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APPLICATION OF DRAFT POWER SENSOR (DPS) CONCEPTS TO PAN SCRAPERS

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16. Abstract (Limit: 200 words) This report documents, from concept through field testing, the pan scraper Wheel Slip Monitor. The function of this device is to instantly warn the scraper operator of wheel slip and thus enable him to take immediate corrective action. Knowledgeable pan scraper people recognize that the preponderance of scraper tire damage and wear occurs during useless wheel slip when the scraper operator attempts to increase machine draft beyond what traction will allow. The resultant shortened tire life has become very expensive. The Wheel Slip Monitor reported here provides the means for relieving the scraper operator of attempting to judge wheel slip on tires he cannot see. Direct and intuitively understandable audible and flashing light warnings tell the scraper operator which wheel is slipping and also indicate the relative magnitude of the slip. Beside the Wheel Slip Monitor's patent utility as a real time operator aid, it has unique potential for application to extended term wheel slip history acquisition under field conditions. This information has never been easily available and it promises practical value in pan scraper management.				
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FOREWORD

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I. SUMMARY AND CONCLUSIONS

Tire maintenance and replacement costs are becoming an increasingly significant part of pan scraper operating expense. Owners and operators of this equipment have long recognized that wheel slip, particularly during the loading cycle, is responsible for a disproportionate share of costly tire wear and damage. This report documents the development, construction and successful field testing of a Wheel Slip Monitor which warns the pan scraper operator the moment slip occurs on any of the wheels. Wheel Slip Monitor use relieves the scraper operator of the task of attempting to deduce wheel slip on hidden tires solely by using machine sound and motion that are subtle and require considerable operating experience to utilize. During local field testing at Southwest Research Institute prototype Wheel Slip Monitor hardware was installed and evaluated on two popular twin-engined pan scrapers, a Terex TS-18 and a Caterpillar 637D*. Subsequent field testing at a working strip mine in Oklahoma employed two Caterpillar 637D scrapers. Installation has been straightforward and is estimated to normally require about 16 manhours as a routine procedure (mechanic plus helper for one shift). Wheel Slip warnings have been reliably produced under a variety of loading conditions during testing. The Wheel Slip Monitor is designed for fabrication using off-the-shelf components save for velocity sensor housings and their integral acoustic horns. It is estimated that Wheel Slip Monitor hardware will cost about \$5,000 as a production item.

We conclude that with consistent use the Wheel Slip Monitor can minimize pan scraper tire wear and damage from uncontrolled wheel slip which routinely occurs during the high tractive effort conditions of loading. In addition to demonstrated utility as an operator aid, the Wheel Slip Monitor offers attractive potential as a unique tire data gathering instrument.

*Reference to specific brands, equipment, or trade names in this report is made to facilitate understanding and does not imply endorsement by the Bureau of Mines.

II. INTRODUCTION AND BACKGROUND

This report describes the development, fabrication, and field testing of the pan scraper Wheel Slip Monitor (WSM). The driving force behind this work effort is the rising cost of tire maintenance and replacement. Pan scraper owners and operators recognize the need for a cost effective device to warn when destructive wheel slip is occurring. It is estimated that at least half the total wear and most of the damage to scraper tires is caused by wheel slip scrubbing during self-loading or loading in a push/pull configuration. In addition to extending tire life, loading with little wheel slip provides best rim pull(1,15,16) and can therefore shorten the loading cycle and allow the machine to clear the pit more quickly. This can increase scraper utilization while at the same time reducing fuel consumption. At the start of this work, two candidate approaches to the problem were chosen. We first investigated the feasibility of a device to measure how fast the bowl is loading, the theory being that when maximum bowl loading rate is achieved, then traction (and therefore draft force) is at its peak and wheel slip is necessarily some small optimum value. This concept is directly related to previous work done with the Draft Power Sensor on bulldozers(2,3,4,5). The second approach considered, and the one actually chosen for prototype hardware development, was implementation of a Wheel Slip Monitor; that is, an electronic device easily and economically retrofitted to existing pan scrapers and capable of sensing and comparing the peripheral speed of the four individual tires to true ground or travel speed. Figure 1 illustrates the control box of this system. If the peripheral speed of any wheel exceeds true ground speed, the Wheel Slip Monitor warns that the wheel is slipping. Both candidate approaches cited were judged to have merit and the advantages and disadvantages of each will be briefly discussed.

The Bowl Loading Rate Monitor (BLRM) approach to improvement of the pan scraper loading cycle, including wheel slip reduction, has great potential for hardware simplicity versus benefits. A sensor attached to the inner bowl surface near the cutting lip would sense moving soil velocity across the lip and into the bowl while a second sensor would simultaneously measure the thickness of the slice of soil being loaded. The product of these values and the fixed bowl width would then yield a continuous relative measure of soil quantity entering the bowl versus time: a "soil flowmeter". The bowl loading rate principle is attractive for several reasons. It would optimize work rate, which is **draft** in relation to **speed**, resulting in most efficient loading. As will be explained later, this also means low wheel slip. Furthermore, it could also warn the operator of the instant the bowl became completely filled. Scraper advance with the bowl down after this point wastefully bulldozes soil in front of the bowl to no benefit. Disadvantages are that this scheme requires novel and unproven technology which must be developed and, unfortunately, the concept is not easily understood by most scraper users. We decided that chances for both technical success and field acceptance of the BLRM approach were somewhat less than the direct and more easily understood Wheel Slip Monitor. We must emphasize, however, that both laboratory experiments and field measurements on the bowls of freshly loaded scrapers confirmed the existence of a definite heat flow temperature gradient from the cutting edge of the bowl back toward the main mass of bowl structural material, and that this temperature gradient (or a similar gradient in a

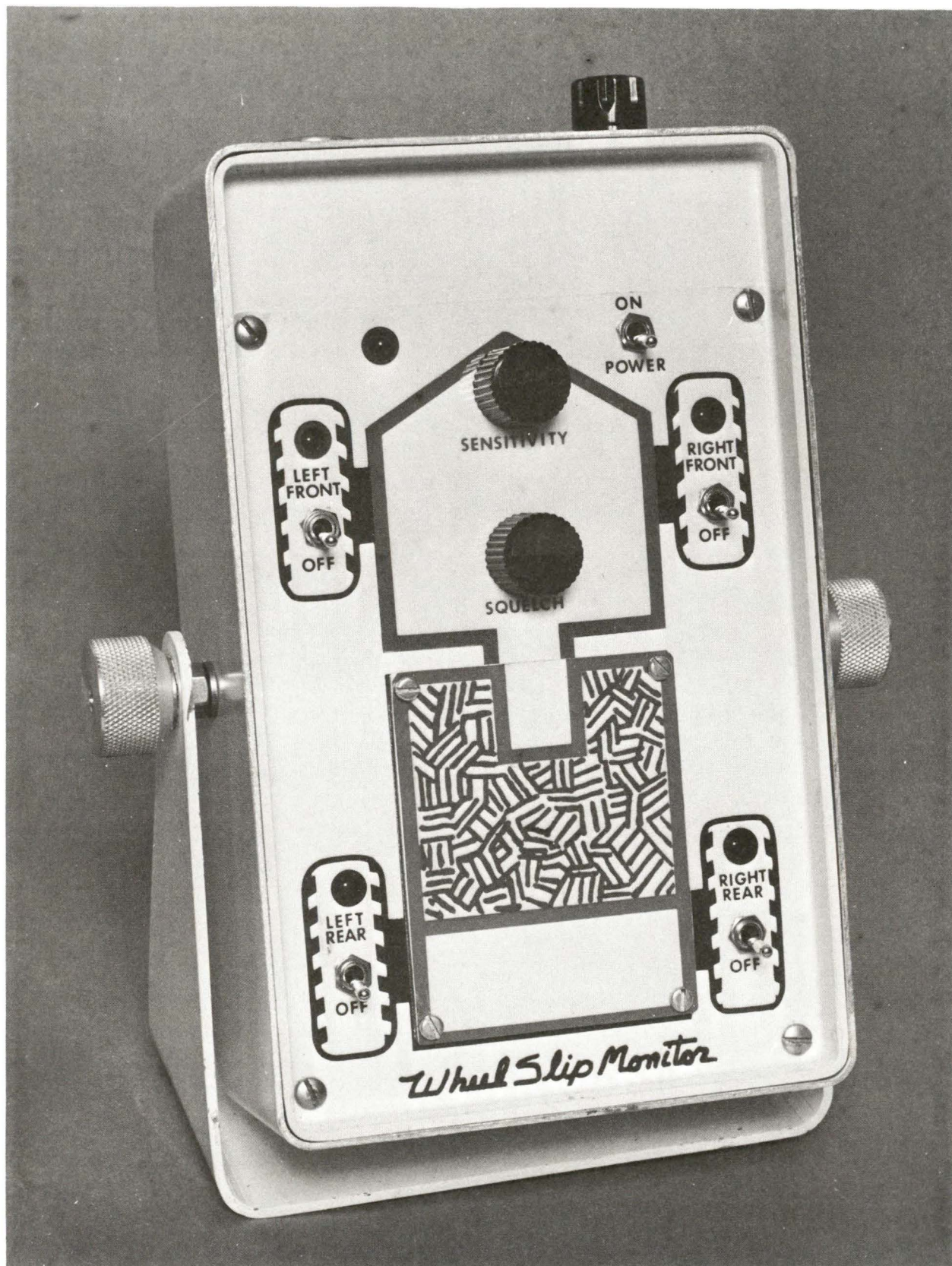


FIGURE 1. WHEEL SLIP MONITOR CONTROL BOX

sensor) can very likely be exploited to infer dynamic soil flow rate*. Regarding the second disadvantage noted above; when the BLRM concept was described to operators in the field, they had difficulty conceiving that such a device would indeed help reduce the destructive wheel slip which they perceive as their paramount concern. These people did, nevertheless, accept and agree that there was significant advantage in indicating to the operator the exact moment the bowl was loaded, after which useless effort does nothing but wear out tires and waste fuel.

Wheel Slip Monitor development to a demonstrated state of practical hardware was judged less risky technically than the indirect BLRM means just described because this technique has a firm footing provided by a fairly extensive body of experimental and applied slip control work conducted over the last few years with tillage tractors, a good portion of it done in foreign countries(6,7,8,9,10,11,12, 13,14). Our task, once we chose to pursue the Wheel Slip Monitor, was to consolidate old and new ideas and from this base to design and test fieldworthy prototype hardware capable of demonstrating cost effective practicality in wheel slip control on pan scrapers. Suitably accurate ground or travel speed determination for comparison with the relative surface velocity of the driven tires is a basic requirement for any wheel slip measuring and warning system. Conventional experimental methods of making this determination have virtually always been impractical for field application. Such things as retractile tapes, fifth wheels or elapsed time between distance markers are certainly direct, and they generally work well enough for experimental data gathering, but they are out of the question in a working pit. Certain reported experiments(10,11,14) had, however, employed hardware methods that were deemed not only practical, but closely related to portions of our prior work with the Draft Power Sensor. From this earlier work(3,4,5) we already had in hand a practical ultrasonic doppler velocity sensor design of suitable accuracy and range for vehicle true ground speed determination. We will not expand here on the specific advantages of acoustic (ultrasonic) versus electromagnetic (microwave RADAR) doppler speed sensing in this particular application, since the point is well covered in the references. Suffice it to say that either technique will work, but ultrasonic doppler has certain advantages. We had speculated, quite some time before beginning our literature search relating to existing wheel slip sensing schemes, on the possibility of using this already developed ultrasonic acoustic velocity sensing hardware in modified short range form to sense peripheral wheel speed, which could then be compared to true ground speed for slip determination. Upon examining the literature, we were pleasantly surprised to find that encouraging results (14) had indeed been reported by investigators in Canada and elsewhere using this selfsame concept on tillage tractors, except with microwave doppler RADAR as the ground and tire peripheral speed sensing means. As it later turned out, practical application was difficult and it was no trivial matter to get reliable surface velocity data off of pan scraper tires, but ultimate results did prove satisfactory. The Wheel Slip Monitor hardware employs five ultrasonic doppler velocity sensors: a reduced sensitivity short target range (about two feet) version for each of four wheels and an unmodified long range (about 20 feet from Draft Power Sensor work) one for true ground speed.

For completeness we should also recognize that there are certainly other valid sensing means that are applicable to the scraper wheels; for example, electromagnetic (toothed wheel or tabs and magnetic pickup) sensors, or any of several other types, might be used to measure individual axle rotational speeds and then from this and tire diameter

*See Appendix Entry 1

derive wheel peripheral speed. Experience has, however, repeatedly shown that sensors of this type are often fragile, difficult and expensive to retrofit and sometimes require that the machine be out of service for an extended time period. The only promising alternative to costly mechanical modification is to have the required monitoring ports built in at the time of manufacture, and we believe that this is not a realistic prospect. Likewise, we must also recognize that even the definitions and terminology employed to describe wheel slip are subject to some variation because wheel slip deals with interactions between deformable tires and terrain: not with rigid bodies. Our chosen definition is straightforward and adequate for the purpose: **any difference between vehicle to terrain relative velocity and vehicle to tire peripheral surface relative velocity is wheel slip.**

The five velocity sensors, mentioned above, each produce an electrical output signal whose **frequency** is proportional to the velocity of the terrain or tire target surface relative to the scraper chassis as the fixed reference point. This frequency information is conveyed through electrical cables to an operator control box mounted in the cab (Figure 1) where it is then converted to voltages proportional to individual wheel speeds and then further processed to turn on blinking lights corresponding to any individual wheel which is slipping, and in synchronism with the light, sound a beeping tone audible to the operator. The **rate** of light blinking and tone beeping is proportional to the **degree of slip**; a readout system was derived from the one which has proven very satisfactory in Draft Power Sensor application. WSM hardware was first field tested at Southwest Research Institute on two different pan scrapers and this testing confirmed that the device is a practical aid to the operator. Any time a wheel slips, the operator is given a series of "beeps" and blinking lights whose repetition rate corresponds directly to the degree of wheel slip which is being generated, and under the influence of these easily interpreted warnings the operator will take appropriate control action. During the course of later field testing at a working strip mine, an alternate flashing light readout scheme was implemented and proved very effective. Two blinking lights, one for the front pair and one for the rear pair of wheels, were placed behind the operator such that they were in his field of view when looking back at the bowl being filled. Thus when slip occurred, he could reduce power on the appropriate drive engine. Since there are few, if any, scrapers on which the operator can directly see the wheels, the WSM is a useful adjunct to day-to-day operations, and we must conclude that with consistent use, it promises a significant reduction in pan scraper tire wear and damage. This should especially prove true of loading operations which involve material containing crushed or blast fractured rock, notorious for causing tire injury, and which are common in many mine earthmoving operations employing pan scrapers. One mining industry source(17) reports that under their severe service conditions, tire life can sometimes be limited to less than 1000 hours. Even a small degree of tire life extension can rapidly exceed the estimated installed cost of this device. Based on current manufacturing costs, an approximate selling price of \$5,000 is projected.

The WSM hardware is conveniently powered by the scraper's electrical system and consumes less than one ampere at 24 VDC. During tests it has been trouble free and we believe that it can readily be brought to a production stage of development.

Finally, beside the demonstrated operator aid usefulness just noted, the WSM is a missing and indispensable link in a recording system allowing accumulation of quantitative wheel slip data over extended periods of time, thus enabling a statistical search for correlations between wheel slip history under various work regimes and resultant tire life.

There is no practical method at present for generating this information of obvious importance in scraper management.

III. SELECTION OF WHEEL SLIP CONTROL METHOD

We first developed criteria against which candidate wheel slip control methods might be judged. Several prospective strategies appeared to be technically feasible, and thus it was necessary to eliminate all save one or two from serious investigation. Candidate selection was predicated upon two interdependent considerations: the promise of acceptable performance and then the choice of technical concept most readily implemented to achieve that performance. Some selection criteria were obviously more important than others, and accordingly each was given a weighting number to reflect its perceived relative impact on hardware development. **Performance** has multiple aspects (how well the system works, cost, reliability, etc.) just as does **Concept** (theory of operation, sensing technique, and so forth). A matrix comparison of the known or estimated characteristics of the several technical schemes versus the criteria was made as shown below. For this comparison we called upon prior experience in the art, the technical literature, industry opinion and practice, theoretical analysis and rudimentary experimentation.

A. CRITERIA

The following random order list first summarizes each criterion and then assigns both weighting and matrix column numbers to it. The weighting numbers quantify how critical to ultimate project success we estimated each criterion to be.

Values of the weighting numbers are:

- 5 - extremely important, critical to success
- 4 - very important, loss greatly reduces chances of success
- 3 - important, loss has negative impact, alternate required
- 2 - needed, improves chances of success
- 1 - desirable, but an alternate probably satisfactory

The criteria:

	<u>Weight, Column:</u>	
● Reliable wheel slip indication (few false warnings)	5	I
● Slip indication can be quantified	3	II
● Hardware reliability, field worthiness	4	III
● Ease of installation (less than 20 man hours)	3	IV
● Low cost (less than \$5,000 installed)	3	V
● Easy to maintain and adjust	3	VI
● Machine operator acceptance	4	VII
● Hazard free (man and machine)	5	VIII
● Fail safe (failure does not disable scraper)	4	IX
● Industry acceptance of concept	4	X

- Low electrical power drain
- Prior successful implementation of concept
- Second sourcing for component parts

Weight, Column:

2	XI
4	XII
3	XIII

B. CANDIDATE SELECTION

Table 1, Candidate Method Rating Matrix, assigns a column to each criterion and a row to each candidate wheel slip control scheme. Each candidate is rated in the boxes of its row under the appropriate criterion column with a number reflecting our best estimate of how well that candidate method can meet the particular criterion. Allowance is made for development success to be reasonably expected during the course of project work for those schemes requiring novel implementation methods. The values given these rating numbers are as follows:

- 5 - meets all requirements
- 4 - meets most requirements
- 3 - meets some of the requirements
- 2 - meets a few of the requirements
- 1 - probably cannot meet any of the requirements

Observe that this arrangement provides the flexibility to judge each candidate from all perspectives while rating it as to how well it meets the requirements of a particular criterion, thus avoiding development of a matrix so large as to become unwieldy. Where a particular technique might be implemented with more than one type of sensor, the more promising candidate configurations are rated separately and the critical sensor(s) indicated in parentheses. The final score which each candidate is given in Column XIV of the table is the sum of the products of each column rating and its respective criterion's weighting number. These scores are ranked by the final numbers at the end in parentheses.

Inspection of Table 1 shows that direct wheel slip sensing most nearly meets the stated system criteria, and that of the several candidate configurations scored, the system employing ultrasonic (acoustic) doppler wheel peripheral and ground speed sensors looks best; although the same technique employing electromagnetic (microwave) doppler sensors scores well also. The advantage goes to the ultrasonic sensors by virtue of cost and complete freedom from Federal Communications Commission regulatory requirements such as those that apply to all microwave radiating devices because of implied microwave communications interference hazard. The implementations using mag pickups, fifth wheel and so forth are feasible, but were eliminated because of the difficulties associated with them as retrofit procedures.

Of the remaining candidates, we eliminated comparison of wheel peripheral speeds to each other (no true ground speed) because it precluded slip quantification (magnitude determination). This "wheels only" slip function could, however, be easily and economically embodied in the chosen direct wheel slip sensing method if desired, thus allowing an alternate system operating mode. Finally, we reluctantly eliminated the candidate methods of inferring slip from the motions of the scraper's differential gearing or alternatively analyzing by doppler means the tire/ground contact area. The first because it required mechanical modification of the scraper drive train, and the second because of a need for complex signal processing: a fact which was confirmed with laboratory

Table 1. Candidate Method Rating Matrix

Candidate Methods	Criteria													Overall Rating and Rank
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	
	Rel. Indication	Quantified Slip	Hdwre. Rel.	Inst. Ease	Low Cost	Ease Maint.	Op. Acceptance	Hazard Free	Fail Safe	Ind. Accp. Concept	Low Power Drain	Prior Use	Second Sourcing	
	(5)	(3)	(4)	(3)	(3)	(3)	(4)	(5)	(4)	(4)	(2)	(4)	(3)	
• Bowl Loading Rate Sensing (soil flowmeter)	4	3	4	3	4	4	2	5	5	2	4	1	3	160 (7)
• Ground Speed (fifth wheel) Vs. Wheel Peripheral	4	4	4	2	2	3	4	3	4	3	4	4	3	161 (6)
• Ground Speed (EM* doppler) Vs. Wheel Peripheral Speed (mag pickup)	4	4	4	2	3	3	4	3	4	3	4	4	3	164 (4)
• Ground Speed (EM doppler) Vs. Wheel Peripheral Speed (EM doppler)	4	4	4	4	3	3	4	4	4	4	4	4	3	179 (2)
• Ground Speed (US** doppler) Vs. Wheel Peripheral Speed (mag pickup)	4	4	4	2	3	3	4	4	4	3	4	3	3	165 (3)
• Ground Speed (US doppler) Vs. Wheel Peripheral Speed (US doppler)	4	4	4	4	4	4	4	5	5	4	4	3	4	193 (1)
• Wheel Peripheral Speeds Compared (mag pickup)	4	1	4	2	2	3	3	4	4	3	4	3	4	152 (8)
• Wheel Peripheral Speeds Compared (EM or US doppler)	4	1	4	4	4	4	3	4	4	3	4	2	4	163 (5)
• Detect Rotation of Axle Differential Gearing (mag pickup)	3	1	4	2	2	3	3	4	4	2	4	2	2	133 (9)
• Relative Velocity Sensing at Tire/Ground Contact Point (US or EM doppler composite signal)	3	3	4	4	4	4	4	4	4	3	4	2	3	165 (3)

* EM = Electromagnetic (Microwaves)

** US = Ultrasonic (Acoustic waves)

experiments. This left us with direct wheel slip and bowl loading rate sensing as the two most promising candidate wheel slip control methods.

1. Bowl Loading Rate Monitor (BLRM)

We elected to investigate the Bowl Loading Rate Monitor concept first. Its fundamental premise is: when bowl **loading rate** is optimized, then reduced wheel slip and tire wear will follow as a predictable result; as will most efficient machine time and fuel utilization. Let us see what evidence supports this premise.

Various investigators report that tillage tractors are most efficient at a small (less than 15%) degree of wheel slip(1,14,15). We would like to apply this information directly to our problem, but it seems unwise to straightforwardly equate scraper wheel slip with that of tillage tractors because the scraper does not operate at fixed machine weight as does the tractor. Pan scrapers must be able to transport heavy gross loads, and they are powered accordingly. The scraper's unloaded power-to-weight ratio is comparatively large and leads to the situation during loading where, because of inadequate tire/terrain pressure, the driven wheels are able to convert only a fraction of the available engine power into draft or tractive effort via available traction before slipping. The loading pan scraper virtually always has engine power far in excess of what the traction coefficient will allow it to use profitably, and we often see this power being squandered in wildly slipping wheels: wearing out tires and wasting high priced diesel fuel in a vain attempt to increase loading speed. This great excess of power, particularly at the start of loading, confuses our intuitive picture of what a bowl loading rate device would really tell us about scraper operation. Among earthmoving machines, the scraper is unusual; it can waste engine power, and still have plenty left for loading. The cited references give the overall impression that **any** draft producing machine with large low pressure cleated rubber tires works best when wheel slip is small and this helps support our premise, but it is still not the confirmation needed. Several complex and totally interdependent variable operating parameters define pan scraper loading performance and this makes analysis difficult, but if we **can** verify our notion that the expedient of working the scraper at the point of maximum bowl loading rate produces best efficiency **with** minimal wheel slip, then such a scheme is superior to monitoring wheel slip alone and of considerable value. Alternate lines of reasoning can help. The simplest of these is qualitative and anecdotal, others more complex.

During the project start up period we talked with personnel at a scraper manufacturing plant (WABCO) to elicit opinion about this development effort and to determine how **they** viewed pan scraper wheel slip and operating efficiency problems. The results were instructive, particularly the comments of one very experienced (30 years as a scraper operator) test technician. This man stated his firm opinion that scrapers load best when the bowl cut is rather shallow and "you keep your speed up and don't slip the wheels." He then proceeded to make his point by rapidly and very smoothly self loading a 22 yard (struck) capacity twin engine machine several times while we observed and shot films. Later analysis of these motion pictures showed a very small and constant wheel slip during loading periods lasting from 30 to 40 seconds: roughly the same loading elapsed times as later observed at two strip mines working equivalent scrapers but **with** push dozers and much wheel slip. This man's demonstration clearly showed that rapid loading, even beyond struck capacity, does not **require** wheel slip: but it left unanswered the question of whether this rapid loading might still be possible with enough excess engine power available to allow the dissipation of much of it in wheel slip losses and still

have an amount left over to provide adequate machine performance. The converse of our premise, rather than the premise itself, was upheld. It can be proven that high wheel slip rates preclude **efficient** loading, but we wanted to confirm that high slip rates also limit attainable bowl loading **rates**; and one way to show that is to find support for the idea that tire traction and resultant scraper draft force pass through a definite maximum at some **low** wheel slip rate. References (1,14) indicate that for certain specified conditions this is true, with the most pronounced maximums(1) occurring in the case of tillage tractor tires at about four to five percent wheel slip on a concrete surface. Consider also that a related traction effect occurs during vehicle braking action. It is a widely acknowledged fact that a locked wheel (100 percent negative wheel slip) provides sharply reduced braking force compared to a rotating wheel that remains very nearly "traction locked" to the braking surface. For this reason brake anti-lock devices are routinely installed on large trucks and aircraft. There is obviously some small and specific value of wheel slip (positive or negative) that provides the best coupling between tire and pavement under a particular set of conditions. Since our primary interest is in scraper tires working on some combination of soil and fractured rock and we have no test data for that case; we are forced to assume, with some reservation, that the two cases are related closely enough to conclude that scraper draft force also peaks just before declining as wheel slip increases beyond a few percent and traction falls. Just how sharp the peak is, and how it is affected by tire condition, terrain characteristics and so on will remain unknown pending future experimental work; however, for the present we need only to recognize that rimpull is wheel slip magnitude dependent; and, that at any selected **constant** vehicle travel or ground speed, **draft** (generated by the sum of rimpull for all driven wheels) passes through a maximum value as wheel slip increases from zero to some high rate. If there is a rare case, such as in very loose sandy soil, where draft simply reaches a plateau, we ignore it as not applicable to this tire wear problem. We also ignore this dependence over the range from zero slip up to the maximum draft point; which, if our assumption is correct, occurs at less than perhaps 10 percent wheel slip. Since pan scraper bowl loading rate is proportional to (among other things) the soil cutting rate produced by draft, we could possibly argue that so long as everything else does not vary then bowl loading rate might be inferred directly from draft forces. Unfortunately, the real world case of a working pan scraper in its loading cycle is much more complex than this because **all** operating factors are variable. This situation is analogous to work rate determination with the Draft Power Sensor in bulldozer applications. There, in order to produce the desired operator information, we derive draft power or work rate by continually computing a **product** of the two controlling variables: namely true ground speed or **velocity** and **draft**. The only way to combine all the pan scraper operating variables into one quantity whose magnitude specifies how well the scraper is loading, is to directly determine bowl loading **rate** at every instant by finding a way to sense the relative **velocity** of the sheet of soil being loaded as it moves past the cutting lip of the bowl and then multiplying this factor by the cross-sectional **area** of the sheet. This procedure accounts for variation in vehicle speed, draft, traction efficiency, net effective power and so on; and our premise says that it also assures that wheel slip stays at a low and most efficient value. Since the width of the sheet of soil flowing into the bowl is mechanically fixed by bowl width, all we must sense, in order to find this **area**, is sheet thickness or depth. Expressed in symbols we then have

$$M_{blr} = VHK \quad (1)$$

where

M_{blr} = Bowl loading rate (yd^3/sec , etc.)

V = Relative velocity between cutting lip and soil sheet

H = Height or thickness of soil sheet

K = Scaling constant: to accommodate fixed bowl width and units chosen for V and H in order that M_{blr} is expressed in the desired units.

Novel sensing methods were needed to implement such measurements, and accordingly we undertook rudimentary laboratory and field experiments to empirically assess the feasibility of developing practical sensors for the operating variables needed.

As a first step, we recorded differential temperature measurements at two closely spaced points on the axis near one end of a $1/4"$ x $1"$ x $24"$ aluminum bar. Very small ($1/16"$ dia.) thermistors were embedded in the bar and then this end was heated by friction from rubbing contact with our moving carpet belt test rig ordinarily used to test and calibrate ultrasonic velocity sensors. We obtained a fair correlation between moving carpet belt surface velocity and temperature differential produced between our thermistor sensing wells by the heat flux flowing from the hot end of the bar (frictional heat input) toward the cold end (sink). Figure 2 illustrates how the heat flux increases with time when friction commences at selected carpet belt velocities. Figure 3 shows in schematic form the experimental arrangement and a plot of the Figure 2 data rearranged to illustrate more clearly the relationships between relative velocity and heat flux. This result encouraged us to analyze comparable frictional heating effects produced by soil/metal rubbing contact as in a loading scraper bowl. Field measurement of metal surface temperature from the cutting lip rearward in a freshly loaded scraper bowl confirmed a substantial temperature gradient.

Beyond these described feasibility experiments, no further action was undertaken on the BLRM because the concept elicited little enthusiasm when described to industry personnel. This is understandable in view of the fact that the concept is difficult to explain and defend in terms acceptable to the operating people who actually need and could use it. The suggestion of having **any** wheel slip at all during loading is not welcomed, even if it does present the prospect of improved machine efficiency that could offset by a wide margin some minimal increase in tire wear compared to **zero** wheel slip operation. We conclude that nothing short of well documented field testing over an extended time period is apt to convince industry people that pan scrapers **can** be operated in such a way as to produce at one and the same time fastest loading, least fuel consumption, shortest time in the pit and tire wear very nearly the minimum obtainable under **any** conditions. From a technical viewpoint, we must say that the "soil flowmeter" appears quite feasible and it represents the critical building block in any future Bowl Loading Rate Monitor development effort. Other required elements, such as soil thickness sensor and signal processing, are matters of straightforward engineering development and should be readily implemented.

Finally we will point out that the very best solution overall is to combine the Wheel Slip and Bowl Loading Rate techniques into one instrument, and this prospect will be elaborated at appropriate times later in this report.

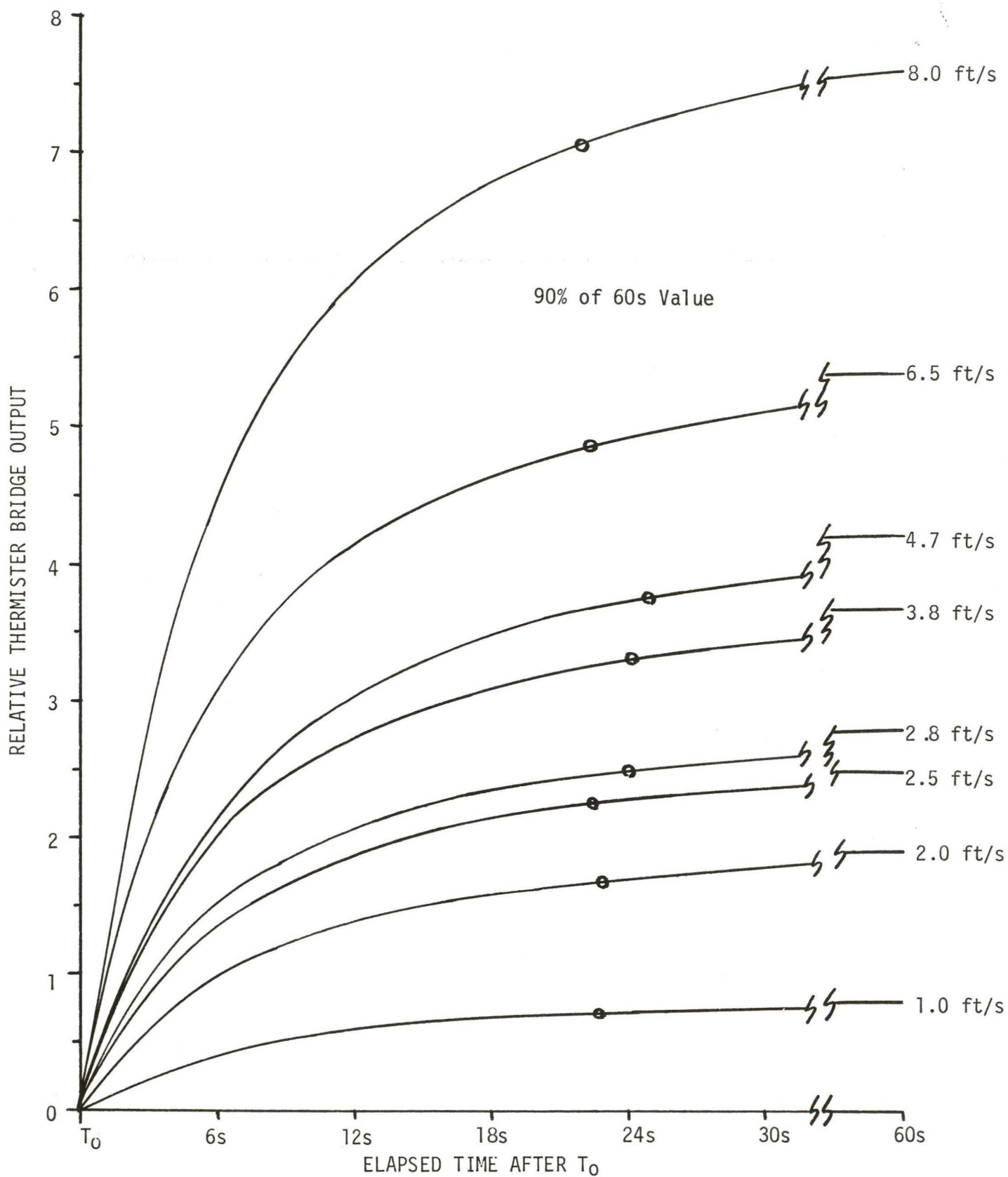


FIGURE 2. HEAT FLUX MAGNITUDE VARIATION IN ALUMINUM BAR

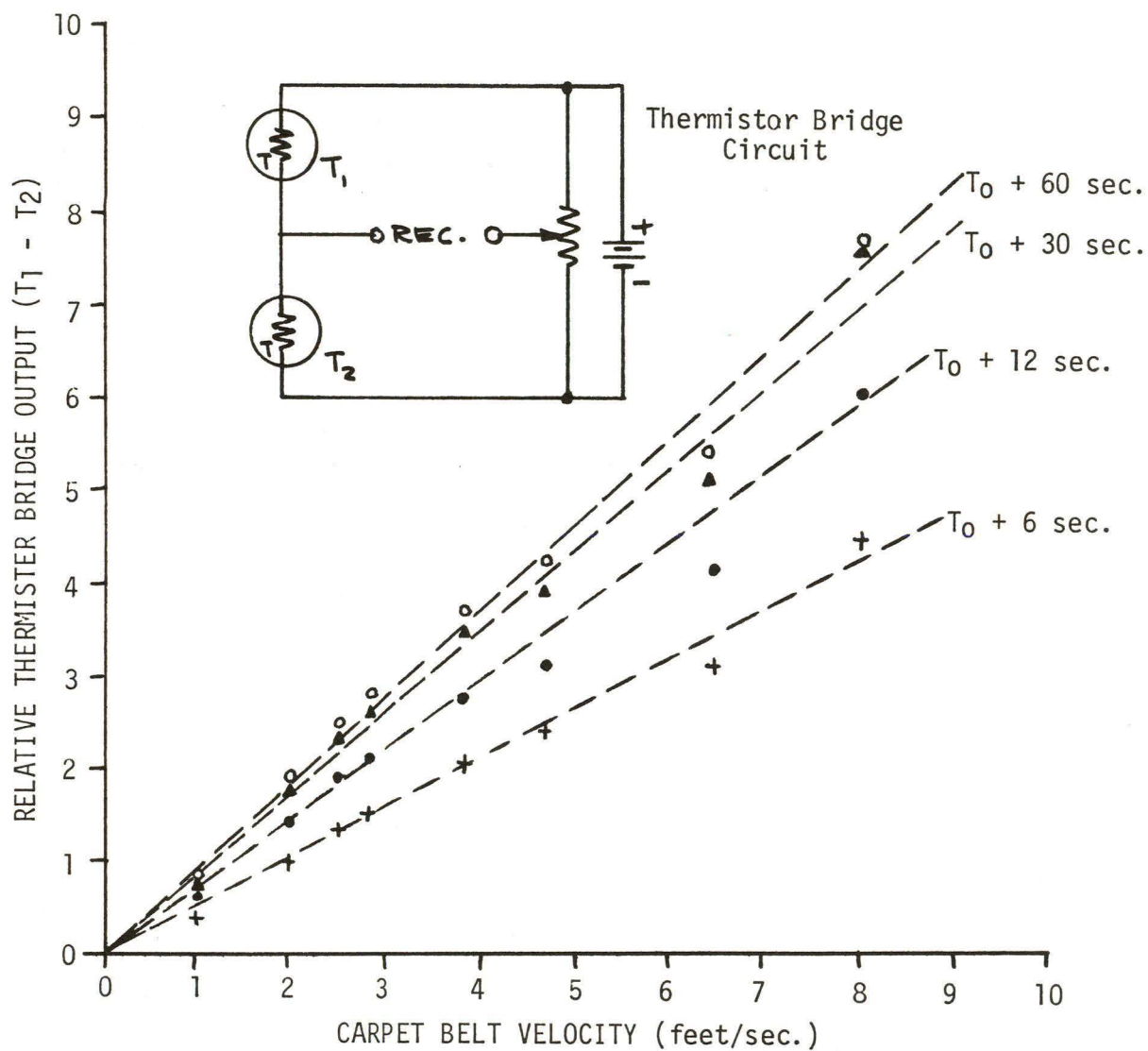
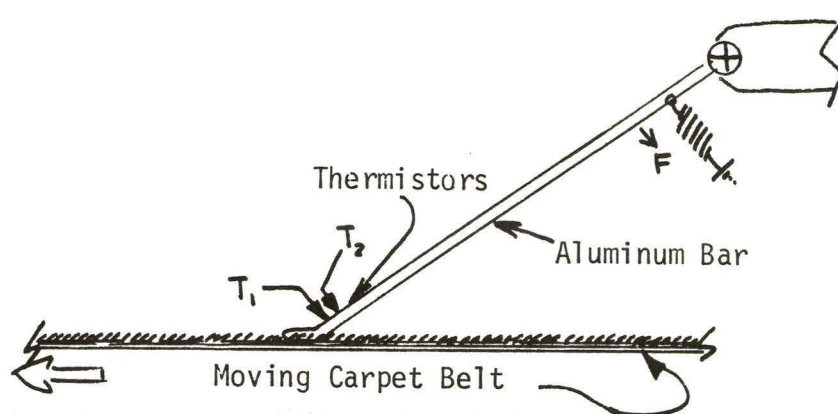


FIGURE 3. VELOCITY VERSUS HEAT FLUX MAGNITUDE

2. Wheel Slip Monitor

After evaluation of Bowl Loading Rate Monitor techniques we began an intensive investigation of the Wheel Slip Monitor concept as then envisioned. Of first priority was resolution of questions about the accuracy of ultrasonic doppler velocity sensing for scraper ground speed, and more particularly for tire peripheral speed determination. Fortunately, just prior to this time the opportunity presented itself to evaluate two commercial tillage tractor monitoring systems that incorporated rudimentary wheel slip measuring function. One used electromagnetic (microwave) doppler and the other fifth (or undriven) wheel means for ground or travel speed sensing. Test results from these proprietary evaluations, when combined with past experience, further reinforced our conviction that the ultrasonic (acoustic) doppler velocity sensing system already in hand from Draft Power Sensor work would prove to be the best choice for pan scraper true ground speed determination. The work described in the next two sub-sections critically examined the potential of each hardware element and then narrowly defined expected function prior to beginning full scale prototype hardware development.

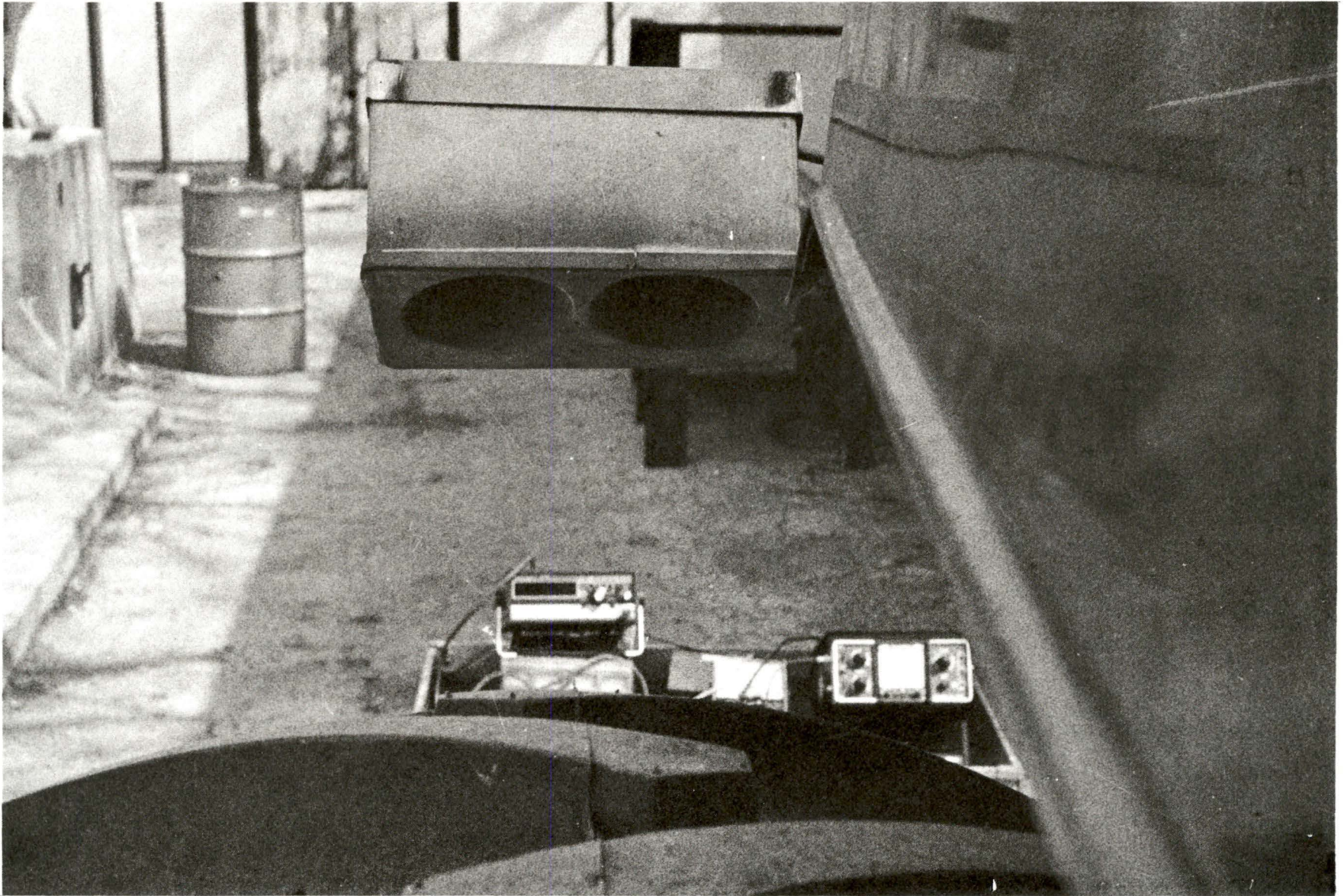
a. Experimental Verification of Feasibility

Concept feasibility rested on the crucial question mentioned earlier. Could the existing ultrasonic doppler velocity sensing hardware design be used (or modified) to produce suitably accurate electrical output response relative to linear tire velocity at the tire periphery? Accordingly, we conducted experiments using an available tillage tractor and a large haul truck. Both vehicle's rear tires were physically comparable in size to scraper tires. The vehicles were blocked up and run with test jigs positioned to hold various velocity sensor ultrasonic acoustic horns at selected angles and distances from their tire surfaces. These test horns were connected to electronic circuitry of the type that had already proven itself in bulldozer ground speed sensing. One of several similar experimental arrangements is shown in Figure 4, and serves to illustrate the technique employed with both the tillage tractor and the haul truck tires. Tire peripheral speed versus velocity sensor output characteristics was investigated for many angles and distances. Figure 5 diagrams a typical experiment and the results obtained. This data promised that existing velocity sensing hardware designs could, in all likelihood, be modified to perform satisfactorily under the geometrical mounting constraints of pan scrapers. Since we anticipated no problems with ground speed sensing or signal processing, these experimental results confirmed feasibility in general terms.

b. Definition of Function and Display Desiderata

The criteria in Section IIIA above state, in broad terms, what characteristics the WSM hardware should have. Now we must precisely define what these criteria mean in hardware functional terms before we can proceed with circuit design, packaging and the other things that culminate in boxes that actually bolt onto the pan scraper. Figure 6 is a functional block diagram of the Wheel Slip Monitor system. This diagram specifies the required action of each system element, and is the framework upon which detailed circuit design was built. In a moment we will describe the function of each diagram block in input/output terms, after we have examined some background information germane to the hardware implementation derived from Figure 6.

A conceptual problem involving the exact strategy for electronically processing the five velocity signals needed to be resolved. Consider, for example, that



**FIGURE 4. WHEEL PERIPHERAL VELOCITY SENSING EXPERIMENT
ON TILLAGE TRACTOR**

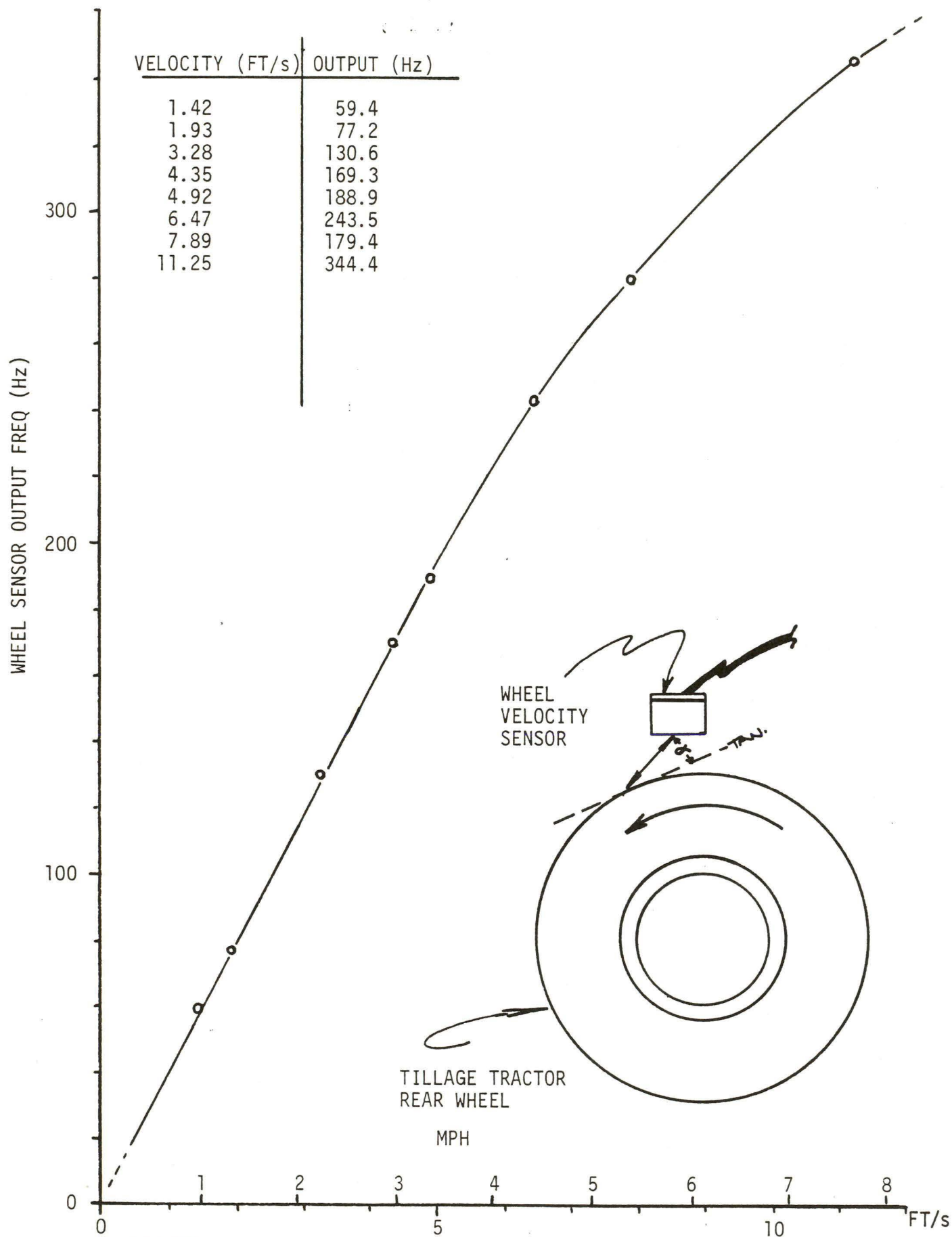


FIGURE 5. WHEEL PERIPHERAL VELOCITY SENSOR PERFORMANCE DURING FEASIBILITY TESTING

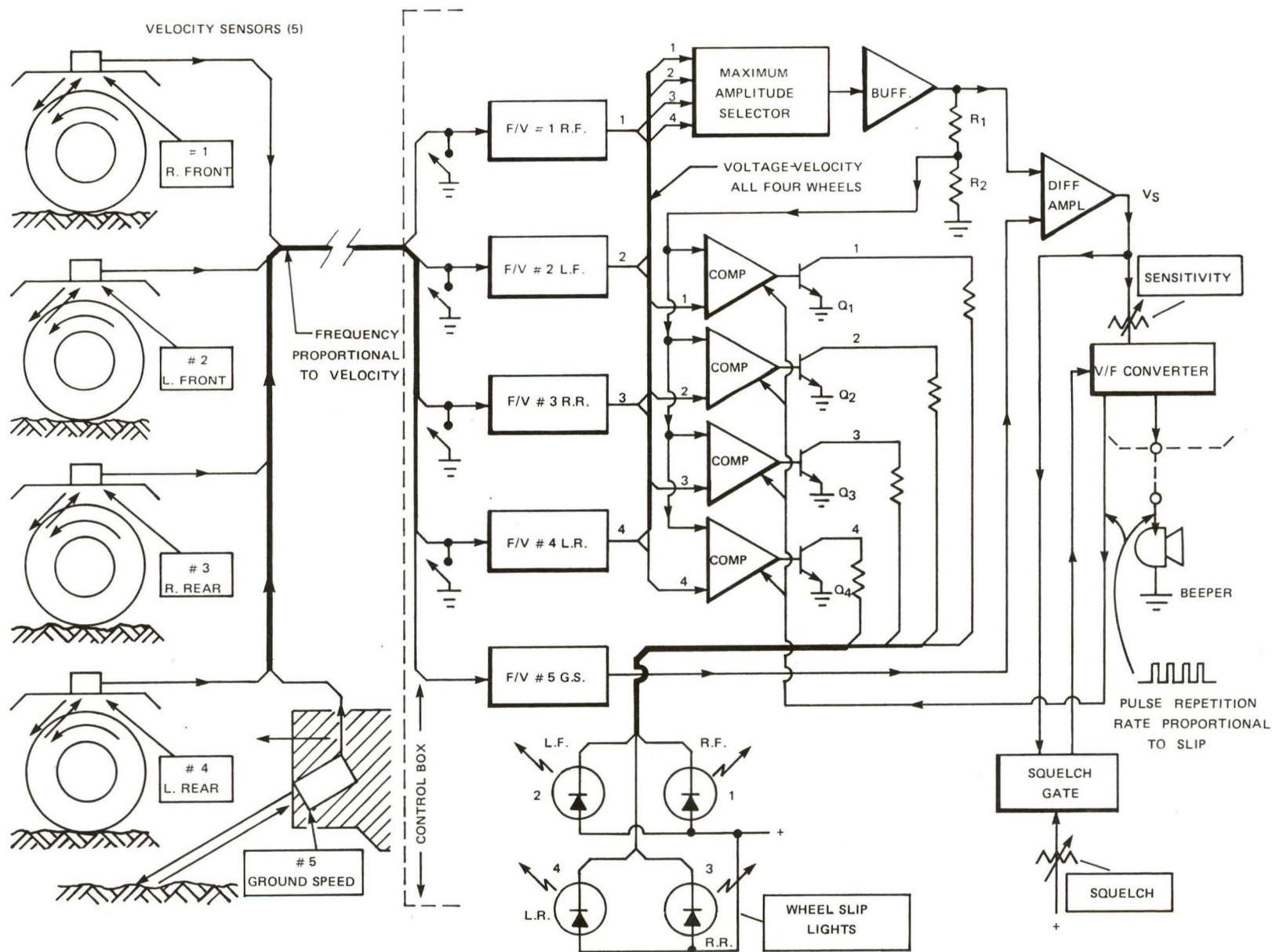


FIGURE 6. WHEEL SLIP MONITOR FUNCTIONAL BLOCK DIAGRAM

comparison of two velocities (say true ground speed versus one wheel's peripheral speed) must be implemented such that a slip warning is always given the operator at the same specified slip threshold over a fairly wide range of scraper travel speeds. The situation is further complicated when all four wheels', plus ground or travel, speed must be compared in any of the several combinations possible. How must the slip threshold be defined? After some thought, an answer suggested itself, but it required discarding some of our established ideas about quantitatively describing wheel slip. When we limited our consideration to the interrelationships between wheel slip, tire wear, and draft as perceived to influence each other and project objectives, we concluded that a device which derived **percent** wheel slip was not satisfactory for this application and this is why: as noted in the previous discussion of the Bowl Loading Rate Monitor, with tillage tractors a wheel slip of a few percent at usual travel speeds is generally considered best for optimum draft force production and most efficient operation overall(1). This slip magnitude remains essentially constant over long periods of time. Wheel slip has been defined in the past for the traction vehicle(14), rather than the actual slipping wheel because this was the only practical way. A common procedure is to compare the distance traveled during a given number of wheel revolutions **with** and **without** slip:

$$\text{Percent Wheel Slip} = \frac{\text{Distance without Slip} - \text{Distance with Slip}}{\text{Distance without Slip}} \times 100 \quad (2)$$

or, if wheel rpm is held constant, let the vehicle travel for equal elapsed time periods and compare the distances traveled both with and without wheel slip. This equivalent procedure allows us to express equation (2) in velocity, rather than distance, terms and helps to clarify the following argument. Since the several driven wheels of a pan scraper rarely slip equal amounts, a more useful wheel slip definition can be formulated using the linear peripheral (tangential) velocity of each driven wheel compared to vehicle travel speed. Thus for an individual tire:

$$\text{Wheel Slip} = \text{Wheel Peripheral Speed} - \text{Vehicle Travel Speed} \quad (3)$$

This expresses wheel slip in terms of the relationship between the individual traction wheel and the terrain surface, rather than the vehicle. More about this in a moment after we clarify our terminology. The words "speed" and "velocity" are used throughout this report in their general, rather than strict, definition and are accordingly considered to mean the same thing. Furthermore, when we say "tire linear peripheral velocity" or "wheel speed" it is implicit that the vehicle chassis adjacent the outermost tire surface is the point of reference, and that we are referring to the linear relative motion between that reference point and some plane that passes through it and is also tangent to the tire periphery.

Most reported wheel slip work concerns itself with best tillage tractor efficiency under more or less steady-state conditions of moderate tire slip rates in benign soil; certainly not on abrasive terrain at intermittent high slip rates, as is the case for many loading pan scrapers. Recall that the stated function of our system is to provide suitable real time wheel slip warning information directly to the pan scraper operator so that he or she will be able to rapidly load the machine consistent with minimum damage

to expensive tires. Equation (3) provides a more general and appropriate descriptive measure than "percent wheel slip". To quantify slip we adopted the term "scrubbing velocity", symbolized V_s , and define it as "the instantaneous velocity difference in ft/sec between terrain and tire periphery". Defined in this way, V_s is applicable to **any** relative motion between the tire and terrain surfaces regardless of direction: wheel slip ($+V_s$), skid from braking action ($-V_s$), or sideways skid in some specified direction. Percent slip is **independent** of vehicle speed, and its use to quantify slip would assuredly produce ambiguous results in our application. As an example, consider wheel slip occurring at a tire peripheral velocity of three feet per second and a true ground speed of two feet per second. Here we have 33 percent slip (the vehicle is moving only 66 percent as fast as the tire's periphery) and **one foot per second** velocity differential (V_s) causing destructive scrubbing action between the tire and terrain surfaces. Let us now increase all speeds by a factor of two so that true ground speed is now four feet per second and the tire peripheral velocity is six feet per second. The percentage wheel slip is still 33 percent, yet we have **doubled** the relative velocity differential (V_s) between the ground and the surface of the tire to two feet/second, and probably have also doubled the tire wear **rate**. This simple example shows why percent slip is not a satisfactory way to quantify traction tire slip over an extended speed range when tread wear is the quantity of interest. While our adoption of V_s might seem innocuous, it completely changed our concept of wheel slip quantification and, as a consequence, our contemplated hardware design for processing, displaying and recording wheel slip information. Let us use first principles for a moment in our reasoning and see why the V_s idea may be considered very important.

Suppose we start with the self-evident assumption that at some **constant** vehicle travel speed a slipping wheel will wear its tire **more** than a wheel that is not slipping, and from this we can then reasonably argue that this slipping wheel tire wear increases if slip (at **constant** vehicle travel speed) increases further. This simply means that wear is in **some way** proportional to our term V_s . Tire wear versus V_s might be travel speed sensitive; that is, a specified value of V_s might result in a different tire wear rate if it occurred at some higher vehicle ground speed. For the scraper loading cycle speed range below about five mph we believe any such effect to be so small that it can be safely ignored, even if it does exist. It seems quite reasonable to expect that tire wear **rate** is, to a first approximation, **directly proportional to V_s** . Since V_s is a rate term it must always be considered in relation to the time span a particular value of V_s persists between tire and terrain: which is simply another way of specifying the total **distance** the tire tread has been dragged over the ground surface during some period. An analogous situation might be to wear down a rubber eraser by dragging it at fixed pressure across a sandpaper surface. So long as we did not go fast enough to heat the rubber appreciably, we would probably find that the eraser wore down an amount directly proportional to how **far** we dragged it, even if dragging speed (V_s) varied considerably. This has important implications. For example, the Wheel Slip Monitor can now make possible the recording of cumulative V_s tire history over an extended operating time period in order to determine just how V_s correlates with tire wear and possibly damage. By similar methods, the effectiveness of this or **any** other wheel slip reduction strategy can be evaluated quantitatively.

Beside the control of obviously damaging gross wheel slip such as we have all seen with smoke and flying chunks of rubber during bad scraper loading conditions, the Wheel Slip Monitor offers, particularly if combined with the BLRM, potential means of prudently trading off **tire wear expense** against **scraper production** in order to

obtain best overall dollar efficiency. Observe that these two factors are usually considered to be at cross purposes, but you can be sure an optimum condition exists if it could be found. No one knows how because there has never before been a practical way to obtain real world data.

With this conceptual problem resolved, we could now specify that the Wheel Slip Monitor System would:

- simultaneously compare true ground speed with the peripheral speeds of all four tires and output a voltage proportional to the instantaneous difference (V_s) between true ground speed and greatest individual tire speed;
- generate an audible "beeping" tone whose beep rate was proportional to the V_s electrical signal and thus warn the operator not only of the presence, but the relative magnitude, of greatest wheel slip;
- turn on the appropriate one of four indicator lights to show which tire was slipping the most, and cause this warning light to blink in synchronism with the "beeper";
- provide buffered V_s outputs suitable for driving recording instruments and thus allow tire V_s history to be accumulated in any of several formats;
- be configured to allow operator control of "beeping tone" loudness and selection of wheel(s) to be monitored;
- allow the scraper operator to "squench", if desired, the slip indication at all V_s values below some selected (low) value. This has the important effect of setting a definite wheel slip threshold and allowing small values of slip to routinely occur without loss of gross slip warning.

Regarding this last function; since pan scrapers are used to handle materials with a wide range of physical properties with resultant loading travel speeds that vary from perhaps five miles per hour down to a fraction of a mile per hour, keying the operator's slip indication (beep and blink rate) to V_s magnitude automatically allows him or her a higher **percentage** wheel slip at low speeds for the same given slip warning indication. We would argue that this closely approximates the action called for.

Referring back now to the Wheel Slip Monitor system block diagram, Figure 6, this is how the hardware works. Shown schematically at the left of the diagram are the five velocity sensors. A wheel speed sensor is mounted near each of the four tires in a suitable fender cut-out to measure each tire's peripheral velocity, and a long range sensor is attached to the scraper's front apron to sense ground speed. The outputs of all five velocity sensors are electrical signals whose **frequency** is proportional to the relative motion between each fixed sensor and the target (tire or terrain surface) that it is illuminating with its ultrasonic sensing beam(3,4,5). The velocity sensors feed the control box and its electronic circuitry via conventional wiring routed along the scraper structure. The right hand portion of the Block Diagram beyond the dashed line depicts the circuitry which processes these velocity signals inside the control box. Sensor electrical signals are

first passed through Frequency to Voltage (F/V) converters. Switches are provided at the input of each wheel speed F/V so that the operator may have (if desired) the option of monitoring any combination of wheels. Each F/V converter output is a direct current (DC) voltage whose magnitude is proportional to the frequency of its input signal. The four DC wheel velocity voltages are fed to a Maximum Amplitude Selector circuit which chooses the largest (the wheel with the most slip), this voltage is buffered and then fed into one input of a Differential Amplifier whose other input is a voltage proportional to ground speed which has been simultaneously generated in the ground speed (G.S.) F/V converter. The Differential Amplifier output voltage is therefore proportional to the **difference** between ground speed and the peripheral speed of the worst slipping wheel; and this difference is the thing we wish to know, namely V_s . The individual outputs of the four wheel F/Vs are also fed to a bank of four voltage comparators which have as their other input a voltage proportional to the greatest wheel slip, but slightly attenuated from full value. This means that the comparator corresponding to the wheel with greatest slip will turn "on", any time it is enabled, and then through its driver transistor (Q_{1-4}) energize the appropriate wheel slip warning light. The V_s voltage output of the differential amplifier is adjustable over a limited range with an operator Sensitivity control before it goes to the Voltage to Frequency converter (V/F) circuit which produces a series of output pulses whose Pulse Repetition Rate (PRR) is proportional to the magnitude of its V_s input voltage. This string of output pulses is gated **on** or **off** by means of a Squelch Gate whose threshold level can be set with an operator Squelch control. When V_s exceeds the threshold or "squelch" setting, then the gate opens allowing the V/F output pulses to drive the Beeper and also to enable the comparators, which in turn actuate the wheel slip warning lights. Squelch action is limited to a V_s of up to about 1.5 ft/sec, beyond which slip warning always occurs. Appropriate power control circuitry is part of the control box, but for simplicity is not shown on the Block Diagram.

IV. WHEEL SLIP MONITOR HARDWARE DEVELOPMENT

For the reader not familiar with the technique, we will briefly discuss how ultrasonic acoustic doppler velocity sensing works before proceeding on to hardware development descriptions of the Wheel Slip Monitor ground and wheel speed sensors that make use of it.

When there is relative motion between the source of **any** kind of waves and a receiver encountering those propagating waves; then the receiver and the source, because of their relative motion toward or away from each other, perceive the same train of waves to have slightly different frequencies. This comes about because frequency is determined by counting how many waves, moving or propagating at a constant speed, pass by a **fixed** point during some time interval. It is easy to see that if the wave receiver is **not** fixed and is, for example, moving toward the wave source, it will meet more waves during this same time interval than it would if it were standing still: the wave frequency will appear to be higher. As you would expect, the reverse situation produces a lower received frequency. This apparent frequency change is called the doppler shift (after its first principal investigator) and it applies to all kinds of propagating waves; sound or acoustic, electromagnetic (including light waves), as well as waves on water and so forth. The Wheel Slip Monitor velocity sensors use the doppler shift in a slightly different form than that just described, but the idea remains the same. These velocity sensors (in common with police microwave speed RADAR, ultrasonic intrusion alarms, and so on) have the transmitter or wave source and the receiver together in the same fixed box. Waves are projected in a narrow beam toward a target which is moving either toward or away from the fixed transmitter/receiver. Some of the transmitted waves are reflected back, and these echoes are captured by the wave receiver. The frequency of the echoes is then compared with the frequency of the waves originally transmitted and the difference frequency, the doppler shift, extracted. This difference frequency is usually referred to as the "doppler frequency" for convenience, and we shall do the same, even though that terminology is not exactly correct. Several of the references listed at the end of this report cover this subject in much greater detail; however, for explanatory purposes all we need to consider is that when one of our ultrasonic doppler velocity sensors is aimed at a moving target (terrain or tire surface) within its range, it will produce an electrical output signal whose frequency is proportional to the target's relative velocity. This doppler frequency output is in the range of 50 to 100 Hz per each ft/sec of target velocity for the WSM sensors under discussion.

A. TRUE GROUND SPEED VELOCITY SENSOR

The ground speed sensing function of the Wheel Slip Monitor makes use of ultrasonic doppler velocity sensor hardware from prior project work with the Draft Power Sensor. No major changes to the design were needed and it has demonstrated adequate performance in Wheel Slip Monitor usage. Figure 7 is a front view of the true ground speed sensor. Dimensions of its housing are approximately 5.75 x 9 x 8 inches overall. Figure 7 clearly displays the transmit and receive acoustic focussing horns which are formed into the steel outer housing with cast in place foam. These focussing horns shape the transmitting/receiving patterns of the ultrasonic transducers, whose active faces can be seen at the far end of each horn, into narrow beams where width is approximately 10°.

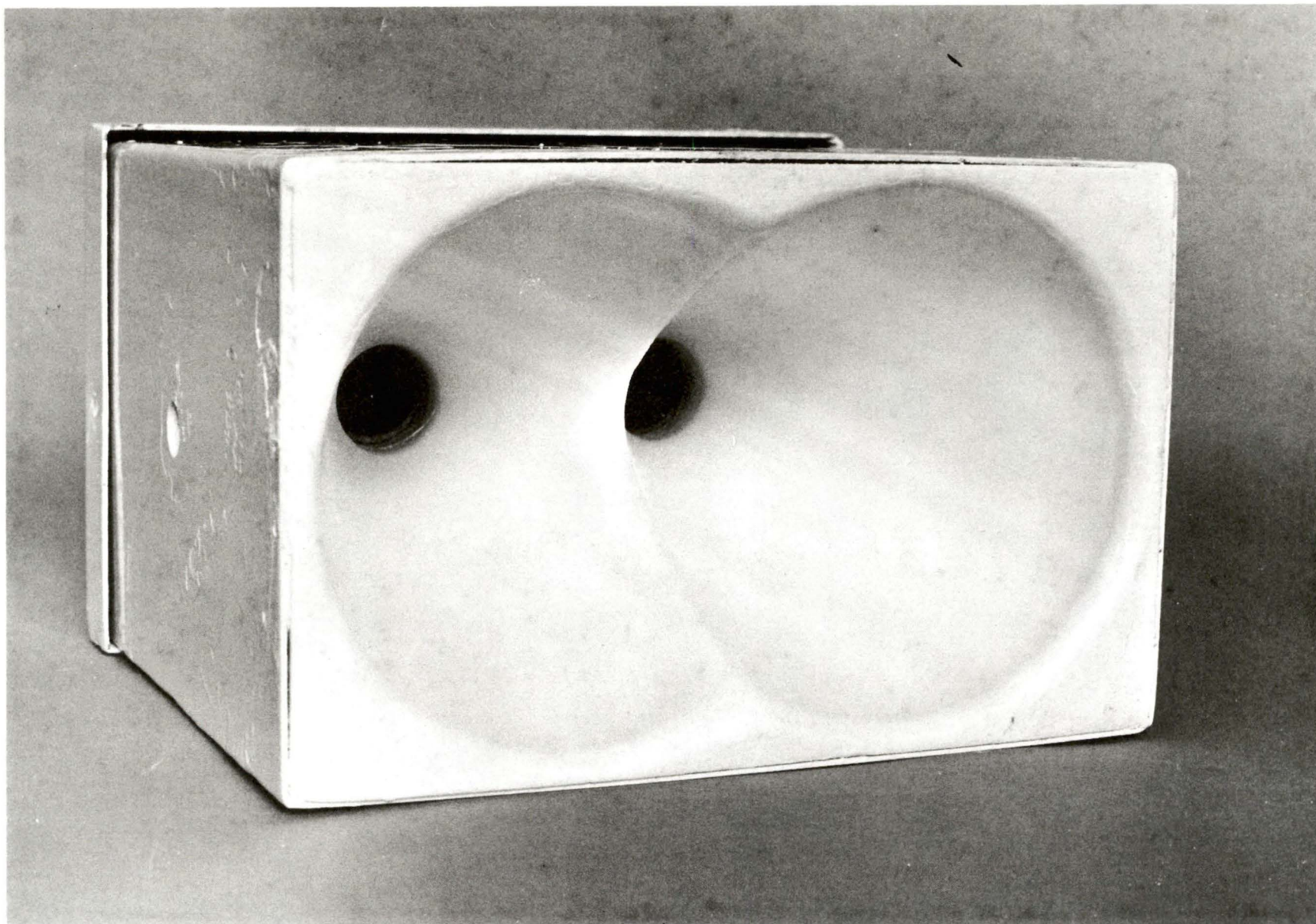


FIGURE 7. FRONT VIEW OF TRUE GROUND SPEED SENSOR

Their axes converge at about 15 feet range. Figure 8 is a rear view of the true ground speed sensor with its cover removed to show the electronic circuit board and the back of the foam block which has the focussing horns molded into its opposite face. The shape of these horns can be inferred from examination of Figure 9 which depicts the male mold over which the metal outer housing is clamped before the foam is injected to expand and fill all spaces. After the foam hardens, the mold is removed leaving cavities of shape calculated to act as focussing horns and component mounting spaces. The ultrasonic transducers are potted in place with room temperature vulcanizing (RTV) rubber and the circuit board installed to complete the assembly.

One significant component change was made in the velocity sensor oscillator circuit from earlier versions. We changed to a ferrite core with a negative temperature coefficient in the oscillator circuit feedback transformer. Oscillation frequency of this circuit is actually controlled by the transmit transducer, which has a negative resonant frequency temperature coefficient. The feedback transformer should track the transducer fairly well or ambient temperature operating range is limited. Figure 10 is a plot of the velocity sensor modified oscillator circuit output frequency versus ambient temperature. These data were obtained by placing the velocity sensor in a test oven and then allowing 15 minutes for it to come to thermal equilibrium at each selected temperature before measuring output frequency. Figure 10 shows that the output frequency versus temperature curve has a slope reasonably close to the transducer spec. sheet temperature dependence value at 25°C of $3 \times 10^{-4}/^{\circ}\text{F}$. At higher temperatures the temperature induced frequency shift of the oscillator begins to flatten out and does not track the temperature coefficient of the transducer quite as well; however, during worst case elevated temperature tests the circuitry functioned properly over a 100°F span with a frequency shift much less than the one KHz transducer bandwidth specified by the manufacturer. The operating ambient temperature range of this improved velocity sensor oscillator circuitry is adequate for field service. As a final step in qualifying the ground speed velocity sensors, they were performance checked in the laboratory on our moving belt ground speed simulator. The plot of Figure 11 shows that at a target range of five feet, velocity sensor output is essentially linear up to a velocity of about eight feet per second, or something over five miles per hour, which includes our speed range of interest in pan scraper loading. Slant angle alpha is in the range of 30 to 40 degrees. This velocity sensor design has, in past field testing on bulldozers, performed quite well at target ranges approaching 20 feet. After completing this evaluation of the long-range velocity sensor hardware design already in hand, we deemed it adequate for use as the ground speed measuring device in our pan scraper Wheel Slip Monitor system.

B. WHEEL PERIPHERAL SPEED VELOCITY SENSORS

As mentioned earlier in this report, some effort was expended in adapting the long-range velocity sensor just described to the measurement of wheel peripheral speed. To avoid unwanted stray reflections, the wheel speed sensors must be mounted as near the tire surface as possible; and this made it necessary to both reduce sensitivity and to change the convergence axes of the focussing horns. At this short target range, approximately two feet, the axes of the horns must cross much closer to the sensor than in the long-range version. Figure 12 is a front view of a wheel velocity sensor derived from the long-range unit and the shortened focussing horns with more sharply angled axes can be seen. Overall dimensions of the Wheel Slip sensor in Figure 12 are 4.4 x 7.3 x 3.5 inches. This package size is less than one-third the volume of the ground speed sensor discussed in the previous section. Figure 13 is a rear view of this same wheel velocity

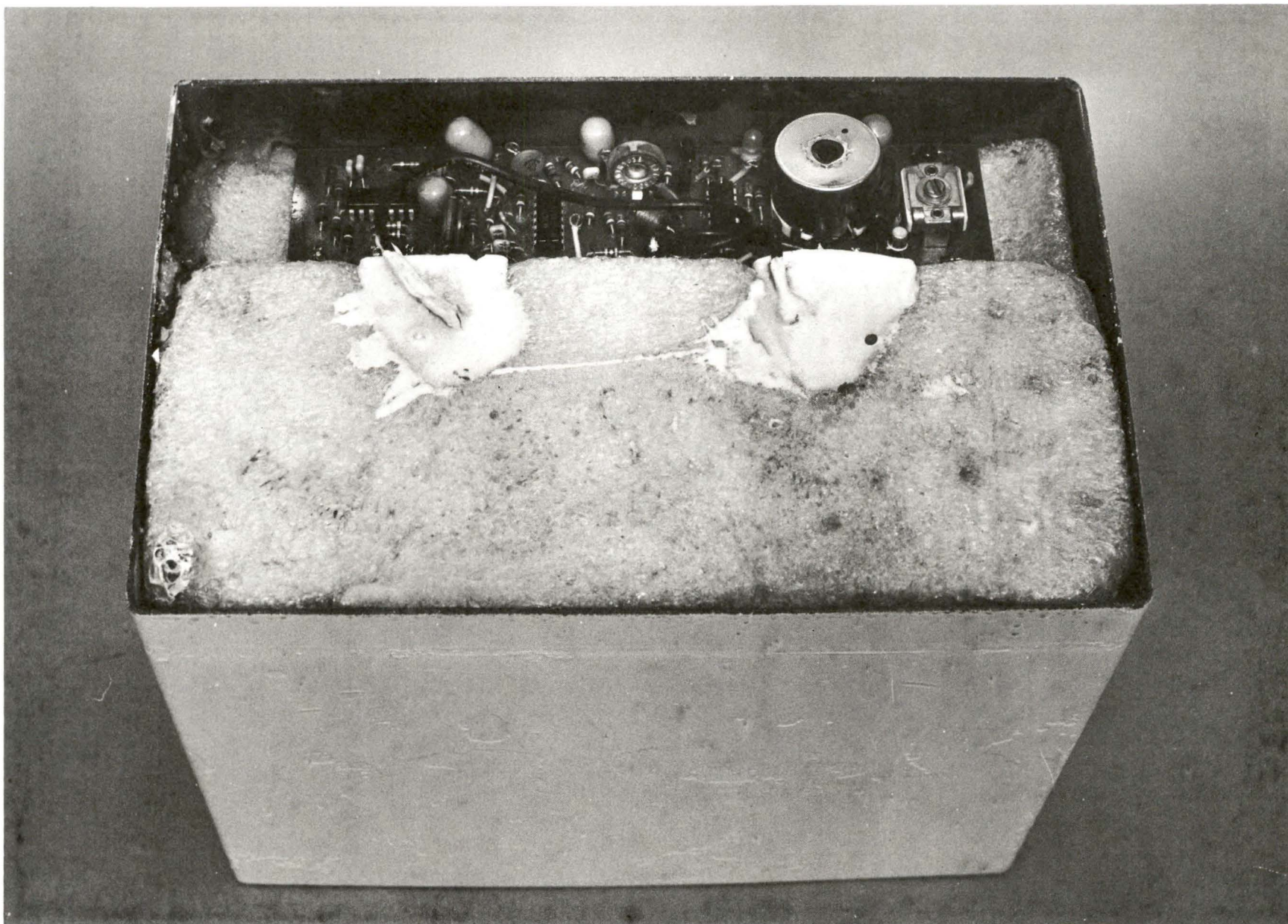


FIGURE 8. REAR VIEW OF TRUE GROUND SPEED SENSOR
WITH COVER REMOVED

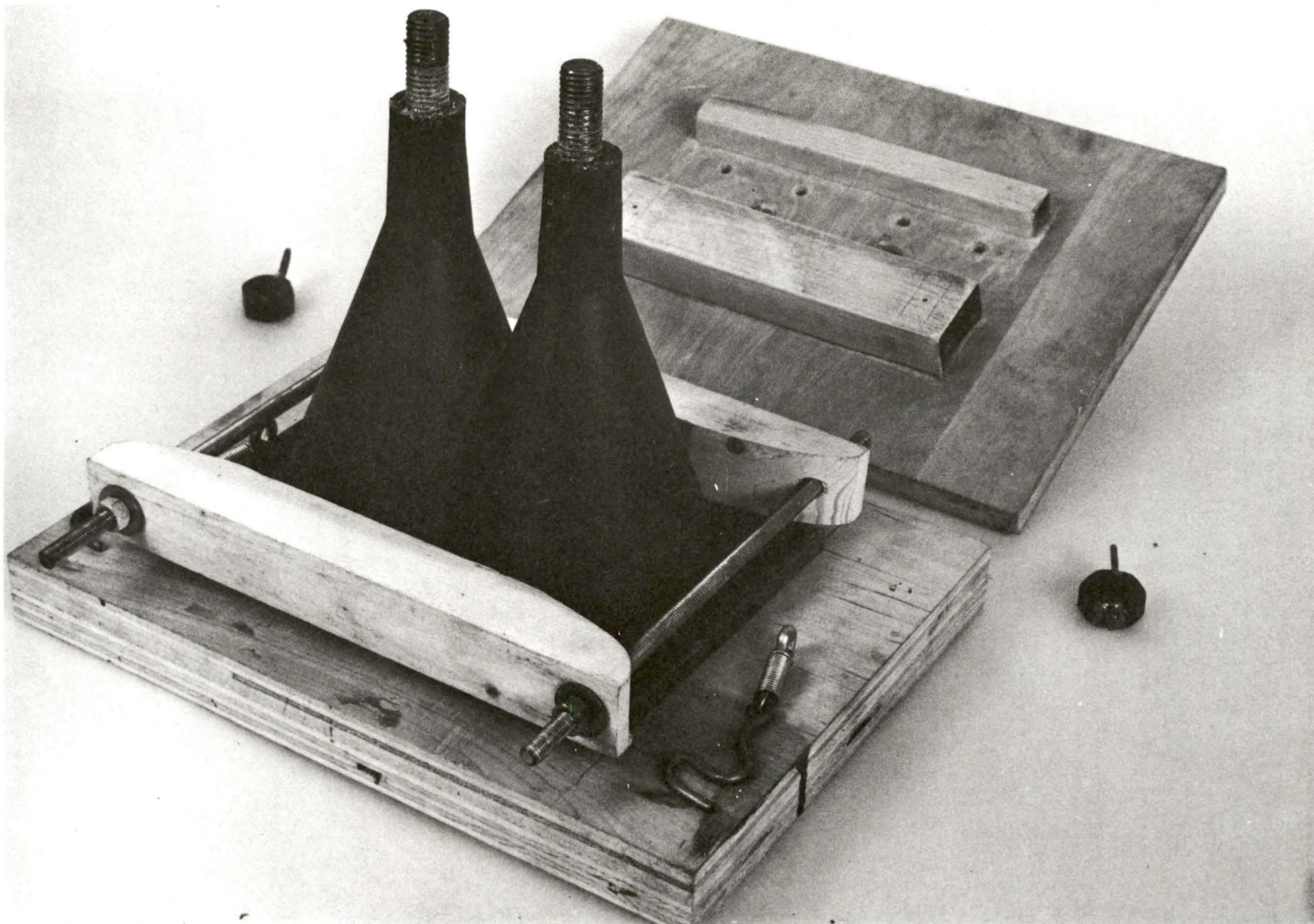
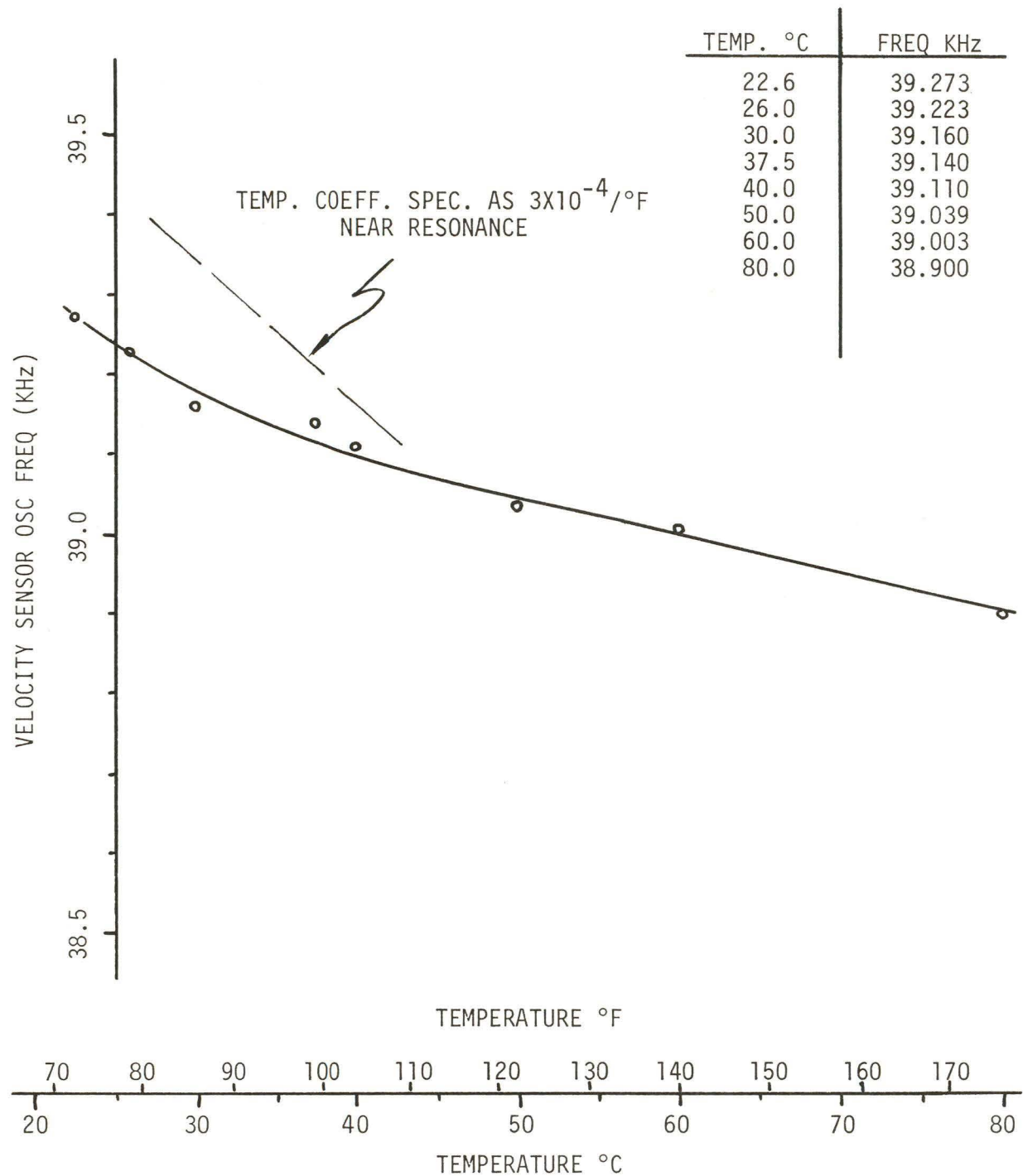


FIGURE 9. FABRICATION MOLD FOR GROUND SPEED VELOCITY SENSOR



**FIGURE 10. VELOCITY SENSOR OSCILLATOR FREQUENCY
TEMPERATURE DEPENDENCE**

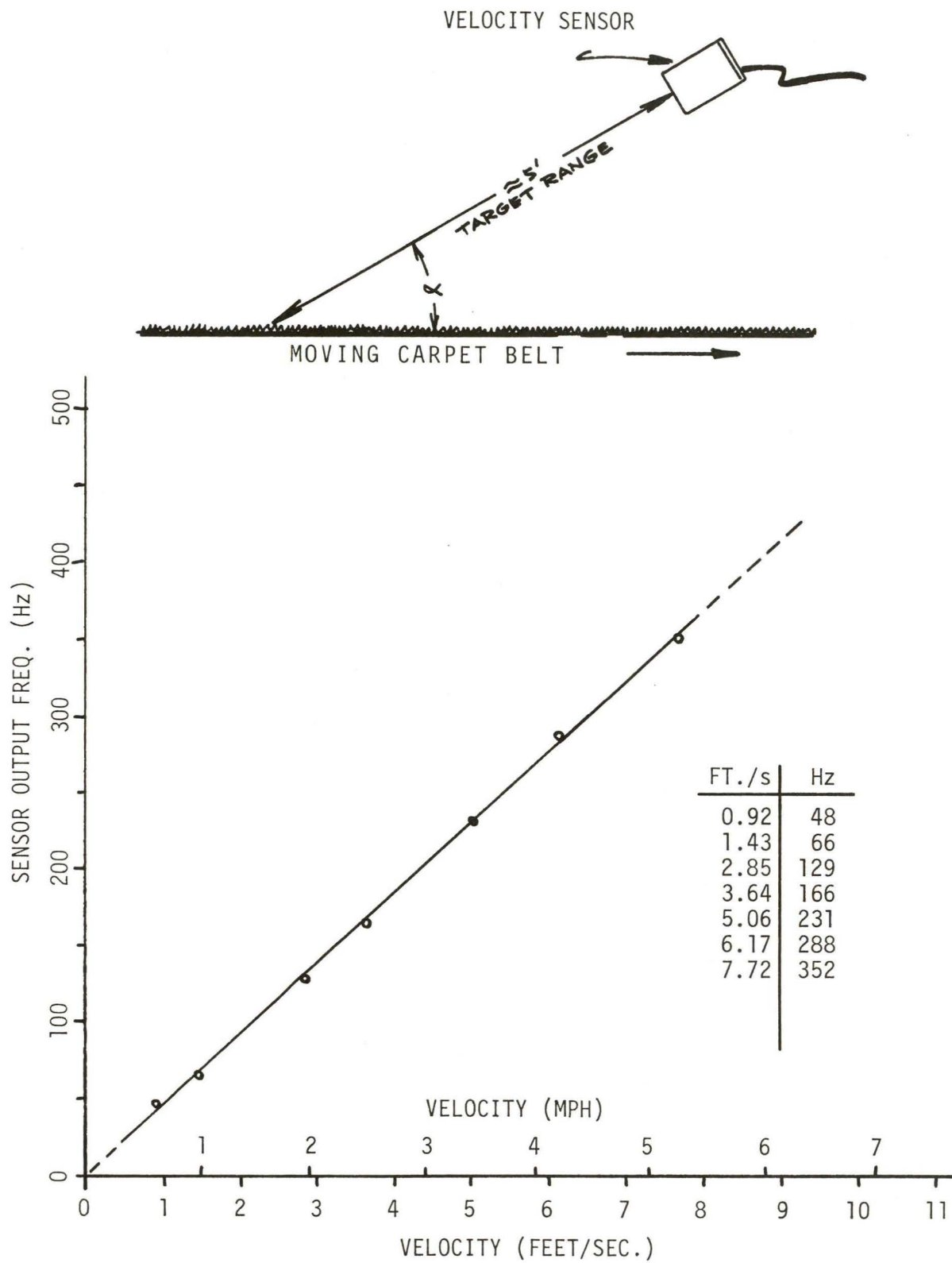


FIGURE 11. LABORATORY PERFORMANCE OF GROUND SPEED SENSOR

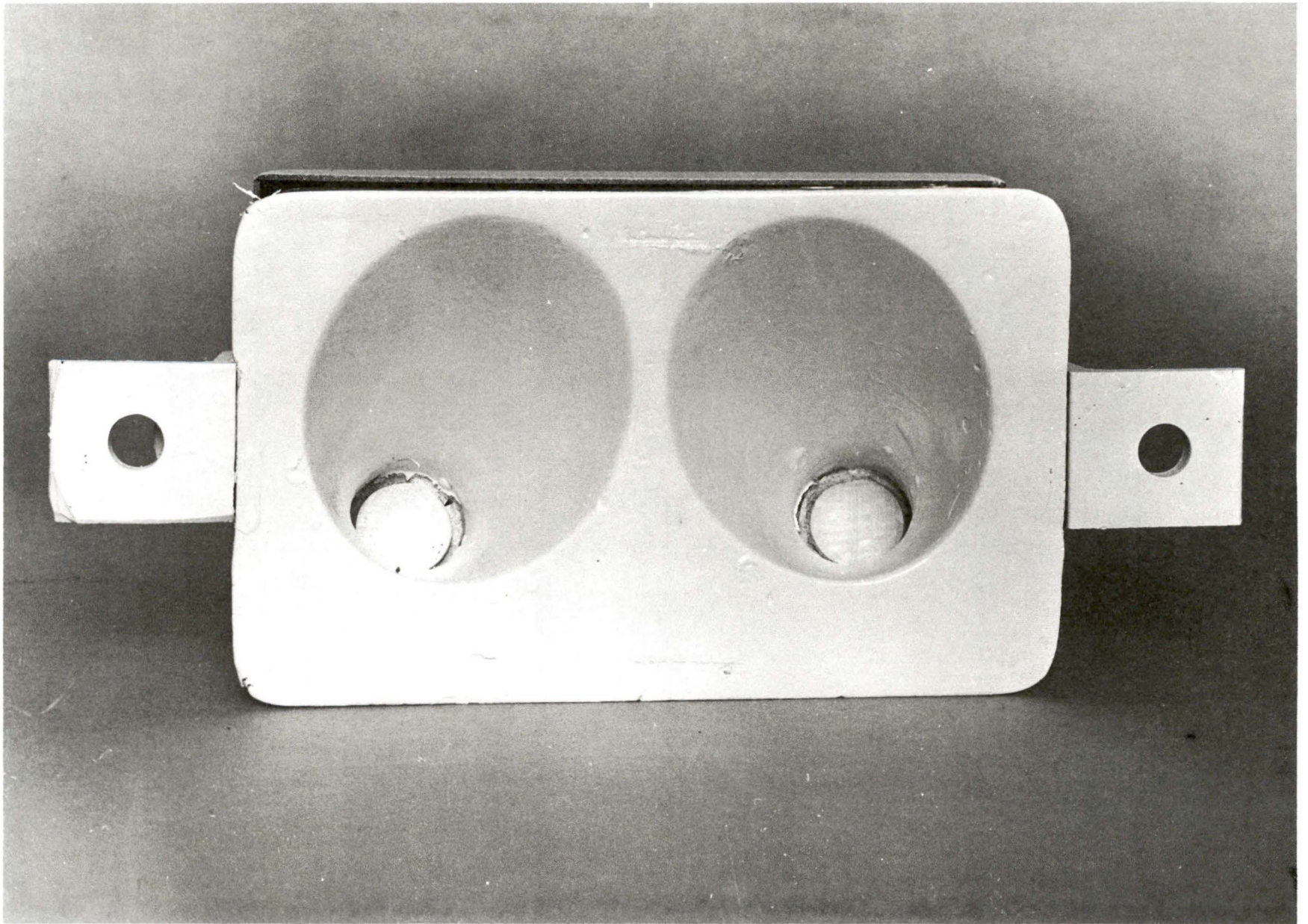


FIGURE 12. FRONT VIEW OF WHEEL VELOCITY SENSOR

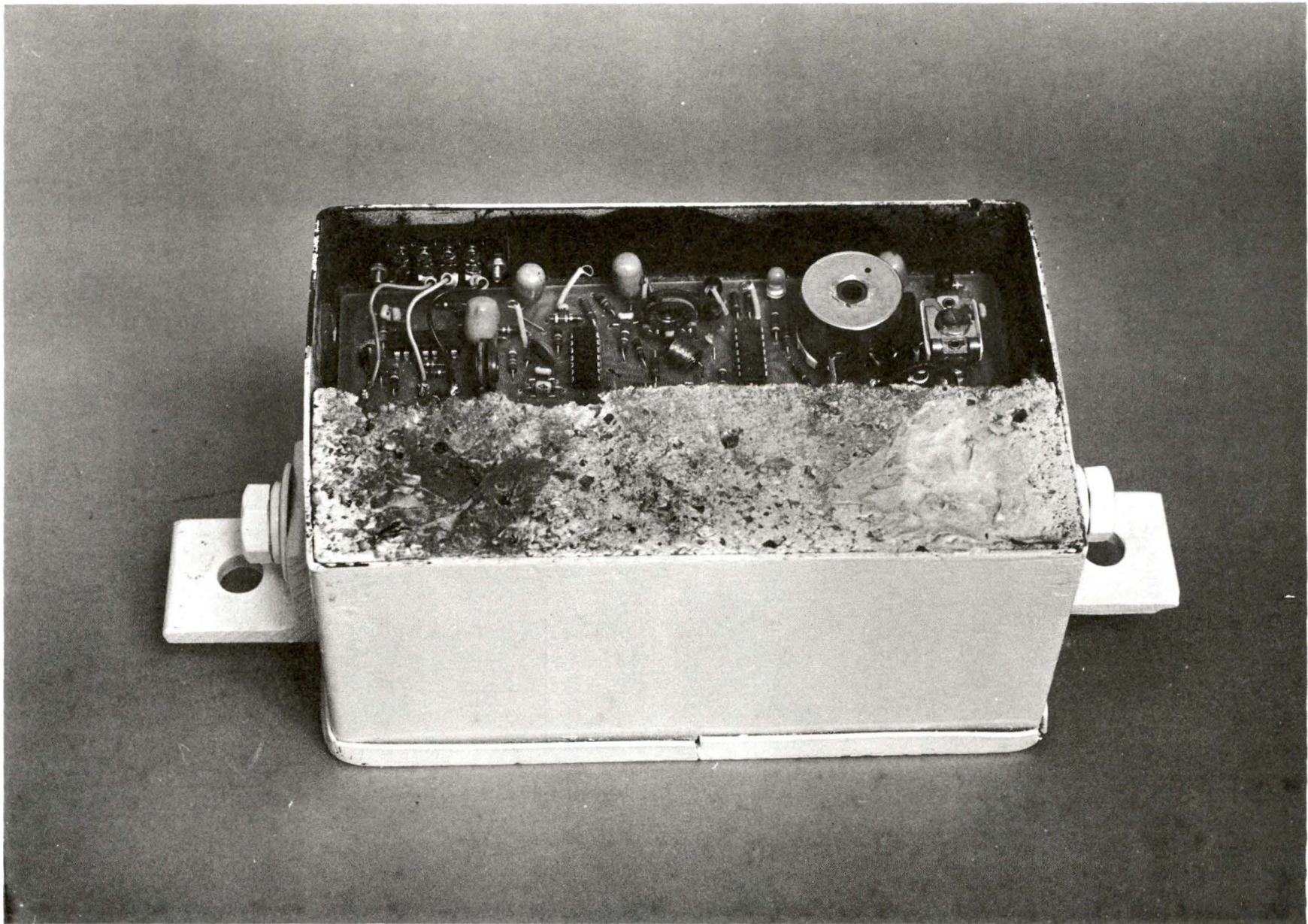


FIGURE 13. REAR VIEW OF WHEEL VELOCITY SENSOR WITH COVER REMOVED

sensor assembly with the cover removed in order to illustrate the internal layout and to show how the mounting brackets on the ends of the housing are used to bolt the assembly in position with its face over a wheel well cutout in the pan scraper fender near the tire's surface. The sharp convergence angle between the axes of the focusing horns, as well as the reduction in package size, can also be deduced from Figure 14, which depicts the male foaming mold used for wheel velocity sensor fabrication. In Figure 14, the metal outer housing has just been clamped in place preparatory to injection of plastic foam. The foam will fill all spaces, harden and adhere to the housing walls. The completed assembly with its foam securely locked in place will be removed from the mold leaving cavities of the proper shape to act as focussing horns and mountings for the ultrasonic transducers. In Figure 15, we have plotted the laboratory performance of four companion wheel peripheral velocity sensors tested on our moving carpet belt. As you can see in the sketch at the top of Figure 15 each velocity sensor was positioned for testing approximately five inches from the moving surface of the belt. Angle alpha in this figure is fixed by horn geometry, but is readily adjusted by sensor positioning in actual use. Figure 15 plots carpet belt velocity versus sensor output frequency for four of the units and it can be seen that output is quite linear and satisfactorily reproducible. The arrangement of Figure 15 approximates what is found in an actual scraper installation save for the curve of the target tire surface.

Beside the wheel velocity sensor configuration just discussed, some other design simplifying ideas were cursorily evaluated early in the project with rudimentary experiments. We anticipated that because of the short target range and reduced sensitivity requirements, the wheel velocity sensor should reasonably be much simpler and cheaper than the long-range version. Individual wheel peripheral velocity sensors are required in every installation, and simplification was and is a worth-while endeavor. The results of these experiments were encouraging, yet performance was never quite good enough for us to abandon the version just described. We will, however, for completeness spend a moment describing some of the alternate design approaches evaluated. First we attempted an acoustic waveguide: a smooth walled conduit to conduct the ultrasonic waves from the transducer to a horn mounted in the wheel well and thus allowing the electronic circuitry to be placed in a more protected location. Operation somewhat analogous to a microwave guide. Initial results were not impressive, and this scheme was abandoned because of time limitations. These experiments foundered for lack of a satisfactory launching and receiving horn with which to terminate the acoustic waveguide. Next we modified one of our conventional velocity sensors to a so-called Janus configuration capable of simultaneously looking both forward and backward. This scheme improved the accuracy of curved tire surface velocity sensing but proved to be impractical. Finally, we reexamined some earlier Draft Power Sensor circuit experiments to determine if a **single** transducer ultrasonic velocity sensor might be useful in this short-range work. We have in the past successfully employed single transducer ultrasonic doppler techniques in liquids and it would be of obvious advantage to also do this in air for this application. Unfortunately, we were not able to achieve adequate sensitivity with air coupled transducers. Because of its far lower density, transducers inherently couple much more poorly to air than to liquids. We breadboarded several circuits known to operate satisfactorily with liquids including, for example, the Class A or marginal oscillator and the well known hybrid transformer single transducer coupling technique. None of these circuits was judged promising enough to pursue further, even though all of them have promise in this and perhaps other special applications.

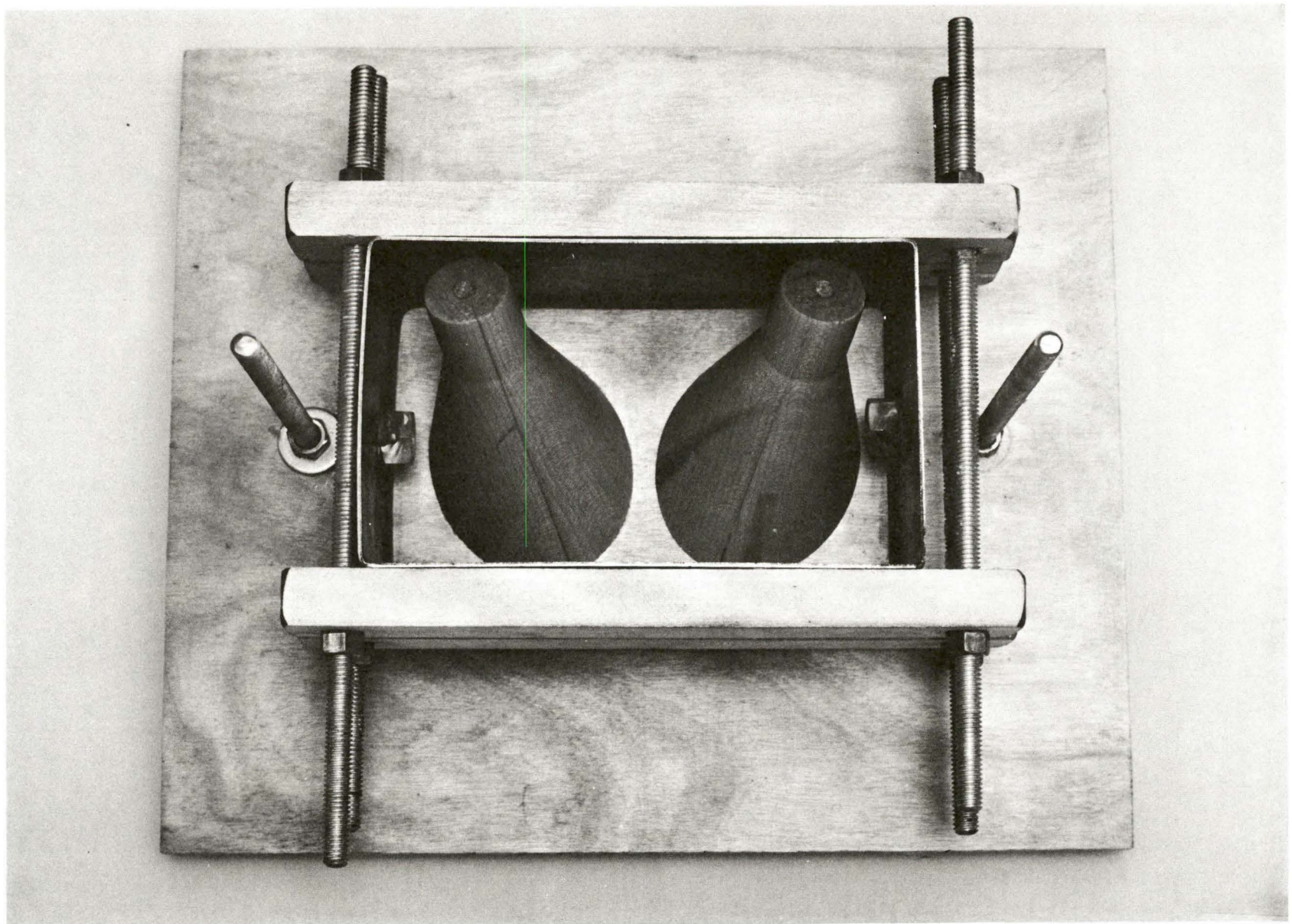


FIGURE 14. FABRICATION MOLD FOR WHEEL VELOCITY SENSORS

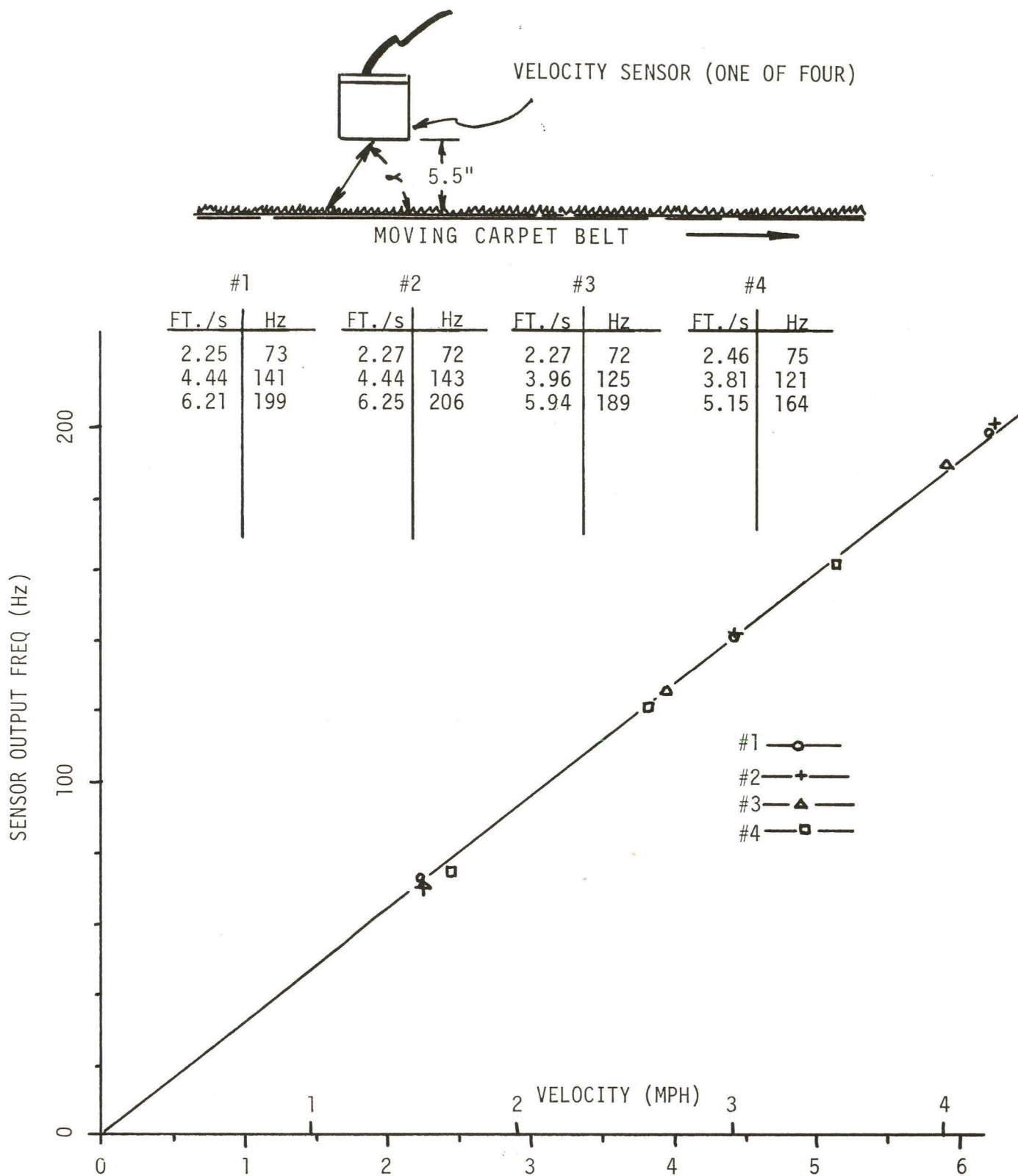


FIGURE 15. LABORATORY PERFORMANCE OF WHEEL VELOCITY SENSORS

C. OPERATOR CONTROL BOX

The signal processing electronic circuitry was designed and checked for proper electrical operation in breadboard form. It was then laid out on a conventional circuit board configured to fit an available commercial housing made of heavy drawn aluminum. As will be discussed in this report's later section on field testing, this initial control box configuration can probably be simplified in future designs without significant loss of function.

1. Signal Processing Electronic Circuitry

Referring once again to Figure 6, System Block Diagram, the circuitry contained within the operator control box is shown to the right of the dotted line. Five frequency-to-voltage (F/V) converters are required, one for each wheel velocity sensor and one for the ground speed sensor, and these F/Vs' DC output voltages must be accurately proportional to the frequency of the velocity signals fed into them. We started with the frequency-to-voltage converter circuit originally used in the Draft Power Sensor. We chose this circuit (with certain improvements to be described in a moment) because the various integrated circuit (I.C.) frequency-to-voltage converters then available "off the shelf" were either too expensive for this application or simply not accurate enough. The transfer curves for the original F/V showed a slight non-linearity and more offset than we could tolerate, although well suited to its intended application. Redesign consisted of replacing the original charge pump bipolar circuitry with CMOS components of much better operating characteristics. A gated CMOS switch is used in each F/V to supply unit pulse current to the charge storage capacitor and the capacitor charge voltage is then buffered with a very high impedance CMOS operational amplifier. This strategy resulted in a linear F/V capable of good drive to the following circuits with minimal loading of the charge capacitor. The transfer characteristics of this improved frequency voltage converter are shown in Figure 16. The Maximum Amplitude Selector function is accomplished using a diode array feeding a very high input impedance CMOS isolation amplifier which removes virtually all diode non-linearity at low input voltage levels. The Maximum Amplitude Selector is followed by a Buffer amplifier which isolates the following circuits and preserves the exact value of the selected maximum amplitude voltage corresponding to the wheel which has the greatest slip. As shown in Figure 6, the output of this Buffer amplifier is fed to the positive input of the Differential Amplifier while the D.C. output of the fifth F/V converter (ground speed) is fed to the Differential Amplifier's negative input. All five frequency voltage converters generate the same magnitude voltage output for a particular target velocity. The differential amplifier thus outputs a voltage whose magnitude is wheel speed **minus** ground speed. This means that so long as no wheel speed exceeds ground speed, there can be no V_s output from the differential amplifier. When slip does occur, the Differential Amplifier output is directly proportional to ground speed less wheel speed, V_s , **independent of vehicle travel speed**. In order to indicate which wheel is slipping worst, the output of the Buffer amplifier is slightly reduced and then used as parallel input to a bank of four comparators. The other input of each comparator is the output of its respective wheel speed F/V. Whichever one of the four wheel F/Vs has the greatest output voltage can now turn on its corresponding comparator. The comparator outputs feed four driver transistors (Q1-4 in Figure 6) which control the wheel slip lights, one for each wheel, positioned on the front panel of the control box to correspond with wheel location on the full sized scraper. The light circuits are enabled by a voltage-to-frequency converter (V/F) circuit, to be described next, which sets their blinking rate. During field testing Q1-4 were also used in an alternate warning

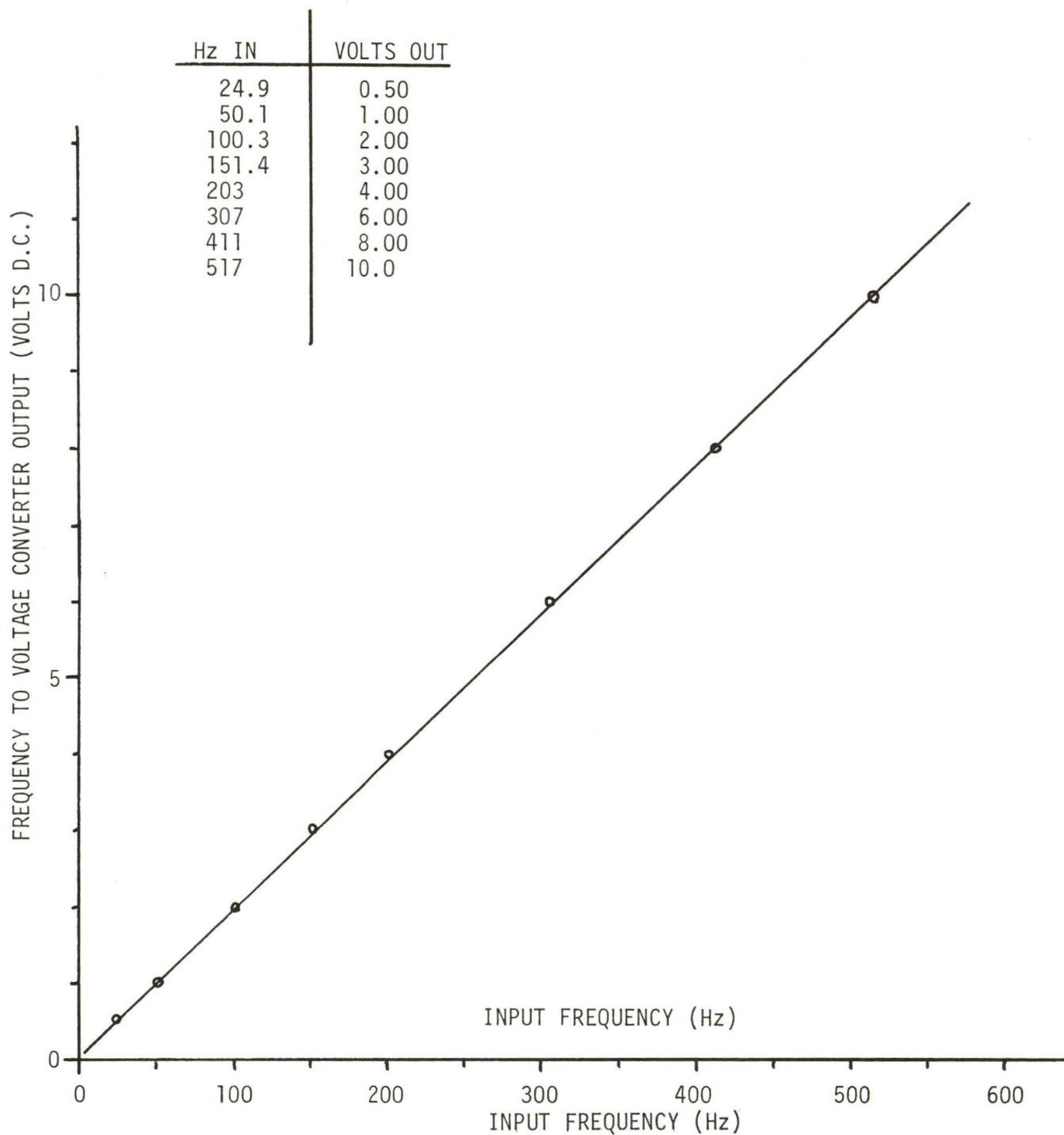
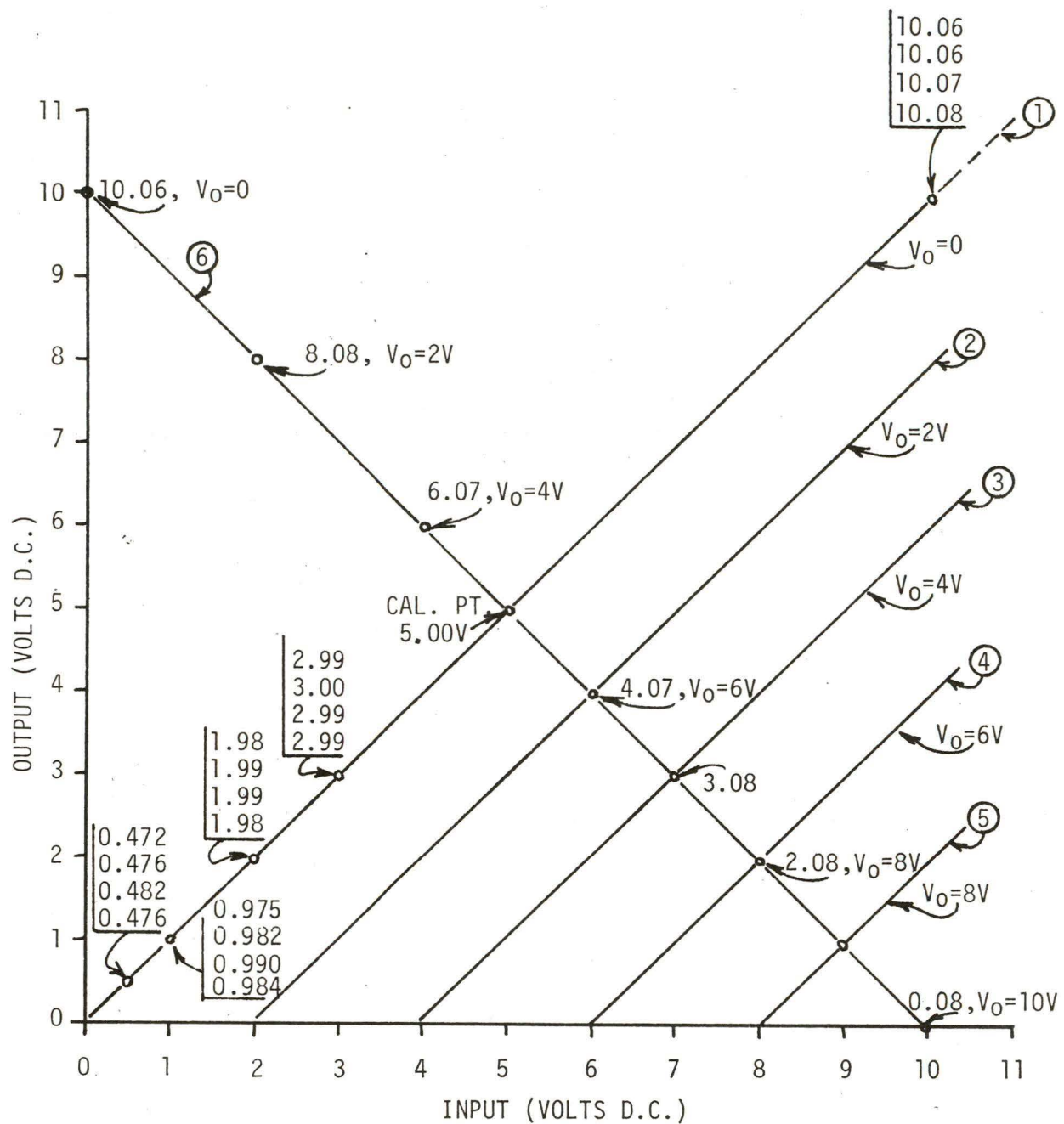


FIGURE 16. FREQUENCY-TO-VOLTAGE CONVERTER TRANSFER CHARACTERISTICS

light scheme (not shown in Figure 6) which had one light for the front set and one for the rear set of wheels. These warning lights were mounted behind the operator so that they were visible while he watched the bowl fill. They proved very successful. Continuing, the output voltage of the Differential Amplifier represents scrubbing velocity V_s that we wish to display for the operator, or perhaps record for future reference. If V_s is to be recorded, the full output of the Differential Amplifier is made available at an output port for this purpose. V_s signal magnitude is partially controllable by an operator Sensitivity control and it is then fed to a V/F converter. The V/F converter is enabled by the Squelch Gate; implemented with a comparator that has one input tied to a reference voltage derived from an operator Squelch control and its other input fed the V_s output voltage from the Differential Amplifier. Over the range of scrubbing velocities from zero to about 1.5 ft/sec the operator can selectively suppress the action of the V/F converter and thus wheel slip warning. Beyond that, the V/F converter always operates and produces an output pulse train whose pulse repetition rate (PRR) is proportional to wheel slip magnitude. This pulse train drives the "beeper", which produces an audible signal that warns of wheel slip, and in addition, as can be seen in Figure 6, enables the four comparators such that the comparator which is "on" will drive its wheel slip light and thus produce a blinking warning in synchronism with the sound coming from the beeper. Even though a good deal of circuitry is involved in this electronic processing, it all resides on one single sided circuit card approximately 4-3/4 inches x 8 inches, which conveniently fits a commercially available drawn aluminum housing measuring 5 x 8.25 x 3 inches.

The accuracy of the transfer characteristics of the control box DC signal processing circuitry between the F/Vs and the output of the Differential Amplifier is important to system calibration. Figure 17 is a plot of the transfer characteristics of this circuitry from the four Maximum Amplitude Selector inputs to the Differential Amplifier output. For the WSM system to function properly and to accurately display scrubbing velocity V_s , we should always have a V_s output voltage from the Differential Amplifier which is a true representation of wheel speed minus true ground speed. In Figure 17 we plot specific input versus observed output for this circuitry, with selected output values listed as precision voltages. Curve 1 of Figure 17 plots the output voltage of the Differential Amplifier with various precise values of voltage input to each of the four channels of the Maximum Amplitude Selector. The four resultant output voltages for each exact input value are shown grouped together for convenience, and it can be seen that the output of the Differential Amplifier very nearly equals the inputs to the four channels of the Maximum Amplitude Selector. Recall that these four channels receive the four voltages developed by the wheel speed frequency-to-voltage converters. Curves 2, 3, 4 and 5 show Differential Amplifier voltage output as a function of increasing ground speed input voltage V_o . The circuit evidently subtracts ground speed from wheel speed quite accurately. Curve 6 plots Differential Amplifier voltage output with wheel speed input voltage held at a constant 10 volts (the upper limit of its span) while ground speed input voltage V_o is increased. Observe the resultant decrease in output of the Differential Amplifier. During bench tests we consistently obtained transfer values accurate within a percent or so and this is perfectly adequate performance because WSM overall system accuracy is limited by the conversion from actual relative target velocity to equivalent D.C. voltage. This comes about through the velocity signal averaging time, necessitated by vehicle bounce and other non-uniform motion. This time constant is a compromise and must be at least a second or so **but can be no longer**; otherwise the WSM cannot respond quickly enough to provide satisfactory wheel slip warning information. Accuracy of this velocity to voltage conversion is within about five percent under average scraper loading conditions. The control box signal processing circuitry can therefore have



- NOTES:
1. PRECISION VALUES OF OUTPUT VOLTAGE (V_s) ARE SHOWN NEXT TO THE DATA POINTS WITH THE GROUPS OF FOUR BEING OUTPUT VERSUS THE FOUR SELECTOR CIRCUIT INPUTS (V_{w1-4}) WITH SEVERAL CONSTANT VALUES OF TRUE GROUND SPEED INPUT (V_0). CURVES ① - ⑤
 2. CURVE ⑥ PLOTS OUTPUT (V_s) VERSUS TRUE GROUND SPEED (V_0) WITH WHEEL SPEED (V_{w1-4}) CONSTANT AT 10 VOLTS.

FIGURE 17. TRANSFER CHARACTERISTICS OF DC SIGNAL PROCESSING CIRCUITRY

little effect on overall system accuracy. We elaborate this point because it bears on field calibration. Short of complex and expensive field operations involving driven wheels mechanically **forced** to slip at fixed rates, there is no way to **sustain a specified** wheel slip rate long enough for equipment calibration. As will be developed in Section V, an indirect calibration approach on these known circuit transfer characteristics has proven to be the only practical way to adjust the WSM such that a given value of V_s output voltage accurately corresponds to a particular scrubbing velocity between tire and terrain.

2. Packaging and Display

Figure 1, shown at the beginning of this report, is a front external view of the prototype WSM control box. As mentioned earlier, a simplified version of this unit may prove adequate; however, for initial field testing it was prudent to put in all the "bells and whistles" and then see what might be eliminated. In Figure 1, we see the various controls and wheel slip warning lights available to the scraper operator. A small standard electrical enclosure containing an off the shelf sound warning device comprises the "beeper". This is illustrated with the Terex pan scraper WSM installation discussed in Section VB. Figure 18 illustrates the Wheel Slip Monitor control box with the front panel and its attached circuit board removed from the housing and laid aside in order that we may see the interior details of its construction. A fuse provides short circuit protection and is mounted as shown for easy replacement from outside the housing. An integrated voltage regulator, which reduces the scraper supply voltage from 24 volts DC to the regulated 15 VDC required by the circuitry, can be seen mounted next to the fuse post. The regulator employs the aluminum housing as its heat sink. The circuit board has been designed to accommodate all control box electronic circuitry including the five F/V scaling potentiometers used to calibrate the velocity signals as well as the slip warning lights and operator Sensitivity and Squelch controls. The scaling potentiometers are easily accessible for adjustment after removal of a small plate on the front panel of the control box during calibration. Figures 19 and 20 illustrate the circuit board layout front and rear. Returning to Figure 1, the four wheel slip warning lights are visible inside each of four small boxes printed on the front panel to pictorially represent the four wheels of the scraper. Below each warning light is the selector switch for that particular wheel. These switches allow the operator to select which wheels, any or all, that he will monitor. During field testing we found it advantageous on occasion to eliminate this function.

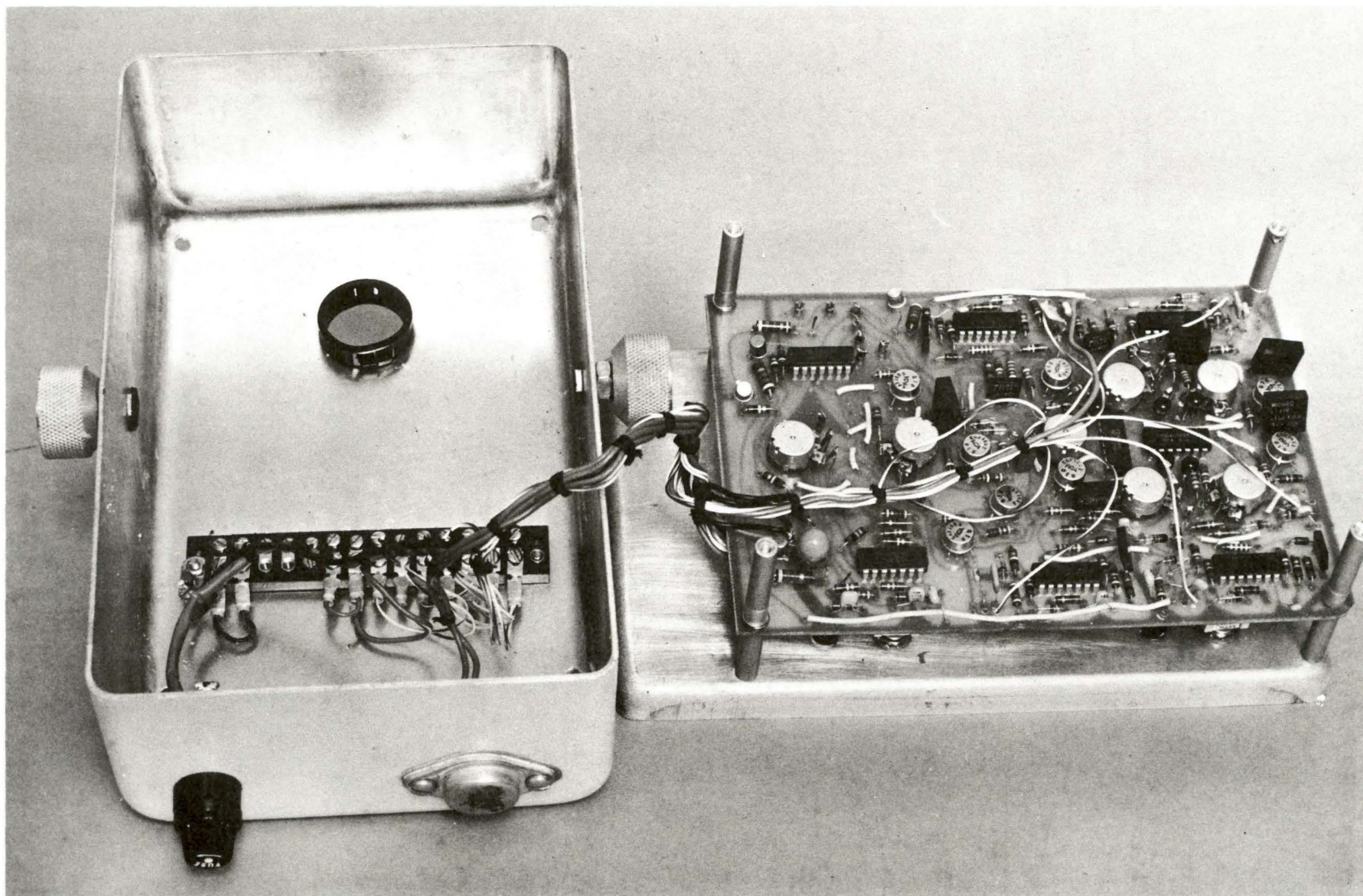


FIGURE 18. WHEEL SLIP MONITOR CONTROL BOX OPENED
TO ILLUSTRATE CONSTRUCTIONAL DETAILS

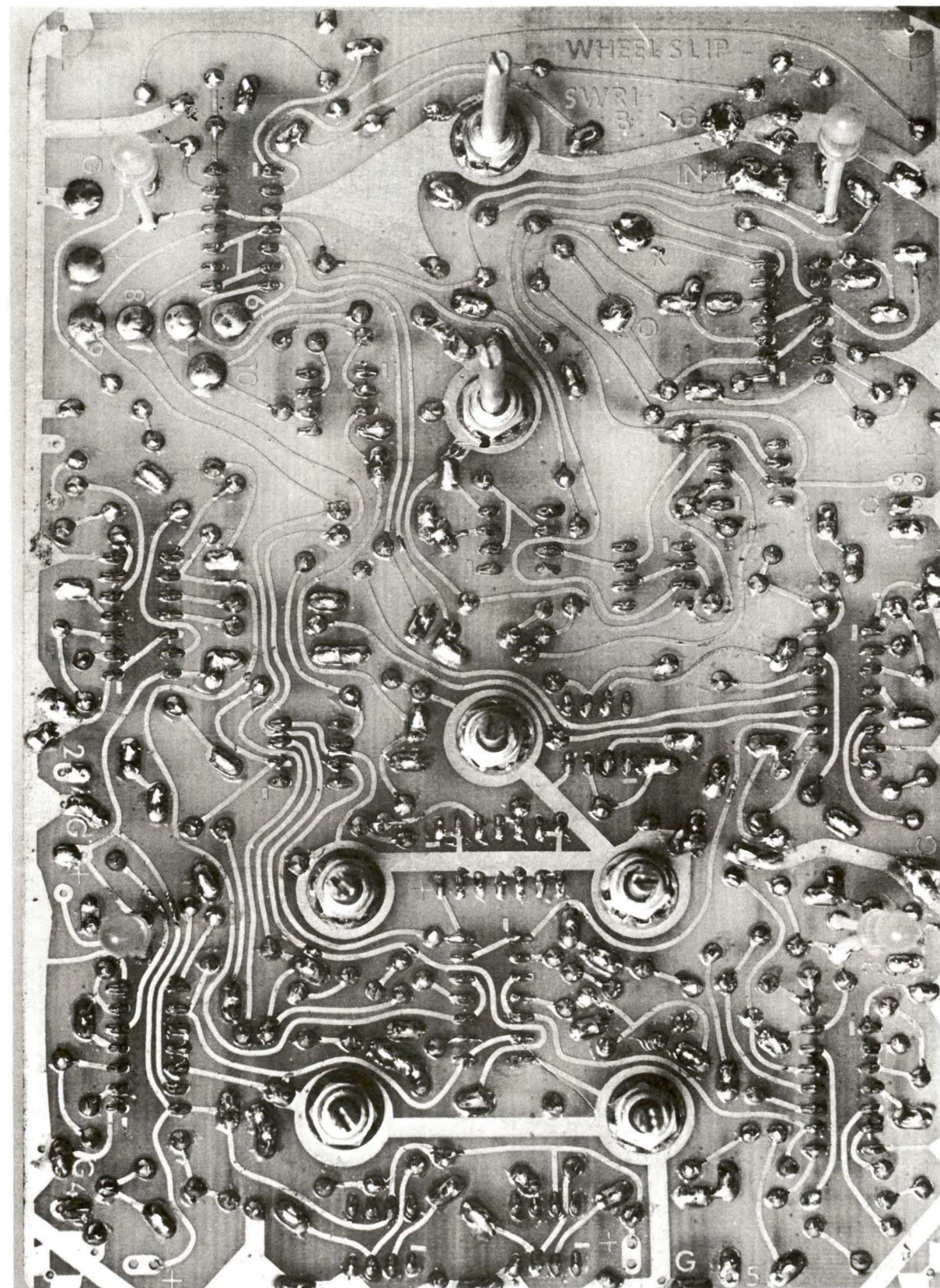


FIGURE 19. FOIL SIDE OF CONTROL BOX CIRCUIT BOARD

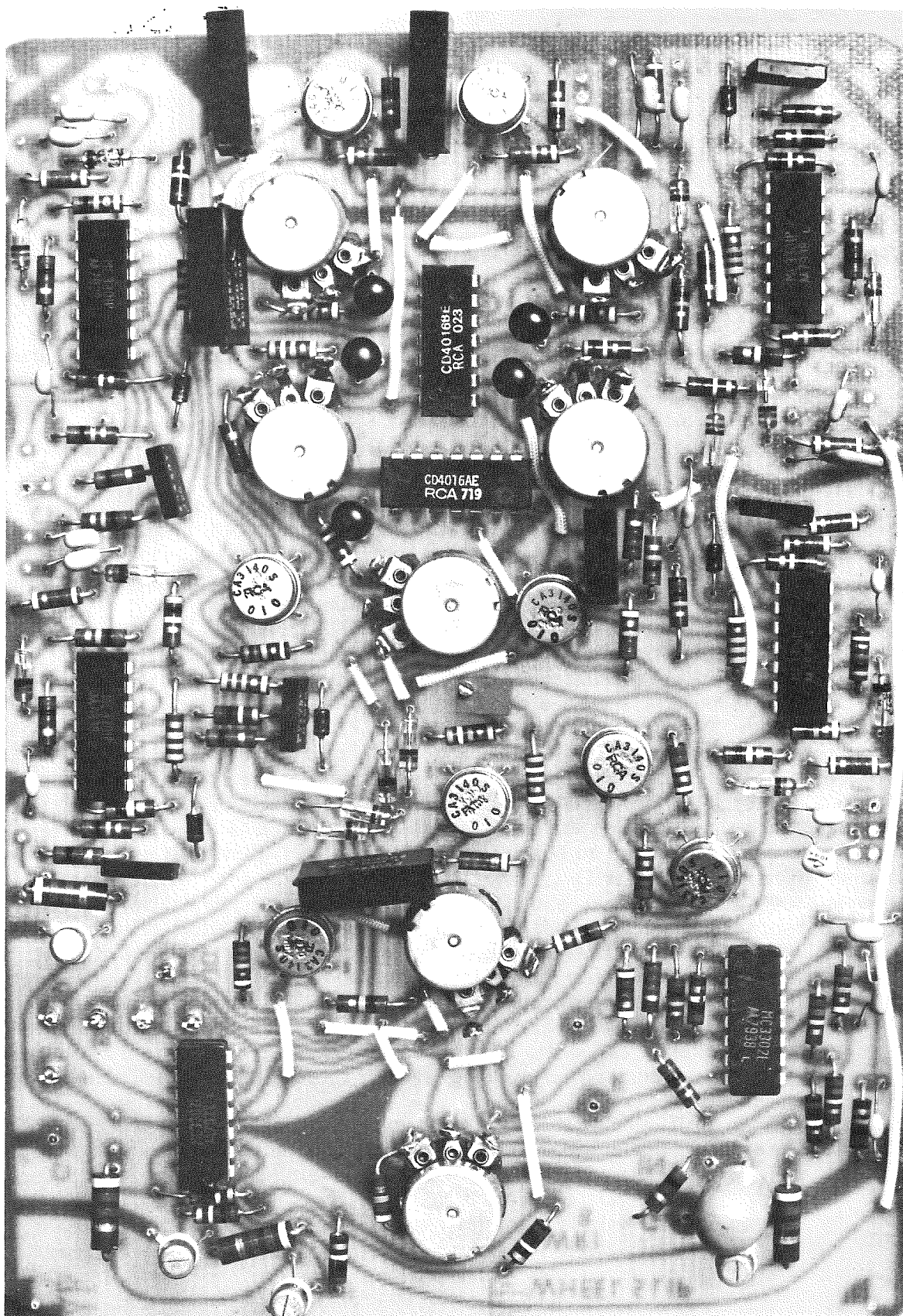


FIGURE 20. COMPONENT SIDE OF CONTROL BOX CIRCUIT BOARD

V. LOCAL FIELD TESTING

Local field testing of the Wheel Slip Monitor equipment was accomplished at two test sites located on the Southwest Research Institute grounds. Caterpillar 637-D pan scraper testing was conducted in a low lying vega (dry flood plain) area which was formerly a gravel pit. This allowed us to disturb large quantities of earth with no environmental restriction. The TEREX TS-18 pan scraper was tested and calibrated at a second site prepared on a well-drained hillside about one-half mile from the first test site.

Figure 21 shows a complete set of Wheel Slip Monitor velocity sensors, as were installed on both pan scrapers. Hardware installation was the same in both cases except that additional readout instrumentation (not part of the WSM) was used on the TEREX scraper in order to continuously monitor calibration.

A. CATERPILLAR 637-D PAN SCRAPER

Figure 22 shows the Caterpillar 637-D pan scraper used in the first period of local field testing. Visible components of the Wheel Slip Monitor system are indicated by arrows numbered 1 through 4. Arrow 1 points out the ground speed sensor. Arrow 2 notes the operator control box installed inside the cab, while Arrows 3 and 4 indicate the location of the wheel speed sensors for the left front and left rear tires, respectively.

1. The first Wheel Slip Monitor installation was straightforward and was accomplished in approximately 30 man-hours. Routine installation procedures should reduce this time by about one-half. The major components of the system are illustrated in their mounting locations in Figures 23, 24, and 25, as well as Figure 22 just discussed. Figure 23 shows the first Wheel Slip Monitor control box installed just below the operator's normal line of vision where he could easily see the warning lights and reach the controls. Observe in Figure 23 that the control box panel has a slightly different shape from that shown in Figure 1. This is because Figure 1 depicts a later version built up after drawn housings were received. Figure 24 clarifies details of ground speed sensor mounting atop the front apron of the Caterpillar 637-D scraper. The sensor mounting ears visible in Figure 24 were welded to the metal plate surface and the ground speed sensor housing attached with bolts. Wires were run along the scraper frame to the control box. Figure 25 depicts the left front wheel sensor installation which is typical. Figure 26 shows this sensor from below and illustrates the relationship of the sensor's ultrasonic horns to the tire surface. The wiring connecting the wheel speed sensors to the control box was routed parallel to hoses and original machine wiring where possible. During field testing at the working mine, described later, a grille was installed over the horn openings and a mud flap added to protect the wheel sensor horn openings.

2. Test methods and procedures used with this first WSM installation were designed for ease of "debugging" the hardware, and we will describe some of the problems encountered and their solutions.

Our first difficulty arose from not getting strong enough velocity sensor returns (reflections) from the moving surface of the scraper's worn slick original tires. The front tires were replaced, and the front velocity sensors then functioned satisfac-

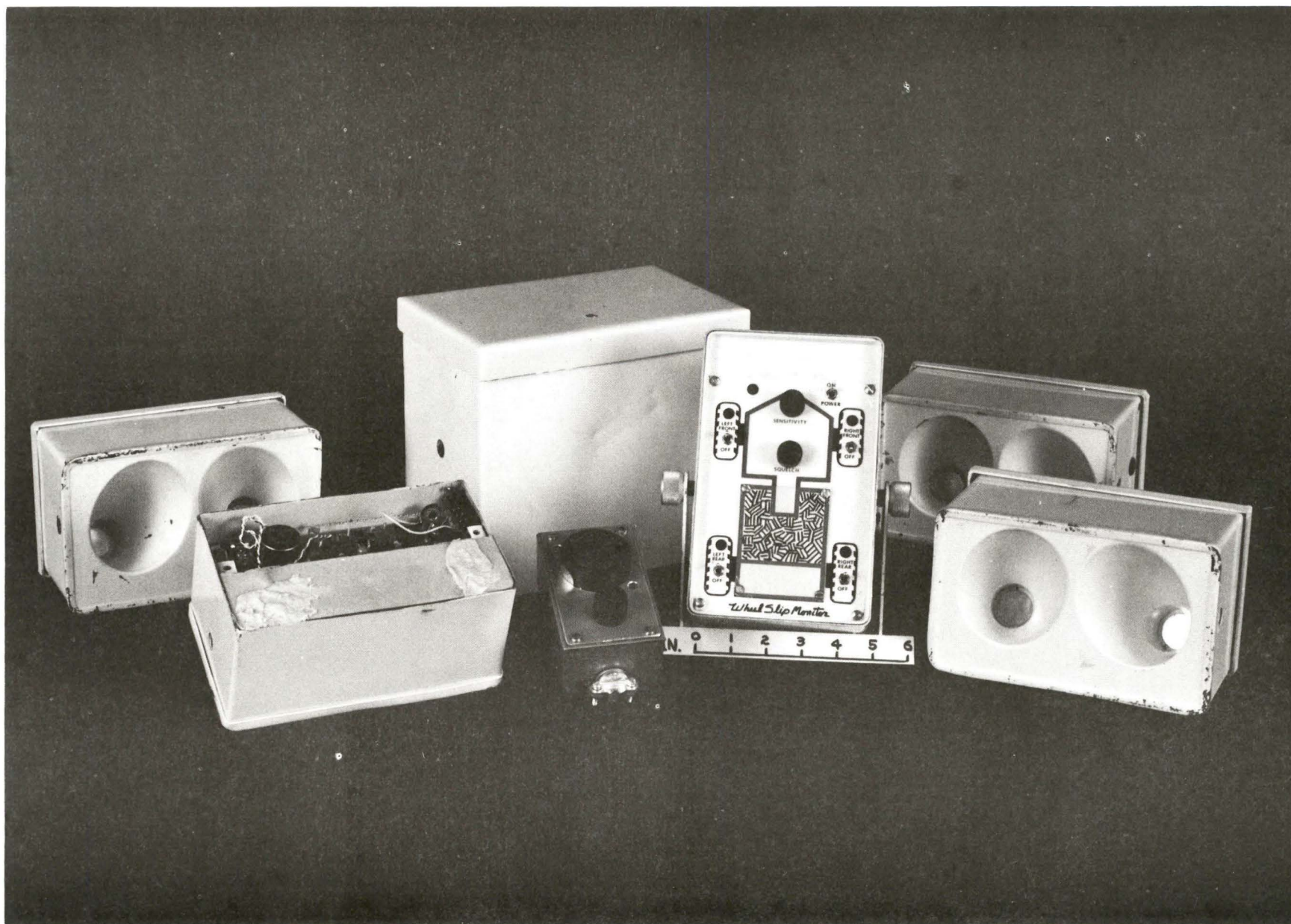


FIGURE 21. WHEEL SLIP MONITOR VELOCITY HARDWARE



FIGURE 22. CATERPILLAR 637D TEST SCRAPER

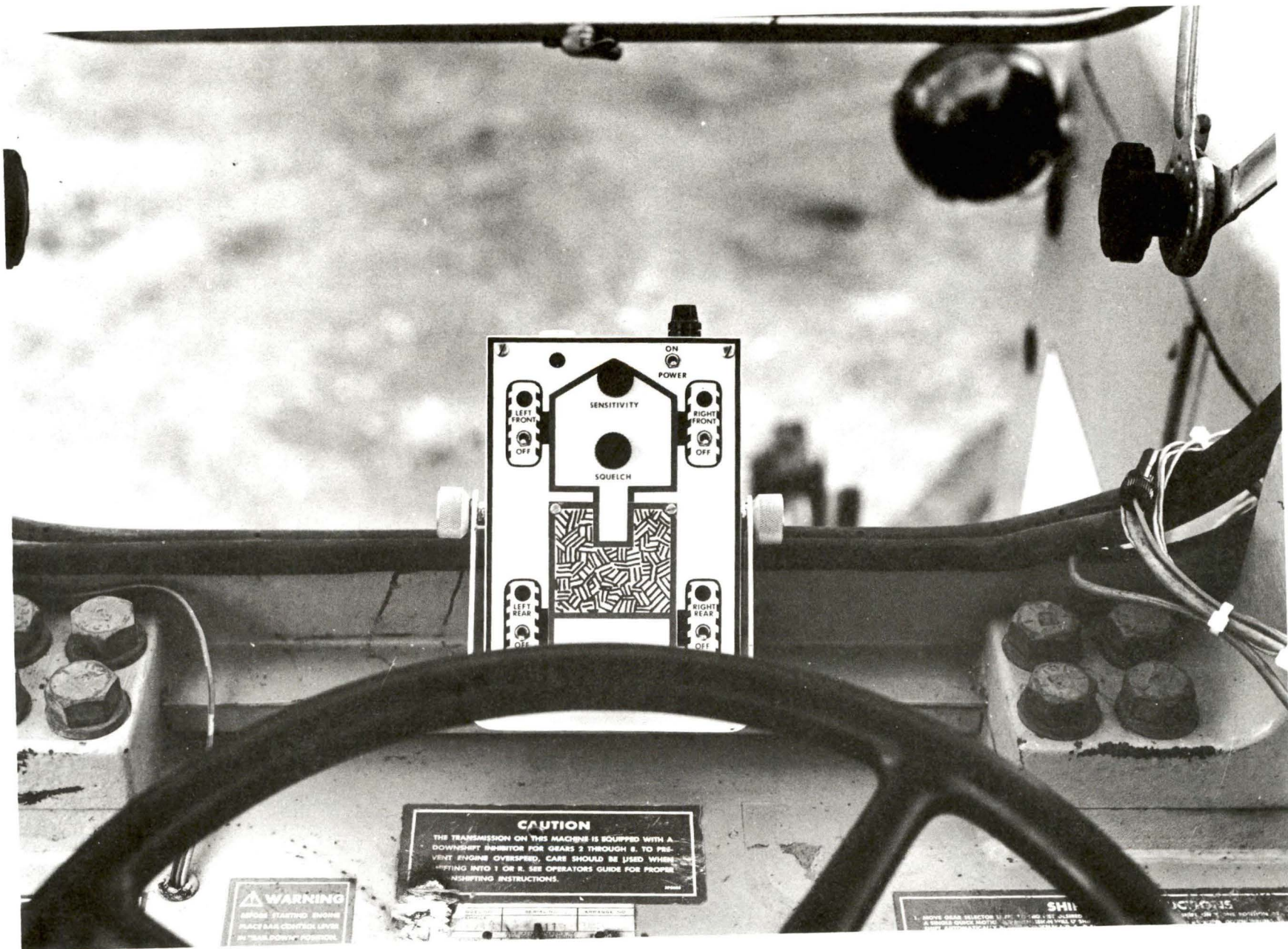


FIGURE 23. CATERPILLAR 637D WSM CONTROL BOX INSTALLATION

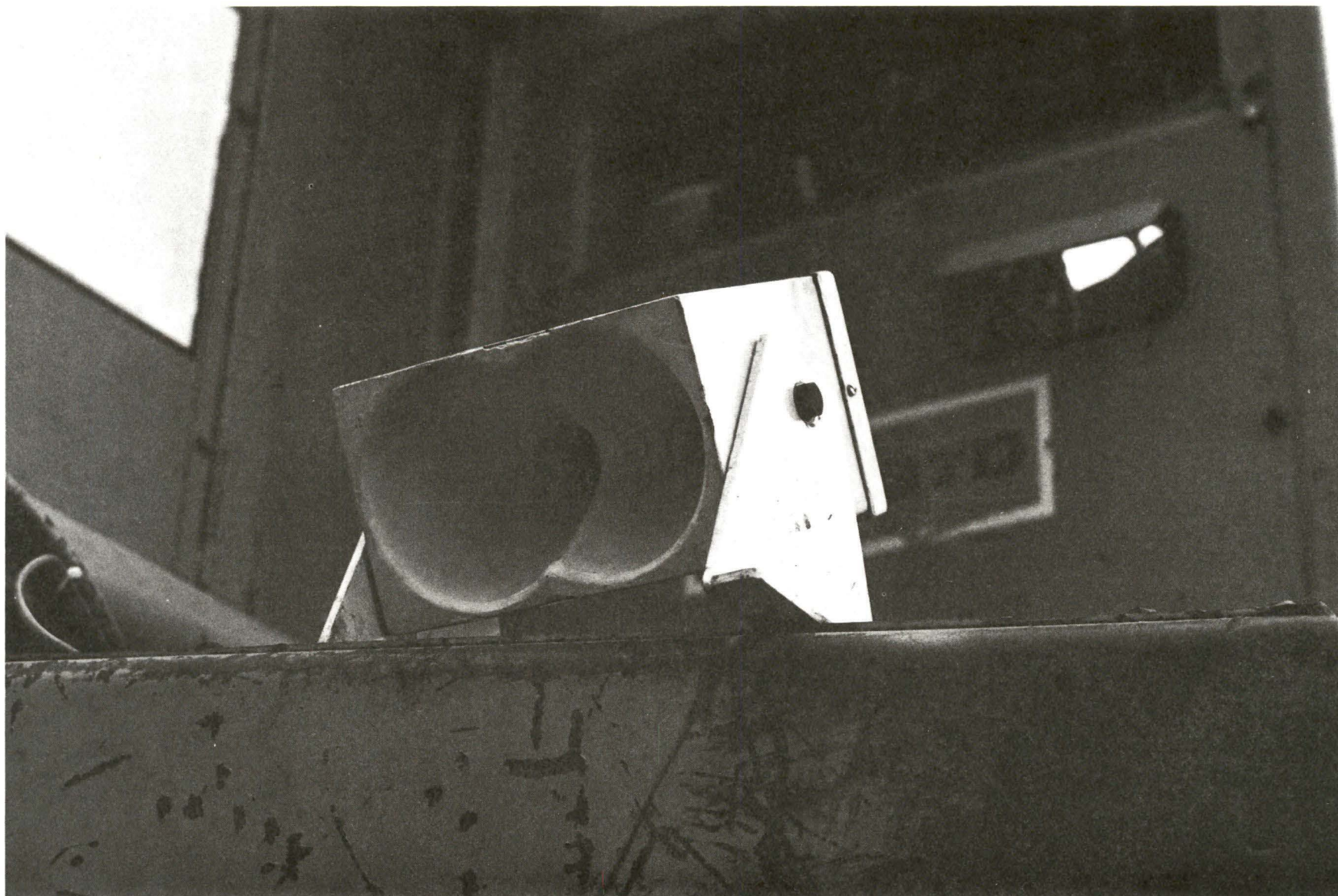
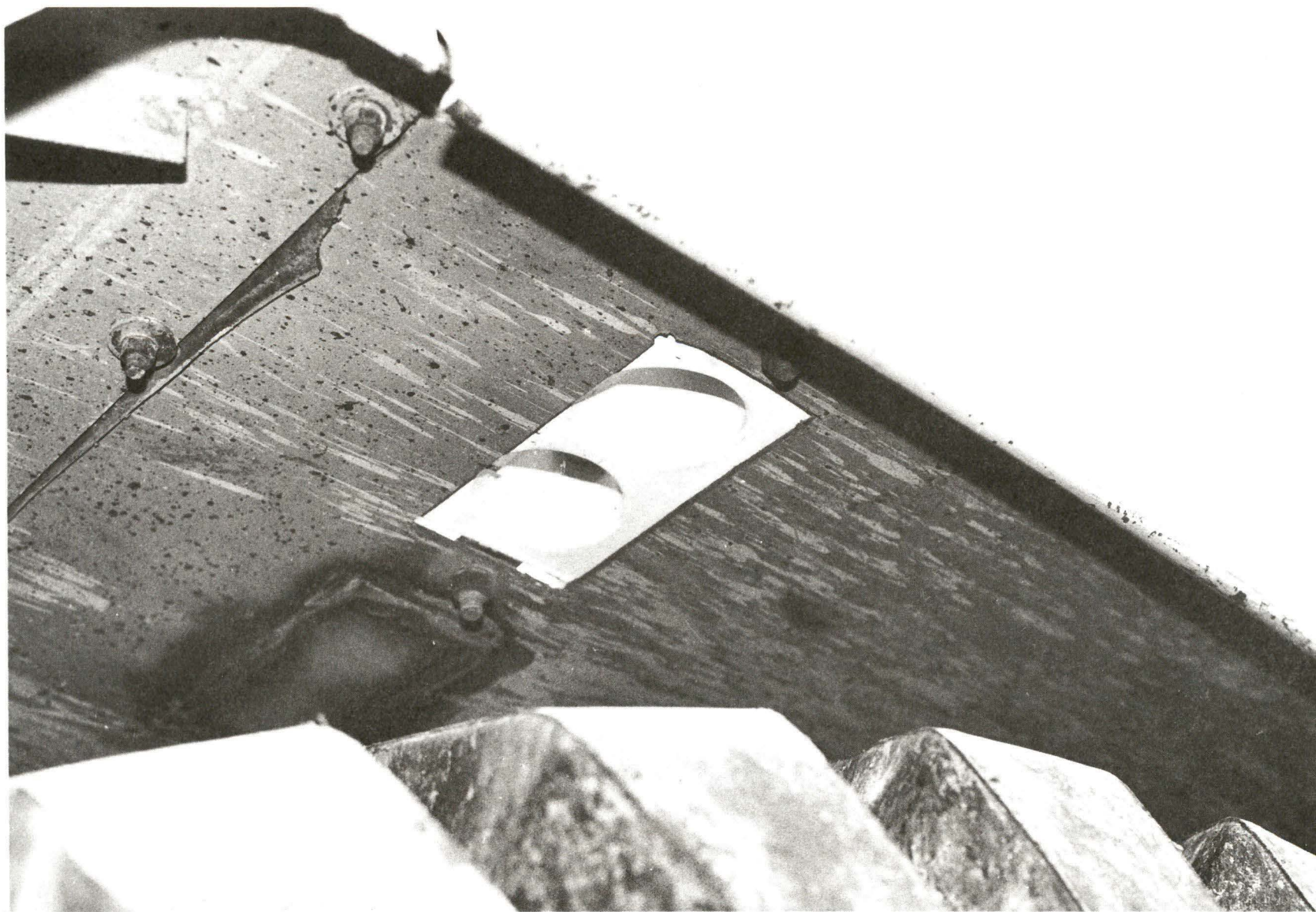


FIGURE 24. CATERPILLAR 637D GROUND SPEED SENSOR INSTALLATION



**FIGURE 25. CATERPILLAR 637D LEFT FRONT WHEEL
SPEED SENSOR INSTALLATION**



**FIGURE 26. CATERPILLAR 637D LEFT FRONT WHEEL
SPEED SENSOR WORKING GEOMETRY**

torily. Using the rear tires, still worn slick, we experimentally determined how satisfactory velocity sensing can be accomplished on a worn tire. We first left one rear wheel sensor aimed at the center of its tire and then made performance comparisons with the other sensor as it was moved about in order to clarify the exact effect of badly worn tire surfaces on velocity sensing. We found it necessary to employ a less desirable sensor mounting location further outboard on the fender in order to obtain satisfactory returns. This location is more prone to mud caking in the sensor horns during wet working conditions; however, the protective measures mentioned above later proved adequate and we subsequently located all wheel sensors in the outer fender location where they scan the outer edge of the tire tread surface. A further difficulty arose from the heated air which enters the rear wheel wells from the rear engine compartment from that engine's cooling fan. This swirling hot air sometimes caused erratic sensor operation. After identifying the cause we installed simple sheet metal baffles to direct the hot air flow away from the velocity sensor horns. After these changes and the cure of some electrical system noise, we proceeded with testing.

Initial test procedure consisted of loading the scraper with high draft effort to produce an observable degree of Wheel Slip, and simultaneously during this action to have the machine operator and an external observer attempt to arrive at a subjective consensus about how the Wheel Slip Monitor was performing. This procedure verified that the Wheel Slip Monitor reliably warned of wheel slip. During this test period we also monitored and compared the magnitudes of the various signal voltages as in the operating WSM equipment. Their observed relationships to each other verified that our signal processing was satisfactory. We next moved to an area of the test track that was muddy and attempted to operate the scraper with constant wheel slip. This proved impossible. Even though the operator received appropriate slip warnings, he could never maintain a steady degree of wheel slip for more than a few seconds. This result eliminated direct calibration as a likely prospect and confirmed that indirect wheel slip calibration methods must be used. We immediately prepared for a series of timed test runs to plot the performance of the five velocity sensors in order that we might use this information in combination with the documented transfer characteristics of the control box signal processing circuitry and thus achieve indirect calibration of verifiable accuracy. Just as we began this test series (approximately ten days before scheduled return of the scraper) the weather became severe and rainfall was almost continuous throughout the remainder of our allocated test time. Our test site, along with most of south Texas, was severely flooded. The Caterpillar pan scraper, which was on loan from a local construction company, had to be released and we were obliged to temporarily terminate local field test activities.

3. Test results during local field testing of the Caterpillar 637-D pan scraper effectively demonstrated that the scraper operator was assuredly aided by the Wheel Slip Monitor. Unfortunately, we failed in our attempts to establish proper calibration procedures during these local field tests.

B. TEREX TS-18 PAN SCRAPER

Figure 27 is a three-quarter front view of the TEREX TS-18 scraper with Wheel Slip Monitor components noted by arrows. Arrow 1 indicates the ground speed sensor mounted atop the front push-guard where performance was excellent. Arrow 2 points out the control box mounting location and a bank of auxiliary test meters installed next to it. Arrows 3 and 4 indicate the left side front and rear wheel speed sensors mounted atop the



FIGURE 27. TEREX TS-18 TEST SCRAPER

fenders. Note that the fenders of the TEREX machine are shaped somewhat differently from the Caterpillar's. The wheel speed sensors performed well in the locations shown.

1. Wheel Slip Monitor components installed inside the cab of the TEREX TS-18 scraper are shown in Figure 28. The control box was mounted overhead because the console in front of the operator is quite narrow. The audible warning beeper can be seen in Figure 28 just to the left of the control box. Just below the control box, along the top of the windshield, is a bank of auxiliary meters. These auxiliary meters allowed monitoring of the five velocity sensors while driving the scraper and were very useful. Just to the left of the meter bank is the control box for an indicator lamp installed atop of the cab. Figure 29 pictures the TEREX TS-18 in operation at field site two and in this figure the lamp assembly can be clearly seen. Figure 30 is a closeup side view of this indicator lamp which flashed brightly in synchronism with the wheel slip warning lights on the operator control box. This action permitted direct external observation of the indications being simultaneously given the scraper operator. In Figure 31, note the white tire markings which simplified visual observation of wheel slip. The wheel speed sensor for the left front wheel can be seen mounted on the fender adjacent the tire surface while Figure 32 depicts this same sensor from below, before addition of the grille and mud flap. Installation time for the Wheel Slip Monitor on the TEREX TS-18 pan scraper was shortened to about 20 man-hours due to experience gained from the earlier Caterpillar 637-D pan scraper installation.

2. The local field testing program using the TEREX TS-18 pan scraper began where the tests described in the previous section had been interrupted by foul weather. We first operated the scraper at constant speeds on a smooth gravel surfaced road and confirmed, by monitoring the bank of auxiliary meters, that under no slip conditions all the velocity sensors' outputs satisfactorily agreed with each other. After determining that the velocity sensors tracked each other, we began calibration. Elapsed time to traverse a measured one hundred foot track with constant indication on the auxiliary test meters was logged and this allowed us to compare and plot velocity sensor outputs versus average ground speed. Replicate speed runs were made under various wind and terrain conditions and these data are presented in the next section.

During this testing we made both still and 16mm motion picture photodocumentation of the scraper self-loading on test track two with periodically slipping wheels. The motion pictures clearly show onset of wheel slip at virtually the instant Wheel Slip Monitor warning begins with flashing of the external indicator lamp affixed atop the scraper cab.

3. Test results obtained with the Terex pan scraper are plotted in Figures 33 through 39. Numerical data for each figure is tabulated adjacent the plots for ready reference. In Figures 33 through 39 voltage-to-frequency (V/F) converter DC output voltage is plotted along the vertical axis. Vehicle velocity, or ground speed, is along the horizontal axis.

Figure 33 data were taken with the ground speed velocity sensor mounted on the front apron of the Terex TS-18 scraper just as shown in Figure 27. Wind speed during this series was approximately 10 mph and alternate test runs were made into and with this prevailing wind. Wind induced errors have proven negligible save those occasions when dust and debris are picked up by very high winds. Velocities are listed in the center column of the tabular data block along with the operator's estimated uncertainty of the

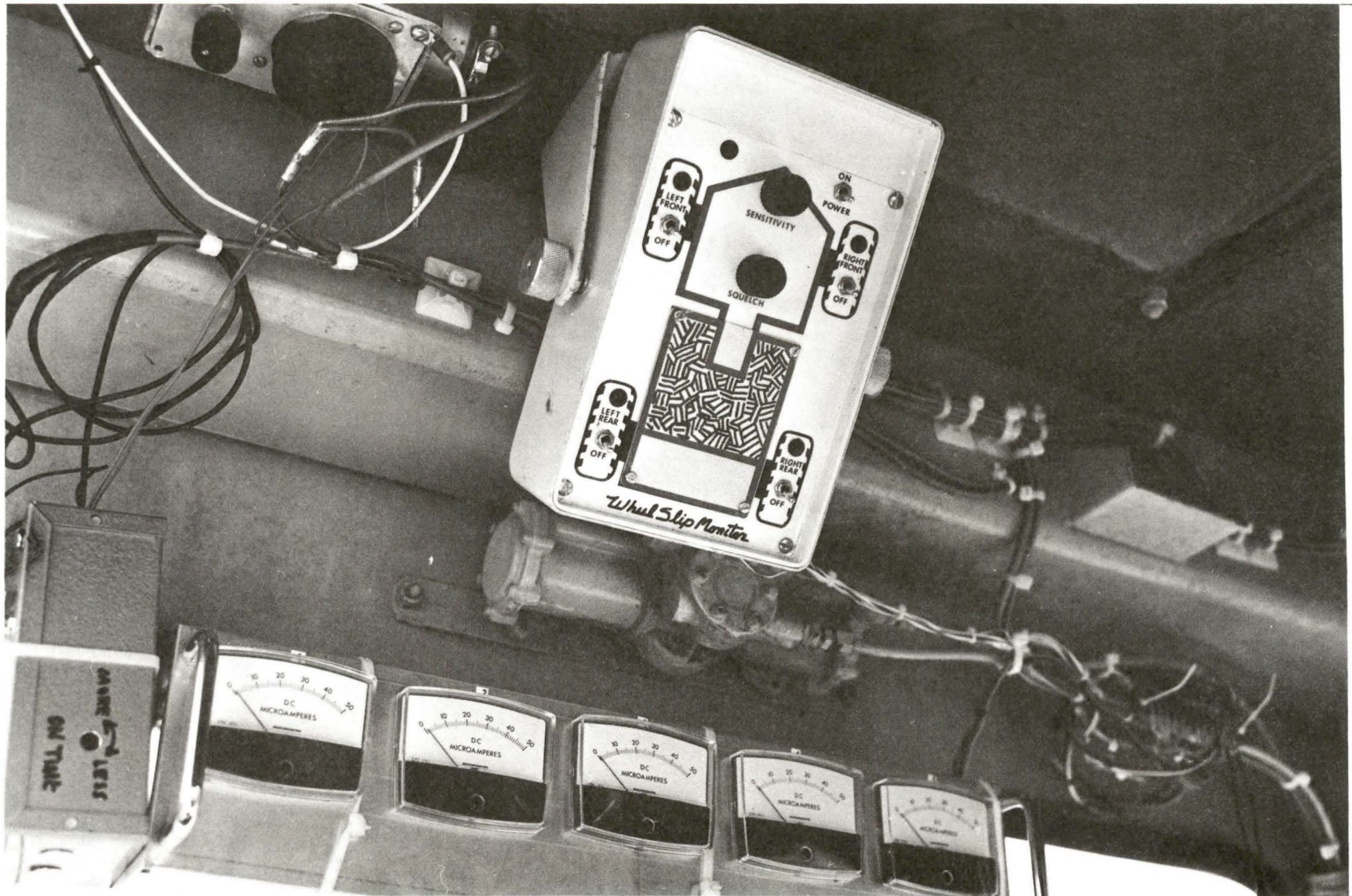


FIGURE 28. TEREX TS-18 WSM CONTROL BOX, BEEPER AND
MULTIPLE TEST METER INSTALLATION



FIGURE 29. TEREX TS-18 ON FIELD TEST SITE

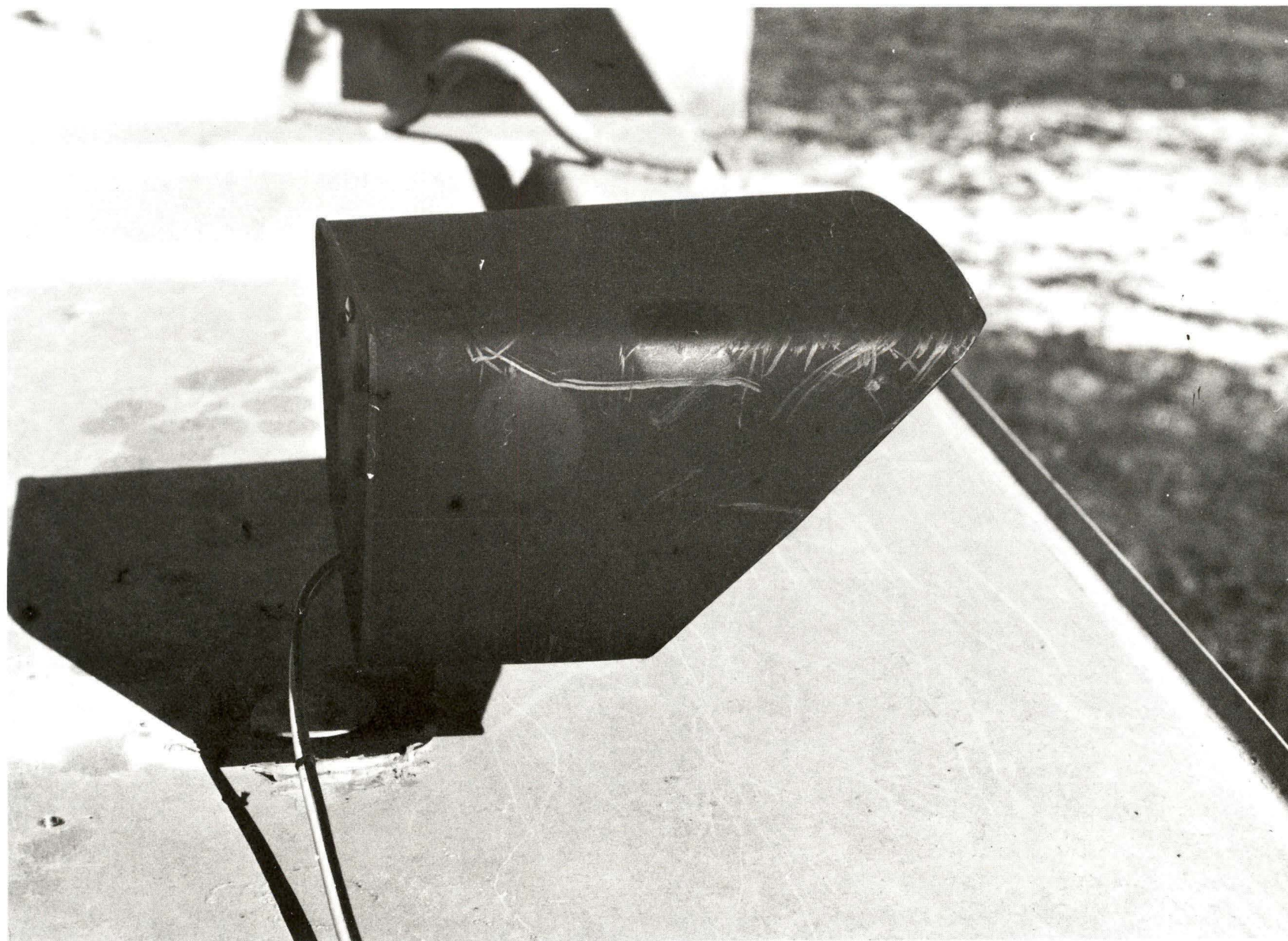


FIGURE 30. CLOSEUP VIEW OF INDICATOR LAMP HOUSING ATOP TS-18 CAB



FIGURE 31. SCRAPER TIRE MARKINGS

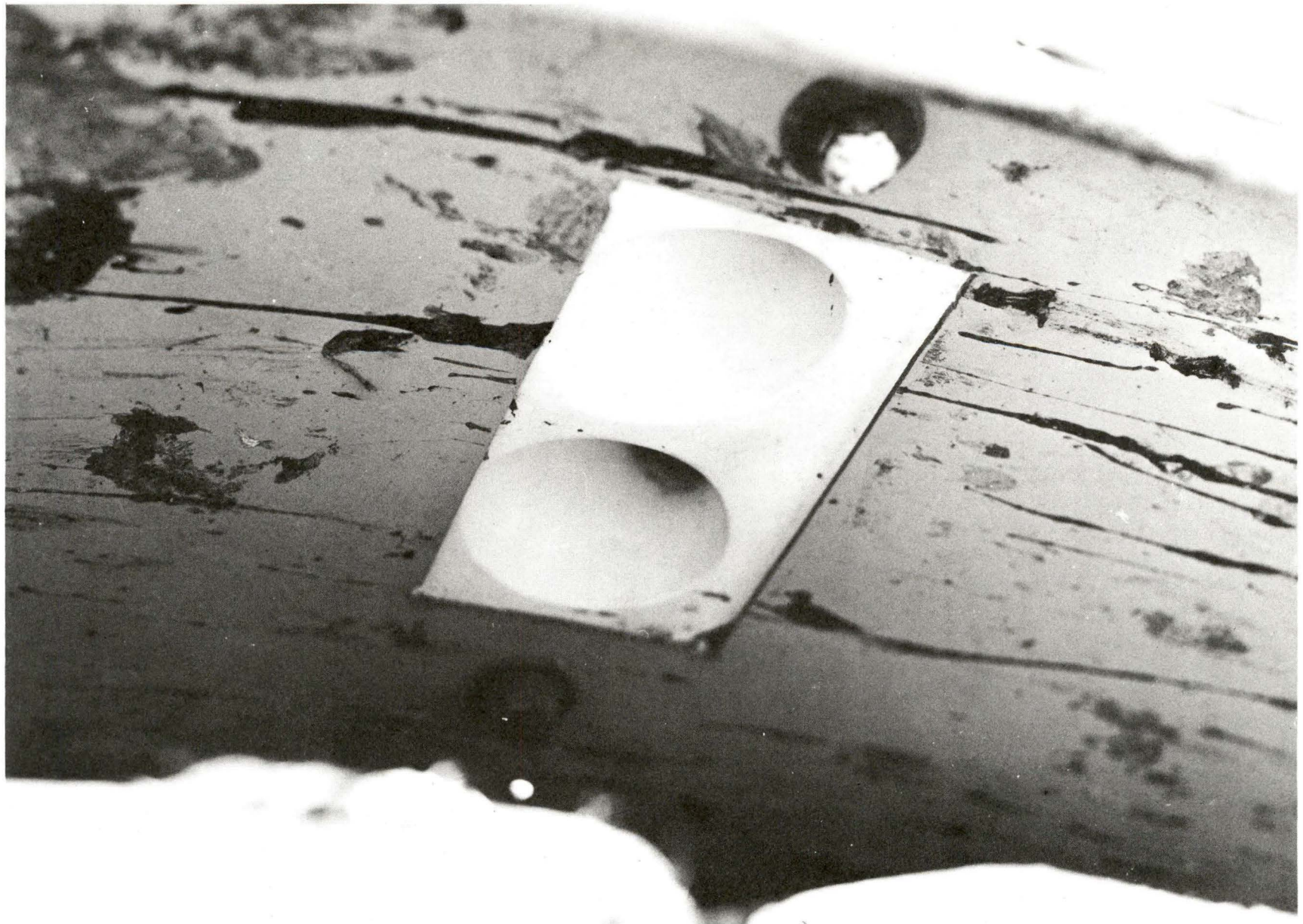


FIGURE 32. TEREX TS-18 LEFT FRONT WHEEL
SPEED SENSOR WORKING GEOMETRY

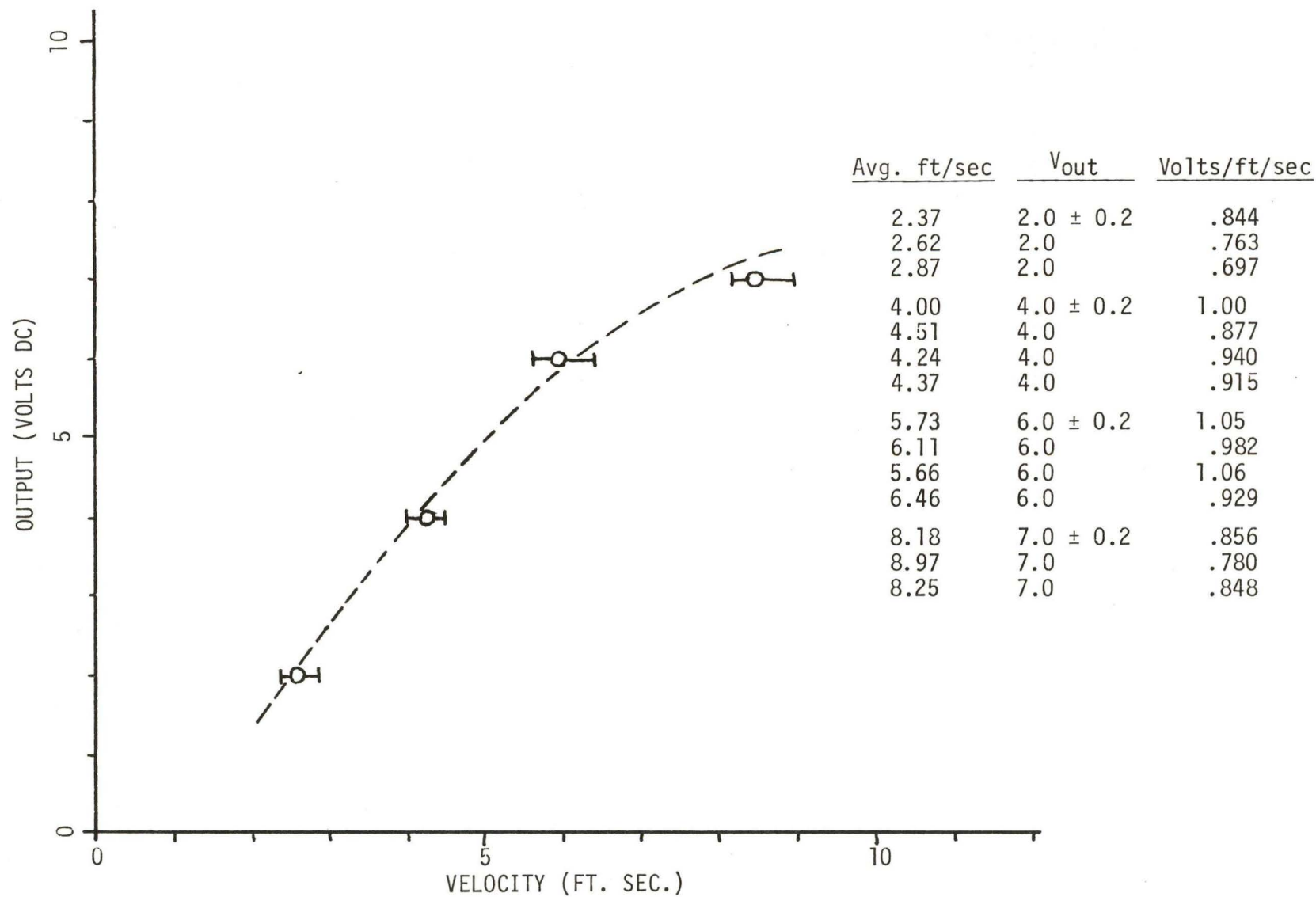


FIGURE 33. TEST RUN NO. 1 GROUND SPEED SENSING

reading. In Figure 33, four averaged data points are plotted with an approximate output voltage versus velocity curve fitted to them. These data points' error bars correspond to the maximum and minimum data values observed around each average point. The curve fitted to the averaged data points shows that the output of the ground speed sensor versus relative velocity was, in that first test, unacceptably non-linear.

Data for Figure 34 was acquired in essentially the same way as that just discussed for Figure 33 save for calm winds. The plotted data in Figure 34 confirmed that our velocity sensor was inaccurate, and that winds were not to blame.

The data shown in Figure 35 was generated with ground speed sensing over a paved surface. We moved to this smoother surface in order to reduce errors due to vertical bouncing machine motions caused by track roughness. The target calibration value was one volt/foot/second; however, the averaged values are actually centered around .95 volts/foot/second which means a scaling correction must be made. This is no problem; what we need is linearity, and it can be seen that the two averaged data points now fall near a straight line through the origin.

After obtaining the data in Figure 35, we continued paved surface ground speed sensing tests to more easily identify sources of measurement error without the complication of rough terrain. We next used more or less random scraper travel speeds while gathering the data shown in Figure 36. Individual data points at ground speeds ranging from two feet per second up to nearly ten feet per second can be seen to lie near a straight line through the origin with a slope of about .95 volts/foot/second. These data confirmed that inherently the ground speed sensing system was capable of satisfactory linearity.

For the test data plotted in Figure 37, we then returned to test track two and resumed testing with multiple replicate runs near 3.5, 6, 8, and 9 feet/second, along with a few random speed single data points as a check. Test meter variation is once again estimated for each numerical value logged. In Figure 37, the averaged data points lie closely along a straight line of one volt/foot/second slope as desired with the slope decreasing above ten feet/second velocity much as expected. Variation away from the desired value of 1 volt/foot/second is within about five percent. These results were considered satisfactory and we next turned our attention to wheel speed sensing.

Figure 38 plots wheel speed sensor output at two calibration settings. Recall that the slope of sensor output voltage versus relative velocity is adjustable with calibration potentiometers that control the output of the individual F/V converters. In Figure 38, output of the right rear wheel velocity sensor is shown during normal operation. The lower curve corresponds to a desired output voltage value of 0.5 volt/foot/second and the upper curve corresponds to a target value of 0.7 volt/foot/second. Both curves confirm linearity adequate for our purposes and indicate that the performance of wheel speed sensing should remain satisfactory independent of the speed used during calibration adjustment to bring wheel speed sensors into agreement with the ground speed sensor.

In Figure 39 we show the results of wheel speed sensing accomplished with multiple replicate runs to allow the determination of average output values. These data show that wheel speed sensing is linear up to nearly 7 feet/second relative velocity, but beyond that point the $V_{out}/ft/sec$ gradually declines from its calibrated value resulting in an output about 20 percent low near 10 ft/sec and with an error approaching ten percent

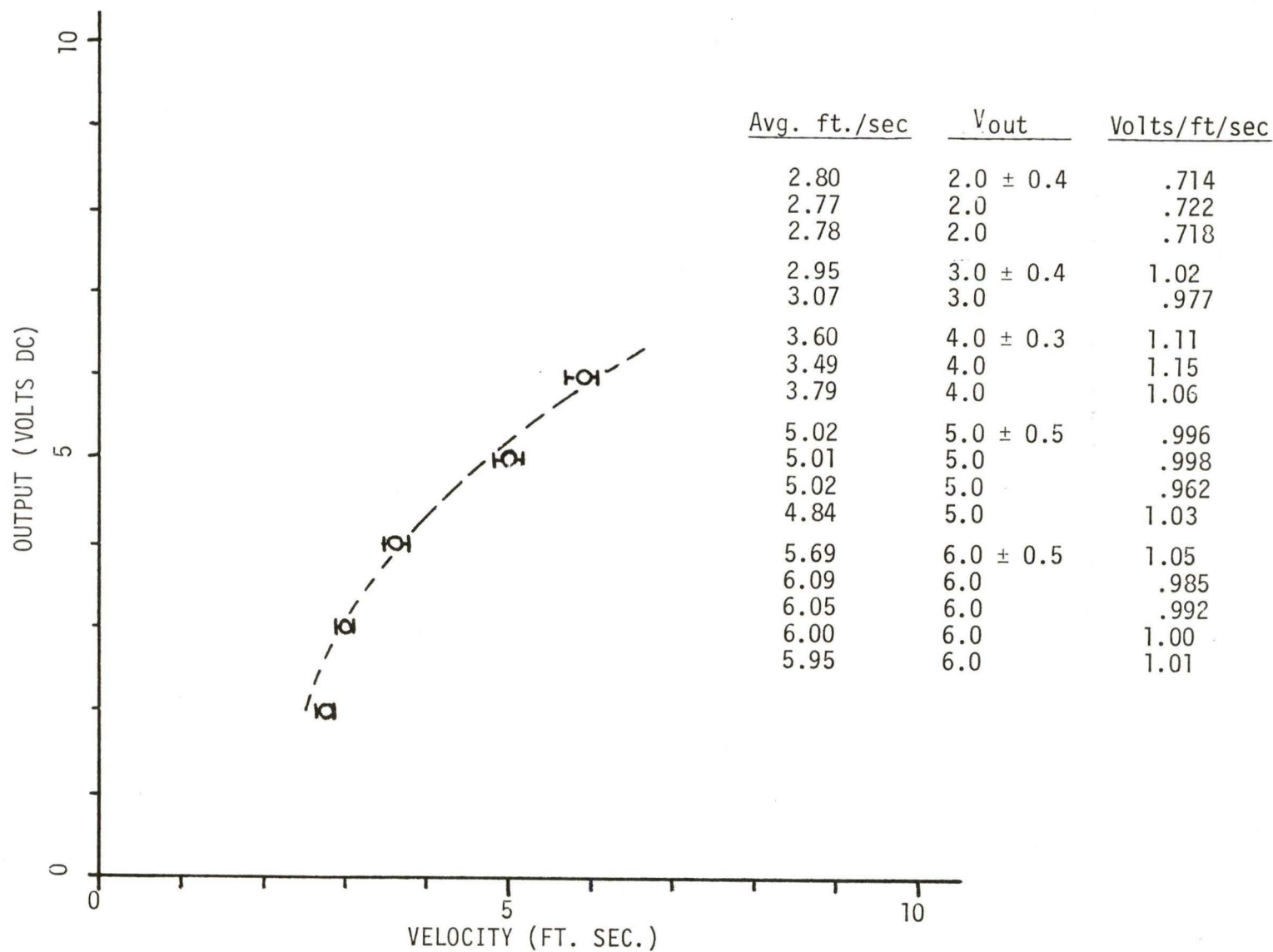
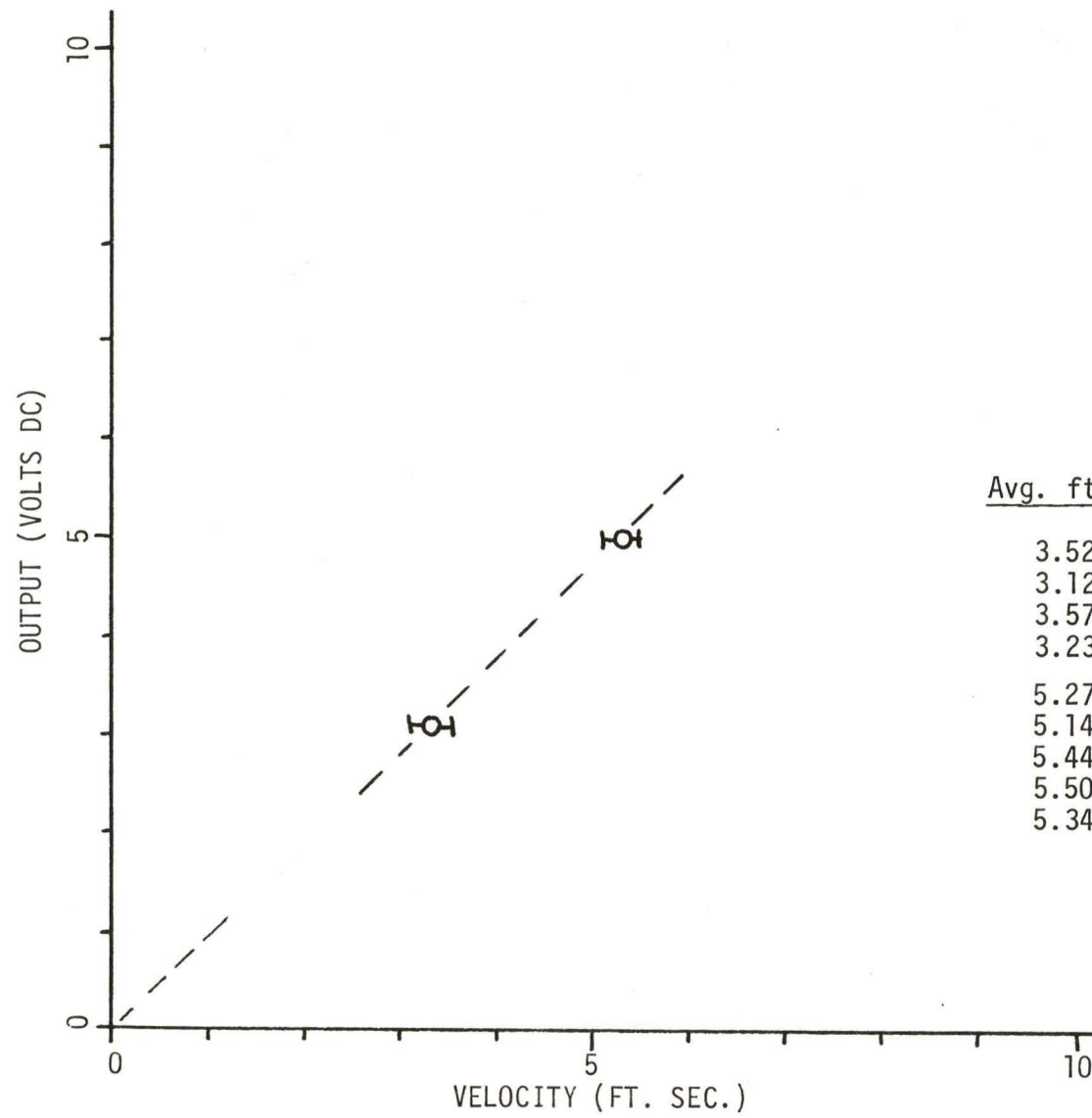


FIGURE 34. TEST RUN NO. 2 GROUND SPEED SENSING



<u>Avg. ft/sec</u>	<u>V_{out}</u>	<u>Volts/ft/sec</u>
3.52	3.2 ± 0.2	.909
3.12	3.0	.962
3.57	3.2	.896
3.23	3.1	.959
5.27	5.0 ± .3	.949
5.14	5.0 ± .4	.973
5.44	5.0	.919
5.50	5.0	.909
5.34	5.0 ± .3	.936

FIGURE 35. TEST RUN NO. 3 GROUND SPEED SENSING

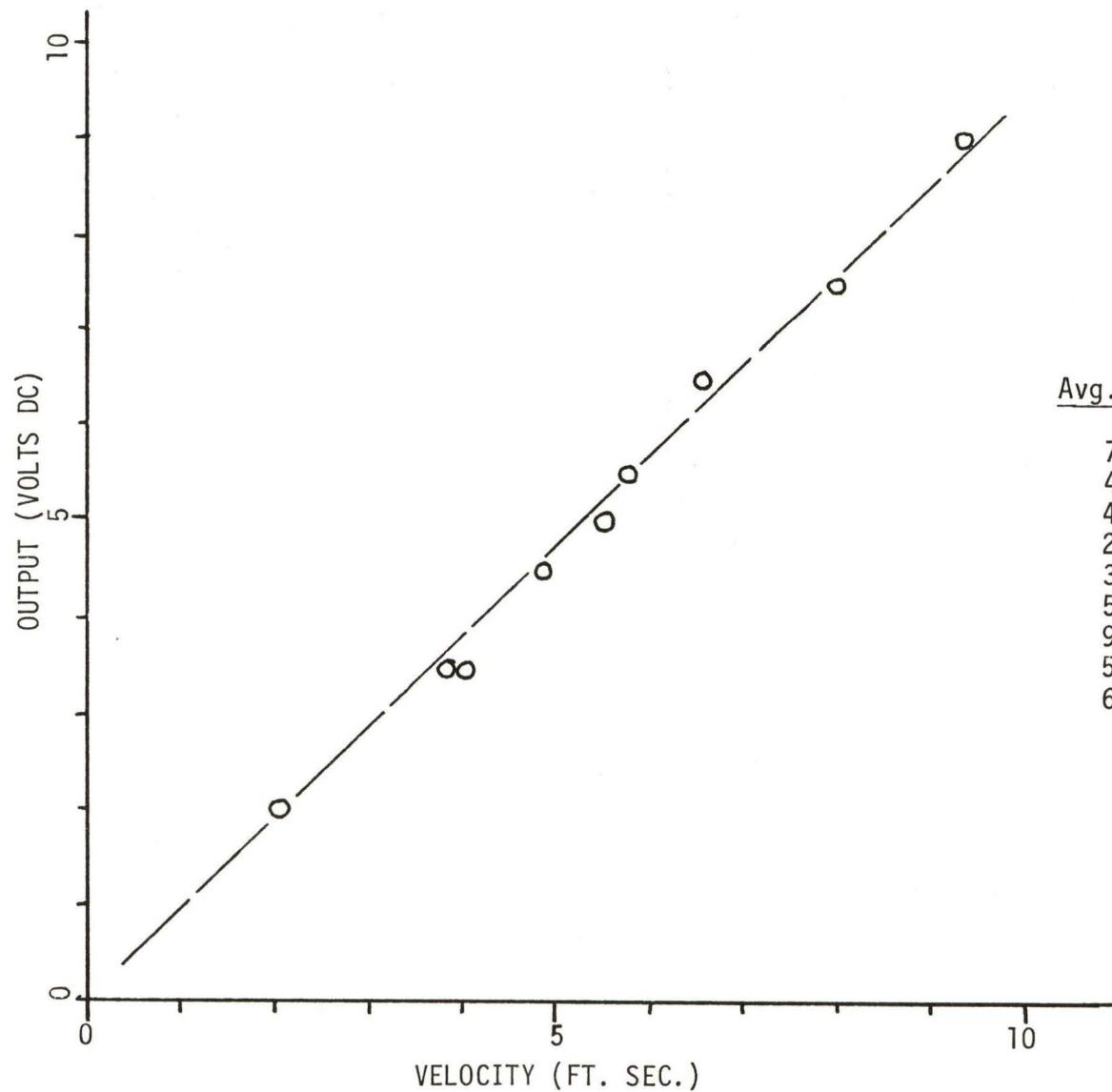


FIGURE 36. TEST RUN NO. 4 GROUND SPEED SENSING

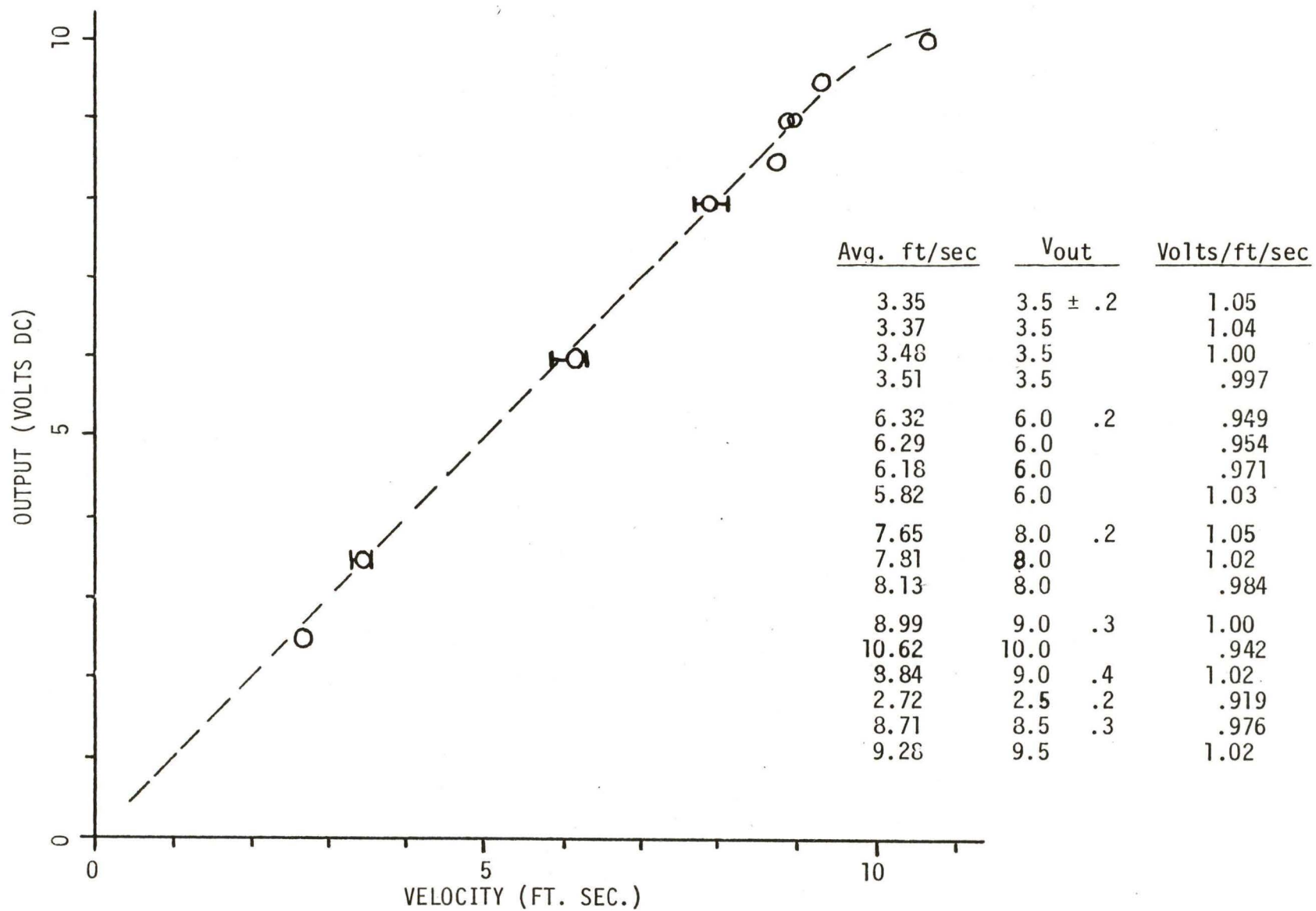
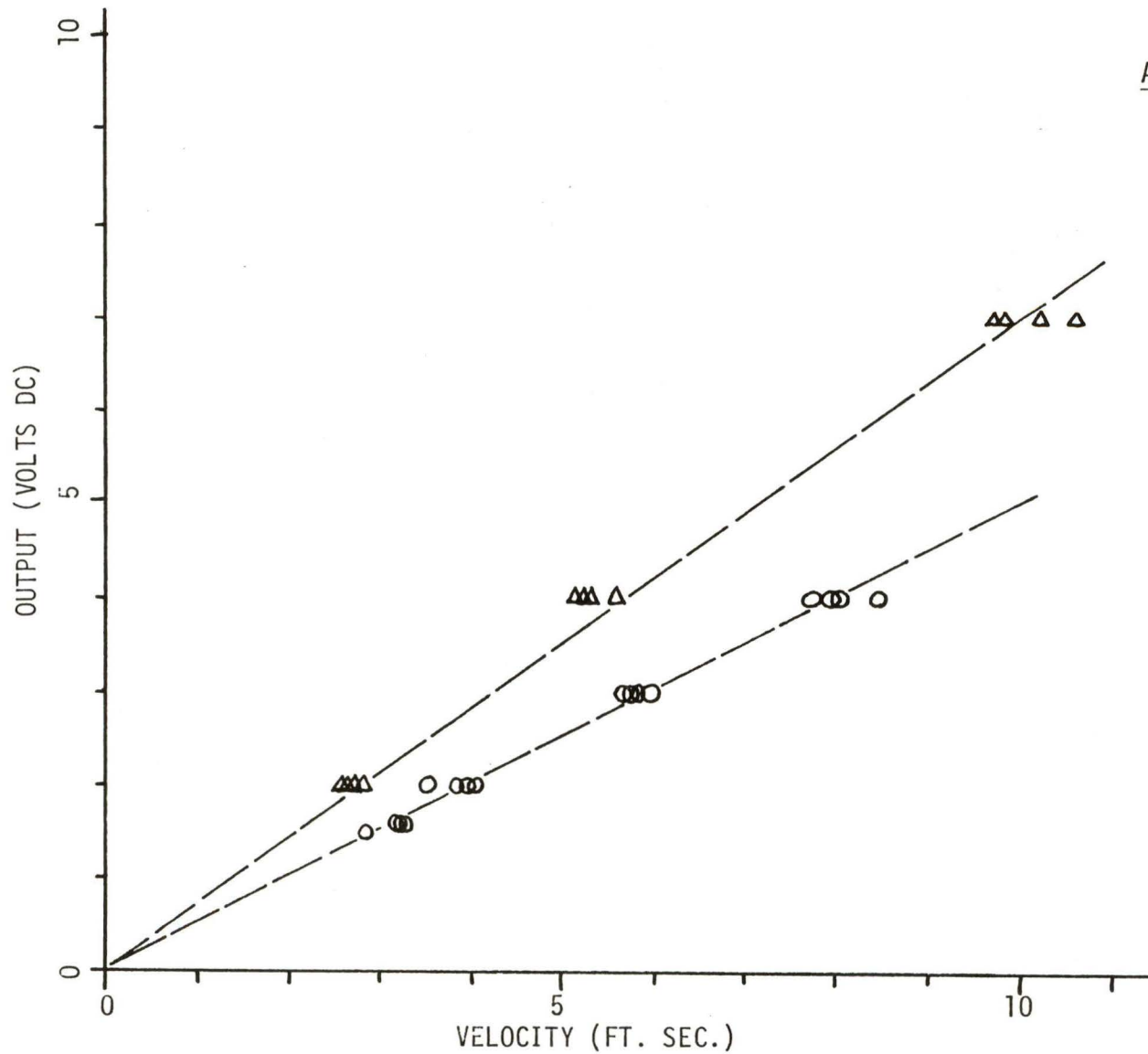


FIGURE 37. TEST RUN NO. 5 GROUND SPEED SENSING



Avg ft/sec	V _{out}	Volts/ft/sec
3.24	1.6 ± .1	.494
3.18	1.6	.503
3.18	1.6	.503
2.86	1.5	.524
3.87	2.0	.517
4.02	2.0	.498
3.53	2.0 ± .2	.567
3.92	2.0 ± .1	.510
5.79	3.0	.518
5.98	3.0	.502
5.72	3.0	.524
5.85	3.0	.513
7.74	4.0 ± .2	.517
8.43	4.0	.474
7.95	4.0 ± .1	.503
7.98	4.0	.501
2.78	2.0	.719
2.72	2.0	.735
2.58	2.0 ± .2	.775
2.73	2.0 ± .1	.733
5.14	4.0 ± .2	.778
5.24	4.0	.763
5.31	4.0	.753
5.60	4.0	.712
10.2	7.0 ± .3	.636
9.85	7.0	.710
10.6	7.0	.660
9.70	7.0	.721

FIGURE 38. TEST RUN NO. 6 WHEEL SPEED SENSING

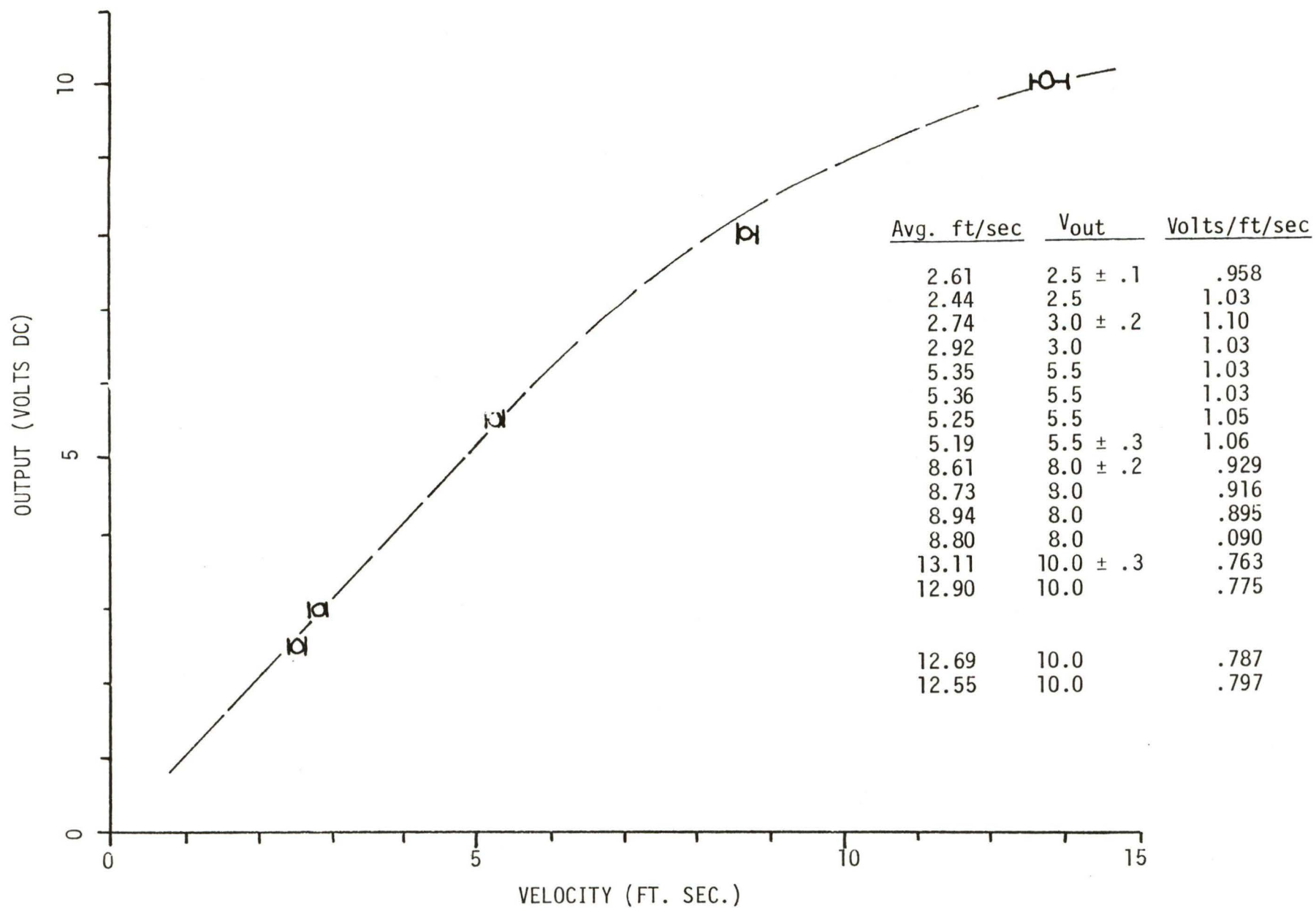


FIGURE 39. TEST RUN NO. 7 WHEEL SPEED SENSING

near the very upper end of the scraper loading speed range. Wheel speed sensing on the working machine proved to be less linear than earlier indicated during static feasibility testing with the rear wheels of the farm tillage tractor and haul truck. This disparity is a candidate for further investigation at some future date when time is available to completely resolve it; however, wheel speed sensing at the present state of development is deemed adequate for practical application. The net effect on Wheel Slip Monitor function of this nonlinearity in wheel speed sensing is that at high travel speeds the WSM will tend to permit greater V_s scrubbing velocities before it signals a warning to the scraper operator. Whether or not the travel speed range above 6 or 7 feet/second is regularly employed in high draft loading is not clear; nonetheless, we feel sure that modest effort can improve the performance of wheel speed sensing so that it approaches the accuracy already obtained with ground speed sensing.

We concluded from these local field tests that the prototype WSM hardware can reliably generate output signal voltages proportional to scrubbing velocity V_s accurate within about five percent from zero up to a vehicle travel speed of six feet/second and useful slip warning indications to speeds near 10 feet/second or about seven mph.

VI. WORKING MINE FIELD TESTING

Wheel Slip Monitor field testing was accomplished at a working strip mine near Chelsea, Oklahoma. Two Caterpillar type 637-D pan scrapers were used: one with the WSM plus a bank of five event counters with internal voltage-to-frequency (V/F) converters for V_s data accumulation, the other with the WSM alone. Field testing was conducted during the period from early February through mid-May 1983. Weather was inordinately wet during the entire period and this tended to limit scraper usage and thus numerical data collection. This loss was offset by the fact that these very bad working conditions provided a perfect opportunity to settle the often asked questions regarding wheel speed sensor vulnerability to mud buildup and also to observe WSM action as the test scrapers worked on unusually slippery terrain. See Figure 40.

A. WHEEL SLIP MONITOR INSTALLATION

Hardware installation on both test scrapers followed procedures used earlier during local field testing and one test scraper was further equipped with five counters which continuously recorded individual wheel slip V_s (all four) plus overall (worst tire) wheel slip V_s .

The ground speed sensors on both scrapers were positioned high enough to provide them a clear path to the ground past the scraper's loading bail. See Figure 41. Operation was entirely satisfactory. Figure 42 illustrates the protective grille and mud flap used on these wheel speed sensor installations. Mud caking presented no problems, even under the severe weather conditions encountered during the test period. The added slip warning indicator package used on both test scrapers can be seen near the center of Figure 43 mounted at the rear cab window and positioned so that the operator can see it while watching the bowl fill during loading.

B. TEST METHODS

Test procedures used during field testing were tailored to pose no interference with day-to-day mine operations. Data was transcribed and the recording counters reset during off hours. Subjective opinion and suggestions were elicited by the SwRI on-site representative during operators' free moments (coffee breaks, etc.) using informal questioning. Past experience has shown this to be the best procedure because anything resembling a formal interview is strange to most of them and is often viewed with some suspicion.

Figure 44 depicts typical scraper tire damage observed during field testing. This view is along the tire's upper surface toward the wheel speed sensor, with an ordinary lead pencil for scale. Tire damage is so severe in some areas of the test mine that pan scrapers are not used there at all. During the test period the scrapers performed a variety of earthmoving jobs, ranging from topsoil removal and overburden stripping to reclamation backfilling. Daily Operation Logs (see Figure 45) were maintained by SwRI personnel and are the source for the reduced data reported in the next section. The Wheel Slip Monitors were operated and data recorded at all times, but readout was given the



FIGURE 40. PAN SCRAPER LOADING ON MUDDY TERRAIN



FIGURE 41. GROUND SPEED SENSOR MOUNTING FOR
WORKING MINE FIELD TESTS

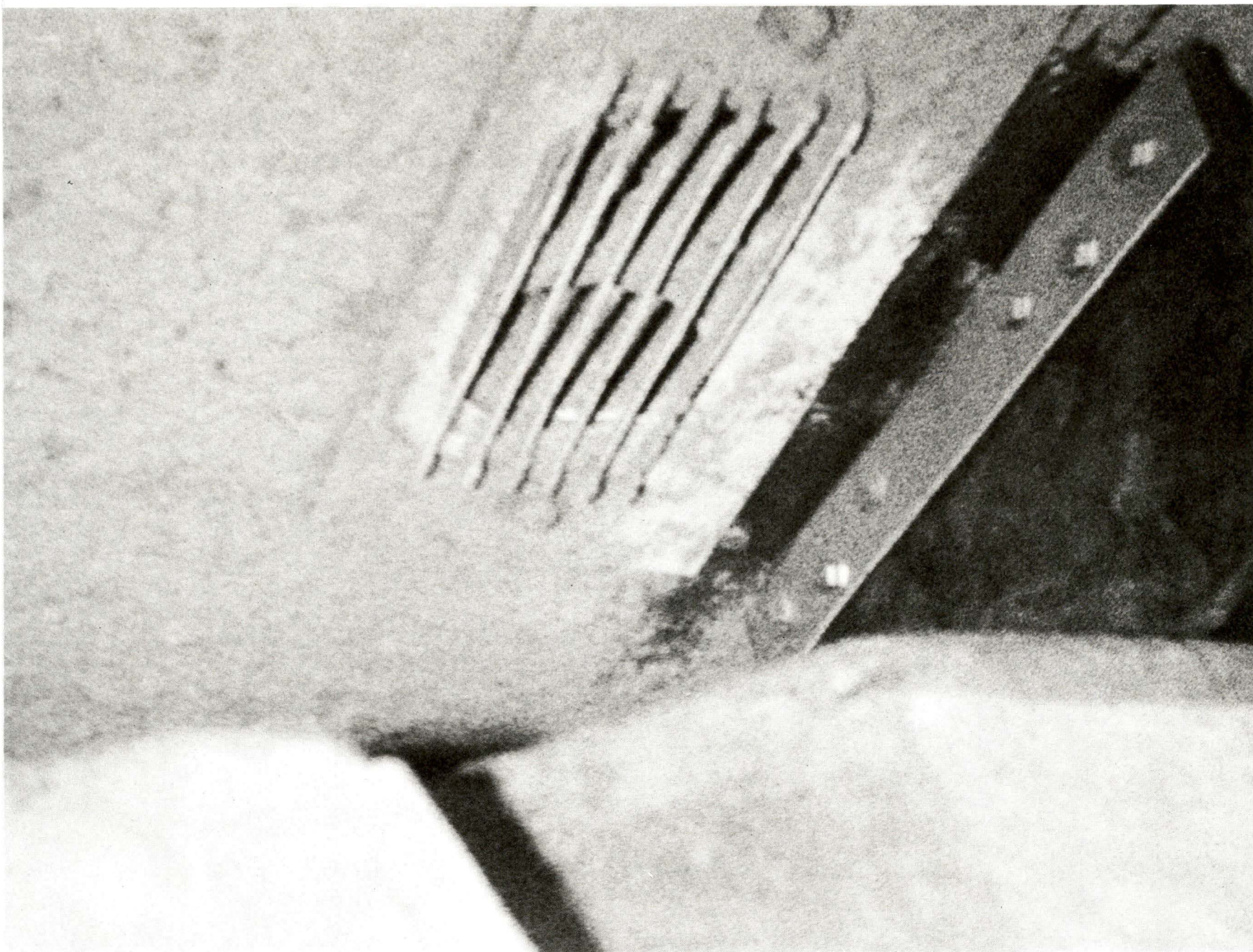


FIGURE 42. TYPICAL WHEEL SPEED SENSOR INSTALLATION
WITH GRILLE AND MUD FLAPS

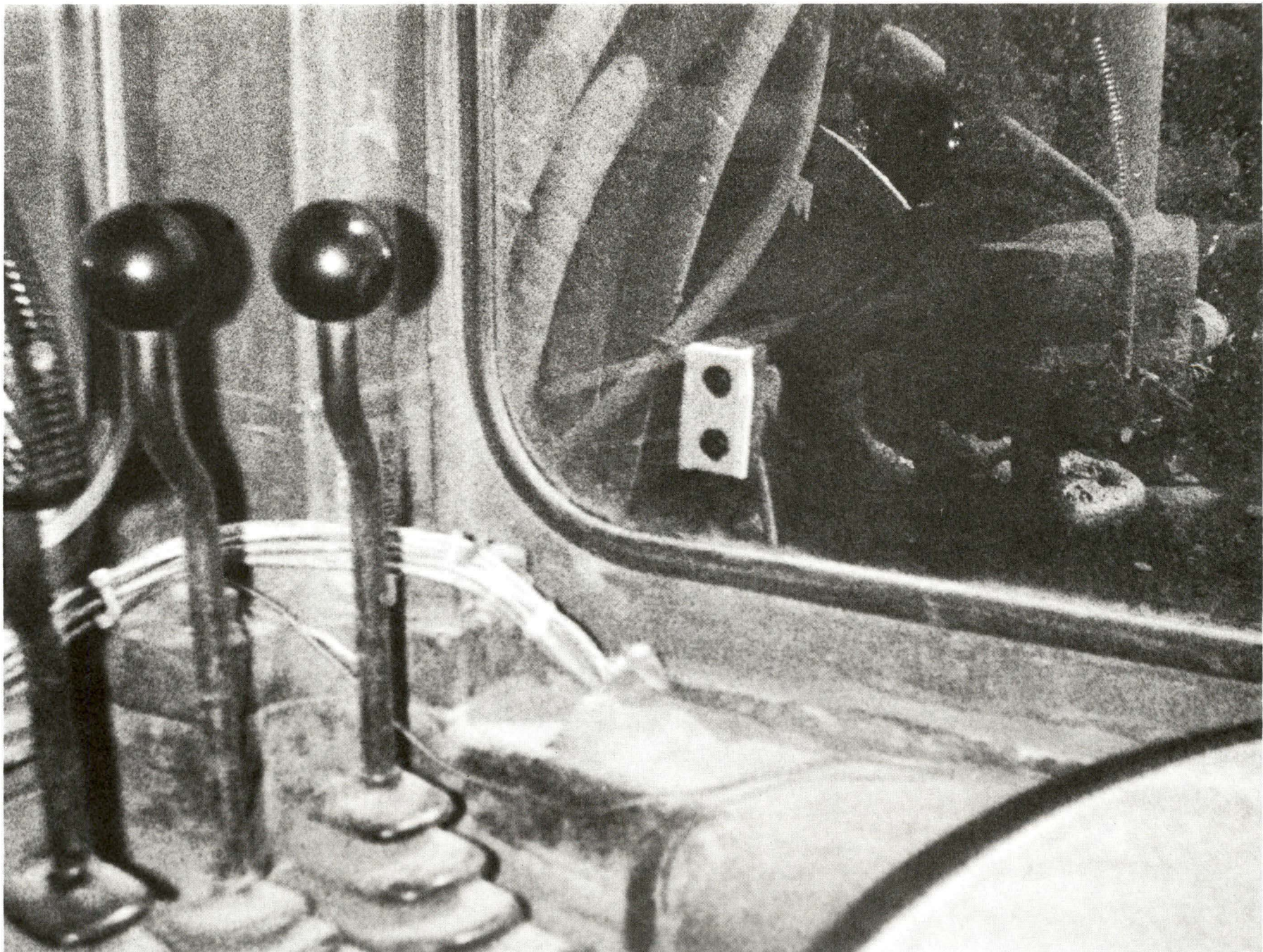


FIGURE 43. TWO LIGHT SLIP WARNING INDICATOR AT REAR CAR WINDOW

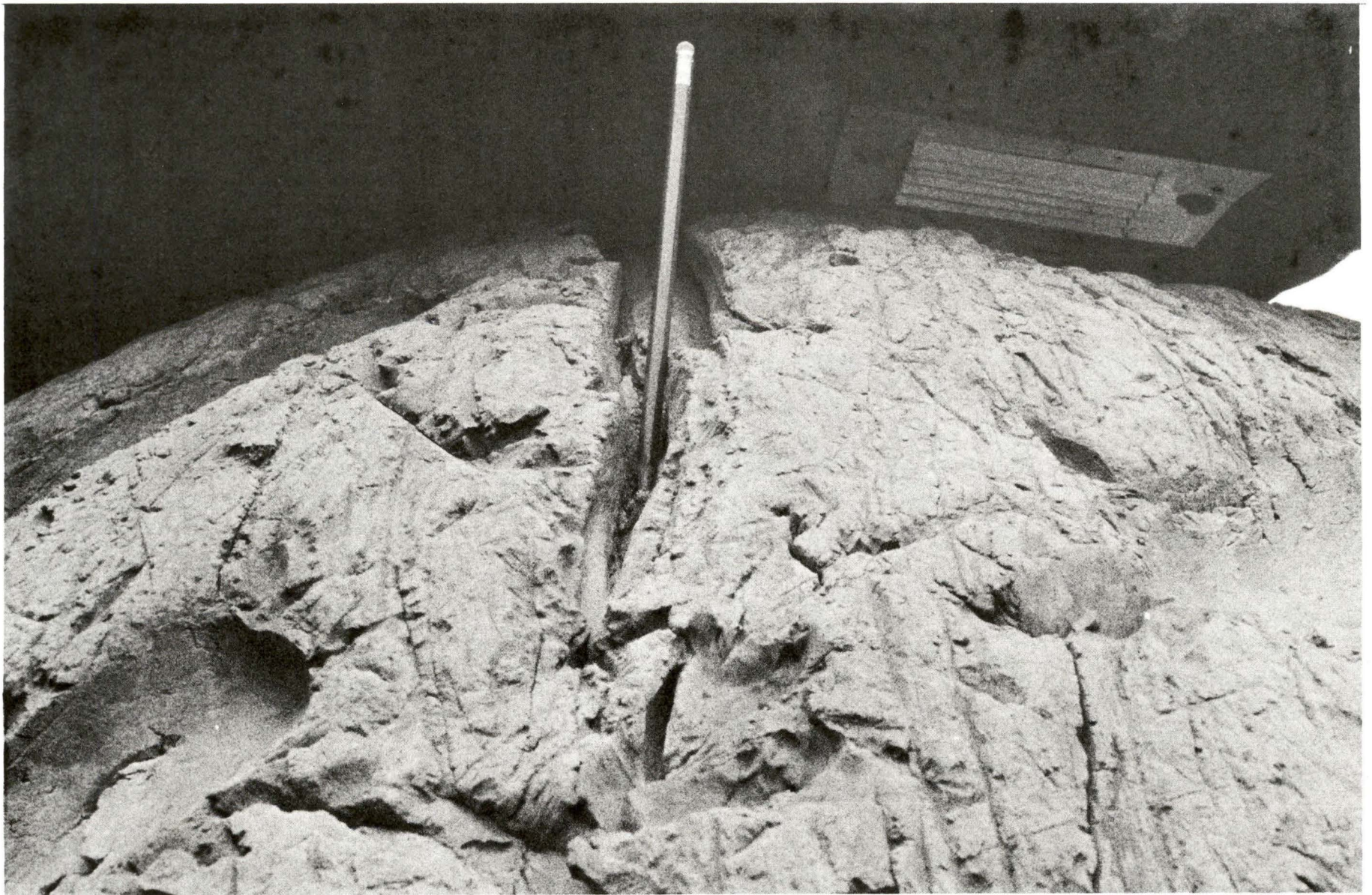


FIGURE 44. SCRAPER TIRE CUT DAMAGE (PENCIL FOR SCALE)

DAILY OPERATIONS LOG
FIELD TEST, WHEEL SLIP MONITOR
Project 05-5661

Date _____ SwRI Representative _____ Page _____ of _____
Equipment Type and I.D. No. _____
Mine _____ Location in Mine _____
Soil Conditions _____
Weather Conditions _____
Comments _____

Time			WSM Status		Equipment Operator	Fuel Usage (gal)	Counter Readout					Operator Comments
Start	Stop	Elapsed	On	Off			1	2	3	4	5	
TOTALS WITH WSM												
TOTALS WITHOUT WSM												

FIGURE 45. SPECIMEN COPY OF DAILY OPERATIONS LOG

scraper operators only about half the time, as noted, so that **with** and **without** comparison could be made.

C. TEST RESULTS

A substantial amount of numerical V_s data was accumulated during the test period; however, only those data gathering periods that meet the strict criteria outlined below were sampled for the information included in Table 2, Wheel Slip Data, which follows. In order to make accurate **with** and **without** WSM usage comparisons we deem it necessary that the paired data logging periods must have:

- directly comparable terrain and weather conditions
- properly operating WSM equipment (no operator tampering and no hardware malfunction)
- similar scraper mechanical condition.

The individual data periods of Table 2 may have had one or several different scraper operators on duty.

1. Numerical Data

In Table 2, Wheel Slip Data, we have paired numerical data from selected work periods (1a/1b, 2a/2b, etc.) that meet the requirements just stated. Facsimilies of the actual Daily Operation Logs from which these data were extracted are found in Appendix Entry IV of this report with appropriate identification. The **Accumulated Counts** numbers listed in this table were periodically transcribed by the on-site SwRI representative with the Daily Operation Log from the recording counters and we call attention to the fact that the sum of the Accumulated Counts for the four individual wheels during any one work period is larger than the Accumulated Counts for the worst wheel. This occurs because the worst wheel number is a measure of scraper **overall** wheel slip derived from the single wheel which is slipping the most at any moment. We consider this the most cost effective of the Accumulated Counts even though, unlike the individual wheel data, it cannot be used to **directly** quantify how far an individual tire has been scrubbed.

The **Average V_s (ft/sec)** figures were calculated from characteristics of the counters' internal V/F converters (1 Volt Input = 2 counts/sec) and the accumulated counts during a known work period length. The Average V_s numbers are small because they represent many short periods of high V_s averaged over an extended work period. We believe this to be a practical procedure in light of the discussion presented back in Section III.B.2.b of this report and consider these numbers to be a reliable means of assaying the utility of the Wheel Slip Monitor in ameliorating pan scraper wheel slip. Average V_s numbers from Table 2 are plotted in bar graph form in Figures 46, 47, 48, 49, and 50 which follow so that we may compare at a glance the effect of Wheel Slip Monitor usage during each data period. In all these figures the **open bars'** heights represent the Average V_s for that portion of the data period **with** the operator given readout information while the **shaded bars'** heights represent the **without** section of the same period.

Table 2. Wheel Slip Data

PERIOD	HOURS	WSM STATUS	ACCUMULATED COUNTS*					AVERAGE Vs (ft/sec)				
			Right Front Wheel	Left Front Wheel	Right Rear Wheel	Left Rear Wheel	Worst Wheel	Right Front Wheel	Left Front Wheel	Right Rear Wheel	Left Rear Wheel	Worst Wheel
1a	7	ON	12,622	46,873	18,221	30,338	35,749	0.25	0.93	0.30	0.60	0.71
1b	12	OFF	23,414	81,027	78,668	29,192	86,314	0.27	0.94	0.91	0.34	1.00
2a	16	ON	57,447	81,055	17,637	12,257	63,417	0.48	0.70	0.15	0.11	0.55
2b	16	OFF	38,762	69,312	55,428	17,012	73,913	0.34	0.60	0.48	0.15	0.64
3a	8	ON	3,374	878	1,879	1,841	2,758	0.06	0.02	0.03	0.03	0.05
3b	7	OFF	10,314	14,190	34,652	15,402	18,473	0.20	0.28	0.69	0.31	0.37
4a	7	ON	14,476	64,524	57,480	55,952	55,212	0.29	1.28	1.14	1.11	1.10
4b	8	OFF	47,948	59,417	126,423	85,401	66,023	0.83	1.03	2.19	1.48	1.15
5a	10	ON	63,512	65,456	148,429	81,959	85,574	0.88	0.91	2.06	1.14	1.19
5b	8	OFF	101,732	124,471	112,212	112,724	103,110	1.77	2.16	1.95	1.96	1.79
6a	8	ON	28,273	59,858	64,588	128,215	66,198	0.49	1.04	1.12	2.23	1.45
6b	7	OFF	23,143	57,887	62,863	123,997	64,972	0.46	1.15	1.25	2.46	1.29
7a	4	ON	18,128	30,815	35,720	70,208	39,124	0.62	1.07	1.24	2.44	1.36
7b	7	OFF	40,217	37,825	104,237	104,799	91,061	0.80	0.75	2.07	2.08	1.81
8a	7	ON	42,613	43,719	63,728	70,136	50,291	0.85	0.87	1.26	1.39	1.00
8b	8	OFF	51,371	63,325	165,643	174,850	85,146	0.89	1.10	2.88	3.03	1.49
	67	ON	240,445	393,178	407,682	450,906	398,323					
TOTALS	73	OFF	336,901	507,454	630,126	663,377	589,014					

* 1 volt V_s = 2 counts/sec = 1 ft/sec scrubbing velocity

Consider first Figure 46, **Worst Wheel (Overall) Average V_s** . Relative heights of the bars clearly show the beneficial effect of real time wheel slip warning as a scraper operator aid. In every data period wheel slip shows to be reduced. If the **without** periods' average V_s are considered normal or baseline, then the **with** periods' average V_s can be conveniently expressed as a percentage of normal; and these **with** percentages range from 1.35 percent (period 3a/3b) to 96 percent (period 4a/4b). This represents **slip reduction** ranging from 86.5 percent to 4 percent of the amount normally expected **without** WSM usage. The average slip reduction of the whole eight period block is about 26 percent. We anticipated (and these figures confirm) a rather wide variation in the apparent effectiveness of the WSM as an operator aid because in any sampling of this type operator acceptance is crucial. Past experience has taught us to expect operator acceptance of novel equipment to range all the way from diligent usage to hostile non-use: sometimes accompanied by malicious equipment damage. These field tests were no exception. Recall that this numerical data pertains to **one** test scraper; however, day-by-day observation of **both** working scrapers by the on-site project representatives is significant in that they expressed subjective estimates of wheel slip reduction that agree well with the numerical data: a one-third to one-fourth reduction in overall wheel slip when the operator had wheel slip warning. As discussed elsewhere in this report, we believe **overall** or worst wheel V_s data recording alone will prove adequate in virtually all scraper tire wear and damage management work.

Average V_s data for the four individual scraper wheels is bar graphed in Figure 47 (Left Front), Figure 48 (Left Rear), Figure 49 (Right Front) and Figure 50 (Right Rear). When we examine them as a group we see at once that the data have several pairs of bars where **without** average V_s is **smaller** than **with** average V_s . A moment's reflection shows why this will almost always be true. The only action that the scraper operator can take to arrest wheel slip, when given a warning, is to reduce power on the appropriate engine, front or rear, in response to the blinking wheel slip lights. This is the reason we eventually settled on, as described earlier, using two (rather than four) warning lights as primary operator display. Whichever of the two pairs of wheels, front or rear, that contains the **worst** slipping wheel will display slip warning. One or both wheels in the other pair may actually be slipping also, but so long as this slip is the smaller, they will give no slip indication. The Wheel Slip Monitor display system was designed to function this way because we believe this to be **all** the specific slip warning information that the operator can be reasonably expected to react to. One or the other of the blinking warning lights, reinforced by beeper sound, is judged best for manual control with the operator left in the feedback loop. Automatic slip control using the V_s signals is an excellent prospect, but beyond the scope of this work effort. Since this readout scheme ignores the less slipping wheels during the time the worst is being corrected, some V_s scrubbing counts below the worst wheel slip level will be accumulated; thus accounting for the bar pairs mentioned. At the bottom of the Accumulated Counts columns we have summed all the counts registered during the entire data block and when these totals are used to compare the individual wheels among themselves and with the worst wheel, we find good agreement with our earlier figures. The right front wheel was scrubbed 22.2 percent **less** than baseline **with** Wheel Slip Monitor usage, the left front 15.6 percent **less**, the right rear 29.5 percent **less**, and the left rear 25.9 percent less.

The Accumulated Counts numbers in Table 2, Wheel Slip Data, may also be readily used to determine the **actual distance in feet** that the individual tire was scrubbed by wheel slip. As mentioned earlier, each counter has its own internal voltage-to-frequency (V/F) converter adjusted to produce pulses (counts) per second for every volt of

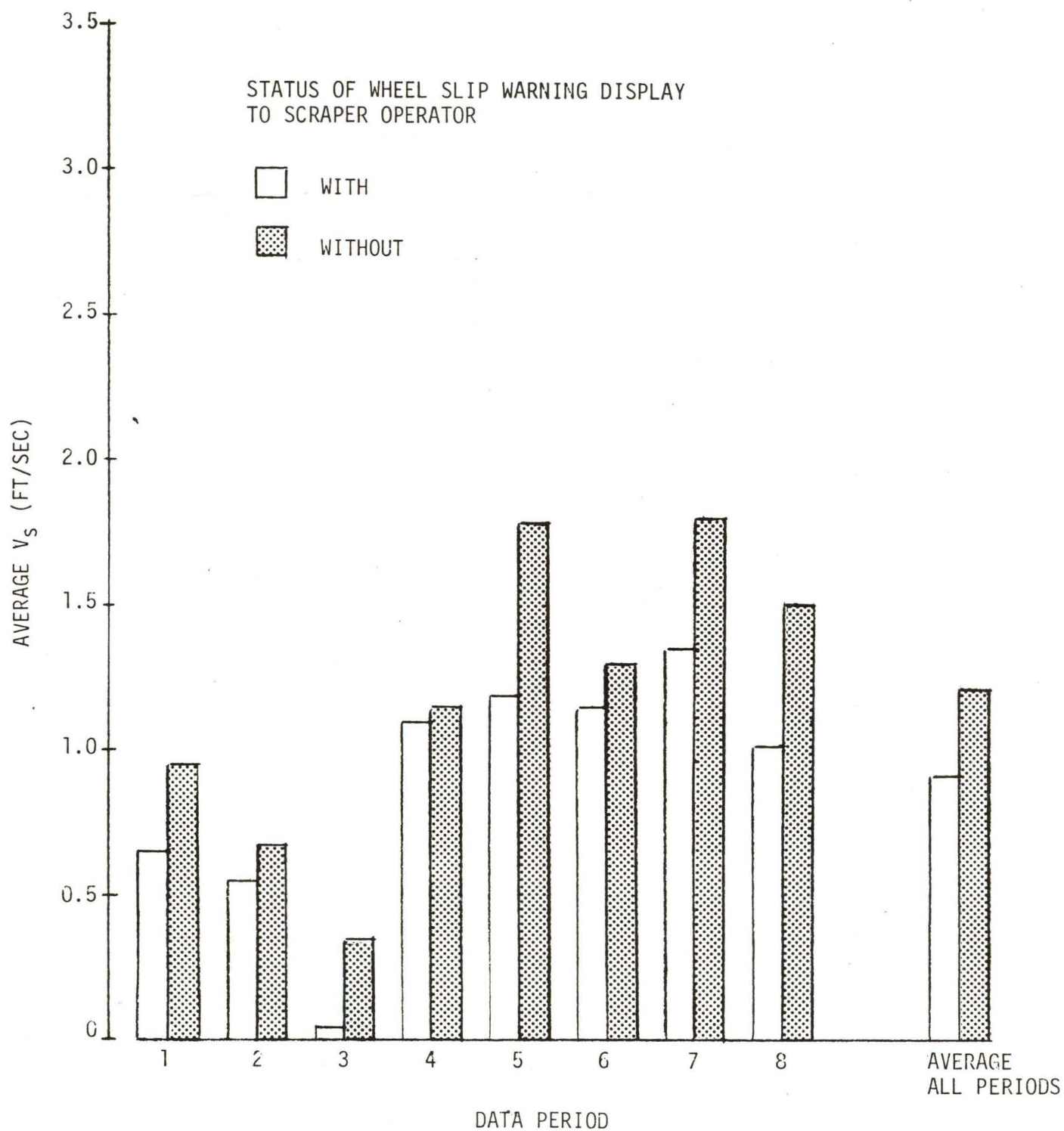


FIGURE 46. WORST WHEEL (OVERALL) AVERAGE V_s

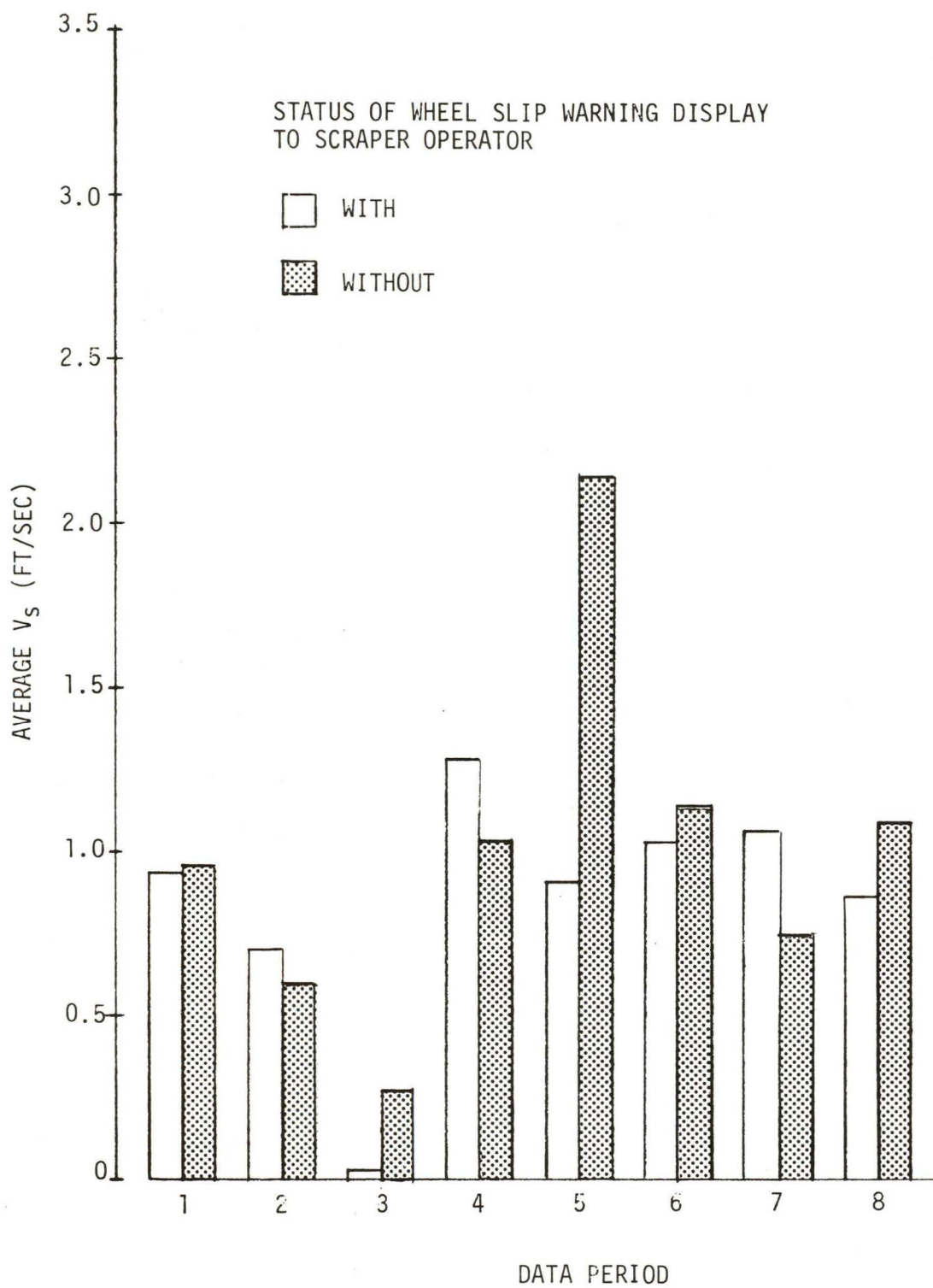


FIGURE 47. LEFT FRONT WHEEL AVERAGE V_s

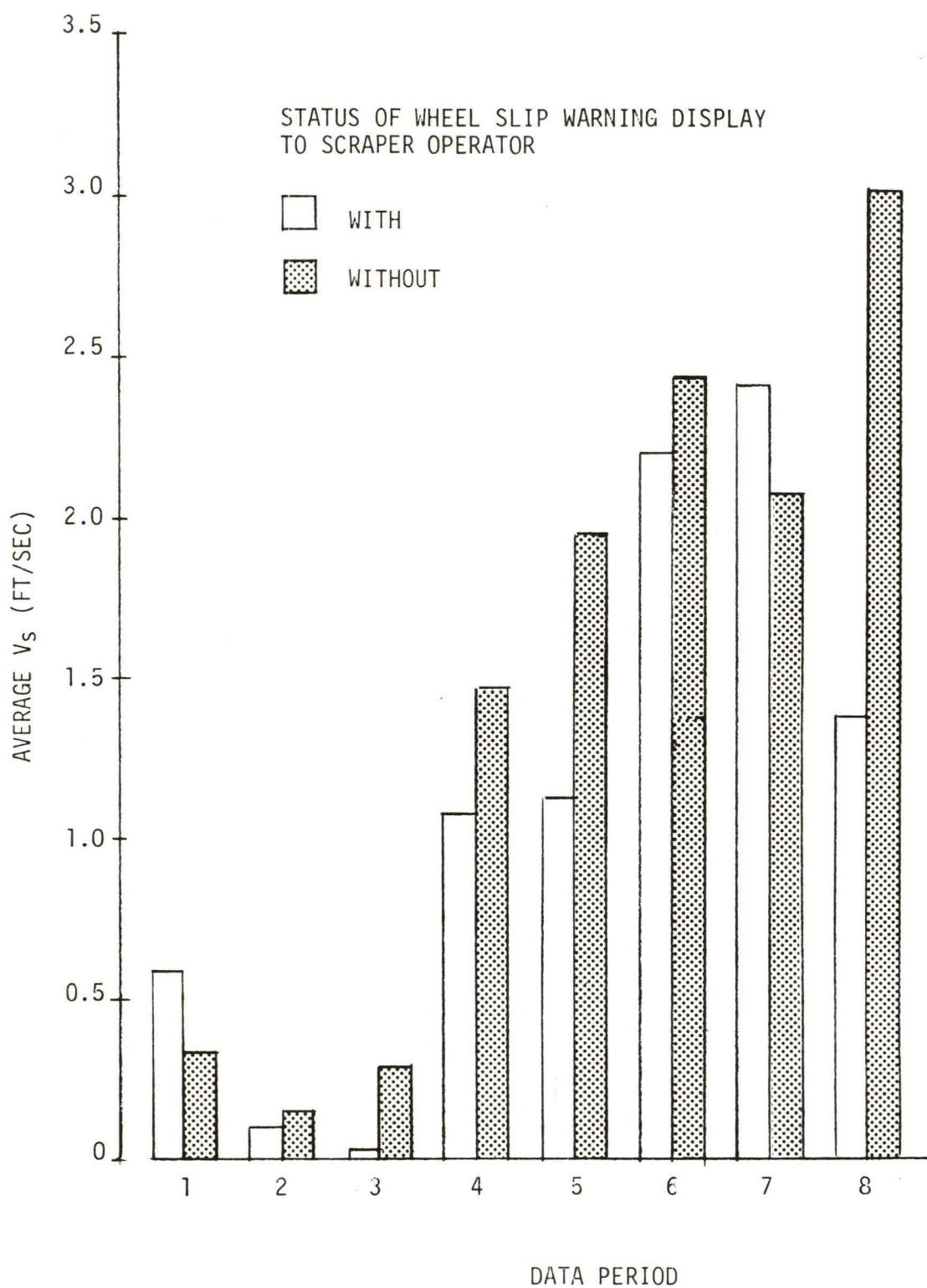


FIGURE 48. LEFT REAR WHEEL AVERAGE V_s

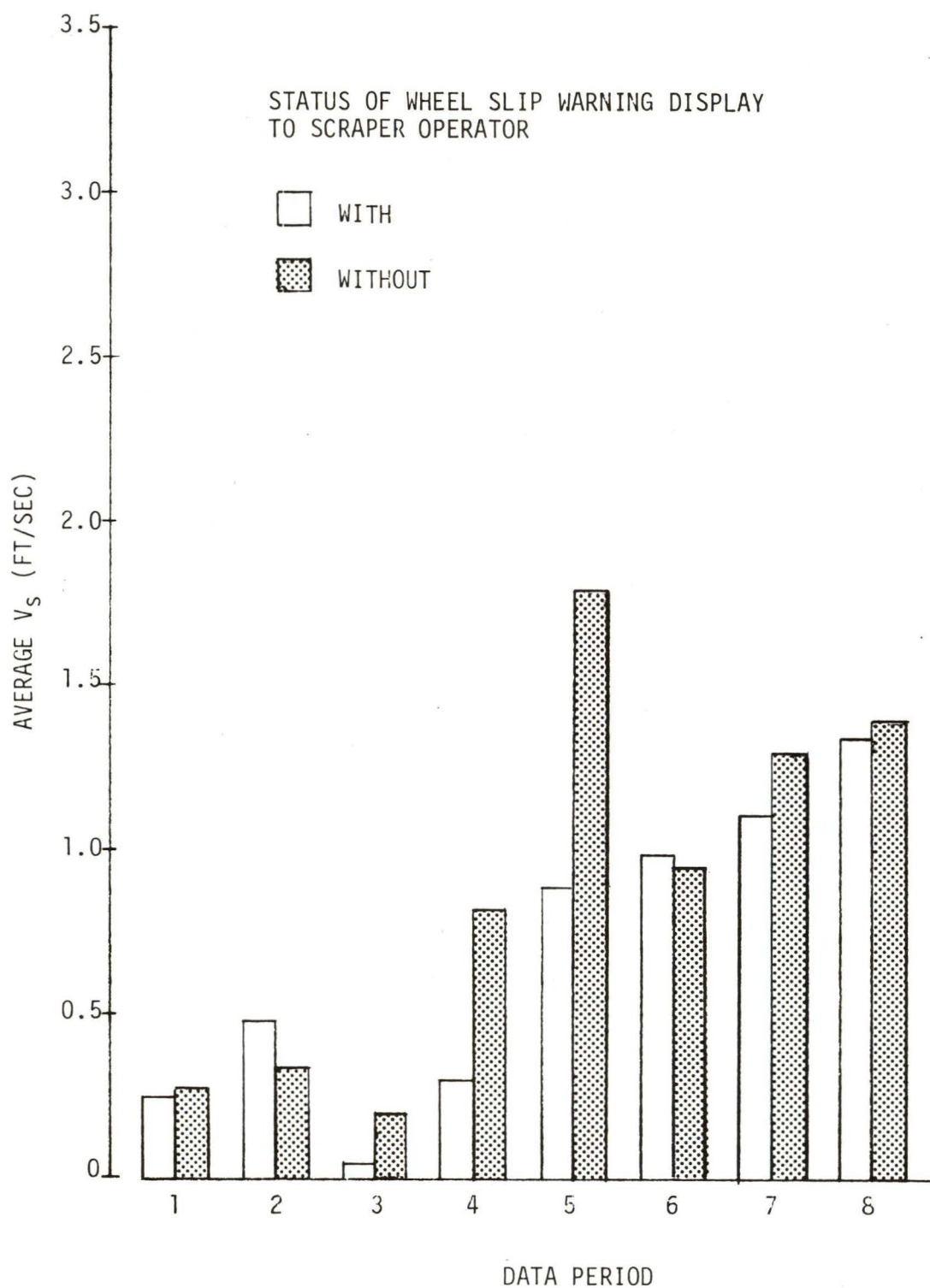


FIGURE 49. RIGHT FRONT WHEEL AVERAGE V_s

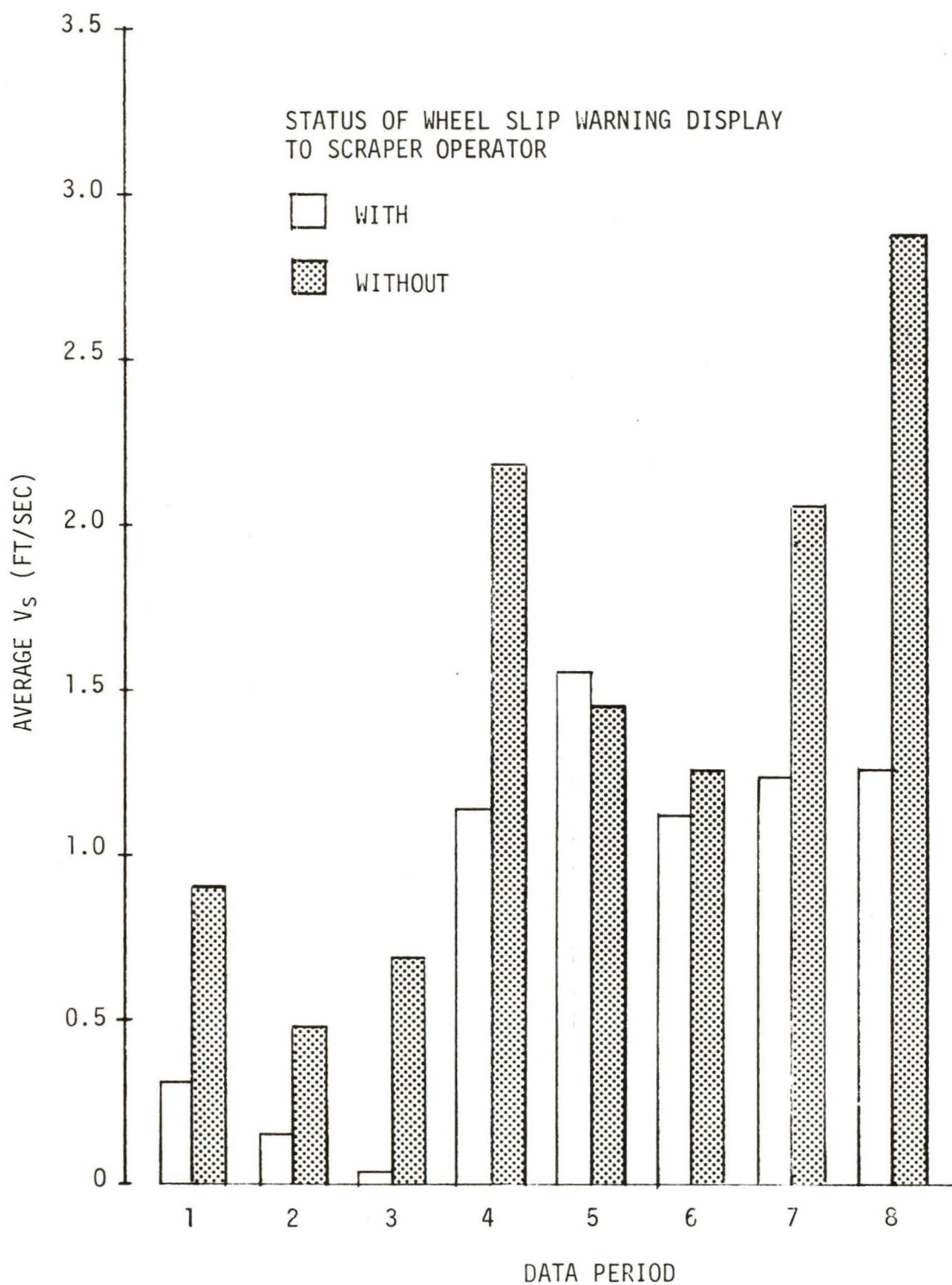


FIGURE 50. RIGHT REAR WHEEL AVERAGE V_s

V_s input. If, for example, a wheel is slipping at a rate of one ft/sec relative to the terrain, then the V_s signal voltage is one volt, and the counter will accumulate two counts each second. Because the counters have excess capacity, this 2:1 ratio was chosen in the interests of improved accuracy, but the ratio could just as well be 1:1 or some other convenient value. Since V_s , by definition, is quantified in **ft/sec**, and the counter records **counts/sec**, the contents of the counter directly indicate **how far** the tire has been scrubbed. The Accumulated Count divided by two (the V/F scaling factor) equals the **number of feet** the tire has been scrubbed: independent of **how fast** or **how long** a time period the counts were accumulated. The six digit counters used during these tests (Veeder-Root Type 7997) have a capacity of $10^6 - 1$ counts and are self-powered by an internal battery with a nominal life of 10,000 hours. Stored count is therefore retained until counter RESET is accomplished with a key. Even under our very slippery test conditions the maximum count accumulated by an individual wheel was about 15,000 counts/hour and the selected worst wheel less than half that. This indicates that with a 1:1 V_s ratio, some 80 hours of individual wheel operating time could be logged between counter resets and probably upwards of 200 hours on the worst wheel channel. The feasibility of recording long-term wheel slip scrubbing data for management purposes was demonstrated during these field tests.

2. User Comment and Observation

For the first few weeks after initial Wheel Slip Monitor installation on the test scrapers we encountered a considerable degree of operator suspicion and some hostility because they regarded it as a "tattletale" device whose purpose was open to question. This is a common, and usually unavoidable, occurrence in field testing and it required some time to gain their confidence and start acquiring reliable test data. Among other things, we found it necessary to limit operator access to certain controls while carefully monitoring equipment operational condition. This whole situation was particularly tedious during these tests because of inordinately foul weather; but it did in time improve, just as past experience promised it would. There is evidently no way to rapidly start up the field testing of novel devices on working equipment because of this human factor, and thus caution in time scheduling should always be exercised when planning such tests.

During the early part of the test period we had rather high winds with blowing snow, rain, dust and so on which caused erratic velocity sensor performance. These effects were minimized with the installation of the grilles and mud flaps described earlier, but while that was in progress we had the comment "how can you rely on this if it shows some slip while standing still?". This was a reasonable comment since the operators regarded the Wheel Slip Monitor as a piece of finished production equipment. This conception of how practical equipment is developed is much different from those of us who actually do it and this is a further human factor that should always be considered. Careful explanation helped, and after the scraper operators became accustomed to the extra "gadgets" in their work environment cooperation improved, along with their interest, and comparative test data began to be accumulated. After the operators became interested in what we, and they, were doing we received several very good suggestions.

"Paint the velocity sensors black so they won't reflect headlamp glare at night during push pull loading."

"The beeper is too loud."

"Turn the beeper off during high speed travel; it is worrisome." (The WSM can become erratic when bits of mud, etc., are thrown up by the wheels during road transport.)

"Move the warning lights to the rear so we can see them while loading."

We may sum up operator comment overall as skeptical, but bear in mind that they were not seeing the recorded data which did, in fact, reveal significant wheel slip reduction when they used the Wheel Slip Monitor warning information.

VII. CONCLUSIONS

We conclude, from consideration of the results reported here, that the Wheel Slip Monitor concept is sound and that it can be implemented in cost effective and practical fashion to provide relief from the increasingly high cost of tire wear and damage due to preventable pan scraper wheel slip. The first generation hardware described in this report has demonstrated that it can be economically prudent to use complex (though operator transparent) monitoring devices on the numerous smaller earthmoving machines such as pan scrapers. Today's electronic components make practical the use of powerful machine monitoring systems heretofore too costly. The situation changes almost day to day with breathtaking speed: heavy iron is ever more expensive; while instrumentation is plummeting in price, even as what can be done with it rapidly grows. The Wheel Slip Monitor and similar high technology devices **will** find a future place in industry on very **ordinary** machines, simply because they can make the owner and operator money. Just as with common nowadays dragline swing counters and boom load indicators, or suction dredge production monitors: their time has come.

VIII. RECOMMENDATIONS

These recommendations follow naturally from the results reported herein. Some of them answer to unanticipated needs discovered during field testing. The remainder suggest more effective or economical ways of accomplishing particular functions whose utility was recognized from the beginning.

First, as mentioned in the body of this report, a smaller and cheaper short-range single transducer ultrasonic wheel speed sensor would be very advantageous. Such a device, tailored to this application, should be developed. This appears entirely feasible.

Second, the control box can be simplified. Our field testing revealed that positioning this assembly within the scraper operator's forward field of view has no advantage. Two, rather than four, wheel slip warning lights are adequate: one light for the front set of wheels and one for the rear set, mounted together just behind the operator where he can simultaneously see both them and the filling bowl during loading, proved to be most effective. This means that the box can be mounted in any convenient location where its controls are within easy reach. Operator controls can thus be limited to SENSITIVITY combined with an ON/OFF power switch and SQUELCH. No major circuit changes are needed: reliability was entirely adequate during testing.

Third, the audible beeper readout should be made an optional feature.

Fourth, the buffered output port which permits recording of overall (worst wheel) scrubbing velocity V_s , for wheel slip history accumulation for the entire machine should be retained. The V_s information for individual tires is useful but can probably be dispensed with save for special applications. The recommended scheme requires only one event counter (rather than five) for data logging: a significant cost savings. This single counter could then be incorporated right into the control box if desired.

Last, the Bowl Loading Rate Monitor concept should be pursued and developed. Combining this function with Wheel Slip Monitor function promises hardware that does it all: warns the operator of wheel slip, simultaneously helps load the bowl with best machine efficiency, and finally signals the instant of completed loading just as soil ceases entering the bowl.

We believe these to be prudent recommendations. They should be implemented forthwith in second generation hardware.

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APPENDIX

Entry I. An Analysis of Thermodynamic Factors Germane to Soil/
Metal Friction

Entry II. Selected Daily Operation Logs

APPENDIX ENTRY 1

SOIL VELOCITY SENSOR

Friction between soil and metal friction plate (sensor) generates heat. Heat generated ($\dot{Q}_{\text{gen}}$) is a function of velocity; $\dot{Q}_{\text{gen}} = K_1 U^n$, where U is the soil velocity past the sensor. The value of n is probably around 2. K_1 is a constant.

The sensor loses heat to the surroundings. $\dot{Q}_{\text{lost}} = \kappa A (T - T_s)$. κ is "thermal loss coefficient", A is effective area of sensor, T is sensor temperature, T_s is temperature of surroundings. A heat balance gives:

$$\dot{Q}_{\text{gen}} - \dot{Q}_{\text{lost}} = mc \, dT/d\theta$$

where m is sensor mass, c is sensor specific heat, $dT/d\theta$ is temperature change of the sensor per unit time.

$$K_1 U^n - \kappa A (T - T_s) = mc \, dT/d\theta$$

$$dT/d\theta + \kappa A/mc \, T = \left(\frac{\kappa A T_s + K_1 U^n}{mc} \right) \quad (1)$$

$$\text{let } x = \frac{(\kappa A T_s + K_1 U^n)}{mc}$$

$$y = \frac{\kappa A}{mc}$$

Solving Eqn. (1) for T :

$$\begin{aligned} T e^{y\theta} &= \int x e^{y\theta} d\theta \\ &= x/y e^{y\theta} + C \\ T &= x/y + C e^{-y\theta} \end{aligned}$$

when $\Theta = 0$, $T = T_0$ (original temperature).

$$C = T_0 - x/y$$

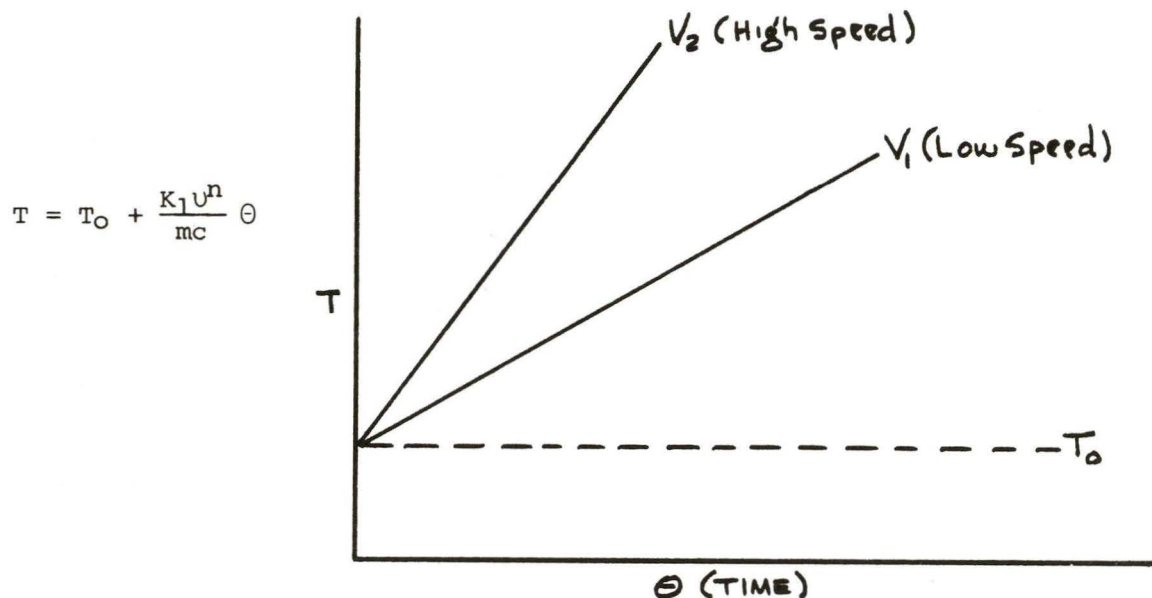
$$T = x/y + e^{-Y\Theta} (T_0 - x/y)$$

$$x/y = T_s + \frac{K_1 U^n}{KA} \quad \{\text{steady-state value}\}$$

$$e^{-Y\Theta} (T_0 - x/y) = e^{-\frac{KA}{mc} \Theta} \left[(T_0 - T_s) - \frac{K_1 U^n}{KA} \right] \{\text{transient value}\}$$

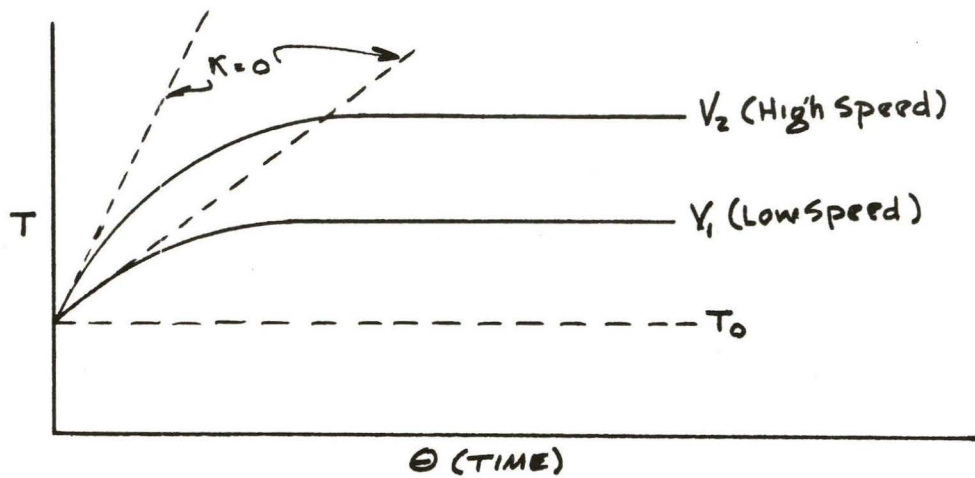
$$T = T_s + \frac{K_1 U^n}{KA} + \frac{1}{\frac{KA}{mc} \Theta} \left[T_0 - T_s - \frac{K_1 U^n}{KA} \right]$$

For the special case of $\kappa = 0$



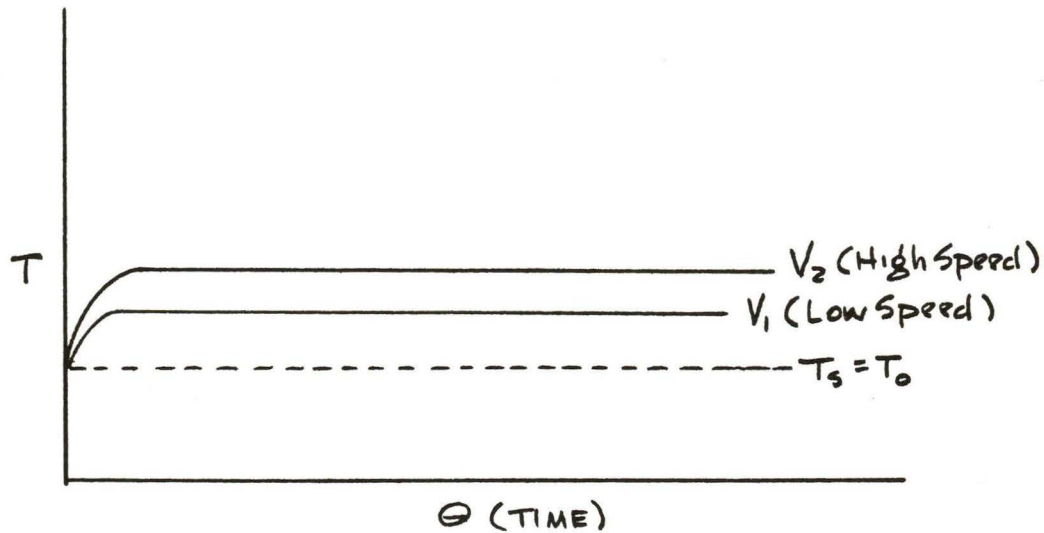
I. Take the case where the sensor is insulated from the surroundings (κ is small) and the sensor mass is large, also the specific heat is large. Then $\frac{KA}{mc}$ is small, and $\frac{K_1 U^n}{KA}$ is large. In this case, the transient is long and the

temperature rise is large. The value of T_s is relatively unimportant.



II. Take the case where the sensor is not insulated from the surroundings (κ is large) and mc is small. The $\kappa A/mc$ is large, and $\frac{\kappa_1 U^n}{\kappa A}$ is relatively small. In this case, the transient is short, and the temperature rise is smaller.

$$T \approx T_s + \frac{\kappa_1 U^n}{\kappa A}$$



III. What we want is a short transient and a large temperature rise. We need a big $\kappa A/mc$ and a big $\frac{K_1 U^n}{\kappa A}$. Since we have no control over $K_1 U^n$, we could make κA small and mc small also. Also note that if κA is small enough, the value (or constancy) of T_s is not important.

- Case I is not attractive because of the long transient.

- Case II is a possibility, if relatively small temperature rises can be detected. (We don't yet know what "relatively small" means -- it might be several tens of degrees even for very low velocities.) For this case, T_0 is close to T_s .

If T_s is the cutting blade of the scraper, it might rise at the same (or higher) rate as the sensor.

- Case III is preferred, but the minimum possible values of κA and mc aren't yet known.

Note that for the limiting case of $\kappa = 0$, you must measure $dT/d\theta$ to determine the soil speed. If κ can be made sufficiently small, this approach is also a good one.