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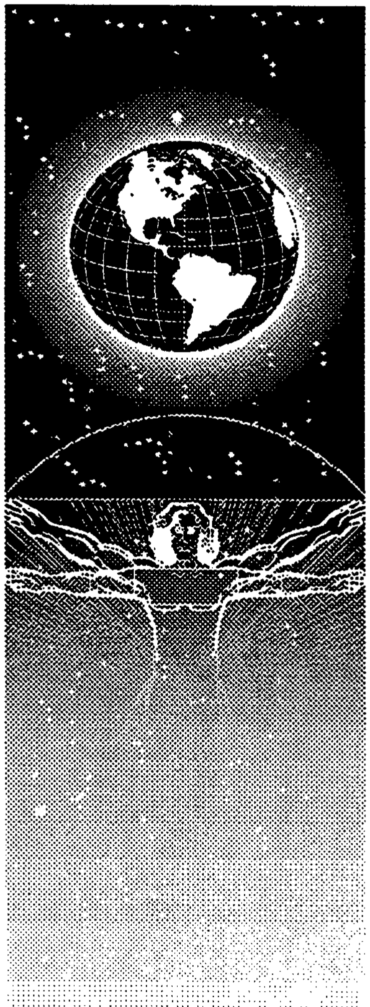

UNITED STATES AIR FORCE RESEARCH LABORATORY

Prevention Effectiveness Foreign Object Debris Study (PrE-FOD)

Tony Gossard
Steven Powers
Dolly Parker
Richard Weimer

WANG GOVERNMENT SERVICES
4027 Col. Glenn Highway
Suite 200
Dayton, Ohio 45431-1672

2Lt Steve Grace
Captain Keith Shaneman
Logistics Readiness Branch (HESR)

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Interim Report for the Period August 1997 to February 1998

Human Effectiveness Directorate
Deployment and Sustainment Division
Logistics Readiness Branch
2698 G Street
Wright-Patterson AFB OH 45433-7604

NOTICES

TECHNICAL REVIEW AND APPROVAL

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This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

ALBERT S. TORIGIAN, Lt Col, USAF
Deployment and Sustainment Division
Air Force Research Laboratory

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Wang Government Services
4027 Colonel Glenn Highway
Suite 200
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13. ABSTRACT *(Maximum 200 words)*

This project investigated the effectiveness of several types of support equipment commonly used to prevent Foreign Object Debris (FOD) from damaging aircraft engines and structures. All of the equipment investigated was designed to collect FOD from the flightline surface, thereby reducing damage risk. The study examined motorized flightline sweepers, towable FOD sweepers (FOD-busters), and magnetic bars. A series of site visits was conducted to operational units in order to get user feedback on the effectiveness of the various pieces of equipment. Additionally, a limited controlled experiment was conducted at Wright-Patterson AFB to quantitatively evaluate each of the equipment types. The user comments and the quantitative evaluation both identified serious shortfalls in the Air Force's current FOD prevention equipment, both in terms of effectiveness and reliability. Several possible actions to address these shortfalls are listed in the report.

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1. ABSTRACT

This study examines the problems associated with the presence of Foreign Object Debris (FOD) on flightline surfaces. Its specific focus is on the equipment used by the Air Force to collect FOD before it causes damage. This project was initiated to determine what the Research and Development (R&D) community might be able to do to enhance the removal of FOD. It documents comments made during interviews conducted at 10 military installations where 449 interview comments were collected from key personnel responsible for local FOD programs. The study also documents a limited experiment conducted at Wright-Patterson AFB in which the most commonly used FOD removal equipment was examined. Observations made during the experiment point out areas in need of further testing, and ways to make personnel using this equipment more aware of the equipment's capability and limitations. The report also lists several opportunities for improvement where new technologies and/or process improvements may reduce FOD problems and improve equipment performance.

2. BACKGROUND

The existence of FOD is a potentially dangerous condition that creates a major hazard to the operation of all aircraft. The presence of Foreign Objects (FO) on the flightline and the damage they cause have plagued aircraft operations for many years. In 1996, over $14 Million in Air Force engine repair and replacement costs could be attributed to FOD. In addition to the monetary costs of FOD incidents, they can also cause system failures that result in loss of life, such as the crash of a FOD-damaged F-16 into Pensacola, Florida in 1996 which caused the death of a young civilian.

The sources of FOD are many and varied, and have remained the same from year to year. Consequently, Air Force and DoD procedures and equipment for controlling FOD have not changed significantly over the past 15 years. FOD walks are still the primary means of FOD removal. FOD Busters, street sweepers, and Magnetic Bars mounted on flightline vehicles are still being used to pick up FOD. Strict tool control procedures and FOD awareness programs are implemented at most bases, fastener control procedures are used, and FOD containers are placed near every aircraft.

There are two obvious ways to improve FOD collection equipment effectiveness. One is to procure newer, more effective equipment, and the other is to determine better ways to use current equipment. The average age of current flightline sweepers is 6 to 12 years - well beyond their recommended life span. Additionally, these sweepers were originally purchased as multi-function (flightline and street) sweepers, but were only initially tested on streets. A strong case can be made for obtaining new sweepers, but it seems unlikely that the required funds will become available. Some organizations are evaluating different attachments to a sweeper that increase the effectiveness; however, the results of these tests are not yet available. An overhaul program exists to refit and readjust the sweepers, but since their performance before and after overhaul is not carefully documented, it is not apparent that the refit process adds any value to the equipment.

The potential seems to exist, then, to improve current FOD prevention equipment. The improvements range from ideas that could be easily implemented with little to no cost, like better calibration and operation closer to optimum speeds, to those that would require redesign and testing, like an electromagnet bar or improved FOD buster gear ratio.

It is clear that before we can recommend improvements, we need to determine the effectiveness and shortfalls of current FOD collection equipment. The research charter of the Air Force Research Lab enables an objective and independent approach to measuring these qualities. Therefore, a major part of this effort dealt with developing a formal testing method with associated test procedures that any organization could use to evaluate the effectiveness of their FOD collection equipment. Note: A pilot test of the procedures used and results obtained are included herein.

The end goal of this program was to better understand the FOD problem and develop procedures for evaluating the effectiveness of the current FOD equipment. This work would then become a foundation for efforts designed to improve the effectiveness of current equipment and thereby reduce FOD damage costs and safety risks.

3. OBJECTIVES

The purpose of this program is to examine the effectiveness of FOD prevention processes and collection methods with regard to FOD produced from the natural breakdown of the flightline surface and aircraft maintenance byproducts. Effective FOD prevention results from a combination of awareness and effective equipment. Because the awareness of FOD prevention is a difficult topic to analyze scientifically, and since the Air Force already seems to have adequate high-level visibility on this subject, the project's research efforts were focused on determining and improving the effectiveness of the equipment. The specific objectives follow:

- Gather information on the nature and extent of the FOD problem by surveying the literature, reviewing available statistical data, interviewing FOD personnel at operational units, and documenting observations of FOD collection procedures at operational units.

- Develop controlled procedures for evaluating the effectiveness of the FOD collection equipment.

- Conduct a "trial" FOD collection equipment effectiveness test, and analyze and present the data.

- Determine the effectiveness of FOD processes and management practices.

- Identify opportunities for research to develop improved FOD prevention methods.

4. FOD PROBLEM ANALYSIS

4.1 Method

Requirements identification and systems engineering techniques were used to identify and analyze the FOD problem. The requirements identification techniques focused on extracting relevant information from available literature and documenting interview comments from FOD subject matter experts at operational units. Systems engineering techniques were used to develop a FOD collection equipment test plan and procedures, and to analyze collected data. Problems discussed in this section were derived from both the equipment tests and the interview comments made during visits to various DoD facilities.

4.1.1 Literature Review

The first step in the analysis process was to identify and obtain copies of documents and reports that provided insight into foreign object damage and methods for its control. The sources used to obtain this information included the Internet, DTIC, DoD military organizations, and commercial FOD collection equipment manufacturers. The types of information targeted for collection included newsletters, articles, policies, operational instructions (OIs), specifications, test plans, etc. Once the information was obtained, it was analyzed for applicability to the effort.

4.1.2 Statistical Review

For the study, data on DoD FOD incidents was obtained from the Air Force Safety Center and the Naval Safety Center. This data, while useful in providing a background on the types of FOD incidents, did not lend itself to extensive statistical analysis. There were three reasons for this: 1) Some of the information held by these organizations is classified and cannot be released, which led to an incomplete data set for analysis. 2) Different military units collect, track and report different types of information. What is considered a FOD incident in the Air Force's Air Combat Command is not necessarily the same thing as a FOD incident in the Navy, or even in other Air Force Major Commands. 3) While all FOD incidents are investigated, the root cause of the incident is never determined in many cases (almost 50%).

Since a statistical analysis was not practical, a systematic analysis of the data collected during the experiment and of the interview comments was conducted. Each set of data (experiment data and interview comments) was reviewed individually to identify key concerns, and then compared with other sets to identify common patterns. This analysis resulted in the identification of problems and potential improvements presented below.

4.1.3 Operational Unit Data Collection

Interviews were conducted with individuals or in small groups, as dictated by convenience to the participants. The interviews were not highly structured, but the following questions were asked of all participants.

1. What kind of FOD Prevention Program do you maintain?
2. Do you conduct regular FOD prevention meetings?
3. Do you document and publish meeting results?
4. Do you have a regular FOD sweeping schedule?
5. Do you have priority areas for sweeping?
6. Who does the FOD sweeping?
7. Who maintains the FOD sweeping equipment?
   - Who insures that the sweeper is properly cleaned prior to use?
   - Who insures that proper sweeping settings are maintained?
8. Are your sweeper drivers trained in proper sweeping procedures?
   - Do you have primary drivers?
   - Do you train alternate drivers?
9. Do you have written procedures for the sweeping operation?
10. Do you use check lists for the sweeper operator to perform by?
11. Do you have an established sweeping pattern i.e. areas laid out in grids, etc.?
12. Do you QA the sweeping operation after sweeping has been accomplished?

Information documented during the interview included the interviewee's name, organization, job responsibility, and answers to questions in the form of interview comments. The people interviewed included the FOD NCO, Air Field Manager, Civil Engineering personnel, and Safety Office personnel. The selection of interviewees was straightforward since one individual was assigned to each of these duties.

Table 1 identifies the military bases visited, the component responsible for the base, and the number of interview comments documented at each base. Note: No Headquarters organizations were visited.

Table 1. Bases visited for FOD data collection

LOCATION	COMPONENT	# COMMENTS
Dover AFB	AF	31
Cape May CGB	Coast Guard	9
Mc Guire AFB	AF	45
Shaw AFB	AF	38
Springfield OANGB	ANG	47
Hurlburt Field	AF	23
Eglin AFB	AF	39
Beaufort MCAS	Marine Corps	57
Travis AFB	AF	57
Edwards AFB	AF	98

4.2 Findings

4.2.1 Literature Review

Very little government literature was found dealing with FOD. Most of the resources discovered came from commercial sources: either FOD prevention equipment manufacturers or the aerospace industry. The primary Air Force FOD regulation, a section of AFI 21-101, sets general policies and stresses awareness, but leaves details up to the MAJCOMs and bases. Almost no mention is made of prevention equipment. FOD policies and procedures found at the base level dealt primarily with FOD awareness issues (Golden Bolt, incentive programs, etc...). Internet searches identified a National Aerospace FOD Prevention, Inc. (NAFPI) Newsletter. NAFPI is a consortium of aerospace professionals, primarily from commercial sources such as Lockheed and Boeing, who promote FOD awareness and preventive measures. NAFPI has a conference every year to increase industry awareness of FOD, and to facilitate the exchange of information to help combat FOD in the aerospace industry. NAFPI also provides a directory of people dedicated to sharing information and ideas about preventing FOD. Most of the NAFPI participants are from industry, but the organization has recently designated a DoD coordinator to encourage increased government involvement.

4.2.2 Statistical Review

The breakdown of incident root causes for the Air Force from 1991 to 1996 is shown in Table 1 below.

Table 2. Total Cost per Type of Incident

TYPE	# OF INCIDENTS	COST
Unknown	292	$24,479,712
Birdstrikes	63	$ 7,500,159
Maintenance Error	83	$ 7,335,262
Sweeper Preventable	73	$ 4,546,629
Faulty Parts/Design	48	$ 4,518,473
Weather	53	$ 1,982,874
Other	28	$ 5,767,961
TOTAL	640	$56,131,070

As discussed earlier, the high number of incidents with unknown causes makes analysis of the data difficult. The only clear result that can be drawn is that a significant number of FOD incidents occurred that should have been prevented by flightline sweeping.

4.2.3 Operational Unit Data Collection

Interview comments were grouped into categories as depicted in Figure 1. The criteria selected for the groupings relate to the areas of interest to the Air Force.

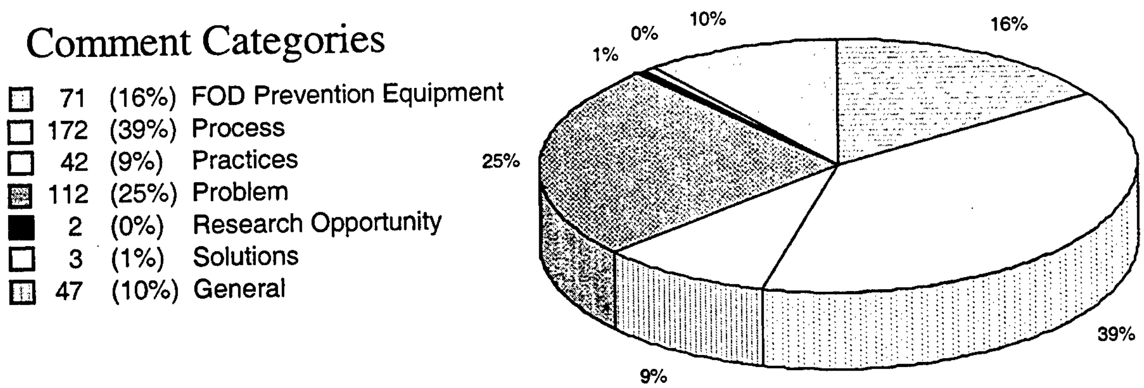

Figure 1. Categorized Interview Comments

A primary concern of the study was the effectiveness of the current FOD removal equipment. To better understand the effectiveness of the equipment, interview comments identifying problems were classified by the type of equipment. The results are presented in Table 3.

Table 3. Breakdown of the "Equipment" Category by Comment Type

Type of Equipment	# of Observations	# of Problem Observations	% Problems
Sweeper	45	19	42%
Magnetic Bar	14	5	36%
FOD Buster	12	9	75%
TOTAL	71	33	51%

There were a high number of interview comments reflecting concern for the effectiveness of the FOD removal equipment. This correlated well with the results of the FOD Experiment (see results below), where performance of the tested equipment was observed to be generally inadequate.

Table 4 reflects the most common problems obtained from the analysis in regards to the overall performance of the FOD removal equipment. The problem is marked with an asterisk (*) if it was validated during the experiment.

Table 4. Listing of Equipment Problem Comments by Type

Equipment	Problems
SWEEPER	Funding is an issue for maintenance repairs.
	Sweepers are multipurpose - used on streets as well as the flight line.
	Sweepers designated for the flight line have better results.
	Drivers are not properly trained on the equipment.
	Drivers do not give 100 % detail.
	*Drivers drive too fast - slower speeds more effective.
	Different organizations are involved.
	Sweepers are not always available when needed.

FOD BUSTER	Funding is an issue - expensive to repair. Brushes and gears wear down. *Slower speeds are not effective.
MAGNETIC BAR	*Not effective because more non-ferrous metallic parts are now being used. *Height of bar determines the effectiveness of FOD collection. Height of bar can create more FOD-uneven surface scrapes FOD off of bar.

The following is a summarization of the remaining observations that are not directly associated to the equipment but are categorized into key areas that require improvement.

- CONTRACTORS - FOD prevention can not be enforced on contractors unless it is stated in each contractor's Statement of Work (SOW).

- FOD SHAKERS - Located at entrances to flightline, but are not used at every base. FOD shakers are known to cause tire damage and have been proven to be ineffective in FOD removal.

- FOD WALKS - Seemed to be the most effective FOD prevention procedure in place. All bases visited performed FOD walks. The only potential downside to FOD walks, other than the amount of labor required to perform them, is if some of the walkers are not fully trained in what to look for. FOD Walks are accomplished at different times: hourly, daily, weekly, bi-annually and as needed. The "Golden Bolt" program, where an incentive is offered for finding a pre-specified object, was not implemented at every site and was found to be somewhat ineffective at some locations.

- FUNDING - "Lack of" was frequently stated. Funding cuts create shortages in manpower which hamper the enforcement of FOD programs. Lack of funding prohibits repairs to equipment and ramps. Statements such as "You have to make do with what you have" were commonly heard.

- PRIORITY - Base beautification is sometimes given a higher priority than flight line repairs. Difficulty maintaining attendance at FOD meetings was a commonly heard statement.

- RAMP - Aging ramps are a major issue. Many ramps are old and are breaking up. Repairs take time, and funding is limited. Proper repair material is not easily available. Continuous breakage requires ongoing inspections. The majority of problem observations not associated to the equipment were directed to the conditions of the ramps.

- REPORTING - Lack of reporting when Fastener, Rag or Tool Control and Blade Bending were referenced. Reporting and tracking procedures are hard to enforce. Since incidents are not tracked accurately, it is difficult to establish patterns or identify trends.

- TOOL / FASTENER CONTROL- Air Force Regulations require flight line technicians working in and around aircraft to maintain absolute control of their tools, expendable parts, and equipment. Consolidated Tool Kits (CTK's) were designed to insure that tools and equipment would not be inadvertently left in areas in and around aircraft where FOD could result. How far tool control programs should go in monitoring tool and part usage is a matter of great debate. At what point do the regulations begin to interfere with unit capability? Debates heard from users included the control of rags and the control of the number of rivets and screws to be used in aircraft repair. An example of the latter was a situation where the removal of a panel included the removal of 146 screws, many of which had to be drilled out. If tool control issued 20 screws to replace those that were drilled out, they expected 20 drilled out screws in return to insure nothing was left in or around the aircraft as FO. Drilled out screws in many cases end up as slivers of metal. Does a handful of these slivers equal 20 screws? Again, how far should the program go?

  For those sites that have a strictly enforced fastener control program, it seemed to work very well for them. They felt that their diligence in this area contributed immensely to their FOD reduction efforts. The team attempted to verify these sentiments through the incident tracking database, but the amount of information was insufficient to draw any firm conclusions.

5. TEST PROCEDURES DEVELOPMENT

5.1 Test Objective

Realizing that the funding and time limitations of the study did not permit a comprehensive evaluation of FOD prevention equipment, one of the goals of the study was to produce procedures and a test plan which other organizations could use to characterize their equipment or to compare the effectiveness of different types of FOD prevention equipment. These test procedures were intended to provide the basis for a quick, simple experiment that could be performed with minimal training and material expense, in order to encourage operational units to perform it. The primary goal of the test procedures is to quantify current equipment performance, with a secondary objective of identifying an optimum speed for equipment operation.

5.2 Possible Experimental Variables

Logistics experts and scientific evaluation experts were consulted to generate a list of possible factors which could influence equipment effectiveness. The following factors were identified:

- Equipment Type (Sweeper, FOD Buster, Magnet, etc...)
- Equipment Configuration
- Equipment Age

- Equipment Maintenance Condition
- Operating Speed
- Operator Skill Level
- Operator Motivation
- Type of FOD being collected (gravel, concrete, work waste, etc…)
- FOD size
- FOD shape
- FOD weight
- Ramp Surface Condition (smooth, pitted, cracked, etc…)
- Ramp Slope (flat, shallow, steep)
- Weather Condition

5.3 Selected Variables

Any of these variables could influence the effectiveness of FOD prevention equipment. However, in the interest of keeping the plan simple, only a few key variables were chosen for inclusion in the test plan. These variables represent most of the important factors in determining equipment effectiveness, and are all extremely easy to measure. These should yield the maximum possible information with the least test effort, however organizations performing the test can always add or substitute other variables to meet specific requirements or objectives. The following independent variables were identified as candidates for collection:

- Equipment Type (Sweeper, FOD Buster, Magnet, etc.…)
- Operating Speed
- Type of FOD being collected (gravel, concrete, work waste, etc.…)
- Equipment Age

The recommended measure of equipment effectiveness (the dependent variable) was defined as the percentage of FOD picked up by the equipment in a single pass at constant speed out of the total amount placed in the experimental area.

5.4 Alternative Measurement Techniques Considered

Since simplicity is a primary goal of the test plan, measurement techniques used must be easy to understand and simple to perform with limited resources. The primary measurements required to conduct the test are the speed of the collection equipment and the amount of FOD collected. Equipment speed is most easily measured by using a set test area of known length and a stopwatch. The speed of the vehicle during the experimental pass can then be arithmetically determined. Two alternatives were considered for measuring the collected FOD. They were to either weigh the FOD or count it. To maintain maximum efficiency, a combination of the two was recommended, where gravel FOD would be weighed, while pieces of work waste were individually counted.

5.5 Generic Test Description

The purpose of the test is simply to determine how much FOD is collected by a piece of equipment in a single pass at a specified speed. A small but measured quantity of FOD is spread in the path of the collection vehicle, the vehicle is emptied of previously collected FOD, and the operator is informed of the desired speed for that pass. The operator then drives over the FOD, stops the vehicle outside the test area and empties the collected FOD from the vehicle. The emptied FOD is then measured and compared with the original amount to determine the percent collected. The test can then be repeated at as many speeds as are necessary to characterize the collection equipment. A detailed test plan description is included in the appendix to this report.

6. PRELIMINARY FOD TEST

A preliminary FOD equipment test was conducted at Wright-Patterson AFB in November, 1997. This test served two important purposes: it provided a validation of the experimental test plan described in the previous section, and it provided preliminary results on the effectiveness of the three major pieces of FOD prevention equipment.

6.1 Test Summary

The experiment was limited to a quick "operational test" of easily available equipment. The experimental plan outlined above was followed. Only a few repeat measurements were made to measure repeatability, and equipment was not closely measured to evaluate all the possible influences on performance. Equipment was set up as closely as possible to its standard operational parameters, and measured accordingly.

6.2 FOD COLLECTION EQUIPMENT TESTED

6.2.1 Street Sweeper

Table 5. Sweeper Test Details

Mfgr Info	TYMCO, Model No. 600
Drivers	Civilian employees from the Motor Pool
Test Area	30 ft Long x 30 inches wide
Ramp conditions	Testing was done on dry surface
Sweeper width	7 feet 11 inches wide
Testing Speeds	1.5 mph - 15 mph
No. of Passes	17 (2-3 in each speed range)
Adjustments	Due to change in sweepers because Sweeper #1 developed an oil leak, the "leaf door" was closed on the last 5 sweeper runs on Sweeper #2. It was never noticed if Sweeper #1 leaf door was opened or closed on prior runs.
Gravel Weight	10 lbs. (20 lbs tested caused damming)
Work Waste Used	30-35 pieces

The current equipment used at most Bases to clean the aircraft parking ramp, taxiway and runway areas is the centrally procured street sweeper, shown below in Figure 2. (NOTE: The centrally procured sweepers were originally purchased as multi-function devices (for both street and flightline sweeping), but initial qualification tests were based only on street sweeping performance) This sweeper uses air instead of conventional rotary brushes, brooms, conveyors, and the various mechanisms required to house or drive them. The sweeper "regenerative air" system is simply a closed-loop in which a single blower, driven by a separate 80 hp engine, draws air through a dust separator and causes a vacuum throughout the hopper, suction hose, and suction inlet. A high velocity stream of air blasts forward and downward through a slot that runs the full length of the pick-up head. This air strikes the ground and picks up any debris in its path. The debris-laden air then moves right in a spiraling motion toward the suction inlet. This powerful stream of air is contained beneath the pick-up head by skid plates at each end and flexible rubber curtains front and rear. As the air stream approaches the suction inlet, vacuum from the hopper combines with the high velocity air stream to lift debris through the suction hose and into the hopper. The air loses velocity as it enters the large hopper, and large debris falls to the hopper floor, leaving only fine dust in the air. The relatively clean air is drawn upward, through a screen (eliminating paper, leaves, etc.) in the top of the hopper and into the dust separator inlet. As the air spins in the separator, centrifugal force throws the fine dust still in the air stream to the walls of the separator, from where it is skimmed off and returned to the hopper. The cleaned air continues to the blower and begins another cycle. This sweeper is not merely a vacuum cleaner. As mentioned before, cleaning is actually done by a blast of high-velocity air along the full width of the pick-up head. A blower furnishes both pressure and suction. Air pressure from the blower, in the form of a full width blast, passes over the surface being swept within the width of the pick-up head. This blast raises debris, and the suction pulls it into the hopper. The debris remains in the hopper, and the air continues on into the blower to be compressed once again for blasting.

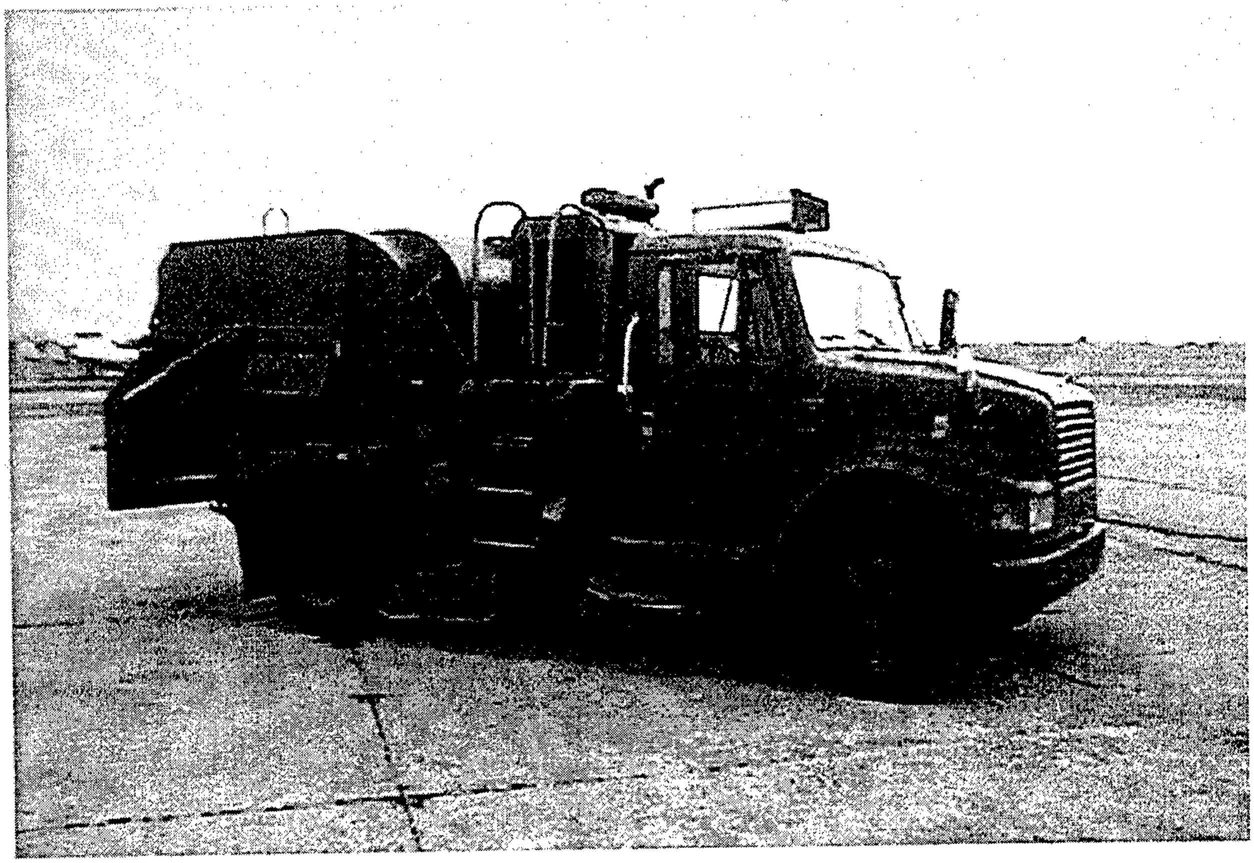

Figure 2. Current Air Force Sweeper

6.2.2 FOD Buster

Table 6. FOD Buster Test Details

Mfgr Info	N/A. Supplied by Springfield Ohio Air National Guard Base
Location	FOD Buster was pulled behind a US Government Expediter Vehicle
Test Area	60 ft Long x 30 inches wide
Ramp conditions	Testing was done on both dry and wet surfaces
Sweeper width	48 inches wide - Pickup area was 36 inches wide
Testing Speeds	1.5 mph - 15 mph
No. of Passes	27
	13 inches = 2
	14 inches = 23
	15 inches = 2
Adjustments	Collector heights from 2 1/2 inches to 1 1/2 inches
	Brush height from 13 to 15
	13 = light pressure
	14 = medium pressure
	15 = heavy pressure

Gravel weight	Tested 20 lbs which the FOD buster could not handle. 10 lbs of gravel was used.
Work Waste	30-35 pieces.

FOD Busters, like the one shown in Figure 3 below, are a relatively lightweight and inexpensive system made up of a rotating brush approximately four foot across that brushes Foreign Object Debris (FOD) into removable containers mounted on a wheeled frame. This equipment can be towed behind any vehicle with a conventional tow hitch. The holding containers have a piece of rubber attached that acts as a ramp allowing the swept FOD to flow into the containers.

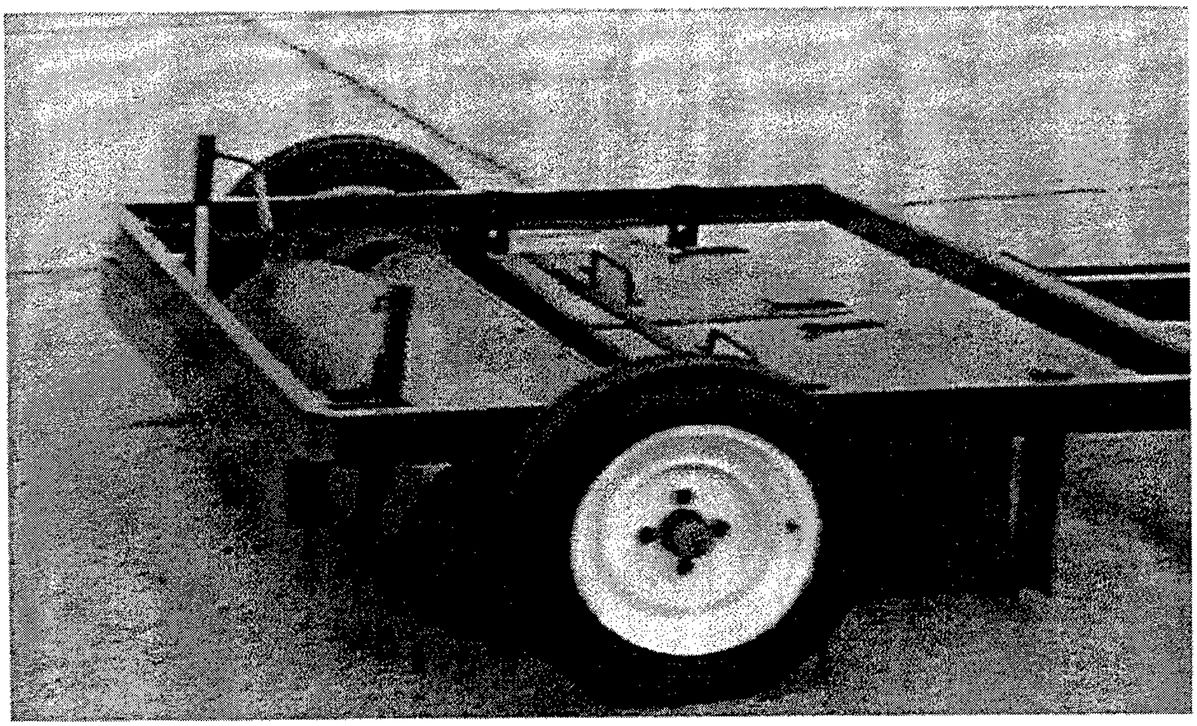

Figure 3. FOD Buster

6.2.3 Magnetic Bar

Table 7. Magnetic Bar Test Details

Location of the bar	Magnetic Bar was hooked onto the front of the US Government Expediter Vehicle
Test Area	60 ft Long x 30 inches wide
Ramp conditions	Dry and wet surfaces
Magnetic Bar Sweep area	6 ft wide
Testing Speeds	1.5 mph - 15 mph
No. of Passes	23
	1 1/2 inches - 13

	1 3/4 inches - 3
	2 1/8 inches - 2
	3 inches - 5
Adjustments	1 1/2, 1 3/4, 2 1/8, and 3 inches
Gravel weight	None
Work Waste	25-35 pieces

Figure 4 shows a magnetic bar attached to the front bumper of a flightline vehicle. The magnetic Bar is a large, pre-magnetized piece of steel, hung from flight line vehicles to pick up metallic FOD. This steel bar is normally covered with approximately 1/4 inch of rubber to make removal of metal objects easier.

Figure 4. Magnetic Bar

6.3 Test Conditions and Facilities

The experiment was conducted using an available ramp area in Area B located at Wright Patterson AFB. The experiment area was configured as shown in Figure 5. The experiment area was laid out on an existing concrete aircraft ramp which has not been in use for some time.

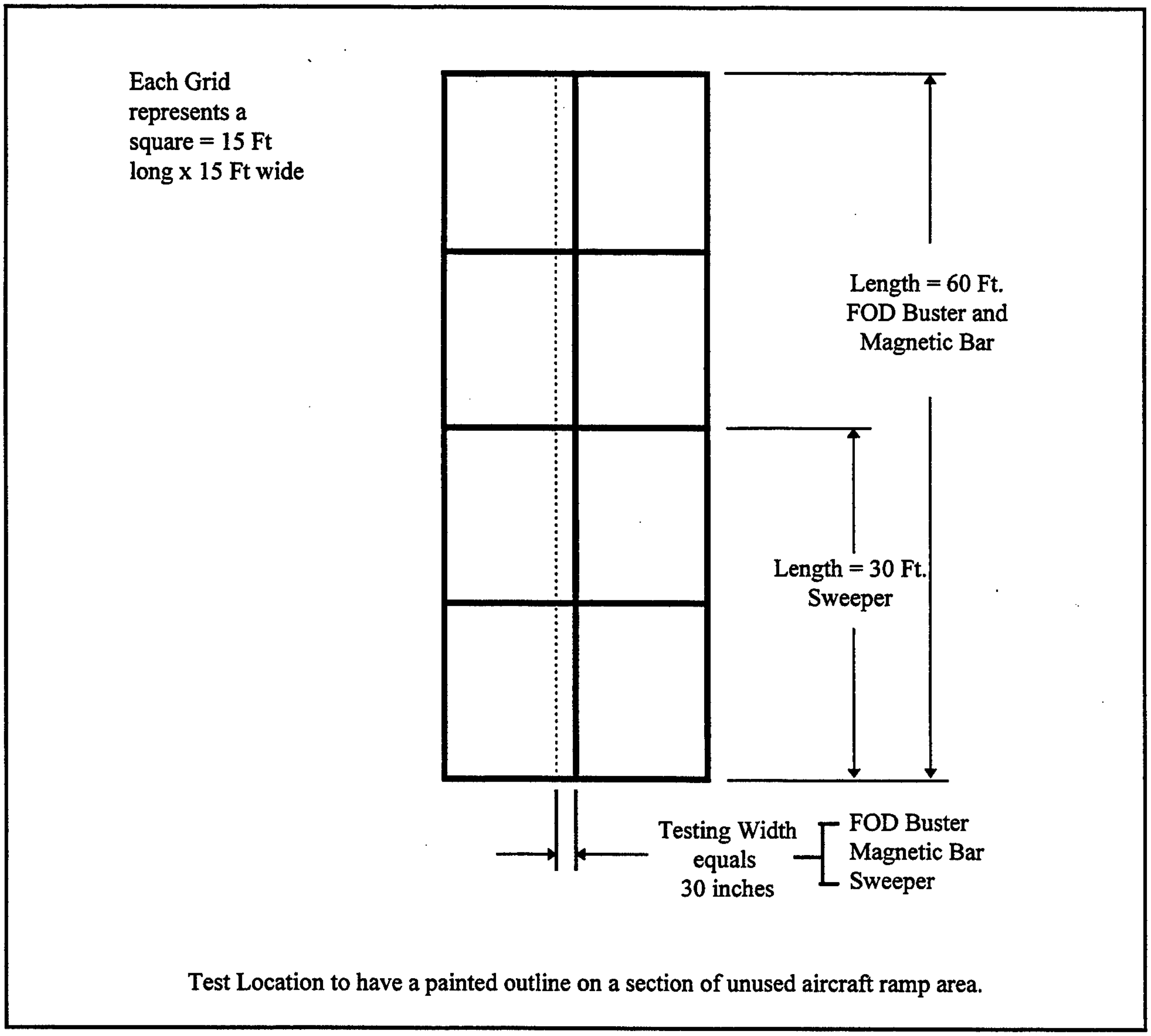

Figure 5. Experiment Layout Area

The overall time to conduct this experiment was derived from the amount of time to set up each pass through the experiment area, have the FOD collection equipment make the pass at the designated speed and then evaluate the experiment area for residual FOD from the sample. Each experimental pass took approximately one half hour. One full week was planned for the conduct of the experiment. One day was used for set up and pre-testing. Four (4) full days were set aside for data collection. The sweeper required the most pre-test adjustment and after test cleanup time. The FOD Buster and Magnetic Bar required minimum setup and cleanup time.

Various types of material were placed in a measured area and each FOD collection equipment's pick-up performance was measured. Five ranges of speed were tested:

- 2-5 mph
- 6-8 mph
- 9-11 mph
- 12-14 mph
- 15-16 mph

The speeds were closely monitored using a stop watch and calculated based on the known length of the test area.

Each individual experimental condition was repeated at least two times at a specific speed to validate the repeatability of the results.

Ten pounds of gravel and various pieces of painted work waste were spread in the cleaned experiment area prior to the FOD Collection Equipment making a pass. Note: Work Waste totaling between 25-45 pieces, consisting of safety wire, large and small bolts, nuts, and washers, machine screws, and small rivets was used. The FOD was distributed uniformly throughout the experiment area. The equipment was driven through the experiment area at the designated speed for each pass. Speed was determined using the vehicle speedometer, and confirmed by a calculation based upon entry time, exit time and length of the test area. After the pass, the area was examined for visible FOD remaining in the experiment area. The gravel was hand swept, collected, and weighed. The work waste was collected and counted to determine the amount of FOD collected for each pass.

At the completion of each pass, the Experiment Area was visually examined to determine the thoroughness of the equipment in picking up the FOD across the Experiment Area. FOD outside the Experiment Area that matched the color of the experimental articles was not included in the weighed and counted amount of FOD collected in the pass, but was considered to have been scattered by the equipment. The proportion of gravel and work order residue collected by the equipment was compared after each test. Visual observation of operation and distribution of the test FOD was made and noted.

6.4 Limitations

Because of the limitations on this experiment, many variables were uncontrolled and may have contributed to the variances in the results. Among the variables that were uncontrolled were:

Weather - The experiment was conducted in all types of weather: rain, snow, sunny and windy conditions. However, there were not enough passes made during the various weather conditions to permit drawing conclusions on their impact.

Sweeper Pick up Adjustments - The sweeper vacuum mechanism is relatively complicated and requires considerable "tuning" to insure maximum effectiveness. The exact settings of the various adjustments on the mechanism were not known on the tested sweepers.

Relative Sweeper Condition - Like the adjustments mentioned above, the condition of seals that allow the vacuum to work and seals that control the face plate leakage were not determined nor controlled.

Accuracy and angle of magnetic bar distance above the ramp surface. The connection of the magnetic bar to the expediter truck was accomplished using a cargo tie down strap. This strap allowed the bar to slide from side to side. At times the bar had to be readjusted because one end would become lower. It was also noted that many times the front of the bar would be lower than the back of the bar making the bar surface unparallel to the ramp surface. No evaluations were made of the effect of either of these occurrences on the efficiency of the pick up.

Ramp angle on FOD Buster. Because of the damming effect at low speeds, it was decided to lower the angle of the ramp by lowering the front end of the pick up containers. The distance from the front of the containers to the ramp was reduced from two and one-half inches to one and one-half inches. There were not enough passes accomplished under the one and one-half inches to draw any meaningful conclusions.

Relative condition of FOD Buster. When the FOD Buster was received, the heavy rubber used as a ramp for the pickup of the FOD was torn two to three inches at each end. On the second day, the rubber ramp was replaced. However, no evaluations were made on the increase (or decrease) in efficiency of the pick up due to this change.

6.5 Test Results

It should be stressed that the results presented here are from a very limited data set. More testing is necessary to determine if the problems observed in this test were anomalous.

6.5.1 Sweeper Tests

During the experiment, the sweepers used did not seem to provide a very effective tool for removal of FOD from the test area. Debris appeared to blow out the drivers side of the pickup head, even at two miles an hour or less. When the sweeper was most effective, it didn't pick up more than 45% of the work waste. The sweeper, as tested, seemed to be both the most inefficient FOD retrieval system and by far the least cost effective.

Because of the amount of debris "blown out" of the pickup head, there were some indications of excessive wear, improper adjustments or improper operation.

The path the sweeper made through the debris was not nearly as wide as the pick up head. The drivers seemed somewhat surprised at the ineffectiveness of their equipment during the tests. When asked to sweep a path through a line of debris, one driver stopped the vehicle over the line in order to insure a path could be seen and evaluated. Although the drivers seemed to think they were cleaning a path six foot wide, the actual path width cleared was normally less than three feet.

A variable not factored into the sweeper test was the RPM of the auxiliary motor driving the vacuum. It was run at 2000 RPM, which is the correct RPM for flight line sweeping, according to the operators.

6.5.2 FOD Buster Tests

The FOD Buster seemed to be a very cost effective solution for controlling flight line FO. Although the speed when the FOD Buster was most effective was very critical (8-12 mph), this speed is a little slower than normal flight line traffic speed.

Speed of the vehicle towing the FOD Buster was very critical to effective removal of FOD. At too slow a speed, FOD dams up at the ramp leading to the holding containers. At too high a speed, the debris appeared to fly everywhere.

6.5.3 Magnetic Bar

The test concluded that when used at the proper height and speed, the magnetic bar was a very effective tool for collecting metallic debris from the flight line. The lower the bar height and the slower the vehicle speed, the better the retrieval results.

The main problem noted with the magnetic bar was one of finding a compromise between an effective height for picking up FOD versus an effective height that will allow the vehicle to travel on and off the ramp without dragging the bar. When the bar is dragged across any type of surface protrusion, it generally scrapes the FOD off the magnet, possibly causing more problems than it is correcting.

A secondary problem is the difficulty in removing FO from the bar once it has been picked up. Because of this difficulty, operators tend to allow FOD to accumulate on the bar with the potential to cause more FOD migration than the bar prevents.

During the experiment, the buildup of large washers and bolts on the magnetic bar seemed to cause some of the smaller work waste to scatter which prevented the smaller items from being picked up. Vehicle speed was also a factor here (The faster the vehicle was traveling, the greater the amount of scattering).

7. DISCUSSION/CONCLUSIONS

During the trips to military installations, it was found that the FOD Prevention Programs were effective in keeping flight line personnel aware of problems associated with FOD. It was also found that the structuring and application of the FOD program differed between bases and military branches. In all cases, findings, recommendations, and conclusions found in this report were based on relatively small sample sizes and should only be used as basis for further research and follow-up. Of all processes noted, FOD walks seemed to be the most heavily relied-upon FOD prevention process. Sweepers, Magnetic Bars, and FOD Buster equipment all seem to have difficulty insuring that **all** FOD is removed from parking ramps, taxiways, and runways. A variety of possible causes for their lack of effectiveness were identified, including: inadequately maintained equipment, equipment not dedicated for FOD use, improper training of operators, difficulty in using equipment, and difficulty with downloading the FOD that was picked up. The Experiment on FOD removal equipment demonstrated this general lack of effectiveness, especially in the range of operation needed for effective FOD retrieval.

The following observations and tentative conclusions are based on the findings of the study:

- A successful FOD prevention program requires the involvement and awareness of the top level managers, the people assigned responsibility for implementing the program and the technicians working on and around the aircraft. It also requires knowledge of the equipment being used.

- USAF equipment used to remove FOD from the work and aircraft travel areas may be less effective than it is assumed to be. It is possible that its use provides some unwarranted comfort level that might in itself be detrimental to the overall FOD Program.

- Operators of FOD removal equipment may not be properly trained on the use of the equipment. Some are not familiar with the adjustments needed to make the equipment effective nor are they knowledgeable about the optimum speeds designed for utilization of the equipment. Part of the problem may lie in the fact that optimum adjustments and speeds are not provided in users manuals, nor in local operational procedures.

- An adequate forum for the sharing of information between USAF FOD monitors does not exist.

- FOD incident data is not accurate nor detailed enough to provide accurate analysis as to causes, locations, etc. Reporting rules and accuracy depend on Major Air Command (MAJCOM) guidance and varies between MAJCOMs and bases.

- Although the constraints on the study prevented collection of sufficient data to support firm conclusions, the data obtained during the data collection trials clearly suggest that the three types of equipment tested have significant limitations, and leave more FOD than is acceptable for an effective FOD program. Further tests are needed to confirm this observations and to firmly establish the limits on the effectiveness of the equipment and identify the best operating procedures to obtain the maximum benefits from the use of the equipment.

7.1 Problems

What follows is a detailed breakdown of some of the problems identified in the site visits or during the experiment trial. Methods for addressing the problems follow in section 7.2.

Problem #1: Information Availability

There is no active forum that allows unit FOD Monitors and participants across military organizations to share information on FOD related problems and solutions. Throughout the interview process, FOD program managers repeatedly asked what other good ideas were identified at other units. Many of the monitors expressed a need for more guidance from higher authority and for ways to share information between FOD managers at different bases. Most indicated that they do informally share information and ideas with local units (other organizations on base or other bases in close proximity) and/or personal contacts (normally through E-mail).

Problem #2: Sweeper Efficiency

The current authorized Air Force street sweepers, as currently used, may not provide adequate pick up of FOD from ramp areas. FOD walks are generally performed every morning, but for the remainder of the day the Airfield managers rely on the sweepers to keep FOD off the active flightline surfaces. Because of this dependence, it is crucial that the sweepers pick up a high percentage of material, even at moderately high speeds (5-10 MPH). The experiment results indicate that the percentage of material actually collected by the sweepers is much lower than what is necessary to maintain safe operating conditions. Discussions with FOD prevention personnel at operational units indicated some awareness of the inadequacies of this equipment, but many Airfield managers are forced to assume that when they call in the sweeper, it has completely eliminated the FOD - they don't have the time to double-check it. The potential then exists for aircraft to operate in an area which still presents a FOD hazard.

Problem #3: FOD Buster Maintainability

The evaluation of the FOD Buster during the experiment indicated that it was adequate and cost effective in picking up FOD. When used within close speed guidelines (unlike the sweeper, the FOD buster has both a maximum **and minimum** effective speed), the FOD Buster picks up a high percentage of both gravel and work waste (over 90%). However, discussions with users indicated they were dissatisfied with both the FOD Buster's reliability and maintainability, and hence seldom used the device. It seems that the high number of moving parts and ground-contacting parts on the FOD Buster mean that it requires constant maintenance and repair. One user commented that his unit spent more in one year maintaining the FOD Buster than they had spent initially purchasing it.

Problem #4: Magnetic Bar Height

The magnetic bar height necessary for a vehicle to maneuver on and off the flight line without dragging the bar is higher than that necessary for effective collection of metallic items from the flight line surface. The magnetic bar was found to be highly effective on ferrous items, with severe speed and height restrictions (slow speed, low heights). When visiting the units, however, it was learned that the normal operating speed reduced the effectiveness on the flightline. In addition, the low ground clearance needed for effective operation resulted in the magnetic bar being drug over obstacles. This knocked previously collected FOD loose from the bar, and increased the amount of hazardous FOD in the area.

Problem #5: Magnetic Bar FOD Removal

The permanent magnetic field on the magnetic bar makes the removal of collected metal FOD inconvenient, difficult, and sometimes hazardous. The removal of collected FOD was very difficult because it had to be pried from the bar with fingers or other objects. Steel slivers collected by this magnetic field proved dangerous and frequently embedded themselves in fingers.

Problem #6: Operator Training

Interview comments indicate a lack of training and instructions on the use of FOD retrieval equipment. Most units cannot afford the luxury of full time dedicated drivers and, therefore, the assignment of these drivers is relatively haphazard. Their training is on the job without any prescribed procedures describing proper performance. This applies to both the sweeper and other FOD retrieval equipment tested. A review of OJT training guides for heavy equipment/sweeper drivers gives no guidance as to the optimum range of speed or operation for flight line FO removal.

7.2 Improvement Opportunities/Recommendations

Improvement Opportunity #1: Share Unit Information at the Air Force and DoD Levels

Investigate the best method to facilitate interaction and sharing of information between the Air Force and other interested DoD units. Possible approaches include an active web site or periodic conferences.

Background: New Internet technologies make the building of a web-site for the sharing of FOD related ideas and problems relatively easy and inexpensive. This forum would allow FOD managers to share information on other approaches, ideas, and problems associated with the FOD Program.

Potential Benefits: Establishing a forum for the sharing of FOD problems and ideas would allow FOD managers at different bases to learn from each other's experiences. FOD managers were constantly asking for the good ideas we had found and contacts they could make to improve their programs. More sharing of information through yearly meetings and/or a FOD web site would be a tremendous benefit to the overall program. The Marine Corps currently performs a weekly teleconference with all it's primary FOD monitors, and has found this to be extremely helpful in proactively identifying potential hazards.

Improvement Opportunity #2: Magnetic Bar Reversible Electromagnetic Field

Investigate the possibility of applying reversible electromagnetic fields on the magnetic bar to facilitate the pick up and removal of metallic FO from flight line work areas. This approach should focus on alleviating the two problems associated with the use of the magnetic bar, i.e., effective height (current magnetic bars are not powerful enough to function effectively with a safe ground clearance) and ease of FO removal once collected.

Background: A more powerful electromagnetic field would allow the magnetic bar to be operated at heights consistent with safe flightline operation. The ability to turn this field off and on (or reverse it) would allow for the easy removal of collected metallic FOD.

Potential Benefits: Making the magnetic bar more useable by making it effective at practical heights would add tremendous FOD removal capability to the flightline. With the use of electromagnetic power, the ease of removal of the FOD would be significantly improved. This approach would overcome the two main reasons the magnetic bar is currently not utilized.

Improvement Opportunity #3: FOD Buster Brush Gearing Change

Investigate the feasibility of re-engineering the FOD Buster concept in order to improve its efficiency and reliability. Brush gearing changes could optimize brush speed efficiency with normal flight line speeds.

Background: Changing the gearing that rotates the brush mechanism could optimize brush speed efficiency with normal flight line speeds. Currently, in order to pick up FOD effectively, a vehicle towing a FOD Buster must operate at a slightly higher speed than desirable for safe flightline driving around aircraft. A gearing change could alleviate this problem fairly easily. Additionally, a study of the unreliable components in this equipment could result in improved reliability and decreased cost of operation. This could cause the unit to be used more effectively on the flight line.

Potential Benefits: Eliminating the obstacles to the current use of the FOD Buster would give the maintenance managers another effective tool to eliminate FOD. Unlike a sweeper, where coordination with other agencies is necessary to gain access, the FOD Buster can be manned and controlled by maintenance personnel.

Improvement Opportunity #4: Combined Equipment

Investigate the possibility of combining the capabilities of 2 pieces of equipment into a single piece of equipment.

Background: Currently, the sweeper is highly ineffective at picking up work waste, even at low speeds. The magnetic bar is extremely effective with work waste, but for obvious reasons cannot pick up rocks or gravel. Many sweeper manufacturers offer sweepers with magnetic bars built in to the front bumper. Some even have adjustable bars which can be raised to prevent the low ground clearance issues discussed earlier.

Potential Benefits: Magnetic bars are generally towed behind vehicles that operate on the ramp areas only, not the runways or taxiways. By adding a magnet to the sweeper, better coverage could be obtained on these areas. Additionally, a magnetic bar which can be raised off the ground would alleviate the concerns of many FOD managers about potential migration of FOD onto the flightline by clinging to the magnet.

Improvement Opportunity #5: Educate Equipment Maintainers on Proper Calibration Settings and Optimum Speed

Investigate the possibility of developing an On-The -Job-Training curriculum for FOD retrieval equipment operators.

Background: Operators of FOD retrieval equipment are not sufficiently trained on the use of the equipment. They are well trained in areas such as flightline driving (i.e., they know not to cross a runway when a plane is landing), and some have years of experience with street sweeping. However, many of the adjustments necessary to keep the sweepers operating at maximum efficiency are considered "operator maintenance". This means that the motor pool is not responsible for making these adjustments - the CE squadrons are left to do it. With the draw downs in personnel, CE no longer has the experience base it once had, and the younger sweeper operators don't have the experience with the equipment to know when it requires adjustment or how to make the adjustments. Additionally, the optimum speed of operation for the equipment differs widely depending on who you ask. Almost every sweeper operator interviewed had a different opinion about what speed to operate their equipment at, and no procedural literature could be found to settle the point.

Potential Benefits: Enable the using organization to obtain the FOD retrieval results the equipment was designed to provide.

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ATTACHMENT 1: EXPERIMENT PLAN

Disclaimer. In response to the Prevention Effectiveness Foreign Object Debris Study Statement of Work (SOW), a rigorous experiment plan was developed and submitted for use. When the contract was awarded, it became evident that funding and time constraints would negate full implementation of that plan. The Government and the Contractor mutually agreed to extract portions of the original plan and conduct a limited experiment. The following outlines the final experiment plan actually used for the study.

8. INTRODUCTION

This Experiment Plan focuses on conducting a controlled experiment to measure the effectiveness of current Foreign Object Debris (FOD) retrieval equipment used by various Air Force agencies. The experiment will be conducted at Wright-Patterson Air Force Base (WPAFB). Limited data samples will be collected from two street/ramp sweepers, a FOD Buster, and magnetic bar. This experiment is part of a larger effort sponsored by the Air Force Research Laboratories Human Effectiveness Directorate Logistics Readiness (AFRL/HESR) Branch. The limited experiment will examine the effectiveness of several FOD retrieval processes and collection methods, with regard to FOD that is produced from the natural breakdown of aircraft parking and taxiway surfaces and to discarded aircraft maintenance by-products. This Experiment Plan implements Human Effectiveness Division SOW paragraph 3.2 (5).

9. MILESTONES

Table 8. Milestones

• Develop Experiment Plan	WANG	Sep 97
• Approval of Experiment Plan	HESR	Oct 97
• Notification of Participants	HESR	Oct 97
• Acceptance by Participants of Experiment Role	HESR	Oct 97
• Experiment Site Approved	HESR	Oct 97
• Sweeper(s) Selected from those Available at WPAFB	HESR	Oct 97
• Simulated FOD Delivered	HESR	Oct 97
• Experiment (Reference Paragraph 7.1. Experiment Description)	WANG	Nov 97
• Analysis of Results	WANG	Dec 97
• Final Report	WANG	Feb 98

10. PARTICIPATION

The following organizations will participate in the Experiment in the role provided:

Table 9. Roles/Responsibilities

Experiment Director	AFRL/HESR
Assistant Director	WANG
Experiment Articles	WPAFB
Support Personnel	WPAFB CE, HESR, WANG
Hardware Performance Specifications	WR-ALC
FOD samples, work waste, gravel, sand, etc.	AFRL/HESR
Paint	AFRL/HESR

AFRL/HESR will task the 88th Civil Engineering Group to provide a sweeper and qualified driver for the duration of the experiment. An operational spare will be identified and be available in case the selected experiment article should fail to operate. WANG personnel will weigh, count, distribute, and retrieve experiment materiel before and after each experiment. The experiment area will be swept prior to and after each experiment. WANG personnel will also perform data collection duties as required and other support roles as identified during the experiment.

11. LOCATION

The experiment will be conducted using a designated Experiment Area at WPAFB. All necessary equipment to support this experiment will be provided to the Experiment Director at the start of the experiment.

The experiment area will be configured as in Figure 1. The experiment area will be a marked rectangle 30 feet long by 30 inches wide for the sweeper experiment and 60 feet long by 30 inches wide for the FOD Buster and Magnetic Bar. The experiment area will be laid out on an existing concrete aircraft ramp with its various seams and holes.

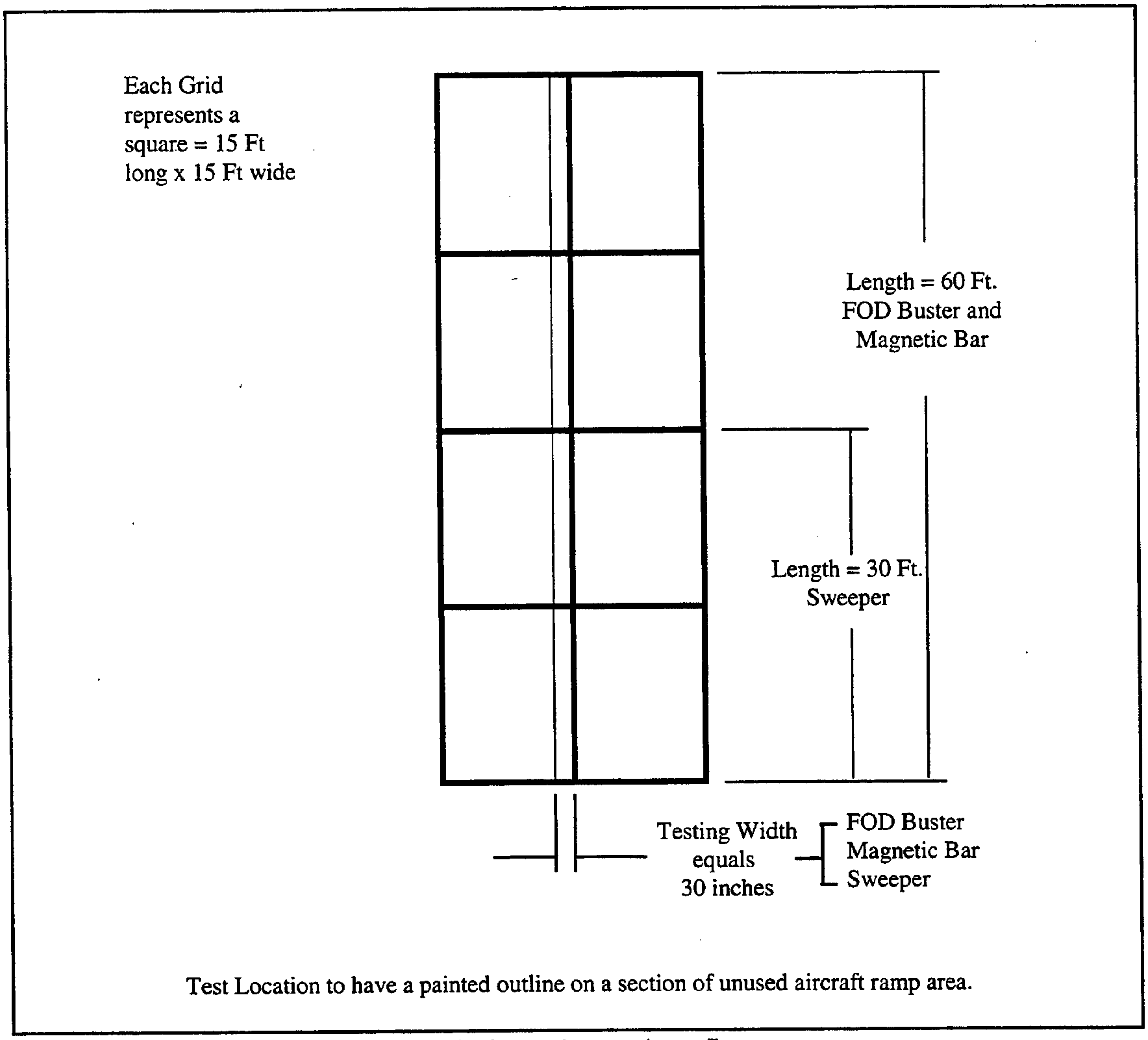

Figure 6. Experiment Area Layout

12. SCHEDULE & TIME REQUIRED TO CONDUCT EXPERIMENT

The overall time to conduct this experiment is derived from the amount of time to set up each pass through the experiment area, have the FOD collection equipment make the pass at the designated speed and then evaluate the experiment area for residual FOD from the sample. Each experimental pass will take approximately one half hour. The following Table summarizes the estimated time to perform the experiment.

Table 10. Experiment Time Estimates

Experiment	Minimum Number of Passes	Minimum Time per Pass	Minimum Time
Sweeper	2 at each speed (5 Speeds)	.5 hour	5.0 hours
FOD Buster	2 at each speed (5 Speeds)	.5 hour	5.0 hours
Magnetic Bar	2 at each speed (5 Speeds)	.5 hour	5.0 hours
TOTAL TIME			**15.0 hours**

One full week is planned for the execution of the experiment. One day will be used for set up and pre-testing. In accordance with Table 3 estimates, four (4) full days should be set aside for the experiment. The sweeper will require the most pre-test adjustment and after test cleanup time. The FOD Buster and Magnetic Bar will require minimum setup and cleanup time. Another week should be available if inclement weather forces delays in the experiment.

13. SECURITY

This effort is unclassified. Access to flightline and ramp areas may require special badges and will be coordinated by HESR.

14. EXPERIMENT OBJECTIVES

The primary objective is to measure the effectiveness of 3 types of FOD collection equipment (sweeper, FOD buster, and magnetic bar) at picking up various types of FOD. Various types of material will be placed in a measured area and each FOD collection equipment's pick-up performance will be measured. Five ranges of speeds will be tested. They include:

1) 2-5 mph
2) 6-8 mph
3) 9-11 mph
4) 12-14 mph
5) 15-16 mph

The time per pass will be closely monitored using a stop watch and speeds will be calculated based on the known length of the test area.

15. MASTER EXPERIMENT LIST

Table 11. Master Experiment List

EXPERIMENT ID	TITLE
1.9.2	Sweeper Experiment.
1.9.3	FOD Buster Experiment.
1.9.4	Magnetic Bar Experiment.

16. EXPERIMENT DESCRIPTIONS & APPROACH

16.1 Experiment Repeatability

Each individual experiment will be repeated at least two times at a specific speed to validate repeatability of the results.

16.2 Sweeper Experiment

This experiment will measure the ability of the sweeper to pick up various types of FOD from the test area.

A 10 pound quantity of gravel and various pieces of painted work waste will be spread in the cleaned experiment area prior to the sweeper making a pass. Note: Work Waste will total 30-35 pieces consisting of safety wire, large and small bolts, nuts, and washers, machine screws, and small rivets. The FOD will be distributed uniformly throughout the experiment area. The sweeper will drive through the experiment area at the designated speed for each pass using the vehicle speedometer confirmed by calculating entry time, exit time and length of the test area. After the pass, the area will be examined for visible FOD remaining in the experiment area. The gravel will be hand swept, collected, and weighed. The work waste will be collected and counted to determine the amount of FOD collected for each pass. Data for each pass will be entered on the appropriate data forms.

The FOD will be spread over the Experiment Area by hand. It will be uniform with FOD extending to both edges. At the completion of each pass the Experiment Area will be visually examined to determine the effectiveness of the sweeper in picking up the FOD across the Experiment Area. FOD outside the Experiment Area that matches the color of the experiment article will be included in the weighed and counted amount of FOD not collected in the pass. The Experiment Area will be hand swept prior to FOD being distributed across the Experimental Area for the next pass.

Speed ranges of 5 mph to 16 mph will be evaluated.

16.3 FOD Buster Experiment

This experiment will measure the ability of the FOD Buster to pick up various forms of FOD from the test area.

A 10 pound quantity of gravel and various pieces of painted work waste will be spread in the cleaned experiment area prior to the FOD buster making a pass. Note: Work Waste will total 35-45 pieces consisting of safety wire, large and small bolts, nuts, and washers, machine screws, and small rivets. The FOD will be distributed uniformly throughout the experiment area. The FOD Buster will drive through the designated experiment area at the designated speed for each pass using the vehicle speedometer confirmed by calculating the speed using the entry time, exit time, and length of the test area. After the pass, the area will be examined for visible FOD remaining in the experiment area. The test area will be hand swept, FOD will weighed and counted to determine the amount of FOD collected for each pass. Data for each pass will be entered on the appropriate data forms.

The gravel will be weighed and the work waste will be counted prior to distribution in the Experiment Area. The FOD will be spread over the Experiment Area by hand. It will be uniform with FOD extending to both edges. At the completion of each pass the Experiment Area will be visually examined to determine the effectiveness of the FOD Buster in picking up the FOD across the Experiment Area. FOD outside the Experiment Area that matches the color of the experiment article will be included in the weighed and counted amount of FOD not collected in the pass. The Experiment Area will be hand swept prior to the FOD being distributed across the Experiment Area for the next pass.

The following speed ranges will be evaluated: 3-16 mph.

16.4 Magnetic Bar Experiment

This experiment will measure the ability of the Magnetic Bar to pick up FOD from the test area.

Various pieces of painted work waste will be spread in the cleaned experiment area prior to the Magnetic Bar making a pass. Note: Work Waste will total 25-35 pieces consisting of safety wire, large and small bolts, nuts, washers, and machine screws. The FOD will be distributed uniformly throughout the experiment area. The Magnetic Bar will drive through the designated experiment area at the designated speed for each pass using the vehicle speedometer and confirmed by calculating the speed using the entry time, exit time and length of the test area. After the pass, the area will be examined for visible FOD remaining in the experiment area. The test area will be hand swept, FOD will be counted to determine the amount collected for each pass. Data for each pass will be entered on the appropriate data forms.

The work waste will be counted prior to distribution in the Experiment Area and after each pass. The FOD will be spread over the Experiment Area by hand. It will be uniform with FOD extending to both edges. At the completion of each pass, the Experiment Area will be visually examined to determine the effectiveness of the Magnetic Bar in picking up the FOD across the Experiment Area. FOD outside the Experiment Area that matches the color of the experiment article will be included in the counted amount of FOD not collected in the pass. The Experiment Area will be hand swept prior to the FOD being distributed across the Experiment Area for the next pass.

The following speed ranges will be evaluated: 3-16 mph.

17. APPLICABLE SPECIFICATIONS

- Sweeper Specification - The HESR Project Manager will provide a copy of the Sweeper Specification to Wang within five working days of receipt of this plan.

- Driver Qualification - The HESR Project Manager will provide specific Air Force or MAJCOM Directives or other documentation on the qualification procedure , testing requirements and training standards for sweeper drivers.

- Concrete Specification - May be able to get this from Army Study.

- Ramp Surface Specification

- FOD Base Level Operating Procedure - (Sweeping Standard Operating Procedures, SOP) for WPAFB where the experiment will be conducted.

18. SUPPORT EQUIPMENT

The following support equipment will be provided by HESR:

- Shovel(s) with a flat bottom (1) and brooms (2).
- Paint to color the FOD for better visibility, at least one or more different colors.
- Tape measure to mark off the experiment area and to place FOD in specific locations.
- FOD samples, pea gravel, stones, work order residue, concrete spalls.
- Digital Camera

19. SPECIAL EXPERIMENT EQUIPMENT

Scale to weigh FOD prior to Experiment and after each Experiment. It must be sufficient to weigh up to 250 pounds. Must be calibrated prior to the Experiment.

20. DATA REDUCTION AND ANALYSIS

Table 12. Data Collection Form

Experiment Director		Driver		Sweeper #		Experiment #			
Date	Time	Pass No.	Entry Speed	Exit Speed	Average Speed	FOD Sample Type	FOD Sample Specify (Wgt / Pcs)	FOD Remaining	Efficiency %

Collected data will be entered into an Excel Spreadsheet to aid in analysis. The final report will use this to define results and support recommendations.

21. GOVERNMENT EXPERIMENT FACILITIES

The Experiment Area will be identified by the Air Force Research Laboratory in coordination with the 88th Civil Engineering Group. The Experiment Area will be a portion of existing aircraft ramp space with ample clear space to allow for efficient and safe maneuvering of the FOD collection equipment and to prevent FOD from being blown outside the controlled experiment area. The Experiment Area will be designated and marked off to provide a controlled experiment environment.

22. VALIDATION PROCEDURE

HESR research scientists will provide an independent evaluation of the Experiment Plan prior to approval. The experiment procedures will then be precisely followed to ensure valid data collection.

ATTACHMENT 2: EXPERIMENT RESULTS

23. SUMMARY

The experiment was conducted 3-7 November, 1997, on an available ramp area in Area B, Wright-Patterson AFB, Ohio. Equipment tested included two ramp sweepers, a magnetic bar, and one FOD Buster. Section 6.2 of the report provides a more detailed description of the equipment.

24. FOD USED IN THE TEST

Foreign Objects used for pick up evaluation included a combination of pea sized gravel and work waste similar to that found on a flight line. Table 13 lists 9 different types of work waste used in the experiment. However, not every item type was used in every test. For every type that was used, five (5) items were distributed in the experiment area prior to each pass and accounted for afterwards. Note: The low ferro-metallic content of the rivet and safety wire prohibited them from being used in the Magnetic Bar tests. Other items may have been used in other tests at one time or other, but were eventually eliminated when they became hard to locate.

Effectiveness of the equipment was measured by the percentage of FOD collected versus the amount left behind or scattered in the test area. Note: A 60 x 30 foot area was designated as the test area and hand swept before and after each test. Ten pounds of gravel and 25-45 pieces of work waste were used during each test. The proportion of gravel and work residue collected by the equipment was compared after each test. Visual observation of operation and distribution of the test FOD was made and noted.

Table 13. Description and Identification of Work Waste Used in the Experiment

IDENT.	DESCRIPTION	SIZE	MATERIAL	NSN
SS	Machine Screw	32 x 1/2"	Zinc plated	n/a
MS	Stove Bolt	24 x 1"	Zinc plated	n/a
BT	Bolt	2 1/4"	n/a	n/a
SN	Small Nut	n/a	n/a	5310-00-550-1467
LN	Large Nut	16 x 3/8" dia	n/a	5310-00-655-9544
SW	Small Washer	n/a	n/a	5310-00-639-7554
LW	Large Washer	n/a	n/a	5310-00-579-2070
RT	Rivet	n/a	n/a	5320-00-117-6890/6891
WR	Safety Wire	.032" dia	Non-electrical	9505-00-293-4208

Note: All references to the Work Waste used in the experiment tests are made using the two letters specified in the Identification column.

25. SWEEPER TESTS

During this experiment the sweepers used did not seem to be a very effective way to remove FOD from the test area as show in Figure 7. Debris seemed to blow out the right side of the pickup head, even at two miles an hour or less. When the sweeper was at its most effective, it picked up less than 45% of the work waste. The sweeper seemed to be both the most inefficient FOD retrieval system and by far the least cost effective FOD retriever.

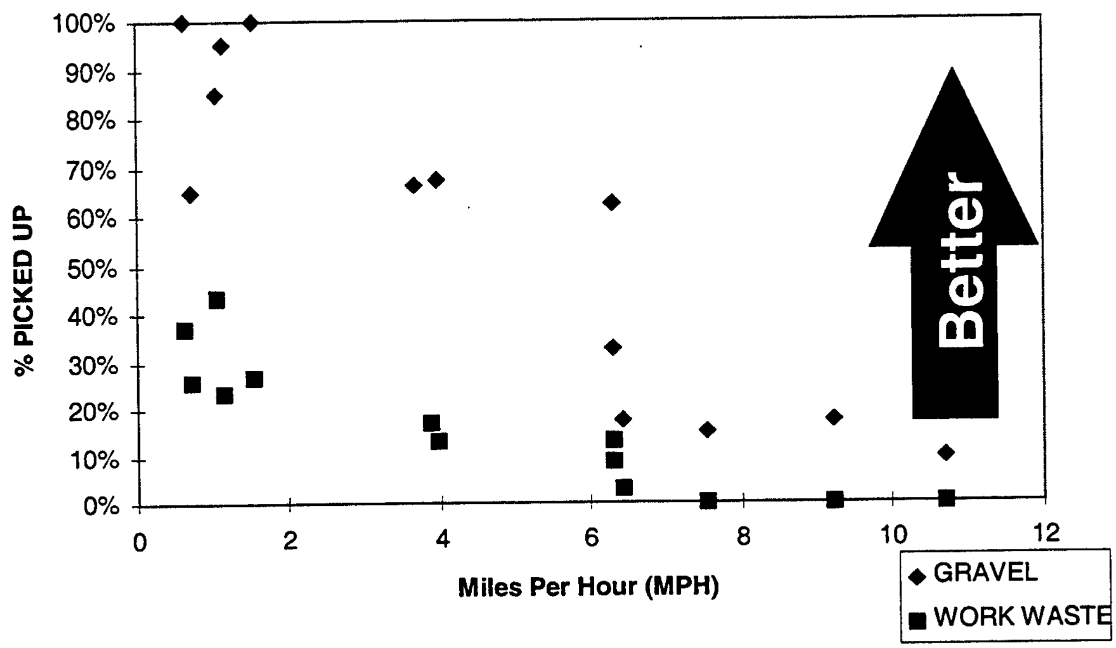

Figure 7. Sweeper Combined FOD Picked Up

The path the sweeper made through the debris was not nearly as wide as the pick up head. The drivers seemed somewhat shocked at the ineffectiveness of their equipment. When asked to sweep a path through a line of debris, one driver stopped the vehicle over the line in order to insure a path could be seen and evaluated. Although the drivers seemed to think they were cleaning a path six foot across, the actual path width cleared was normally less than three feet. Note: This test is inconclusive because the relative condition of the sweeper being tested was not known. Because of the amount of debris "blown out" of the pickup head, there were some indications of excessive wear, improper adjustments or improper operation. A variable not factored into the sweeper test was the RPM of the auxiliary motor driving the vacuum. It was run at 2000 RPM, which is the correct RPM for flight line sweeping, according to the operators.

A newer, factory adjusted, sweeper should be tested under similar circumstances in order to form a baseline for sweeper operations. It is essential to determine the complexity and amount of technical skill and training needed to carry out and maintain this "tuning" of equipment. Should this show that normal operations of the current Air Force sweeper's at base level cannot approach this baseline, decisions should be made on the cost-effectiveness of the use of these sweepers as a primary FO retrieval system.

Table 14 summarizes the test environment.

Table 14. Sweeper Test Environment Summary

Mfgr Info	TYMCO, Model No. 600
Drivers	Civilian employees from the Motor Pool
Test Area	30 ft Long x 30 inches wide
Ramp conditions	Dry surface
Sweeper width	7 ft 11 inches wide
Testing Speeds	1.5 mph - 15 mph
No. of Passes	17
Adjustments	Two sweepers were used. Sweeper #1 developed an oil leak. The "leaf door" was closed on the last 5 sweeper runs on Sweeper #2. It was never noticed if the "leaf door" on Sweeper #1 was opened or closed on prior runs.
Gravel Weight	10 lbs. (20 lbs tested caused damming)
Work Waste Used	30-35 pieces

Data Collection and Analysis Results

Table 15 presents the data collected during the experiment.

Table 15. Sweeper Data Collection Sheet

					Begin	Collect	Begin	WORK WASTE																							
		Plan		Aver	Gravel	Gravel	Work	HOPPER PICKED UP								REMAINING								DRAGGED							
Date	Pass	Speed	Timed	MPH	Wgt	Wgt	Waste	LN	WR	SS	MS	LS	RT	LW	SW	LN	WR	SS	MS	LS	RT	LW	SW	LN	WR	SS	MS	LS	RT	LW	SW
5-Nov	1	5 mph	5.62	3.64	20 lbs	8.25	NONE																								
5-Nov	TEST				20 lbs	10.5	NONE																								
5-Nov	1	5 mph	3.25	6.29	10 lbs	6.25	30	1			1				2	4		4	4	4		5	3			1		1			
5-Nov	2	10 mph	2.22	9.21	10 lbs	1.75	30									5		5	5	5		4	5							1	
5-Nov	TEST																														
5-Nov	3	2 mph	18.12	1.13	10 lbs	9.5	30				1	2		1	4	4		2	4	4		3	1	1		1		1		1	
5-Nov	4	Slow	13.15	1.56	10 lbs	10	30				3	5		1	4	1			1			4	1	4			1				
5-Nov	5	5 mph	5.16	3.96	10 lbs	6.75	30				1	1		1	1	5		4	4	4		4	4					1			
5-Nov	6	10 mph	1.91	10.71	10 lbs	1	30									4		5	5	3		4	5	1				2		1	
5-Nov	7	8 mph	2.72	7.52	10 lbs	1.5	30									4		5	4	4		5	5	1			1	1			
5-Nov	8	SLOW	19.37	1.06	10 lbs	8.5	30			4	2			3	4			1		2		2		5			3	3			1
7-Nov	1	SLOW	5.56	3.68	10 lbs	1	35			2	1		3		1	5		3	3	5	2	5	4				1				
7-Nov	2	SLOW	29.31	0.70	10 lbs	6.5	35			1			5		3			1						5		4	5	5		4	2
7-Nov	3	SLOW	33.03	0.62	10 lbs	10	35			3			5		5									5		2	5	5		5	
7-Nov	4	SLOW	5.28	3.87	10 lbs	6.75	35			1			4		1	2				2		3		3		4	5	3		2	5
7-Nov	5	SLOW	3.19	6.41	10 lbs	1.75	35						1			5		5	4	3	4	5	4				1	2			1
7-Nov	6	SLOW	3.25	6.29	10 lbs	3.25	35						3			5		4	5	5		5	3			1			2		2
7-Nov	7	SLOW	2.88	7.10	10 lbs	2	NONE																								

The best results for picking up FOD were at extremely slow speeds as noted in Figure 8. The sweeper was almost at a stand still.

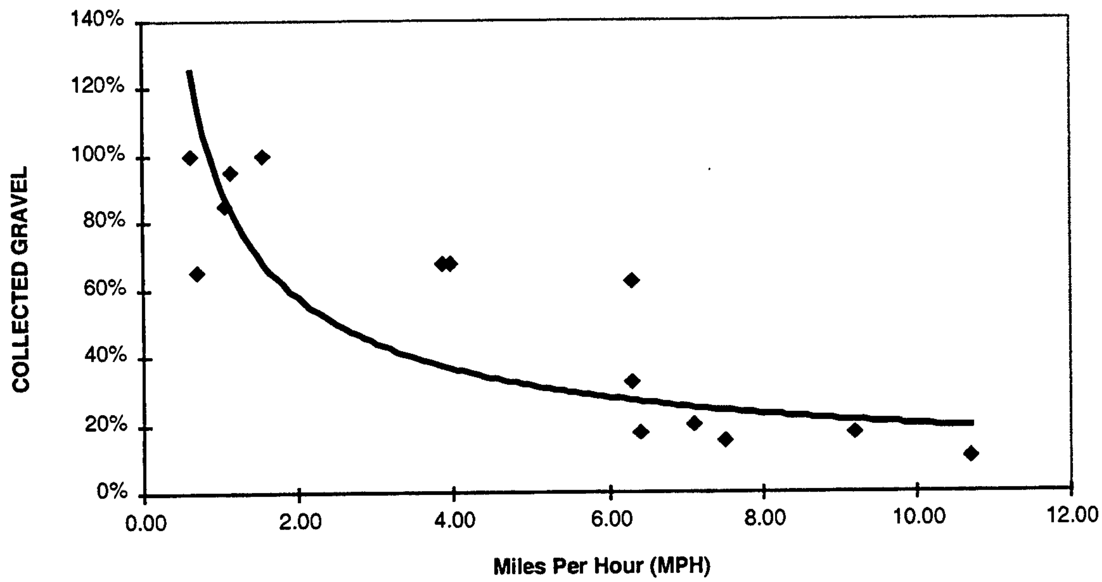

Figure 8. Collected Gravel

From Figure 3, the sweeper's best results for the collection of work waste were at the slowest speeds.

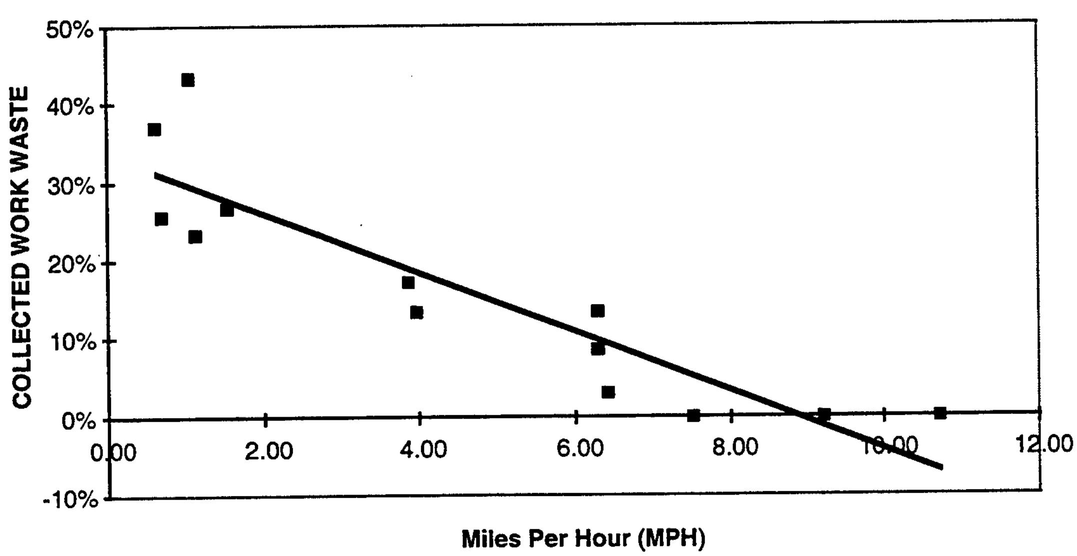

Figure 9. Collected Work Waste

Figure 10 reflects that the lightest work waste (e.g. rivets) usually were picked up. However, the heavier items (e.g. the large bolts, nuts and washers) were either left on the payment or dragged by the sweeper to outside of the experiment area. The shape of the large nut may also have played a factor in its low retrieval rating.

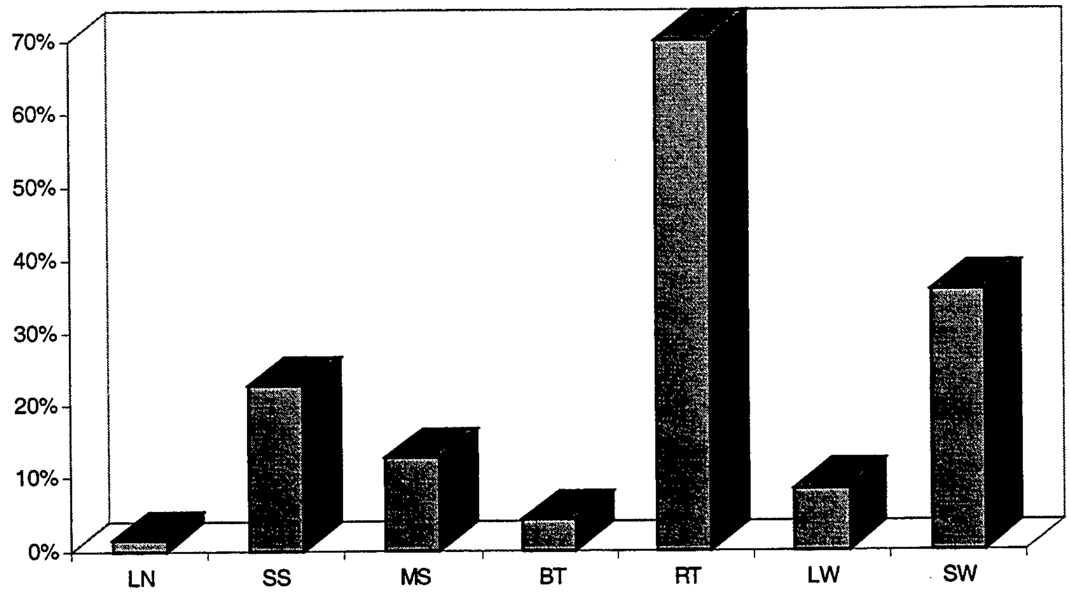

Figure 10. Breakdown of Collected Work Waste

26. FOD BUSTER TESTS

The FOD Buster seemed to be an effective solution for controlling flight line FO, as indicated in Figure 11. Speed of the vehicle towing the FOD Buster was very critical to effective removal of FO. At too slow a speed, FO dams up at the ramp leading to the holding containers. At too high a speed, the debris seemed to be thrown everywhere. Note: The speed the FOD Buster was most effective (7-9 mph) is a little slower than normal flight line traffic speed.

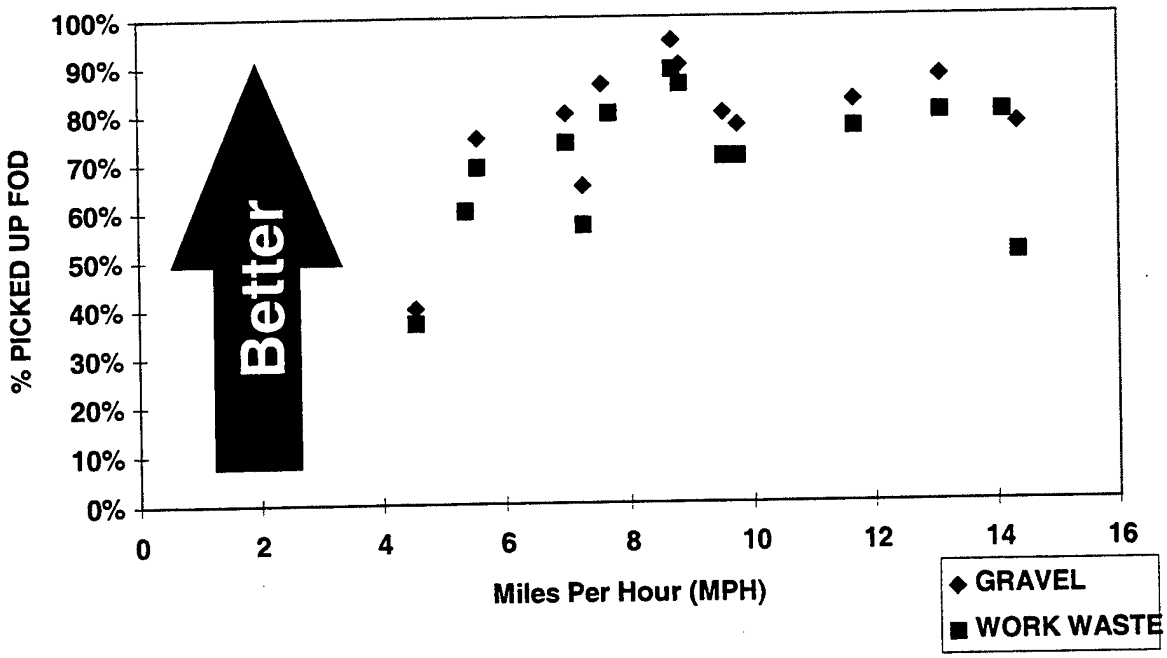

Figure 11. Combined FOD Picked Up

Table 16 summarizes the test environment.

Table 16. FOD Buster Test Environment Summary

Mfgr Info	N/A. Supplied by Springfield Ohio Air National Guard Base
Location	FOD Buster was pulled behind a US Government Expediter Vehicle
Test Area	60 ft Long x 30 inches wide
Ramp conditions	Testing was done on both dry and wet surfaces
Sweeper width	48 inches wide - Pickup area was 36 inches wide
Testing Speeds	1.5 mph - 15 mph
No. of Passes	27
	13 inches = 2
	14 inches = 23
	15 inches = 2
Adjustments	Collector heights from 2 1/2 inches to 1 1/2 inches
	Brush height from 13 to 15
	13 = light pressure
	14 = medium pressure
	15 = heavy pressure
Gravel weight	Tested 50 lbs which the FOD buster could not handle. 10 lbs of gravel was used.
Work Waste	30-35 pieces.

Data Collection and Analysis Results

Table 17 presents the data collected during the experiment.

Table 17. FOD Buster Data Collection Sheet

							Begin	CLTD	Beg	R&D	WORK WASTE																										
		Brush	Cltr	Plan		Aver	Gravel	Gravel	Work	Work	PICKED UP									REMAINING									DRAGGED								
Date	Pass	HGT	HGT	Speed	Timed	MPH	Wgt	Wgt	Waste	Waste	LN	SN	WR	SS	MS	LS	RT	LW	SW	LN	SN	WR	SS	MS	LS	RT	LW	SW	LN	SN	WR	SS	MS	LS	RT	LW	SW
3-Nov	1	14 inch	2 1/2"	5 mph	Test		50 lbs	DNM	50																												
3-Nov	2	14 inch	2 1/2"	5 mph	7.65	5.3	10	6	35	14																											
3-Nov	3	14 inch	2 1/2"	10 mph	5.85	7.0	10	8	35	9																											
3-Nov	4	14 inch	2 1/2"	15 mph	4.28	9.6	10	8	35	10																											
3-Nov	5	14 inch	2 1/2"	10 mph	5.31	7.7	5	4.5	35	7																											
3-Nov	6	14 inch	2 1/2"	15 mph	4.47	9.2	0	0	35	12																											
3-Nov	7	14 inch	2 1/2"	20 mph	None	20.0	10	1																													
4-Nov	1	14 inch	2 1/2"	10 mph	4.69	8.7	10	9.5	35	4	4		5	5	5	4		3	5	1					1		2										
4-Nov	2	14 inch	2 1/2"	10 mph	4.63	8.8	10	9	35	5	4		5	5	5	4		2	5	1					1		3										
4-Nov	3	14 inch	2 1/2"	5 mph	7.35	5.6	10	7.5	35	11	1		4	5	5	4			5	3		1			1		3		1							2	
4-Nov	4	14 inch	2 1/2"	15 mph	2.9	14.1	10	8	35	7	5		5	3	4	4		3	4				2	1	1		2	1									
5-Nov	1	14 inch	2 1/2"	5 mph	9	4.5	10	4	35	23	2		3	2	1	1		1	2	1		1		2	1		2	2	2		1	3	2	3		2	1
5-Nov	2	14 inch	2 1/2"	8 mph	5.62	7.3	10	6.5	45	15	5	5	3	4	3	3	3	1	3			1	1	2	2						1				2	4	2
5-Nov	3	14 inch	2 1/2"	12 mph	3.12	13.1	10	8.75	45	7	5	4	5	5	4	4	4	4	3		1			1		1	1	2						1			
5-Nov	4	14 inch	2 1/2"	10 mph	4.19	9.8	10	7.75	45	10	5	4	5	4	4	3	5	3	2		1		1		1		1	3					1	1		1	
5-Nov	5	14 inch	2 1/2"	15 mph	2.85	14.4	10	7.75	45	17	4	2	3	4	4	5	4		2		2	1	1	1			5	3	1	1	1				1		
5-Nov	6	14 inch	2 1/2"	12 mph	3.5	11.7	10	8.25	45	8	4	3	5	5	5	5	5	2	3	1	2						2	2								1	
6-Nov	1	15 inch	2 1/2"	10 mph	3.86	10.6	10	7.25																													
6-Nov	2	15 inch	2 1/2"	10 mph	4.03	10.2	10	7																													
6-Nov	3	13 inch	2 1/2"	10 mph	4.31	9.5	10	8.5																													
6-Nov	4	13 inch	2 1/2"	10 mph	4.06	10.1	10	8.25																													
6-Nov	5	14 inch	2 1/2"	10 mph	4.07	10.1	10	8.5																													
6-Nov	6	14 inch	2 1/2"	10 mph	4.41	9.3	10	8.75																													
6-Nov	7	14 inch	1 1/2"	5 mph	8.38	4.9	10	5																													
6-Nov	8	14 inch	1 1/2"	10 mph	3.66	11.2	10	8.5																													
6-Nov	9	14 inch	1 1/2"	10 mph	4.19	9.8	10	8.75																													
6-Nov	10	14 inch	1 1/2"	15 mph	2.59	15.8	10	8.375																													
6-Nov	11	14 inch	1 1/2"	15 mph	2.84	14.4	10	8																													

The best results for the FOD Buster were speeds between 7-9 MPH, as represented in Figure 12. Slower speeds experienced damming while faster speeds threw gravel over the collector containers. Overall collection for gravel was 73%.

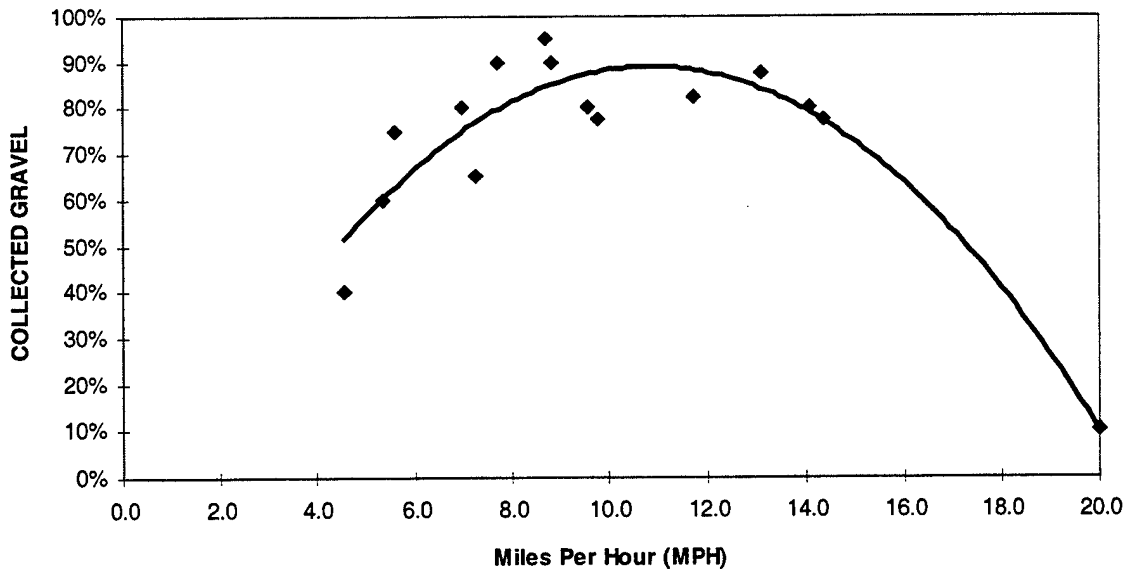

Figure 12. Percentage of Collected Gravel

Figure 13 shows that the average work waste collected was 72%. Best results for retrieval of work waste were at speeds between 8-11 MPH.

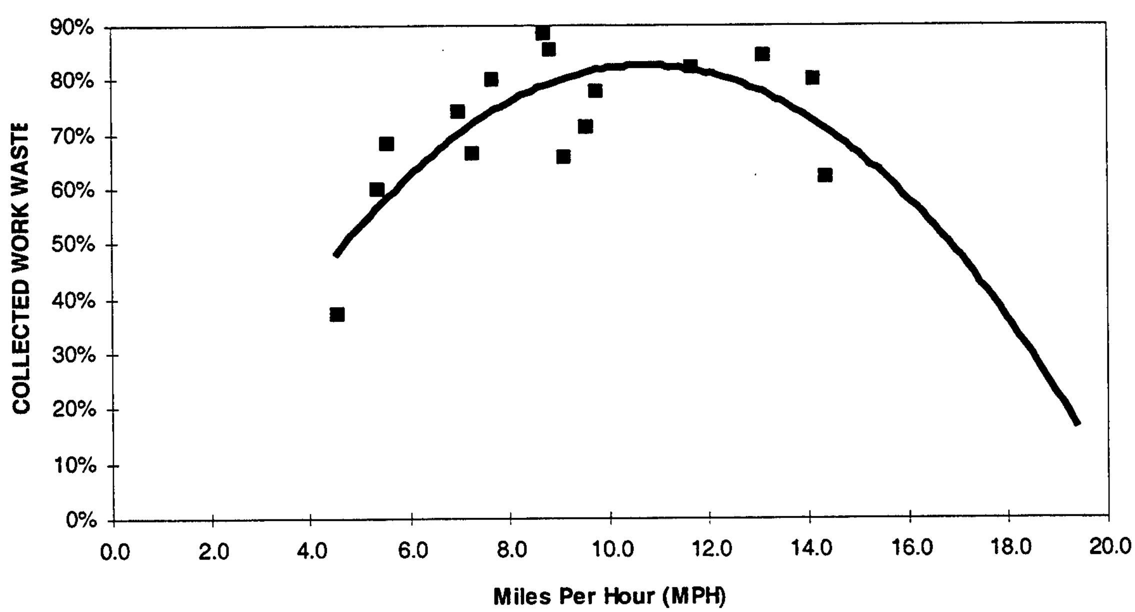

Figure 13. Collected Work Waste

Figure 14 reveals that the FOD Buster collected at least seventy per cent (70%) of all work waste used in the tests except for the large washer. The weight and thickness may have contributed to the large washer's low retrieval percentage (40%).

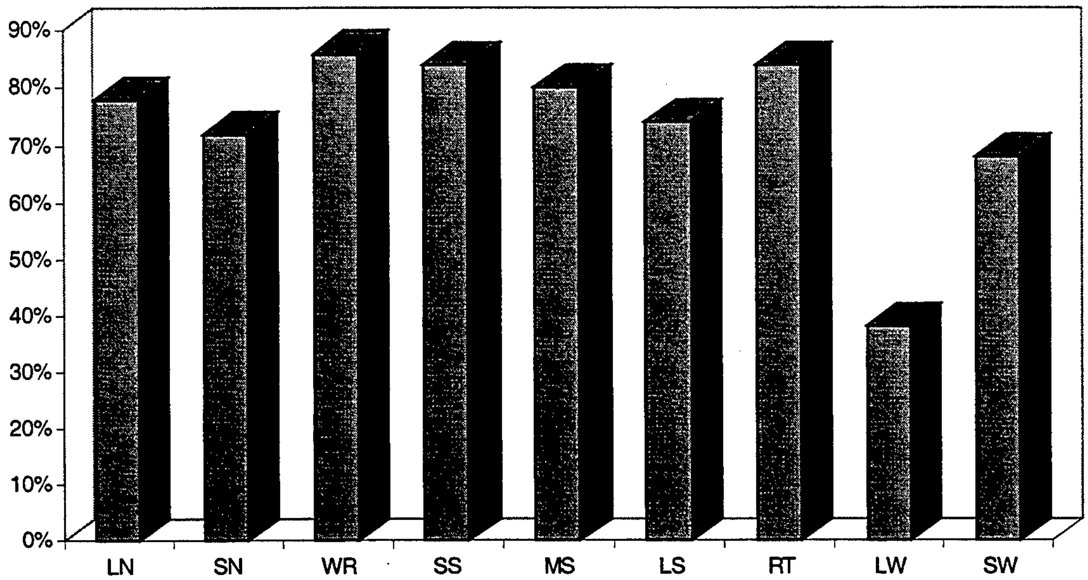

Figure 14. Breakdown of Collected Work Waste

27. MAGNETIC BAR TESTS

Figure 15 shows that when used at the proper height and speed, the magnetic bar was a very effective tool for collecting metallic debris from the flight line. The lower the bar height and the slower the vehicle, the better the retrieval results. The main problem with the magnetic bar was one of finding a compromise between an effective height for picking up FO versus an effective height that will allow the vehicle to travel on and off the ramp without dragging the bar. When the bar is dragged across any type of surface protrusion, it generally scrapes the FO off the magnet, causing more problems than it is correcting. A secondary problem is the difficulty in removing FO from the bar once it has been picked up. Because of this difficulty, some organizations have let the FOD accumulate on the bar with the potential to cause more FOD migration than it prevented. During the experiment, the buildup of large washers and bolts on the magnetic bar seemed to scatter some of the smaller work waste which prevented the smaller items from being picked up. Vehicle speed was also a factor here.

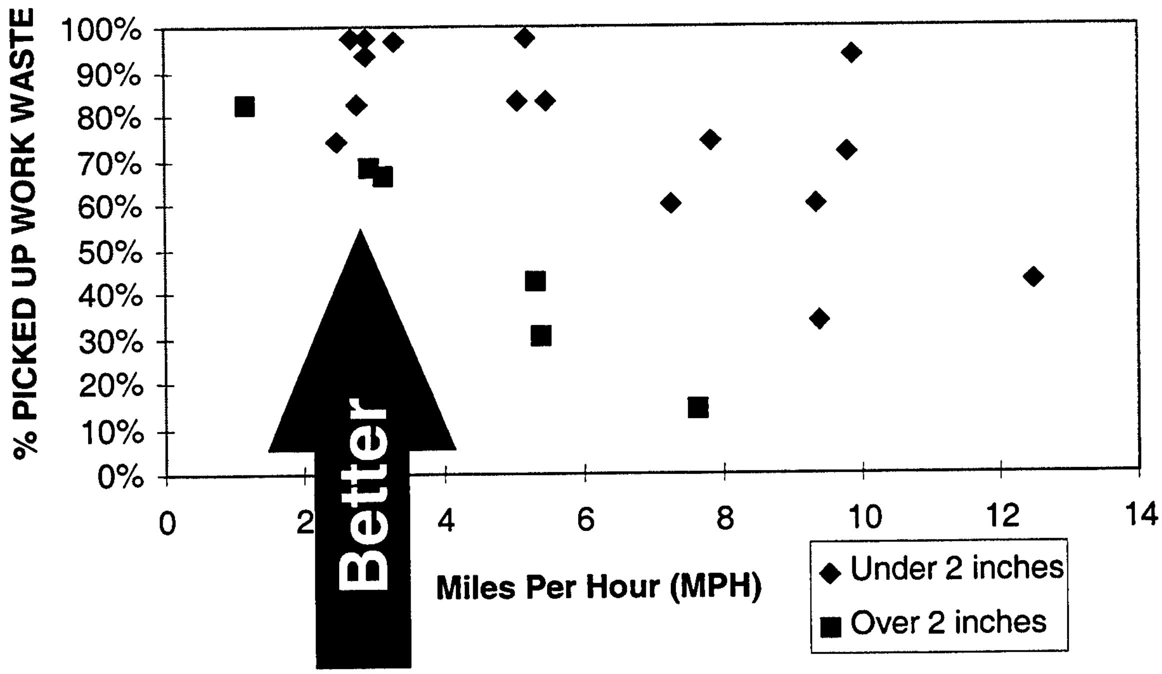

Figure 15. Combined FOD Picked Up

Table 18 summarizes the test environment.

Table 18. Magnetic Bar Test Environment Summary

Location of the bar	Magnetic Bar was hooked onto the front of the US Government Expediter Vehicle
Test Area	60 ft Long x 30 inches wide
Ramp conditions	Dry and wet surfaces
Magnetic Bar Sweep area	6 ft wide
Testing Speeds	1.5 mph - 15 mph
No. of Passes	23
	1 1/2 inches - 13
	1 3/4 inches - 3
	2 1/8 inches - 2
	3 inches - 5
Adjustments	1 1/2, 1 3/4, 2 1/8, and 3 inches
Gravel weight	None
Work Waste	25-35 pieces

Data Collection and Analysis Results

Table 19 presents the data collected during the experiment.

Table 19. Magnetic Bar Data Collection Sheet

						Begin	WORK WASTE																										
		BAR	Plan		Aver	Work	PICKED UP									REMAINING									DRAGGED								
Date	Pass	Hgt	Speed	Timed	MPH	Waste	LN	SN	WR	SS	MS	BT	RT	LW	SW	LN	SN	WR	SS	MS	BT	RT	LW	SW	LN	SN	WR	SS	MS	BT	RT	LW	SW
4-Nov	1	1 3/4	5 mph	7.5	5.45	25				5		5		5	5	5																	
4-Nov	2	1 3/4	2 mph	12.4	3.30	25	4			5		5		5	5	1																	
4-Nov	3	1 3/4	10 mph	4.38	9.34	25	1					2		4	3	4			5		3		1	2									
4-Nov	4	1 1/2	5 mph	8.07	5.07	30	3	4		4		5		5	4	2	1		1														1
4-Nov	5	1 1/2	3 mph	14.15	2.89	30	5	4		5		5		5	4		1							1									
4-Nov	6	1 1/2	15 mph	4.15	9.86	30				2						5	5		3		5		5	5									
4-Nov	7	1 1/2	10 mph	4.35	9.40	30		1				4		4	1	5	4		5		1		1	4									
4-Nov	8	1 1/2	8 mph	5.63	7.27	30				4		4		5	5	3	5		1		1				2								
4-Nov	9	2 1/8	5 mph	7.57	5.40	30						2		4	3	5	5		5		3		1	2									
4-Nov	10	2 1/8	3 mph	13.03	3.14	30	1	3		3		4		4	5	4	2		2		1		1										
6-Nov	1	1 1/2	SLOW	16.47	2.48	35	5			2	5	5		5	3		5		3					2									
6-Nov	2	1 1/2	SLOW	14.68	2.79	35	3	5		4	5	5		5	3	2			1					2									
6-Nov	3	1 1/2	SLOW	15.21	2.69	35	5	5		5	5	5		4	5								1										
6-Nov	4	1 1/2	SLOW	14.09	2.90	35	5	5		5	5	5		5	4									1									
6-Nov	5	1 1/2	SLOW	7.88	5.19	35	5	5		5	4	5		5	5					1													
6-Nov	6	1 1/2	SLOW	5.22	7.84	35	2	2		4	5	3		5	5	3	3		1		1									1			
6-Nov	7	1 1/2	10 mph	4.18	9.79	35	2	1		3	4	3		5	5	3	4		2	1	1									1			
6-Nov	8	1 1/2	12 mph	3.28	12.47	35	5	4		1	2	2			1		1		4	3	1		5	3						2			1
6-Nov	9	3	SLOW	13.94	2.93	35				5	5	5		5	4	5	5							1									
6-Nov	10	3	SLOW	7.72	5.30	35				4	5	3		2	1	5	5		1		2		3	4									
6-Nov	11	3	8 mph	5.37	7.62	35					2	3				5	5		5	3	2		4	4								1	1
6-Nov	12	3	10 mph	3.56	11.49																												
6-Nov	13	3	SLOW	34.81	1.18	35	3	2		4	5	5		5	5	2	3		1														

Figure 10 reflects that the best results for collection of the work waste was at extreme slow speeds. For the best results, speeds between 3-6 MPH were the most effective. Collection of work waste had an average of 70%.

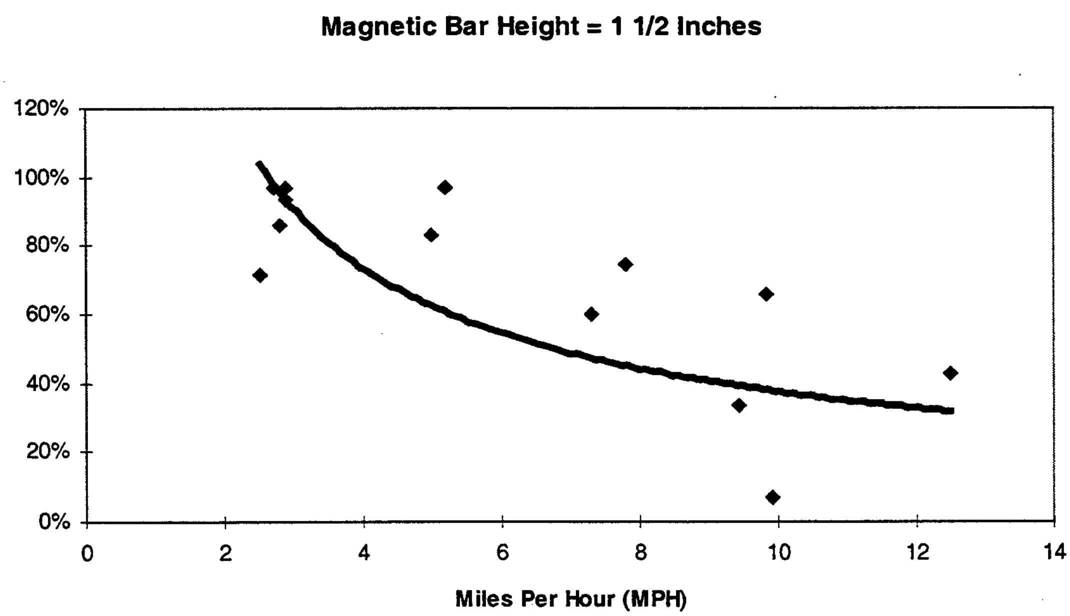

Figure 16. Collected Work Waste

Figure 11 reflects that the best results for collecting work waste with bar heights of one and three-fourth inches and over is at very slow speeds. Best speed results were 3-5 MPH with 58% collected overall.

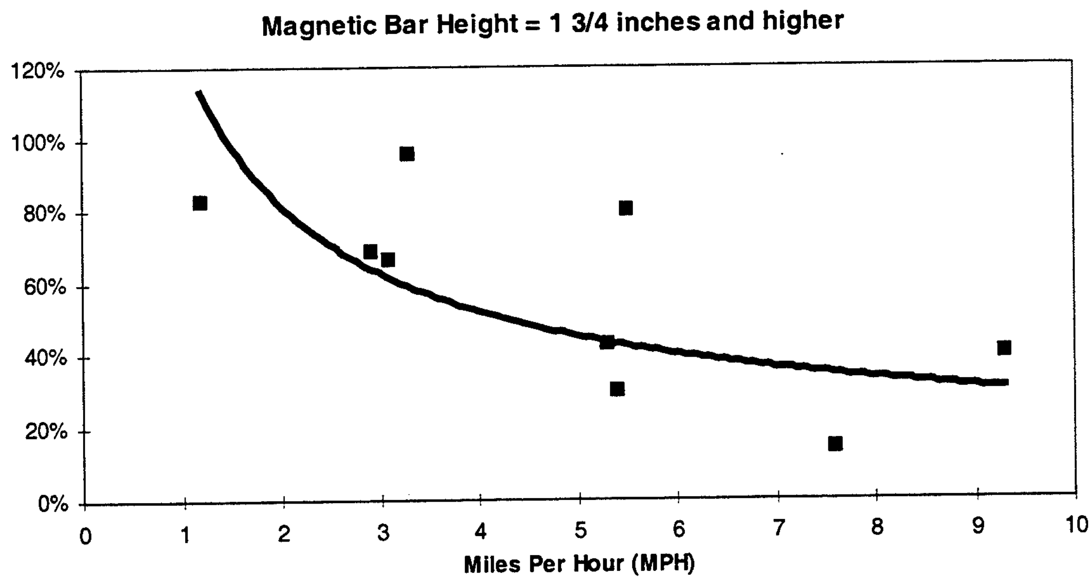

Figure 17. Collected Work Waste

Figure 18 shows the breakout of collected work waste. The shape of the large and small nuts along with their metallic content may have played a factor in the retrieval of these items. In addition, the small screw's metallic content may have also contributed to its low retrieval percentage.

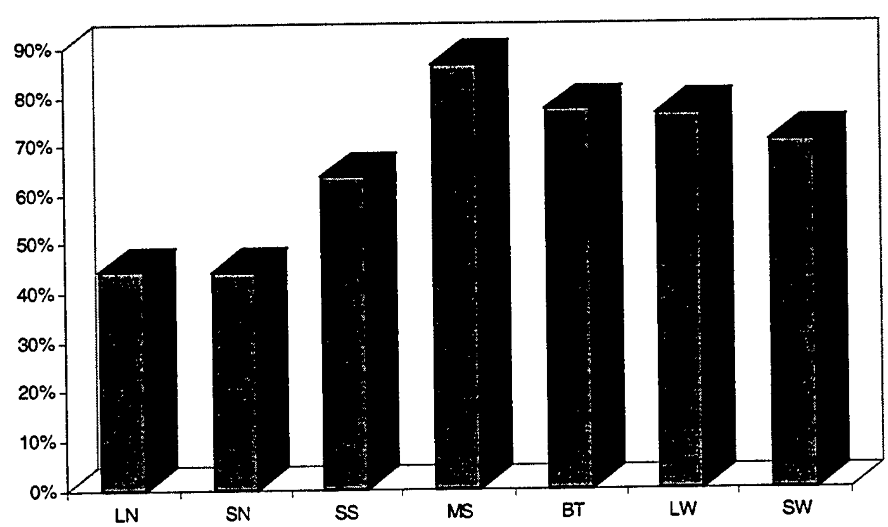

Figure 18. Breakdown of Collected Work Waste