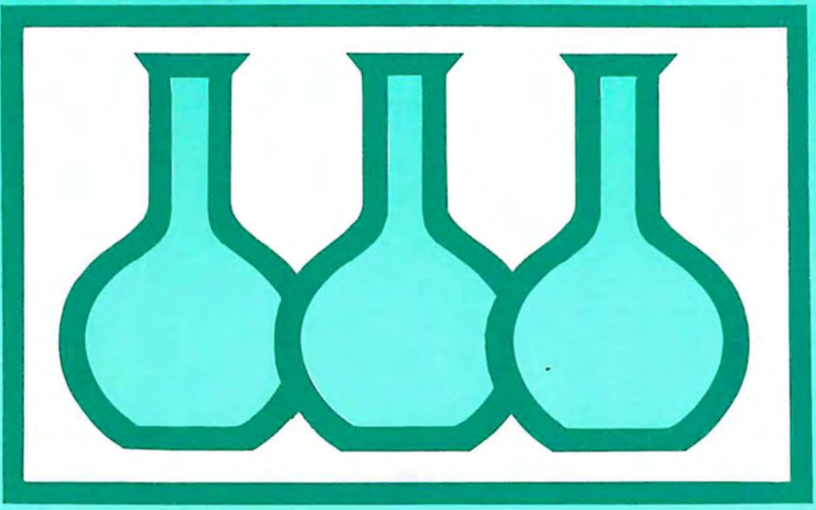

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