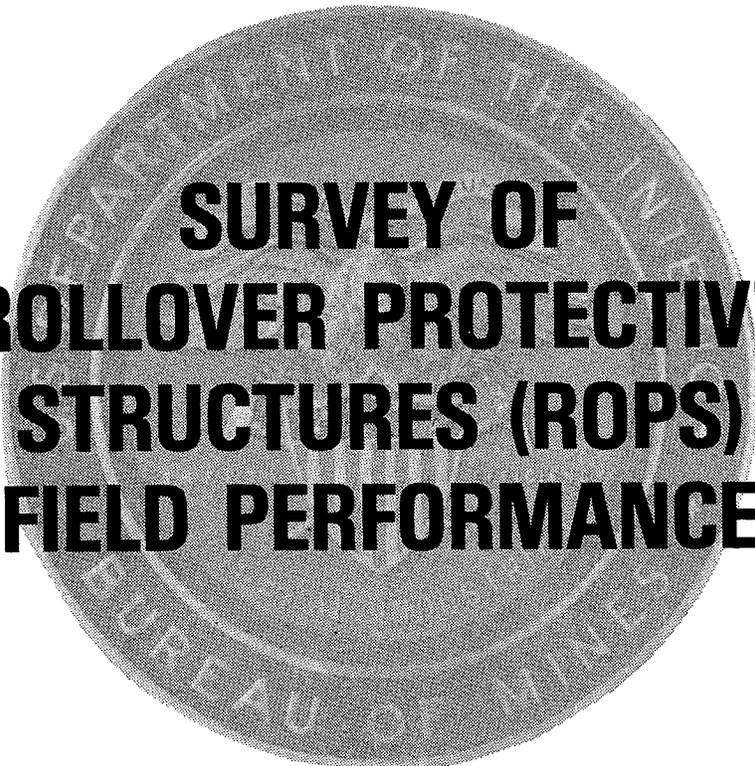


**A minerals research contract report
November 1980**



**SURVEY OF
ROLLOVER PROTECTIVE
STRUCTURES (ROPS)
FIELD PERFORMANCE**

Contract J0285022
Woodward Associates, Inc.

OFR
85-87

EAU OF MINES ★ UNITED STATES DEPARTMENT OF THE INTERIOR
Minerals Health and Safety Technology

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FOREWORD

This report was prepared by Woodward Associates, Inc., San Diego, California under USBM Contract Number JO285022. The contract was initiated under the Minerals Health and Safety Technology Program. It was administered under the technical direction of the Twin Cities Research Center with Mr. Stephen Swan and Mr. Kelly C. Strebis acting as Technical Project Officers. Mr. Larry Rock was the contract administrator for the Bureau of Mines. This report is a summary of the work recently completed as a part of this contract during the period May 1978 to April 1980. This report was submitted by the author on November 21, 1980.

Woodward Associates, Inc. expresses its appreciation to the many individuals throughout the mining and construction industries who assisted in the gathering and compiling of data used in this report. This cooperation was especially important since data from state and federal government sources were not sufficiently detailed to allow the analyses desired in certain important areas.

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SECTION 1.0

INTRODUCTION

This report presents the results of a study to determine the effectiveness of certain safety regulations promulgated by federal and state agencies during the past several years. The safety regulations addressed by this research study are those that require the installation of rollover protective structures (ROPS) on various types of mining and construction machines. These regulations have affected a large number of machines used in these industries; the total number of machines fitted with ROPS is estimated at over 500,000 units.

This study can be viewed as an attempt to quantify the success of the requirement to install ROPS on the types of machines that occasionally experience rollovers during the course of performing earthmoving and related functions on job sites. It is also an attempt to provide technical guidance to those whose interests lie in the areas of improving further the safety of mobile machine operators.

In performing this study, Woodward Associates, Inc. has drawn on its extensive background in conducting research aimed at increased mobile machine operator safety and, specifically, in the promotion of ROPS and seat belts as viable means to protect operators in the event these machines are involved in rollover accidents. The cooperation of the industries affected by ROPS requirements — the equipment manufacturers, the ROPS manufacturers, the regulatory agencies, and the mining and construction companies — has been necessary and welcome in performing this study.

This report contains, as Section 2.0, a comprehensive summary of this study. This summary, in almost identical words and format, was published as a Society of Automotive Engineers' technical paper and presented at the SAE Earthmoving Conference held in Peoria, Illinois in April 1980. The paper is designated SAE Technical Paper 800679 and is entitled "ROPS Field Performance — A Status Report" (1)*. Minor changes have been made to include

*Underlined numbers in parentheses refer to items in Appendix C.

information received subsequent to publication of the SAE technical paper. The remaining sections of this report describe the procedures used to collect the necessary data, the data analyses conducted, and give additional information on the conclusions and recommendations reached by Woodward Associates.

Several photographs of rollover accidents are shown in Figure 1-1.

The Bureau of Mines has several research contracts under way that will influence and benefit future ROPS progress. A listing of these is given below:

- USBM Contract No. J0357110, "Design Criteria and Guidelines for Falling Object Protective Structures (FOPS)."
- USBM Contract No. J0366016, "Development of Plastic Canopy Computer Program." (Developed finite element computer program that allows inexpensive computation of ROPS structural performance.)
- USBM Contract No. H0377101, "Development of Materials and Strategies for Pre-Shift Equipment Inspection." (Prepared a special training module emphasizing value of ROPS and seat belts.)
- USBM Contract No. J0387221, "Haulage Truck Training System." (Contains training material advocating the use of seat belts.)
- USBM Contract No. J0295013, "Novel Cab Designs to Improve Large Haulage Vehicle Safety." (Describes new haulage truck design concepts that provide for increased operator protection.)
- USBM Contract No. J0199139, "Service Life Analysis of Rollover Protective Structures (ROPS) on Surface Mining Machines." (Provides for initial investigations into effects of vibration on service life of ROPS. Defines potential problems and suggests direction for further research.)

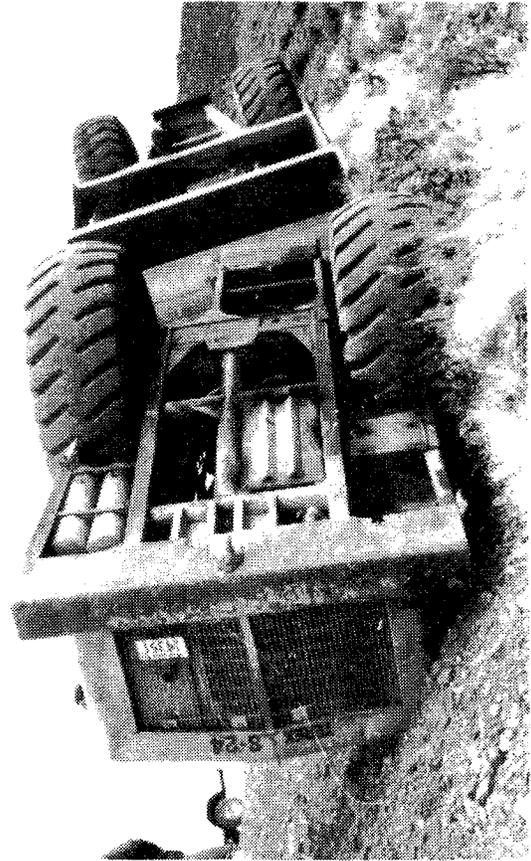
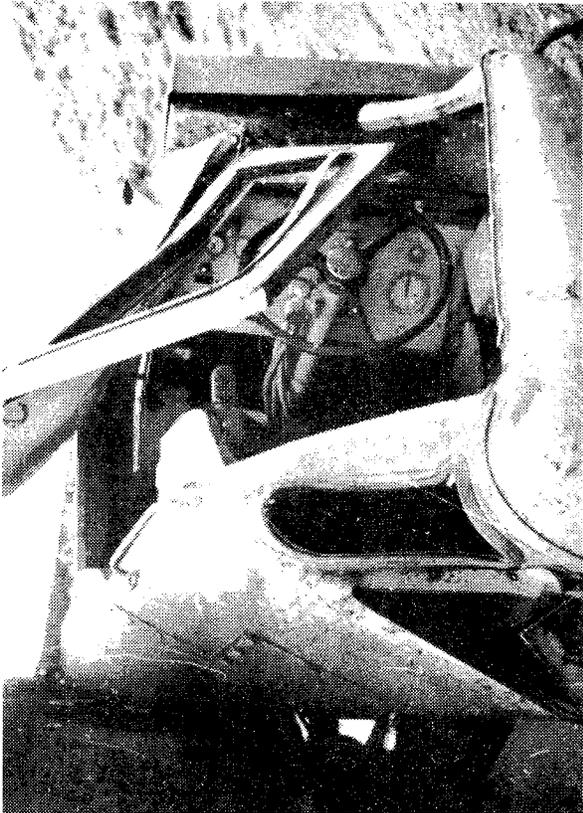


FIGURE I-1-1. Representative Rollover Photographs



FIGURE 1-1. Representative Rollover Photographs (Cont)

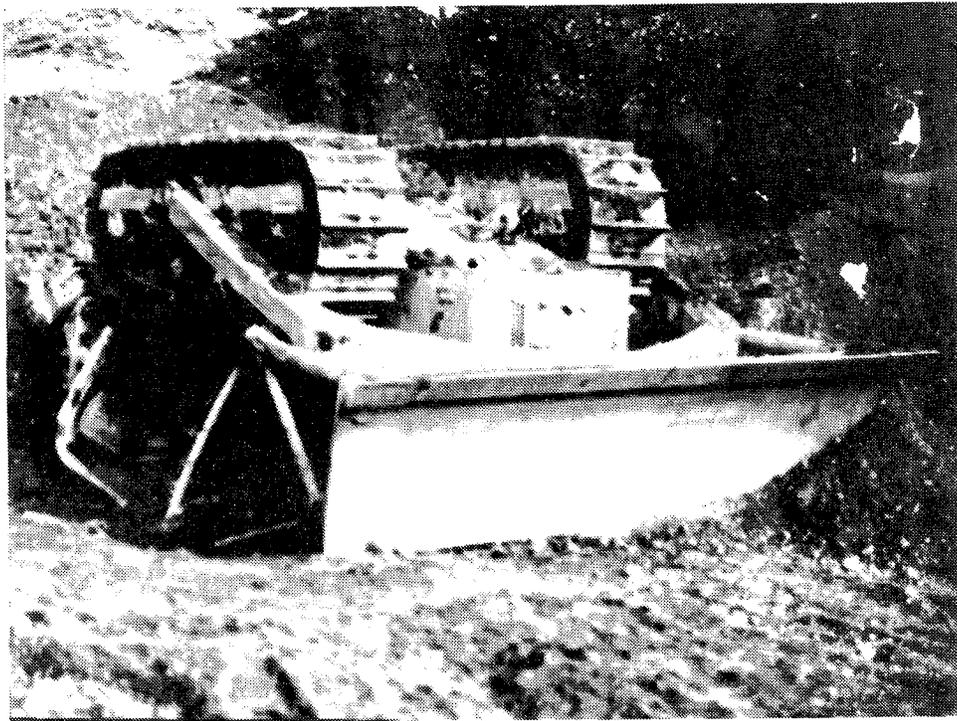


FIGURE 1-1. Representative Rollover Photographs (Cont)

- USBM Contract No. HO292020, "Development of ROPS Performance Criteria for Large Mobile Mining Equipment." (Provides for static and dynamic testing of ROPS for large wheel loaders to aid SAE in developing new performance requirements.)
- USBM Contract No. HO292006, "Development and Demonstration of an Omni-directional Fire Suppression System." (Developed fire suppression system that will function after machine rollover.)
- USBM Contract No. HO202005, "Development of Improved Seat Belt Systems for Surface Mining Equipment." (This project will address seat belt designs that are more desirable to machine operators.)
- USBM Contract No. HO308034, "Front-End Loader Training System." (Contains training material advocating the use of seat belts.)
- USBM Contract No. JO308008, "Research Study to Determine the Applicability of New Methodologies in Mine Accident Investigations." (Develops accident data gathering approaches that will produce more complete accident reports.)

SECTION 2.0

SUMMARY

A high percentage of certain types of mining, construction, earthmoving, agricultural, and forestry equipment is equipped with rollover protective structures. The types of mobile machines commonly equipped with rollover protective structures (ROPS) include crawler tractors and crawler loaders; motor graders; wheel loaders and tractors; skid-steer loaders; and the tractor portion of tractor-scrapers. It is not uncommon to observe off-highway haulage trucks and water trucks that have ROPS installed.

The widespread use of ROPS, in the United States, Canada, and other countries, is due to the relative recent awareness of the extent of accidental rollovers of mobile equipment during field use. The development and implementation of accident record collection and analysis activities at various government and private groups has helped determine the numbers of injuries and deaths due to machine rollovers. Federal and state safety agencies have promulgated regulations requiring the installation of ROPS and seat belts on these types of equipment in an attempt to reduce the numbers of injuries resulting from rollover accidents. Although these regulations require that the employer who owns the machine equip it with ROPS to provide a safer work environment for his employees, most of the manufacturers of the machines are installing ROPS on their machines before they are shipped to their dealers.

The ROPS regulations promulgated by the Occupational Safety and Health Administration (OSHA) in 1972, the Mine Safety and Health Administration (MSHA) in 1974 and 1977, by the state of California's Division of Industrial Safety (Cal-DIS) in 1970, and by several of the Canadian provinces base the ROPS structural performance capability on criteria developed by the Society of Automotive Engineers (SAE). It is recognized within the SAE technical committees responsible for developing ROPS performance criteria that, while these criteria are probably the best available, improvements are still possible and are, in fact, being introduced frequently.

The U.S. Bureau of Mines has assumed an increasing role in helping the mining industry raise the level of safety for mine workers. During the

past 10-15 years, the Bureau of Mines has been responsible for many technological advances that have provided increased safety for mining operations with no negative effects on mine productivity. This interest in mine worker safety has prompted the Bureau to investigate the field performance of rollover protective structures. This report summarizes the data gathered during 1979 and presents the author's opinions on the success of ROPS on mining and construction machines.

2.1 INFORMATION GATHERING

The primary goal of this study was to answer, within the limitations of the data available, the question, "Are ROPS providing adequate operator protection?" The answer to that question requires addressing many more specific questions which provide the information to answer the general question. Some of these specific questions are given below:

1. Have the numbers of deaths and injuries as a result of machine rollovers been reduced since the promulgation of ROPS regulations?
2. Is there information available describing the relative severity of injuries to the operators of machines with ROPS that are involved in accidental rollovers versus the operators of machines without ROPS that roll over?
3. Are there differences in the characteristics or severity of rollovers experienced by different types of machines?
4. What are the implications of machine operator reluctance to wear seat belts?
5. Do the SAE recommended practices that provide the ROPS performance criteria represent the structural capability of the ROPS being manufactured and installed on machines?
6. Does the size of the machine have any influence on the likelihood of a rollover accident?

Answers to these questions required that several different categories of information be gathered and analyzed. These data requirements were

generally divided into field accidental rollover reports and ROPS performance certification test results.

2.1.1 Field Accidental Rollover Reports

The sources of this information included OSHA and MSHA, the state of California's Division of Industrial Safety, British Columbia's Ministry of Mines and Petroleum Resources, the manufacturers of construction and mining machines, and labor unions.

Over 1,400 rollover accident reports were gathered covering a period from 1970 through 1979. Examination of these reports indicated that, in some instances, the same accident was reported by as many as four sources. For example, a fatality in a California mine would result in a report from MSHA, a report from Cal-DIS, a report from the labor union, and a report from the equipment manufacturer. To preclude an analysis situation where serious rollover accidents would be "overreported," each data source was treated as an independent data base. This ground rule reduced the number of accidents treated together in any single analysis, but, in retrospect, did not reduce the ability to draw conclusions from the accident data.

Since model specific information was not available from most of the accident reports, the influence of machine size on rollover severity could not be determined. This analysis was not attempted from the data available.

The accident data were most important in providing insight into the status of mobile equipment operator protection. The results of the accident analysis are presented later in this summary.

2.1.2 ROPS Performance Certification Test Results

At this time, the ROPS regulations in effect require verification of the structural performance capability of the ROPS by conducting a static test to assure that the ROPS can withstand a specified minimum level of side force and that it can absorb a minimum level of energy without deforming into the area that would be occupied by the machine operator. Additional requirements include a vertical load subjected to the top of the ROPS and assurance that the steel used in the ROPS meets certain material specifications. The SAE Recommended Practice J1040c (2) provides detailed instructions on how the

static loading of the ROPS shall be accomplished and how the minimum force and energy requirements shall be calculated. Prior to the publication of SAE J1040c in the 1980 SAE Handbook, other SAE recommended practices were used to guide the testing of ROPS. In fact, the OSHA and MSHA ROPS regulations specify which SAE recommended practice should be followed to assure strict compliance with their regulations.

A question was raised early in this study relative to the structural performance capability of ROPS. The question was stated as follows:

"If the accident data gathered indicates that ROPS designed to meet SAE criteria are successfully saving lives in roll-over accidents, does that assure us that the SAE criteria are producing ROPS with adequate structural performance?"

It was further speculated that current ROPS might be significantly "overdesigned" and that this "overdesign," or greater structural capability, was necessary to assure operator protection. If it was determined that ROPS were currently providing satisfactory operator protection, could this operator protection be diminished as the ROPS designers developed better analysis procedures, generated more comparative test data, and were able to reduce the structural capability of ROPS down to a smaller margin over the minimum performance required by the SAE criteria? After all, the stronger ROPS are usually heavier and the cost of manufacturing the ROPS is usually related to the weight of material used in the ROPS. Wouldn't there be a cost incentive to reduce the strength of the ROPS down to the minimum acceptable level? With the recent development of sophisticated finite element computer programs that are capable of inexpensively predicting the static test performance of ROPS, the ROPS designer is able to tailor the design of a ROPS for minimum cost and still be confident that it will successfully pass the static load tests.

This area was explored by requesting the results of static certification tests from the manufacturers of ROPS and from the manufacturers of the mining and construction equipment. The required information included the maximum expected gross weight of the machine, the minimum gross weight, the side force attained in the static test, and the SAE criteria used to guide

the design. The equipment industry was very responsive and provided data on over 400 static tests. These data are analyzed later in this summary.

2.2 DATA ANALYSIS

As mentioned earlier, the accident data received from the different sources was analyzed independently. The quality of the reports received varied widely in detail and completeness. Some sources provided great detail on the description of the accident area but little detail on the description of the rollover or the machine involved. Many did not comment on the use or nonuse of seat belts by the operator. The ROPS manufacturer was rarely identified; similarly, the ROPS performance certification information was almost never given. (Every ROPS is required to have a certification tag or label permanently affixed to the ROPS.) In general, the ROPS reports were lacking in the detail necessary to perform useful statistical analyses.

A series of graphs and tables have been prepared to illustrate the useful data derived from the accident reports. Table 2-1 presents a comparison of the injury severity resulting from rollover accidents involving machines with ROPS and machines without ROPS. In interpreting this table, the reader is cautioned to reflect on a few possible circumstances that might influence the data presented. First, it is probable that a great many rollover accidents that do not result in injury to the operator are not reported to any of the sources that provided reports to Woodward Associates, Inc. Interviews with mining and construction firms suggest that if a machine "tips over" and no one is injured, it is simply "righted," checked for damage to assure that it is operable, and then placed back in service. It might be speculated that this type of "safe" rollover occurs more frequently with ROPS-equipped machines than non-ROPS machines simply because, in even a minor rollover, the probability of the operator being injured on a non-ROPS equipped machine is greater. After all, ROPS are supposed to protect the operator! Thus, it is probably not accurate to examine Table 2-1 and conclude that 14.7% of the rollovers with ROPS-equipped machines resulted in fatalities. Fatalities do occur in accidents with ROPS-equipped machines, but the percentage is probably much lower than Table 2-1 indicates. Similarly, it is probably not true that 48.5% of the rollover accidents in which machines

TABLE 2-1. ROPS Effectiveness in Earthmoving Equipment Rollovers

	Machines Equipped With ROPS (102 Accidents)	Machines Not Equipped With ROPS (101 Accidents)	Machines ROPS Status Unknown (28 Accidents)
No injury	37.3%	13.9%	35.7%
Minor injury	25.5%	13.9%	10.7%
Major injury	18.6%	21.8%	14.3%
Fatalities	14.7%	48.5%	21.4%
Unknown	3.9%	1.9%	17.9%
Total	100.0%	100.0%	100.0%

without ROPS are involved result in fatalities. However, it may be that the relative numbers of fatalities on machines with and without ROPS is also misleading. The figures in Table 2-1 suggest that fatalities occur about 3.3 times as frequently on non-ROPS machines as on ROPS-equipped machines. This may understate the safety contribution of ROPS. More accidents with ROPS may go unreported than accidents without ROPS since the operator is more likely to be injured in a machine rollover without ROPS. It might be said that ROPS usage has cut the frequency of rollover fatalities to less than one-third the frequency in machines without ROPS. And most likely the reduction has even been more!

Another interesting facet of the data presented in Table 2-1 is that 14 of the 16 fatalities occurring on ROPS-equipped machines were not using their seat belts. One of the two others was crushed when the ROPS collapsed. It is not known if he was wearing his seat belt. It probably would not have helped. In the other 14 accidents, seat belt usage might have saved several, if not all, of the machine operators.

Figures 2-1, 2-2, and 2-3 present histograms comparing the number of rollover revolutions experienced in the rollover accident. All of these rollovers were with crawler tractors. Figure 2-1 suggests that a significant

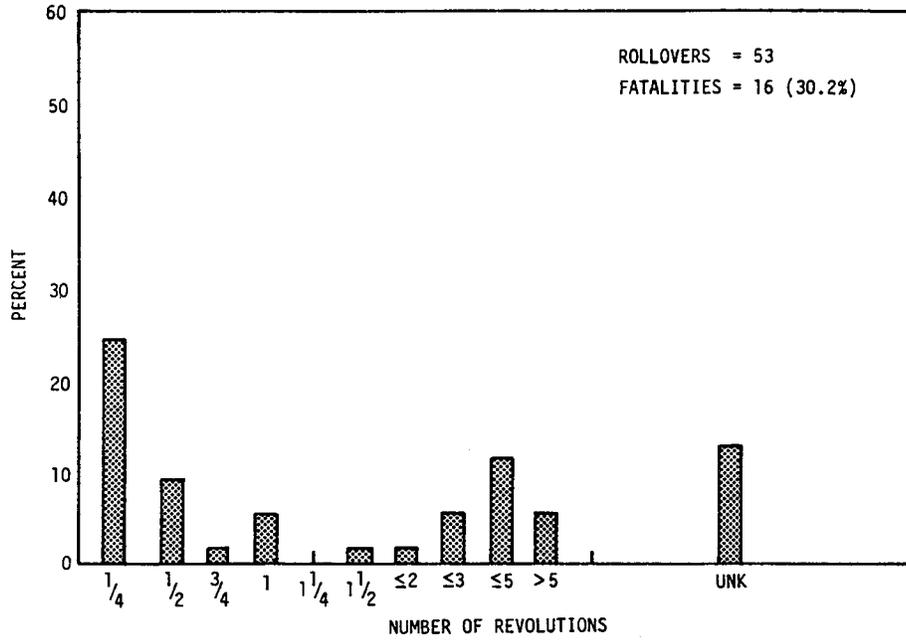


FIGURE 2-1. Roll Revolutions, Crawler Tractors

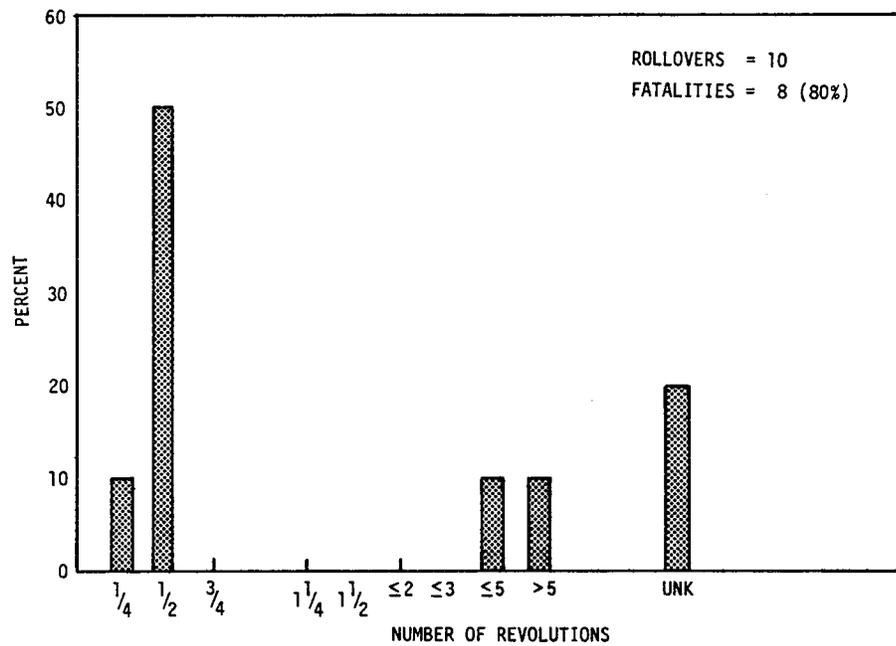


FIGURE 2-2. Roll Revolutions, Crawler Tractors Without ROPS

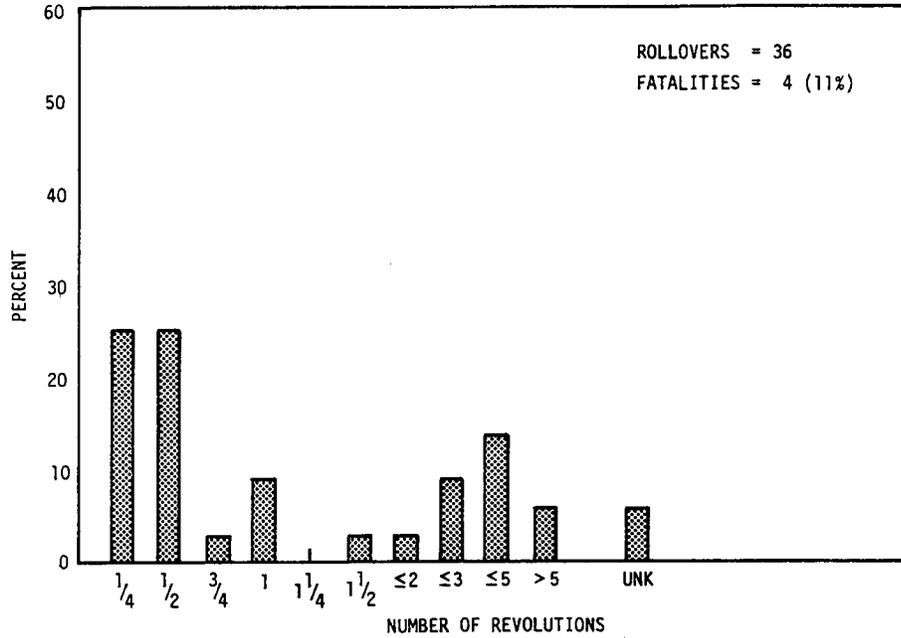


FIGURE 2-3. Roll Revolutions, Crawler Tractors With ROPS

number (26.5%) of the accidents involved rollovers of greater than one revolution (360°). It also suggests that 5.7% of these crawler tractor rollovers completed over five revolutions. Again, as with all the accident data analyzed, the unreported accidents could influence the relative percentages for each number of revolutions category. Figure 2-2 presents information on 10 rollovers of crawler tractors without ROPS. As is noted, 8 of these resulted in fatalities. Figure 2-3 presents information on 36 rollovers of crawler tractors with ROPS. Here, only 4 resulted in fatalities, a significant reduction in fatalities per rollover.

Figures 2-4, 2-5, and 2-6 present similar information on wheel loaders. It is interesting to compare the relative frequency of rollovers greater than one revolution experienced with wheel loaders (6.8%) with crawler tractors (26.5%). Does this information indicate that the ROPS structural performance capability should anticipate more severe rollovers for crawler tractors than for wheel loaders? The answer to that question is yes. There does not seem to be any rationale that would support the contention that all types of machines, regardless of configuration and work practices, would

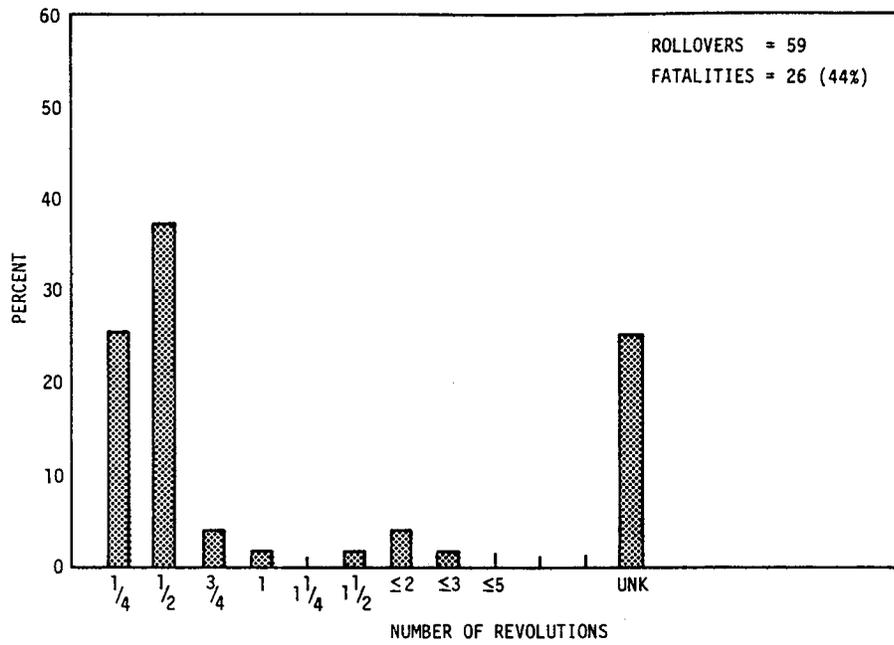


FIGURE 2-4. Roll Revolutions, Wheel Loaders

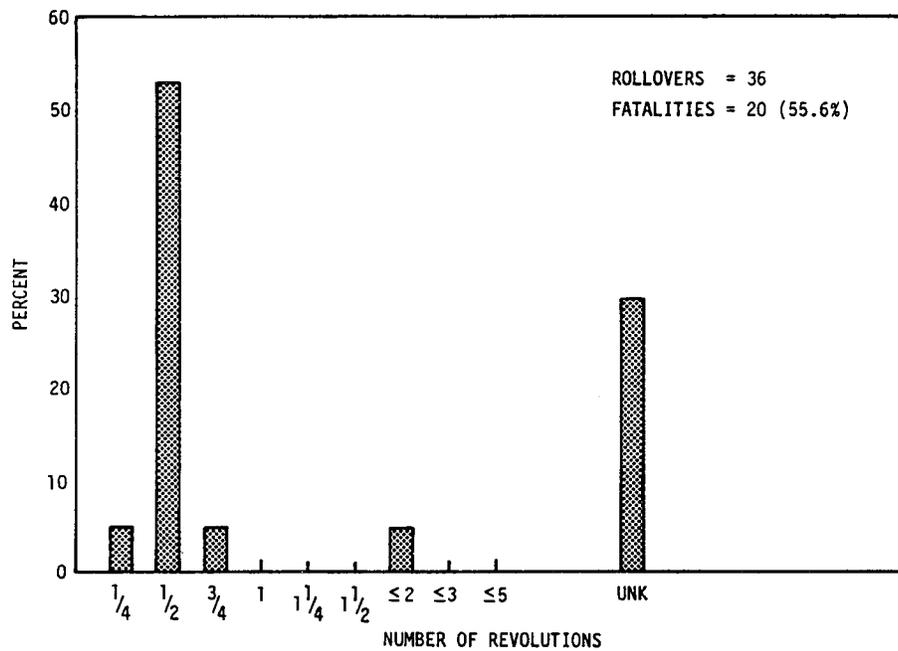


FIGURE 2-5. Roll Revolutions, Wheel Loaders Without ROPS

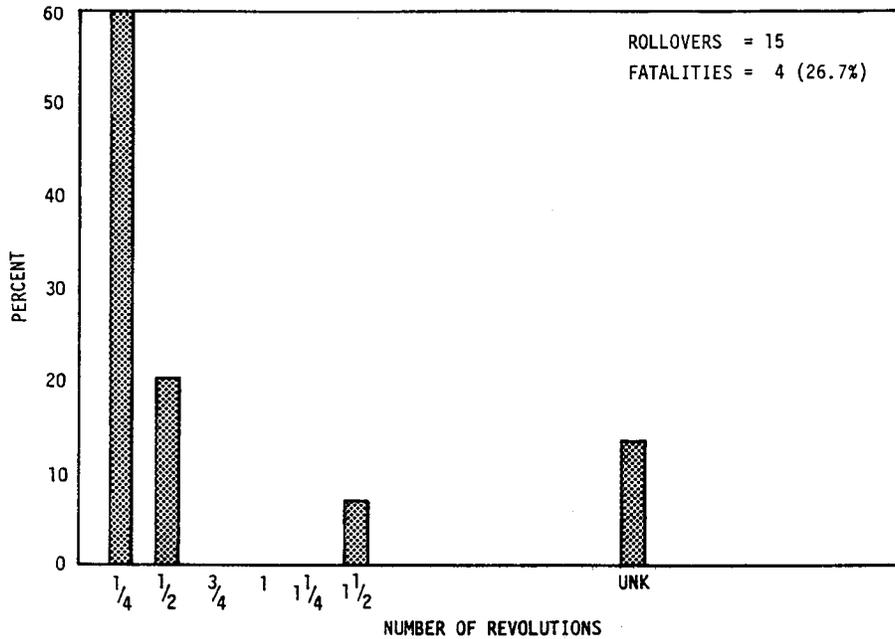


FIGURE 2-6. Roll Revolutions, Wheel Loaders With ROPS

experience the same rollover conditions. Some machines, and crawler tractors are a good example, work in field environments that could likely lead to multi-revolution rollovers while other machines, motor graders and rollers are examples, customarily work in field environments that reduce the likelihood of multi-revolution rollovers.

Figure 2-7 illustrates the reduction in fatalities due to rollover accidents in California between the years 1960 and 1978. California first introduced ROPS regulations for some machines in 1966 and increased the types of machines for which ROPS were required in the following years. Today, ROPS are required on most of the construction and mining machines manufactured since 1960. Almost all of these types of machines in use in California have had ROPS installed. The reduction in fatalities is dramatic. It appears that 17 or 18 fatalities per year were being experienced prior to the promulgation of ROPS requirements and that today's rate has been reduced to the 3-5 fatalities per year level.

Figures 2-8 and 2-9 present the rollover fatalities per year experienced in U.S. coal mines and metal/nonmetal mines. It is difficult to draw

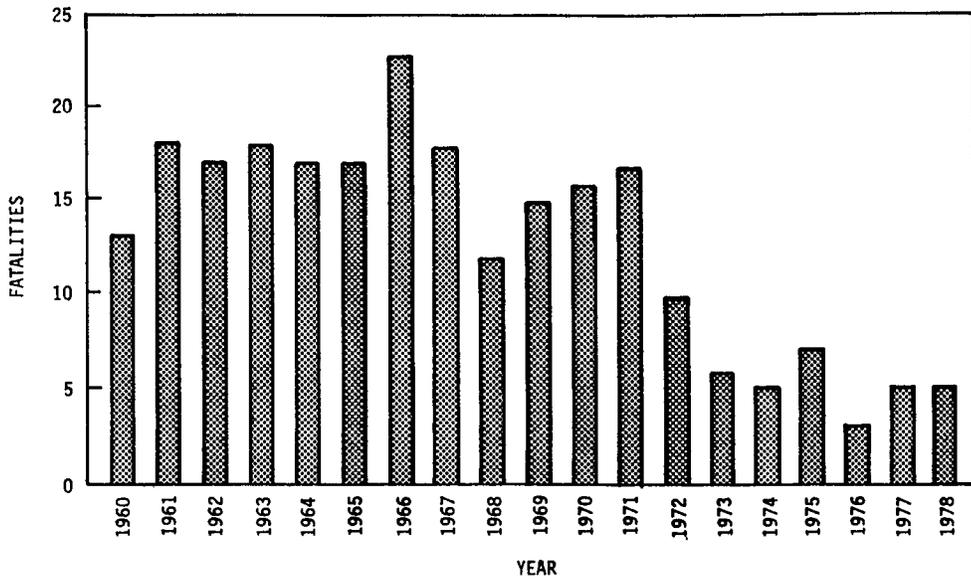


FIGURE 2-7. State of California Rollover Fatalities by Year (Earthmoving Equipment)

any clear conclusions from these figures. An MSHA regulation requiring ROPS on machines used in coal mines was promulgated in 1974; a similar MSHA regulation was promulgated for metal/nonmetal mines in 1977. The OSHA ROPS regulations promulgated in 1972 may mask the effect of the MSHA regulations. Many manufacturers started equipping their machines with ROPS as a standard item rather than as an option in the early 1970s. These figures do seem to indicate that rollover fatalities are being reduced in the mining industry.

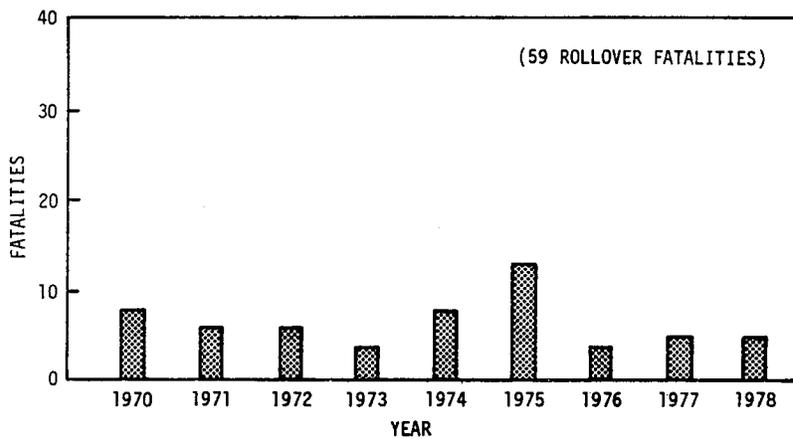


FIGURE 2-8. Rollover Fatalities by Year, Coal Mines (1970-1978)

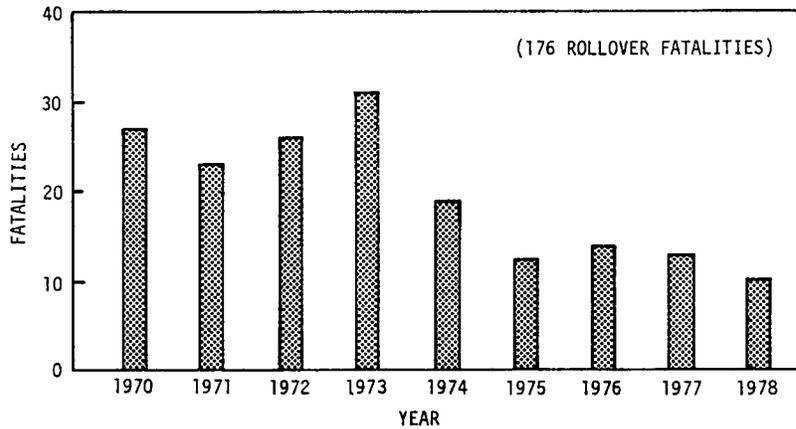


FIGURE 2-9. Rollover Fatalities by Year,
Metal/Nonmetal Mines (1970-1978)

During the review of rollover accident reports, special attention was given to examining reports that described an accident in which the ROPS had failed to protect the machine operator. It was soon evident that, in most cases, where an operator was killed or injured in a rollover involving a ROPS-equipped machine, the operator had attempted to jump or had been thrown from his machine. He may have partly exited from the machine only to have a part of the ROPS catch him and crush him into the ground, or he might have been thrown clear on the downhill direction only to have the machine catch up and roll over him. In most incidents of this type, the ROPS sustained little damage and it could be speculated that, if the operator had been constrained within the protective volume provided by the ROPS, the severity of the injuries received would have been lowered. Increased use of seat belts in ROPS-equipped machines should have a very positive effect on the potential survival of operators involved in rollover accidents. In previous studies for OSHA and the Bureau of Mines (3,4,5), Woodward Associates, Inc. has conducted field surveys to determine the extent of seat belt use by machine operators. With some encouraging exceptions, most mining operations and construction operations are not able to cause their machine operators to wear their seat belts.

There are accidents when the ROPS has failed to protect the operator because of structural failure. Of the over 1,400 accident reports reviewed, about 15 ROPS failures have been noted. Due to the incompleteness of several

of these reports, it is not possible to definitely state that all 15 of these structural failures involved ROPS designed to meet accepted performance standards. It is possible, from the descriptions given in the accident reports, that two or three of these failures were to "canopies" that met no ROPS performance criteria and that were really just "strong weather canopies." It is also fact that at least three of these failures were ROPS that were designed to meet ROPS performance criteria other than the SAE recommended practices. In fact, none of the failed ROPS were clearly identified as ROPS meeting SAE standards. Of the six ROPS failures where the manufacturer of the ROPS was clearly identified, four had one thing in common. These four were all manufactured by the same manufacturer. These four ROPS failures resulted in the deaths of five employees (one accident killed three employees) and the serious permanent disability of a sixth employee. In one of the accidents involving this company's ROPS, Woodward Associates, Inc. personnel conducted an in-depth analysis of the accident for a private industry client. The accident site was visited, the failed ROPS was examined, metallurgical laboratory test reports reviewed, videotape taken at the accident scene during removal of the victims viewed, and engineering calculations of the ROPS performance capability conducted. It appears that, in addition to incorrect engineering assumptions and poor design practices, the fabrication of the ROPS was unsatisfactory. Inadequate weld penetration at critical structural joints produced a ROPS with structural capabilities far below the required levels. This ROPS did not have the structural integrity to provide even minimal operator protection.

2.3 STATIC CERTIFICATION TEST DATA ANALYSIS

As mentioned earlier, a question had been posed as to the extent that current ROPS designs exceeded the SAE performance requirements. The static test data received from the manufacturers were used to obtain an indication of the "overdesign" or margin designed into ROPS in use on today's machines.

The static side force capability of the ROPS is used by SAE ROPS performance standards as an analog of the ROPS' ability to sustain the dynamic loads received during a rollover. The equations that provide the side force requirements given in SAE performance criteria use the machine's maximum

expected mass as a variable and thus produce the requirement that ROPS on heavy machines have higher side force capabilities than ROPS used on lighter machines. The different generic type machines have different side force equations because of the differences in expected machine behavior in a "standard" rollover. As stated in SAE J1040c:

"Although ROPS meeting these criteria may not give crush protection under all conceivable circumstances in which a machine could overturn, it is expected that crush protection will be assured under at least the following condition: An initial forward velocity of 0-16 km/h (0-10 mph) on a hard clay surface of 30 deg maximum slope, 360 deg of roll about the machine's longitudinal axis without losing contact with the slope."*

Examples of the relationship between machine mass and side force capability requirements given in SAE J1040c are shown in Figures 2-10 and 2-11. Figure 2-10 describes the side force versus machine mass relationship for crawler tractors and Figure 2-11 presents this relationship for motor graders. (Appendix B contains side force, side energy, and top force relationships for all SAE recommended practices.)

The static test information received from the equipment manufacturers was compiled to determine the following information on each static test:

1. Maximum Recommended Machine Mass — This represents the maximum machine mass that is anticipated by the ROPS designer in preparing the ROPS design for this specific model of machine. It does not include soil, mud, rocks, limbs, debris, etc., that commonly adhere to or lay on machines in actual use. It does anticipate the use of various optional attachments that may increase the mass of the "bare" machine.
2. Minimum Possible Machine Mass — This represents the mass of a machine without optional attachments. It is usually the mass of a "bare" machine.

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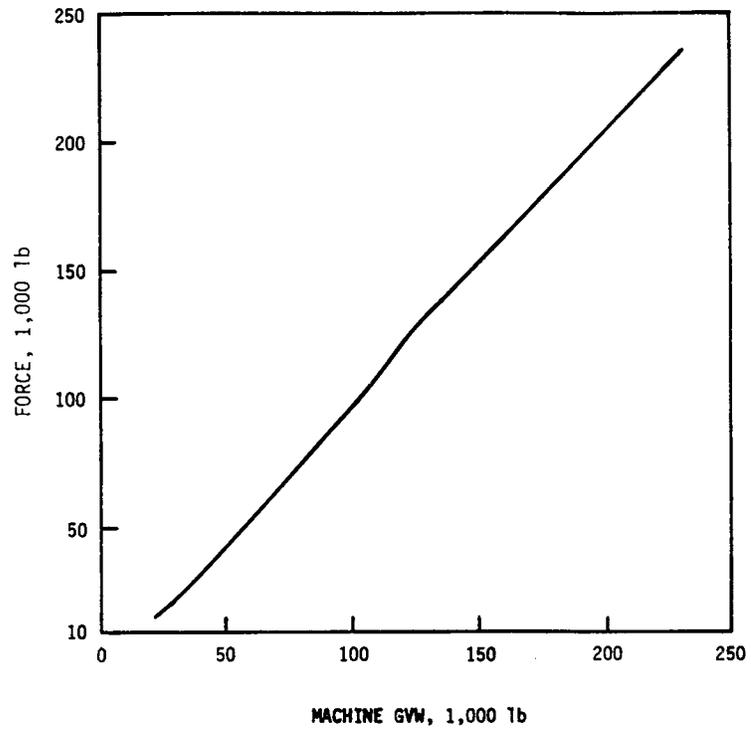


FIGURE 2-10. Crawler Dozer and Loader ROPS Performance Criteria (SAE J1040c)

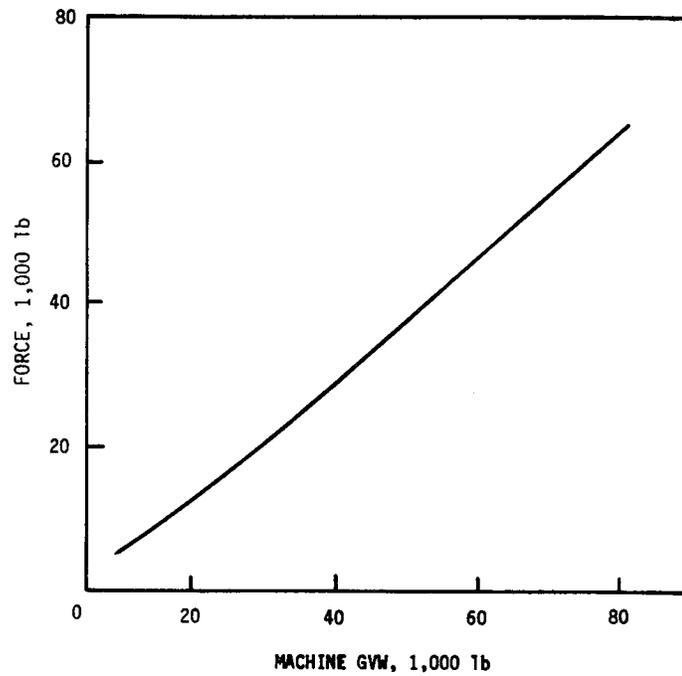


FIGURE 2-11. Motor Graders ROPS Performance Criteria (SAE J1040c)

3. Maximum Side Force Attained in Static Test – This is the maximum side load experienced by the ROPS during the static test.
4. Minimum Acceptable Side Force Requirement (Maximum Gross Vehicle Weight) – This is the minimum side load that must be attained to satisfy the SAE ROPS criteria for the maximum recommended machine mass.
5. Minimum Acceptable Side Force Requirement (Minimum Gross Vehicle Weight) – This is the minimum side load that must be attained to satisfy the SAE ROPS criteria for the minimum possible machine mass.

These values were compiled and aggregated for the 404 static tests to reveal the following information:

1. Assuming that all machines actually in use in the field had machine masses equal to the Maximum Recommended Machine Mass:
 - a. 70% of the ROPS designs exceeded the SAE side load requirement by at least 20%.
 - b. 50% of the ROPS designs exceeded the SAE side load requirement by at least 40%.
 - c. 15% of the ROPS designs exceeded the SAE side load requirement by at least 100%.
2. Assuming that all machines actually in use in the field had machine masses equal to the Minimum Possible Machine Mass:
 - a. 90% of the ROPS designs exceeded the SAE side load requirement by at least 20%.
 - b. 85% of the ROPS designs exceeded the SAE side load requirement by at least 40%.
 - c. 70% of the ROPS designs exceeded the SAE side load requirement by at least 70%.

- d. 50% of the ROPS designs exceeded the SAE side load requirement by at least 110%.
- e. 15% of the ROPS designs exceeded the SAE side load requirement by at least 210%.

Clearly, neither of the above assumptions correctly reflects the actual masses of machines in use. Some machines have very few attachments and approach the minimum mass and some machines have been outfitted with heavy attachments and approach the maximum recommended mass. It could be speculated that a reasonable expectation of the actual representation of the field situation is that perhaps 75% of the ROPS designs in the field exceed the SAE requirements for the machine on which they are mounted by at least 40%. And perhaps 50% of the ROPS in the field exceed the SAE requirements by at least 70%. During this compilation, many ROPS designs were reviewed that had very high side load capability; some exceeded the SAE requirement by as much as 300-400%.

The SAE ROPS performance criteria also require demonstration of the energy absorption capability of the ROPS. This requirement is similar to the side load requirement in that it increases with increasing machine mass. The energy absorption "overdesign" could be examined in the same manner as side load capability if the ROPS were side loaded to the point where the ROPS started to invade the Deflection Limiting Volume. It is industry practice to apply the side load until the required energy is attained (with perhaps 5% overtest) and then stop. In many tests the ROPS is still several inches from the Deflection Limiting Volume. It is also true that, in many static tests, the maximum side force attained is not the maximum side force that could be attained if the side loading was continued. This fact adds more margin to the ROPS design capabilities mentioned earlier.

2.4 CONCLUSIONS

The above information provides a basis with which to attempt to answer some of the questions posed earlier in this summary. The author's opinions can be stated as follows:

1. ROPS do the job for which they are intended. There has been a significant reduction in deaths due to mining and construction machine rollovers.
2. Many ROPS designs currently in use on equipment in the field have structural performance capabilities that significantly exceed the requirements given in SAE recommended practices. This industry practice may have a positive influence on the excellent life-saving record of ROPS.
3. This study was unable to confirm the adequacy of the structural performance criteria presented in SAE recommended practices. As stated in conclusion 2 above, the performance of ROPS that are saving lives in the mining and construction industries exceeds the minimum SAE requirements by significant margins. It is possible that ROPS designed to exactly meet the SAE recommended practices would provide less satisfactory operator protection.
4. If machine operators can be persuaded to wear their seat belts and stay with the ROPS-equipped machine, their chances of surviving an accidental rollover are many times greater than if they attempt to jump or if they are thrown off the machine.
5. Different types of machines have been shown to experience different severities of rollover. The general characteristics of rollovers for different generic types of machines can vary widely from one machine type to another. There is a different "typical" or

"standard" rollover for each type of machine and perhaps some differences within some generic types. Perhaps the ROPS performance criteria should be based on protecting the machine operator in a high percentage (say 95%) of the possible rollover accidents for each generic class of machine. No information is available to indicate that different sizes of machines within a given generic class experience different rollover characteristics or different rollover potentials. This is not to say that some specific models of machines are not more likely to roll over than other models.

6. As with any product, there are some manufacturers that do not follow sound engineering and fabrication practices and that produce a product that does not measure up to industry standards. This is unfortunate; it appears that several lives have been lost because of an inferior product. It is encouraging, however, to observe the general high level of engineering practice and manufacturing quality demonstrated by the manufacturers of ROPS.

2.5 RECOMMENDATIONS

The recommendations for future actions, activities, etc., are divided into those directed at the Bureau of Mines, the Mine Safety and Health Administration, and the Society of Automotive Engineers, Inc. These recommendations draw from experience and information gathered during operator protection studies conducted over the past ten years as well as information gathered during the performance of this study.

2.5.1 Recommendations to the Bureau of Mines

1. Continue efforts to increase the acceptability and use of seat belts in surface mining equipment. This area of effort has great potential for reducing deaths and

injuries in rollover accidents. This activity can be readily divided into two major endeavors. The first is the design, development and demonstration of seat belts that possess characteristics that make the wearing of them more desirable to the machine operators. The second activity to continue is the inclusion of seat belt benefit training in the equipment operator training programs being developed by the Bureau of Mines.

2. Continue investigations into the ROPS structural degradation problems brought about by vibration-induced fatigue. Attempt to define design approaches that minimize this potential problem.
3. Encourage MSHA and OSHA to gather detailed information on accidental rollovers. Monitor the accident data carefully to determine if increases in ROPS failures begin to occur.

2.5.2 Recommendations to the Mine Safety and Health Administration

1. Encourage MSHA field personnel to become more knowledgeable in ROPS. Use the USBM ROPS Field Inspection Manual to aid in examining ROPS at mining operations.
2. Consider updating the ROPS regulations to make the requirements for coal mines consistent with the requirements for noncoal mines. Evaluate the benefits of developing new ROPS regulations that require ROPS with higher levels of structural performance.
3. Gather detailed information on accidental rollovers of mining machines. Be alert for increases in the frequency of ROPS structural failures.

2.5.3 Recommendations to the Society of Automotive Engineers, Inc.

1. Conduct an analysis and review of the results of this survey project, coupled with the results of other ongoing

USBM ROPS research projects, and modify the existing ROPS recommended practices to more accurately reflect rollover accident experience.

If necessary, prevail upon the equipment manufacturers and, if practical, government agencies such as OSHA to gather more empirical rollover data through the conduct of rollover tests on "standard" roll hills.

2. Prepare an Information Report that discusses the potential vibration-induced fatigue problem and suggests some of the approaches to reducing the probability of fatigue failures.

SECTION 3.0

ROLLOVER ACCIDENT REPORTS

The information needed to provide answers to the many questions asked about the effectiveness and adequacy of ROPS regulations falls into two general classifications. The first general area, and most important to the performance of this study, was the area of reports covering accidental rollovers of machines in the field. The second area of information needed for this study was the results of ROPS structural performance testing conducted by the manufacturers of ROPS.

3.1 FIELD REPORTS OF ACCIDENTAL ROLLOVERS — DATA ACQUISITION AND ANALYSIS

At the outset of this study, the acquisition of large numbers of field accidental rollover reports was identified as important in formulating answers to several of the questions posed by government and industry personnel. The following list illustrates the types of questions that could be answered through analysis of rollover accident reports:

1. Have there been significant reductions in the deaths and injuries resulting from rollovers because of ROPS regulations?
2. Do the ROPS performance guidelines prepared by SAE provide adequate operator protection?
3. Are there differences in the characteristics of accidental rollovers of different types of machines?
4. Does the size of a machine affect the likelihood or the severity of an accidental rollover?
5. Do machine operators experiencing accidental rollovers in machines fitted with ROPS receive less severe injuries than those in accidents in machines without ROPS?
6. Are there accidents where ROPS create safety problems?
7. Do machine operators wear the seat belts?
8. Do seat belts fail in rollover accidents?

9. Are there types of machines, in addition to those currently required to have ROPS, that should also be required to have ROPS installed?
10. Does anything happen to a ROPS during machine use that reduces its capability to provide operator protection?

These questions, and others closely related, can be distilled to a simple general question. "Are ROPS providing adequate operator protection and are there things that could be done to improve operator protection?"

In order to gather the maximum number of accidental rollover reports for future analyses, Woodward Associates, Inc. solicited information from a broad spectrum of potential sources. These sources included public agencies such as the Health and Safety Analysis Center (HSAC) of the Mine Safety and Health Administration (MSHA), the Occupational Safety and Health Administration (OSHA), and the State of California's Division of Industrial Safety (Cal-DIS). Private sources including the Construction Industry Manufacturers Association (CIMA), the Society of Automotive Engineers (SAE), various manufacturers of construction and mining equipment and of ROPS, and the Woodward Associates, Inc. accident record files. A condition placed on Woodward Associates, Inc. by several of the private sources concerned the maintenance of confidentiality as to specific identification of manufacturer and model number of the machine involved in the accidental rollover. This requirement presented no handicap; all data from all sources were treated in the aggregate.

In all, over 1,400 accidental rollover reports were reviewed during this study. These represented accidents occurring between 1970 and 1979. Early in the review of accident reports it became evident that some accidents were reported by more than one source. This was especially true for accidents resulting in fatalities. The reporting of the same accident by more than one source allowed comparison between reports and often resulted in gaining additional information on the accident circumstances.

While the MSHA-HSAC offices have very complete accident reports on all types of mining accidents, the reports from this group have very little detail on rollover characteristics important to this study. The rollover

accident data provided by some of the equipment manufacturers contained the needed detail on various pertinent characteristics of the rollovers.

Requests to OSHA for accident data produced nothing. It was discouraging to find that the federal government agency that first required ROPS installations on construction machines on a nationwide basis, and is undoubtedly involved in the investigation of many rollover accidents in the construction industry, does not seem to have a workable system to readily retrieve accident information.

Accident reports from labor unions were especially interesting in presenting added detail through witness narratives. Similarly, information revealed in product liability suits concerning rollover of machines with and without ROPS has added much detail to certain accident reports.

To prevent the "overcounting" of rollover accidents that were reported by two or more sources, the accident reports received from each source were maintained in separate data bases. The total number of rollover accidents in any single analysis was limited by this approach and further limited by the fact that some of the accidents submitted were not usable because of missing information on specific rollover characteristics. Relatively few reports contained all of the information desired. Missing information included the model of the machine involved, the size of the machine involved, the number of revolutions, the condition of the ROPS after the rollover, a description of the slope the roll occurred on and, sometimes, whether there was any type of protective structure installed. These inadequacies in the data have implications as to the statistical validity of the analyses complete; the conclusions reached and the analyses displayed in this report are "semiquantitative" at best and, in some areas are the qualitative judgment of the author. The following paragraphs present information that attempts to answer the questions posed earlier in this section of this report.

Question 1 — Have there been significant reductions in the deaths and injuries resulting from rollovers because of ROPS regulations?

The answer to this question is a definite "yes." The best illustration of a reduction of fatalities due to rollovers was found in examining accident reports and information received from Mr. Kevin O'Gara and Ms. Sara Behman

of California's Division of Labor Statistics and Research. A summary of the California experience is given in Figure 3-1.

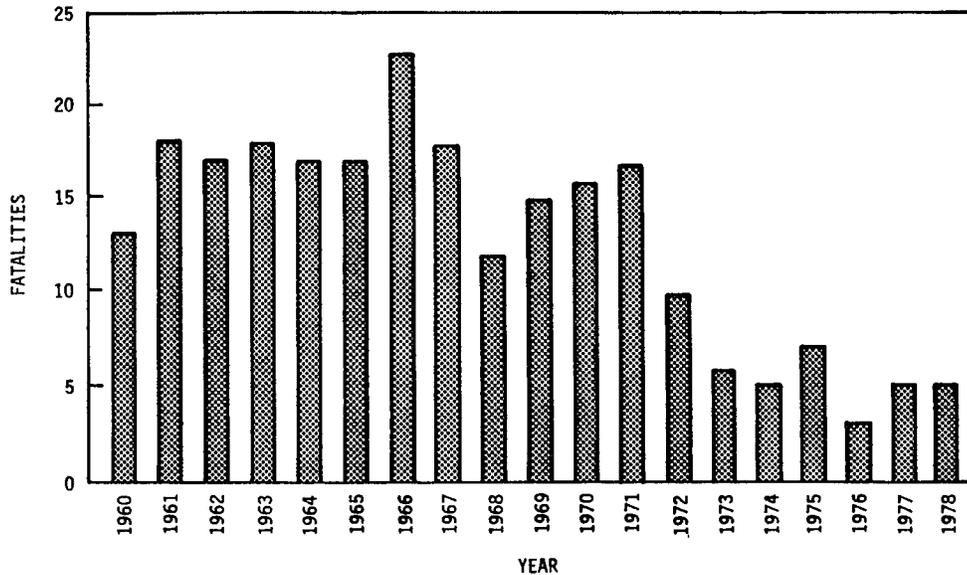


FIGURE 3-1. State of California Rollover Fatalities by Year (Earthmoving Equipment)

The state of California has led the United States in requiring ROPS and seat belts on earthmoving equipment. California first introduced regulations requiring ROPS and seat belts on scrapers and front-end loaders in 1966. Earlier regulations required operator protection on crawlers used in brush clearing and pioneering operations. In the years following 1966, California increased their requirements for ROPS to include additional types of machines and to cover machines manufactured after 1960. A high percentage of the earthmoving machines operating in California are equipped with ROPS. As can be seen in the figure, there has been a very significant reduction in fatalities resulting from rollover accidents. The 1973-1978 yearly fatality average is approximately one-third of the yearly fatality average for 1960-1972. California's Division of Industrial Safety is pleased with this success and is of the opinion that increased use of seat belts would result in even lower fatality figures.

The effect of ROPS in reducing fatalities in mining operations in the United States is not as clear as the California history. The OSHA ROPS

regulation was promulgated in 1972 and many manufacturers had, through responsiveness to the California requirements, already been fitting their equipment with ROPS or offering ROPS as safety options. These two actions resulted in the installation of ROPS on many machines entering mining operations. When ROPS regulations were promulgated for coal mining operations in 1974 and for metal/nonmetal mining operations in 1977, the effect was largely a retrofit requirement. Most new earthmoving equipment in use in those mines already had ROPS as standard equipment. Figures 3-2 and 3-3 present the rollover fatalities per year experienced in U.S. coal and metal/nonmetal mines. The reduction of fatalities is not as dramatic as was the

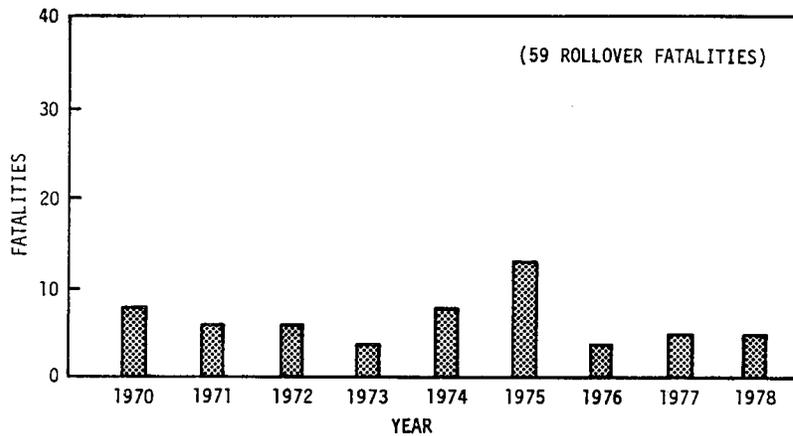


FIGURE 3-2. Rollover Fatalities by Year, Coal Mines (1970-1978)

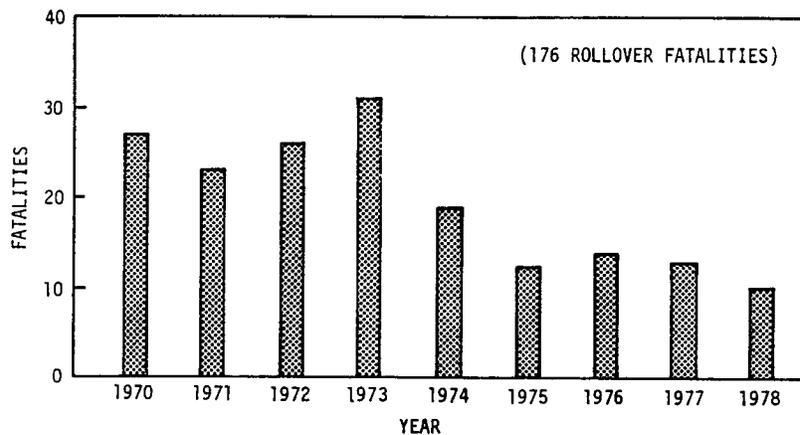


FIGURE 3-3. Rollover Fatalities by Year, Metal/Nonmetal Mines (1970-1978)

case with California. It does appear that the general trend is for a reduction in rollover accident fatalities. Again, increased use of seat belts would further reduce the yearly fatalities.

These figures indicate a higher number of rollover fatalities is experienced in metal/nonmetal mines than in coal mines. The reason for this is not immediately evident. Though information is available on the population of earthmoving machines in use in U.S. coal mines, similar information on machines in use in metal/nonmetal mines is not available. It may be that the numbers of rollover fatalities reflect the numbers of machines in use. The exposure to rollover in metal/nonmetal mines may be greater simply because more machines are in operation. It is also possible that a different circumstance exists. Perhaps the work practices and the work areas in some types of metal/nonmetal mines present the opportunity for more severe rollovers. Though no data was gathered to support a conclusion that the rollover hazard is greater at any particular mine type, readers familiar with mining practices will probably agree that the work areas of large open pit metal mines appear to present more rollover hazards than the typical strip coal mine.

Question 2 — Do the ROPS performance guidelines prepared by SAE provide adequate operator protection?

The rollover accident reports gathered during this project resulted in the identification of 15 accidents where it appears that the ROPS failed to protect the operator because of structural failure. It is probable that several of these failures were to sunshades, weather canopies, or other similar structures that were not true rollover protective structures. The information presented in the accident reports is insufficient to accurately determine if the "canopy" is a ROPS and if so, what type of ROPS. At least three of the failures were definitely to ROPS that were designed to meet the Corps of Engineers performance criteria. In fact, none of the ROPS that failed resulting in death or injury to the machine operator were clearly a ROPS designed to meet the SAE standards. In an accident involving a 1978 crawler tractor, the ROPS cab sheared off the tractor and remained intact. The operator was thrown out and injured. The newness of the tractor suggests that it was fitted with a design tested to meet SAE performance criteria but the report does not specify the ROPS type. The only certain incident of an

SAE ROPS failure was in an accident experienced by a front-end loader. The operator was not in the machine when it rolled and therefore received no injuries. The ROPS collapsed during the roll; if an operator had been in the machine it is likely he would have received serious injuries or have been killed.

It appears that the ROPS that have been designed to meet SAE performance criteria are providing adequate operator protection. There is no evidence to contradict this position. The reader is advised to study Section 4.0 of this report entitled "ROPS Structural Performance Tests" for more discussion on a different aspect of this position.

It is not true that ROPS designed to meet Corps of Engineers ROPS performance criteria have an untarnished record. As previously mentioned, at least three ROPS failures were to ROPS designed and certified as a Corps of Engineers ROPS. It is probable that at least three more of the ROPS failures were to Corps of Engineers ROPS. Of the six ROPS failures where the manufacturer of the ROPS was clearly identified, four had one thing in common. These four were all manufactured by the same manufacturer. These four ROPS failures resulted in the deaths of five employees (one accident killed three employees) and the serious permanent disability of a sixth employee. In one of the accidents involving this company's ROPS, Woodward Associates, Inc. personnel conducted an in-depth analysis of the accident for a private industry client. The accident site was visited, the failed ROPS was examined, metallurgical laboratory test reports reviewed, videotape taken at the accident scene during removal of the victims viewed, and engineering calculations of the ROPS performance capability conducted. It appears that, in addition to incorrect engineering assumptions and poor design practices, the fabrication of the ROPS was unsatisfactory. Inadequate weld penetration at critical structural joints produced a ROPS with structural capabilities far below the required levels. This ROPS did not have the structural integrity to provide even minimal operator protection.

These failures to ROPS designed to meet Corps of Engineers performance criteria do not suggest that the performance criteria are inadequate. Indeed, if correctly designed to meet the Corps of Engineers criteria, these ROPS could provide better operator protection than ROPS designed to meet SAE ROPS

criteria. A major difference between the Corps of Engineers requirements and the SAE recommended practice is in the area of demonstrating compliance with the requirement. The Corps of Engineers requirement states that the ROPS must have specific structural performance capabilities; no testing is required. The SAE requirement defines a static test procedure for verifying the performance capability. A prototype ROPS must be subjected to the static tests and must successfully demonstrate the load carrying capability. Engineering design or computational errors that produce an inferior ROPS would be discovered during the static load test. Errors in designing a Corps of Engineers ROPS are not discovered until a rollover accident.

With any ROPS, be it Corps of Engineers or SAE design, it must be fabricated correctly with adequate welds and with the proper materials.

Question 3 — Are there differences in the characteristics of accidental rollovers of different types of machines?

An examination of the types of machines that are required to have ROPS installed, and the work practices of these machines, would suggest that both the probability of rollover and the potential severity of a rollover are different for the various types of machines. Crawler dozers are used in pioneering operations in rough, hilly terrain; scrapers operate at high speeds on narrow haul roads; haulage trucks are regularly traveling up and down haul roads and often back to dump areas; and front-end loaders tram to and from loading areas and operate near steep drop-offs. These situations would seem to offer opportunities for rollovers. The potential severity of rollovers involving crawler dozers seems obvious and is supported by accident records. Operation on the side of steep hills and during the initial development activities at mines present both the opportunity for rollover and the possibility for rolling the machine several revolutions down a steep incline. Scrapers operate in a manner to present a much different set of rollover possibilities. The high speed operation, coupled with the possibility of running off a narrow haul road, can produce a rollover accident that has dynamic loads that are very much different than the low speed side overturn experienced by most other types of machines. The forward velocity of the scraper can introduce high longitudinal loads into the ROPS during a rollover.

The photographs shown in Figures 3-4, 3-5, and 3-6 show the results of a high-speed rollover. The accident report summarizes the accident as follows:

"The operator was driving the scraper at a fairly high speed (45 mph estimated) when he drove off the haul road and over a small berm. The scraper became airborne as it bounced over the berm onto a smooth downhill slope. When the scraper hit the ground, the gooseneck broke, the engine dug in, and the loaded scraper bucket ran up on the prime mover, rolling it over on its top (see Figures 3-4 and 3-5). The ROPS unit was torn from the prime mover (see Figure 3-6) — the operator was killed."

As can be seen in Figure 3-6, the ROPS was unable to sustain the high structural loads experienced in this rollover.

In contrast to the rollover potential of crawler dozers, front-end loaders, and scrapers, the work practices of motor graders and rollers are such that rollover accidents are not an "expected" type of accident and when they do occur, they are generally "lay-overs" (90° side overturn). The rollover protective structure serves its purpose in preventing serious injury

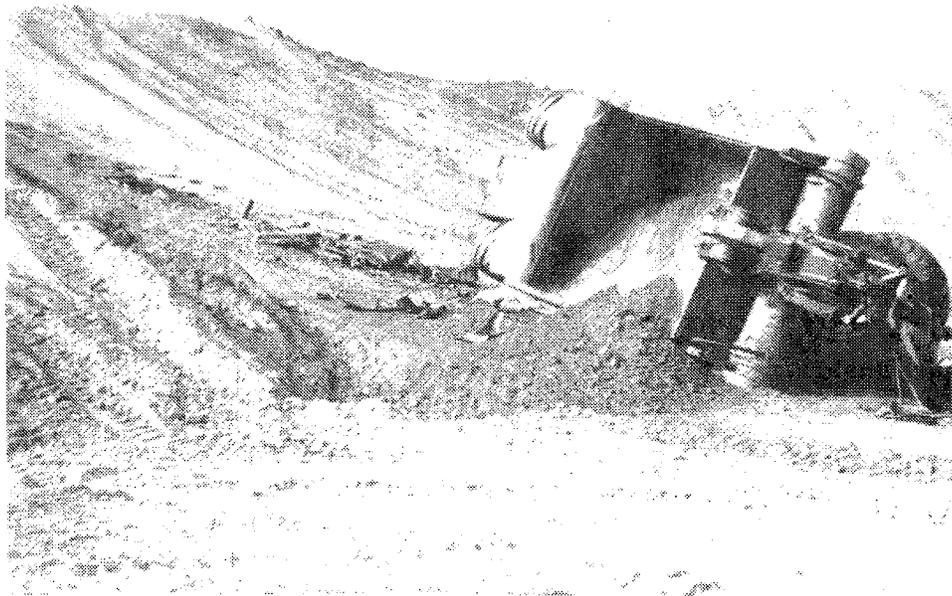


FIGURE 3-4. Rollover Accident — Scraper



FIGURE 3-5. Close-up of Scraper Rollover Accident



FIGURE 3-6. ROPS After Rollover Accident — Scraper

or death to the machine operator in a rollover accident and additionally acts as an anti-roll device in helping prevent the machine from rolling more than 90°.

In an effort to quantify the differences in rollover severity that might be characteristic of different types of machines, Woodward Associates, Inc. collected information on the number of roll revolutions experienced in rollover accidents. Figure 3-7 represents the percentage of rollovers observed for different amounts of rollover revolution for all types of earth-moving equipment. The accident sample used for this display was from one

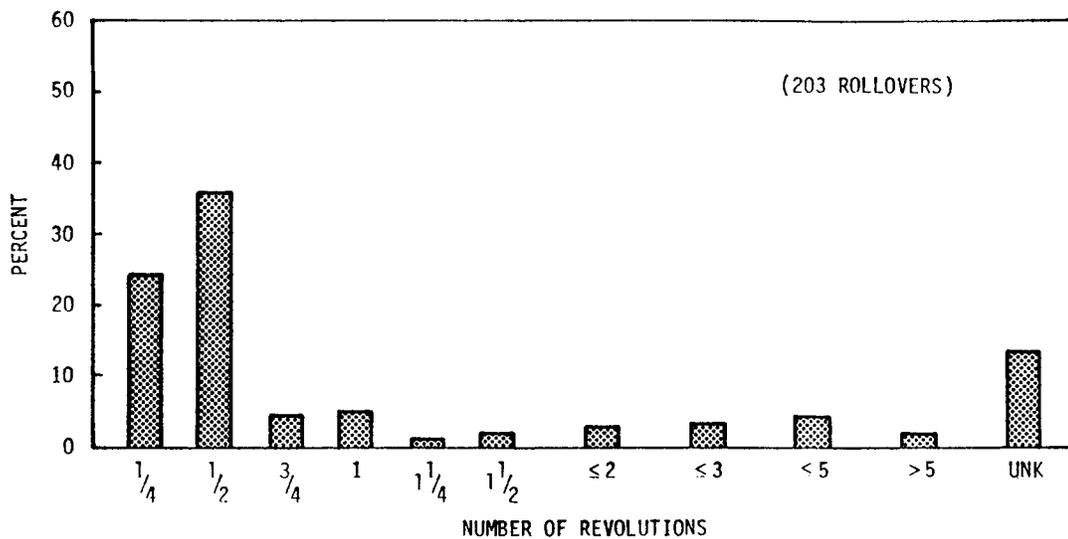


FIGURE 3-7. Roll Revolutions - Earthmoving Equipment

specific data base in which the machines were clearly identified as to type and it was known whether the machine had a ROPS installed or did not. The number of machines in this data base totaled 203. Figure 3-8 illustrates the roll revolution by percentage for machines without ROPS and Figure 3-9 illustrates the roll revolutions by percentage for machines with ROPS. Figure 3-10 further separates this data base into generic types of machines. Figures 3-11 and 3-12 present similar data for wheel loaders; Figures 3-13 and 3-14 present similar data for crawler dozers.

A qualifying statement as to the accuracy of the data presented in these figures must be made. These data probably understate the numbers of rollovers that are minor and only result in a 1/4 overturn. This type of "tip over" may not result in injury to the operator or much damage to the

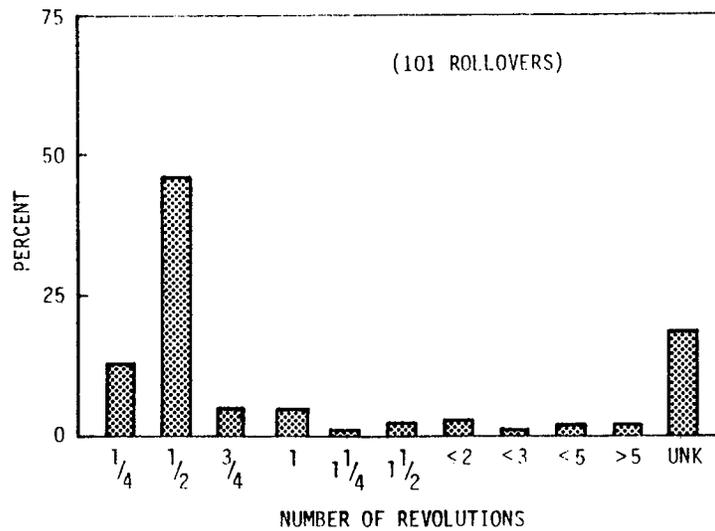


FIGURE 3-8. Roll Revolutions - Machines Without ROPS

machine. It may not be reported to anyone. The machine may be placed upright, checked for damage to assure that it will operate correctly, the battery and hydraulic systems checked for fluid levels, and then placed back in service. It may be then, that the figures presented are representative of rollovers that, for either personnel injury or equipment damage, were reported to the data source.

Examination of these figures leads to several general conclusions:

1. There are definite differences in the characteristics of accidental rollovers experienced by different types of machines. The percentage of rollovers greater than

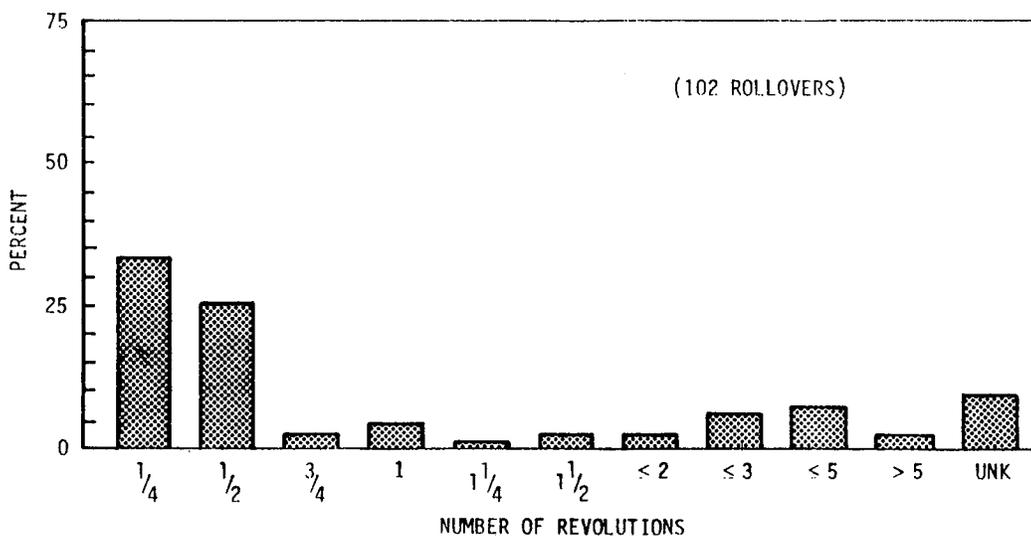


FIGURE 3-9. Roll Revolutions - Machines With ROPS

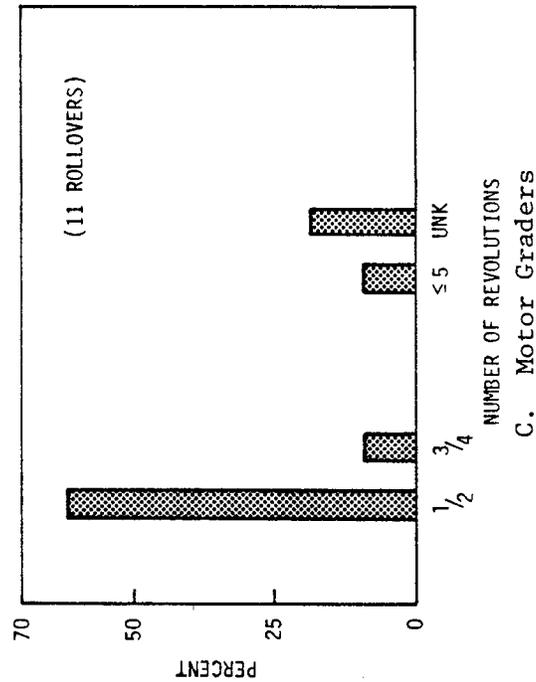
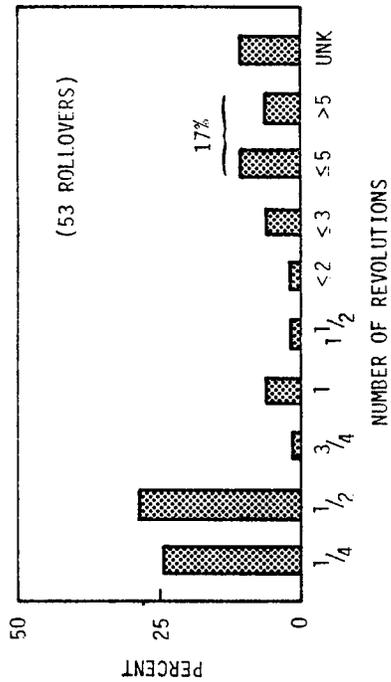
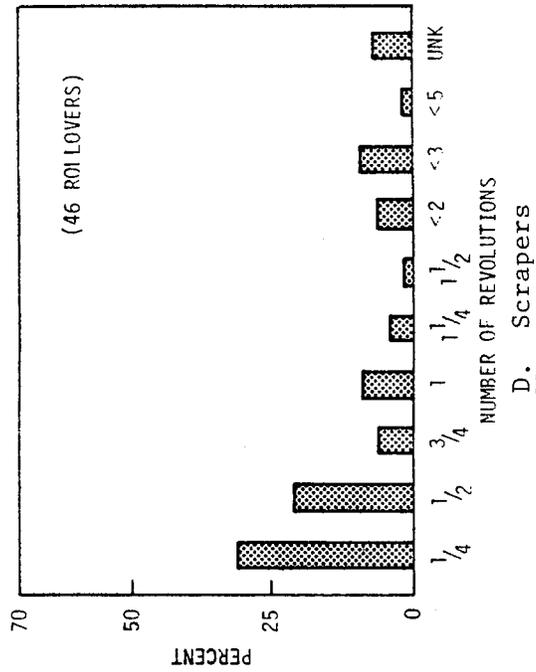
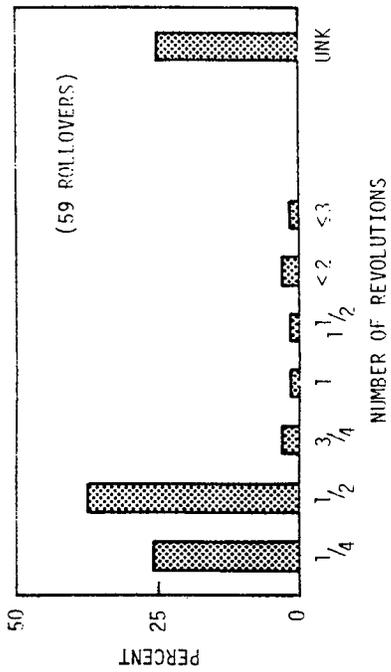


FIGURE 3-10. Roll Revolutions - Generic Type Comparison

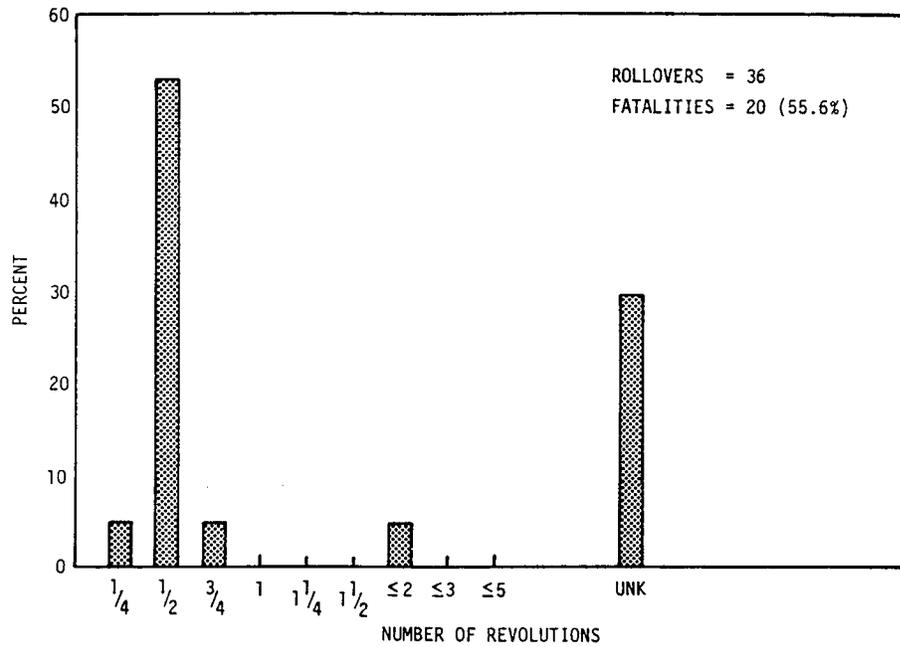


FIGURE 3-11. Roll Revolutions — Wheel Loaders Without ROPS

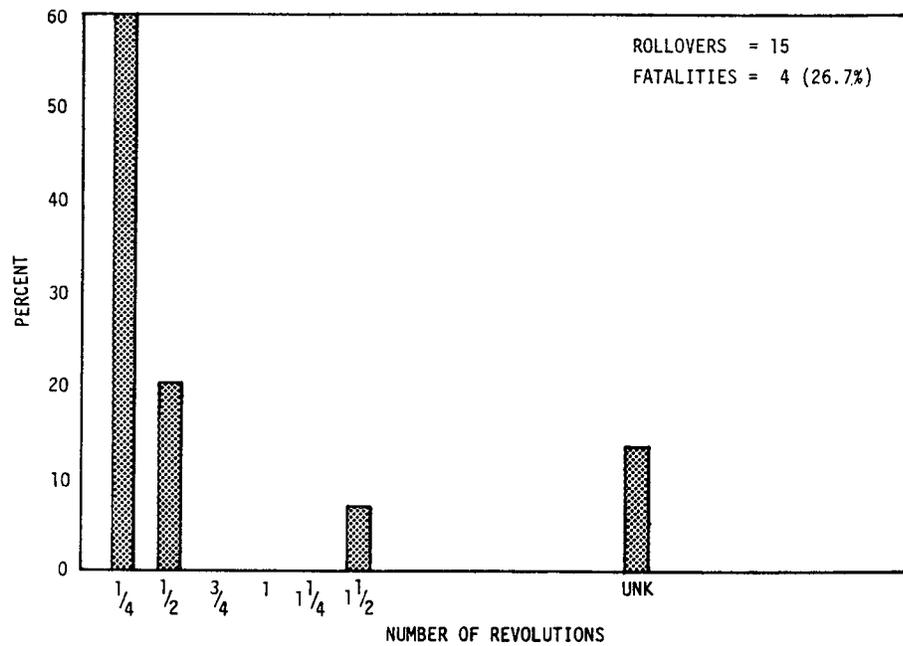


FIGURE 3-12. Roll Revolutions — Wheel Loaders With ROPS

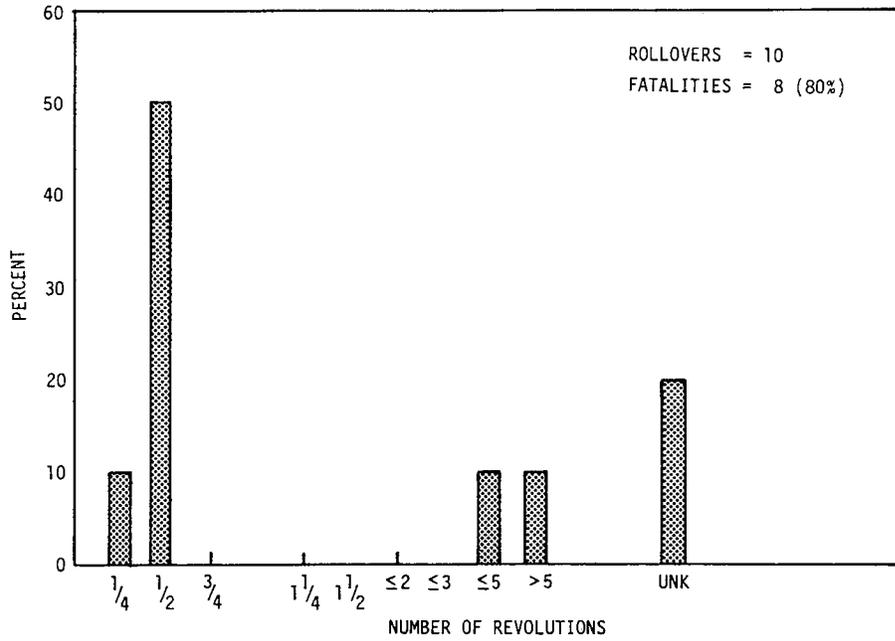


FIGURE 3-13. Roll Revolutions - Crawler Tractors Without ROPS

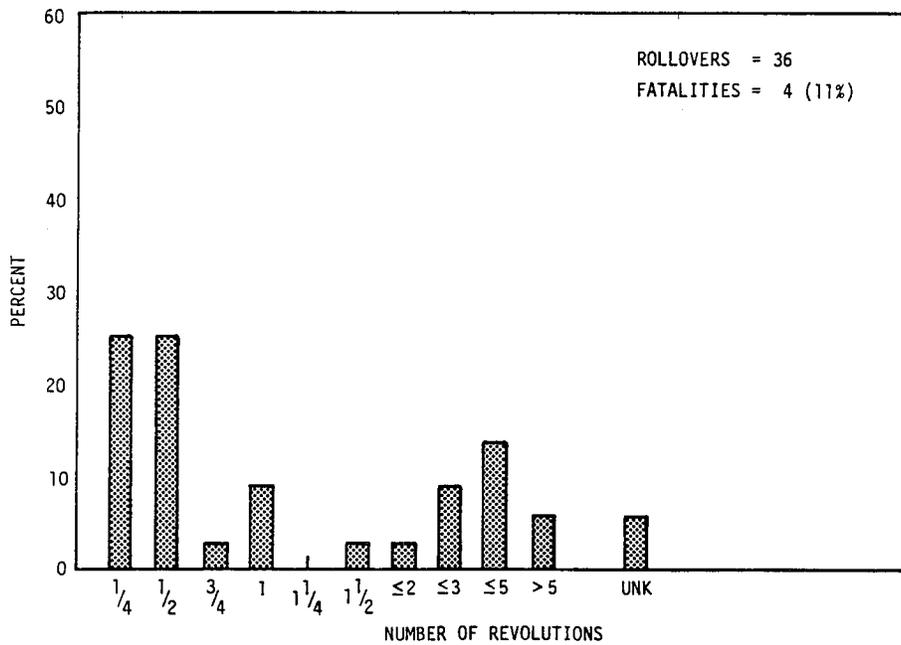


FIGURE 3-14. Roll Revolutions - Crawler Tractors With ROPS

one revolution is 9.1% for wheel loaders, 30.4% for crawler dozers, and 25.6% for scrapers — that is, the percentage of rollovers greater than one revolution when comparing the machines in which the roll revolutions are known. The data sets for the different types of machines all had significant numbers of reports where the exact roll revolution information was not available. It is assumed that the unknowns would produce the same distribution as the knowns.

Another significant difference in rollover characteristics is the amount of forward velocity that may be introduced into the rollover. Scrapers and haulage trucks may be traveling at far greater speeds than dozers or wheel loaders. A significant longitudinal force may be applied to the ROPS during rollover.

2. Since the effect of 1-1/2 or more revolutions in a rollover is that the ROPS structure impacts the earth two times or more in the accident, a comparison of the frequency of this occurrence is important in determining whether the following statement in SAE ROPS Recommended Practices correctly represents the actual field rollover situation. As stated in SAE J1040c:

"Although ROPS meeting these criteria may not give crush protection under all conceivable circumstances in which a machine could overturn, it is expected that crush protection will be assured under at least the following condition: An initial forward velocity of 0-16 km/h (0-10 mph) on a hard clay surface of 30 deg maximum slope, 360 deg of roll about the machine's longitudinal axis without losing contact with the slope."*

The following table presents a comparison of wheel loaders, crawler dozers, and scrapers, and the relative

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percentages of rolls that cause one, two, or three or more ROPS impacts with the earth. It is seen from Table 3-1 that while 25-30% of the crawler dozer and scraper rollovers caused the ROPS to impact at least two times, the wheel loader experienced ROPS impacts of two or more times in less than 10% of the rollovers. It would seem that ROPS designed for use on crawler dozers and on scrapers should anticipate that the magnitude of structural loads that may be expected in a rollover would be consistent with rollovers that cause at least two impacts of the ROPS and perhaps three impacts. Though the wheel loader experiences less multi-revolution rollovers, that fact that almost 10% might receive two impacts suggests that it might be prudent to design for this more demanding case.

TABLE 3-1. Percentage of Rollovers*

	One Impact of ROPS	Two Impacts of ROPS	Three or More Impacts of ROPS
Wheel loader (44 rollovers)	90.9%	6.8%	2.3%
Crawler dozer (46 rollovers)	69.6%	4.3%	26.1%
Scraper (43 rollovers)	74.4%	7.0%	18.6%

*Comparing only rollovers where the revolutions are known.

Question 4 - Does the size of a machine affect the likelihood or the severity of an accidental rollover?

The accident data gathered and analyzed during this project did not contain clear evidence that machine size had any influence on rollover probability or on the severity of a rollover. Woodward Associates, Inc. personnel visited several mine sites and observed the operation of machines of different sizes. These direct observations were limited to the operation of wheel

loaders up to 300,000 pounds gross weight and crawler dozers up to 200,000 pounds gross weight. While these observations confirmed that these large machines are used in work areas where rollovers can occur (and in fact, one operator told of almost rolling a large wheel loader), nothing was learned that led Woodward Associates, Inc. to believe that large machines are more likely to roll. It was noticed that the operator has restricted visibility in some large machines, especially when backing or tramping in reverse. This probably represents some increase in likelihood of collision or of striking personnel or other objects.

Question 5 -- Do machine operators experiencing accidental rollovers in machines fitted with ROPS receive less severe injuries than those in accidents in machines without ROPS?

The answer to this question may seem to be obvious. The ROPS are installed on machines for the express purpose of reducing injuries and fatalities. The degree of injury or fatality reduction had never been quantitatively documented and Woodward Associates, Inc. attempted to gather data that would place the success of ROPS in perspective.

The same accident report data base previously used to describe the frequency of multi-revolution rollovers was used to prepare Table 3-2.

TABLE 3-2. ROPS Effectiveness in Earthmoving Equipment Rollovers

	Machines Equipped With ROPS (102 Accidents)	Machines Not Equipped With ROPS (101 Accidents)	Machines ROPS Status Unknown (28 Accidents)
No injury	37.3%	13.9%	35.7%
Minor injury	25.5%	13.9%	10.7%
Major injury	18.6%	21.8%	14.3%
Fatalities	14.7%	48.5%	21.4%
Unknown	3.9%	1.9%	17.9%
Total	100.0%	100.0%	100.0%

As with the information presented previously on multi-revolution rollovers, the accuracy of the table can be questioned. The underreporting of noninjury rollovers is sure to cause a skewing of the data. The percentage of rollover accidents resulting in fatalities is no doubt much smaller than that presented in Table 3-2. It can be speculated that there are more unreported rollovers with ROPS than unreported accidents involving machines not fitted with ROPS. The table suggests that ROPS are providing a valuable lifesaving function. The table infers that fatalities occur approximately 3.3 times more frequently on machines without ROPS compared to machines equipped with ROPS. This comparison probably understates the true safety contribution offered by the use of ROPS. More accidents with ROPS may go unreported than accidents without ROPS since the operator is less likely to be injured in a rollover in a machine equipped with ROPS.

Question 6 — Are there accidents where ROPS create safety problems?

The history of the development and acceptance of many safety innovations has shown that while the benefits of a particular safety improvement may be obvious, its introduction may introduce new unexpected safety problems. Eight years have passed since OSHA promulgated the first nationwide regulation requiring broad application of ROPS.

The answer to the question posed above generates at least two categories of answers. First, do ROPS create safety problems when the ROPS system is used correctly? And second, are there common misuses of ROPS systems that can lead to accidents?

In addressing the first variation of the basic question, interviews were conducted with equipment users, accident reports were reviewed, and ROPS manufacturers were asked their opinions. The only negative information received pertained to limitations to the operational practices of machines equipped with ROPS. Stories were related about some ROPS-equipped machines being over height regulations when loaded on transport trailers and then impacting an overpass during transportation from one job site to another. The use of small wheel loaders for cleanup under conveyors is a problem with ROPS on the machine. But no specific accident phenomena were identified that were the result of ROPS.

The second variation on the question has a much different answer. The incorrect use of the ROPS and seat belts, the incorrect installation of ROPS, or the improper modification of ROPS and faulty manufacturing practices have all contributed to increasing the seriousness of a rollover accident. Several accident reports contain details of ROPS being incorrectly attached to the machine or being incorrectly altered either during installation or subsequent to installation. As discussed earlier in this report, one accident was investigated in which three employees were killed when a wheel loader overturned. The ROPS was inadequately designed and was improperly installed. The ROPS broke into several pieces during the 180° rollover. Examination of the ROPS revealed inferior manufacturing practices; several critical structural joints had inadequate weld penetration. This ROPS was not structurally capable of providing operator protection in any rollover.

As with many safety products, the ROPS must be correctly designed and fabricated to perform its function properly. No information was received during this study to indicate that ROPS systems have created new safety problems.

Question 7 — Do machine operators wear the seat belts?

The information presented in Table 3-2 indicated that 14.7% of the rollover accidents involving machines equipped with ROPS resulted in fatalities. Of the 16 fatalities included in the 102 accidents reviewed in that column of Table 3-2, 14 were not using their seat belts. One of the two others was crushed when the ROPS collapsed. It is not known if he was wearing his seat belt. It probably would not have helped. In the other 14 accidents, seat belt usage might have saved several, if not all, of the machine operators.

Though not the focus of this study, many accident reports were reviewed that contained information that demonstrated the value of wearing seat belts in accidents other than rollovers. The nonuse of seat belts by the operators of machines is a frequent contributor to operator injury in rollovers, machine collisions, collisions with stationary objects, and in accidents where the operator is bounced about because of striking large bumps or rocks in a roadway.

In previous studies conducted for OSHA and the Bureau of Mines, surveys of machine operator use of seat belts have been conducted. Almost every construction and mining operation surveyed had problems convincing their machine operators to use their seat belts. The management at some mines didn't seem to be completely convinced that wearing seat belts was that important. This attitude might be expected when, according to other surveys, about 86% of the U.S. population doesn't use seat belts in their own automobiles.

The Bureau of Mines has emphasized the need to use seat belts in recent machine operator training programs. The Operator Engineers Union, in their operator training programs, encourages the use of seat belts.

The design of a more comfortable seat belt and the need for a seat belt that allows easier movement for the operator are two suggestions given frequently by machine operators and safety officials. The increased safety realized through increased use of seat belts is important. Serious consideration should be given to the development and demonstration of advanced machine operator restraint systems.

Question 8 – Do seat belts fail in rollover accidents?

In only one of the hundreds of rollover accident reports reviewed was there any implication of a seat belt failure. Further investigation of this particular accident suggests that the seat belt did fail and this failure may have been due to lack of maintenance of the seat belt system. No other indication of seat belt failure was discovered.

Question 9 – Are there types of machines, in addition to those currently required to have ROPS, that should also be required to have ROPS installed?

Tables 3-3 and 3-4 illustrate the relative numbers of fatalities that different generic types of surface mining equipment experienced in recent years.

Rollover accidents are claiming a high number of haulage truck operators. The reduction of injuries and deaths due to haulage truck rollovers should be addressed from at least four perspectives. First, some of the accidents were the result of truck operator inexperience or lack of knowledge as

TABLE 3-3. Rollover Accident Fatalities by Machine Type - Noncoal Mines
(1970 through 1978)

Machine Type	1970	1971	1972	1973	1974	1975	1976	1977	1978	Total
Wheel loaders	5	9	10	17	10	7	5	5	4	72
Haulage trucks	9	10	11	10	5	6	5	8	5	69
Crawler dozers	7	1	1	2	2	0	1	0	0	14
Scrapers	1	1	0	0	0	0	3	0	0	5
Others	5	2	4	2	2	0	0	0	1	16

TABLE 3-4. Rollover Accident Fatalities by Machine Type - Coal Mines
(1970 through 1978)

Machine Type	1970	1971	1972	1973	1974	1975	1976	1977	1978	Total
Wheel loaders	4	3	5	1	1	5	1	1	3	24
Haulage trucks	1	1	0	1	2	4	2	2	0	13
Crawler dozers	1	0	1	0	3	2	1	0	1	9
Scrapers	0	0	0	0	1	1	0	0	0	2
Others	2	2	0	2	1	1	0	2	1	11

to how to correctly handle a truck in certain emergency situations. Training could have helped prevent some of those accidents. Second, the haulage plans and design of haul roads at some mines may contribute to the potential for haulage truck rollovers. Third, the structural capability of the haulage truck's rock guard and operator cab may not be sufficient to protect the operator in rollovers. Fourth, many truck operators do not wear their seat belts and, during a rollover accident, are thrown from the cab and are injured or killed.

From the accident reports reviewed, it is evident that many of the haulage truck rollovers are not side tip-overs but are either rear flip-overs occurring as a rear dump truck backs through the dump area and slips over the dump bank (see Figure 3-15) or are high-speed forward rollovers as a runaway truck goes through the berm on a haul road and tumbles down an embankment.

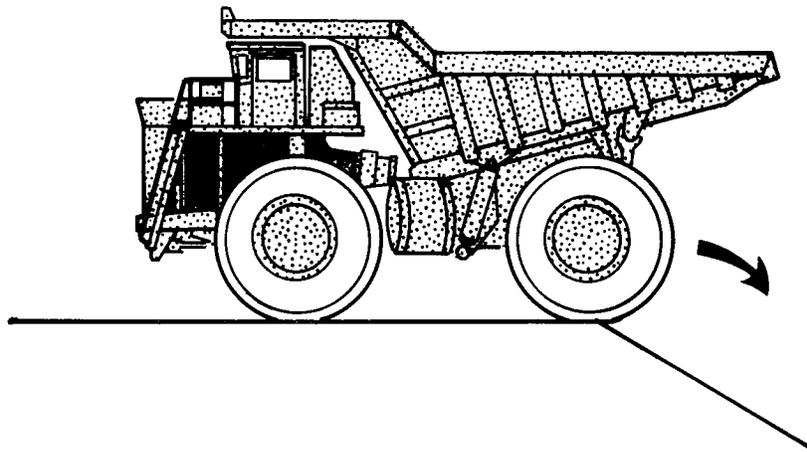


FIGURE 3-15. Dump Truck Backing Over Embankment

The SAE has prepared a recommended practice for the structural performance requirements of haulage truck ROPS designs. This recommended practice was not formulated from analyzing the conditions of actual field accidental rollovers. The protection afforded the operator of a haulage truck through adoption of the SAE recommended practice is not known at this time.

Question 10 — Does anything happen to a ROPS during machine use that reduces its capability to provide operator protection?

Recent studies sponsored by the Bureau of Mines have attempted to further define the potential structural degradation that might be accumulated through vibration-induced fatigue of the ROPS. A report describing this area of research has been recently published and is entitled "Service Life Analysis of Rollover Protective Structures (ROPS) on Surface Mining Machines" (6). This report predicts that, as time passes and ROPS-equipped machines accumulate more and more service time, ROPS will begin to exhibit fatigue-related failures of welded connections or joints. It is stated that this degradation in ROPS structural capability will be caused by the growth of minute flaws or cracks in the ROPS' welded connections or joints. The accidental rollover of a machine equipped with a degraded ROPS could result in ROPS structural failure and injury or death to the machine operator.

The structural integrity of ROPS is also diminished through improper maintenance. During this study, ROPS were observed with nuts and bolts missing from mounts, worn or missing rubber isolators, evidence of impacts on ROPS tubing, dents, and visible cracks. Some ROPS had been damaged in previous rollovers or collisions; the structures had been permanently distorted. The Bureau of Mines is also sponsoring the preparation of a ROPS field inspection manual that can be used by mine maintenance personnel and by MSHA inspectors. This manual will help guide field personnel in the proper maintenance of ROPS and will aid MSHA inspectors in determining if the ROPS complies with regulations.

3.2 CONCLUSIONS

The collection and analysis of rollover accidents has permitted the following conclusions:

1. ROPS are saving lives. The requirement that ROPS be fitted on surface mining and construction equipment has been responsible for important reductions in deaths and injuries due to rollover accidents.

2. Additional reductions in deaths and injuries could be realized if machine operators could be persuaded to wear their seat belts and "ride out" a machine rollover. Many operators have been injured or killed when they have attempted to jump from the machine or when they were ejected during a rollover.
3. The accident records examined revealed only one definite instance of structural failure of a ROPS designed to meet SAE performance criteria. At least three, and perhaps six, ROPS designed to meet Corps of Engineers criteria failed during rollovers resulting in death and injury to operators. The Corps of Engineers criteria were not at fault; faulty engineering, inadequate welds, and improper mountings were responsible for the structural failures.
4. The rollover accident scenario used in SAE ROPS recommended practices (360° side rollover, 30° hard clay slope, etc.) does not represent the rollover accident experienced by some types of earthmoving machines. Crawler dozers are much more likely to have multi-revolution rollovers than motor graders; scrapers receive high longitudinal impacts in some high-speed rollovers; haulage trucks sometimes have rearward tip-overs off dump sites; and rollers rarely roll over more than one revolution.
5. Haulage trucks are involved in many rollover-type accidents, and are responsible for many deaths and injuries. Approaches to reducing the numbers of these injuries and deaths include improved operator training, changes in haulage truck dumping procedures, and development of protective cab structures.
6. ROPS may have short service lives when mounted on some types of machines and used in some rigorous environments. The fatigue effects on ROPS structural integrity are not well understood. The possibility that ROPS would have to be replaced periodically has large economic implications.

SECTION 4.0

ROPS STRUCTURAL PERFORMANCE TESTS

Prior to 1966, operator protective structures were generally referred to as "canopies," "overhead guards," and sometimes "roll cages." Many different performance criteria and design criteria guided the design and fabrication of operator protective structures. None of these pre-1967 operator protection structure guidelines required any types of physical test to demonstrate that the fabricated structure achieved the structural performance specified in the guideline. It was assumed that the engineers designing these structures could satisfactorily predict the performance of their designs. Some of the early protective structure guidelines limited design approaches by specifying the steel tubing to be used in the construction of the protective structure.

In 1966 and 1967, the Society of Automotive Engineers developed an operator protective structure performance criteria that was unique. It required demonstration, through static load tests, that the structure would meet the performance required by the criteria. It was also unique in that it required that the structure absorb a defined amount of energy as well as support a defined static load. From the development of the first SAE ROPS recommended practice for scrapers in 1967, technical committees of SAE have continued to improve and modify ROPS performance criteria in an ongoing effort to provide the best practical operator protective structures. In addition to scrapers, recommended practices have been developed for wheel loaders and dozers, crawler loaders and dozers, motor graders, off-highway haulage trucks, rollers, compactors, and industrial and agricultural tractors. In 1974, the Society of Automotive Engineers incorporated several separate independent ROPS recommended practices into one recommended practice that covered all machines. The basic approach to static testing is the same for all machines covered; the side force and side energy equations are different and specific for each type of machine. The various SAE recommended practices are referenced in Appendix B and the performance equations given.

The major portion of the ROPS in use on machines has been designed to meet the structural performance of either the SAE recommended practices for ROPS performance or the criteria specified by the Corps of Engineers. These two structural performance guidelines are generally viewed by industry as applying to different ages of machines. The Corps of Engineers ROPS criteria have generally been applied to the older machines -- those manufactured prior to 1969 and to some extent, to some models manufactured up to about 1975. The SAE ROPS performance criteria have been generally applied to machines manufactured after 1972 and to some manufactured previous to 1971. All construction and mining machines manufactured after 1978 and used in mining or construction operations are fitted with ROPS that meet the SAE recommended practices. Appendix A lists ROPS regulations and ROPS performance criteria that have been or are now in use in the United States.

The manufacturers of construction and mining equipment have been designing ROPS to meet various ROPS requirements since the late 1960s. During this span of time, ROPS design engineers have conducted hundreds of ROPS structural tests and recently have developed computer-aided structural analysis techniques to help predict the structural test results. The structural performance verification tests required by the SAE recommended practices are conducted using the machine or machine frame for which the ROPS has been designed. Horizontal static loads are applied to the ROPS' top normal to the longitudinal axis of the machine and vertical static loads are applied downward to the top of the ROPS. The magnitude of these static loads is calculated from formulae provided in the SAE recommended practices. The ROPS must also absorb energy as calculated from additional formulae. These formulae, and graphs illustrating the relationship between machine weight and ROPS structural requirements, are presented in Appendix B.

To aid the reader's understanding, the following example is given. A ROPS design engineer is charged with designing a ROPS for a crawler tractor. The engineer determines that the gross weight of the tractor is 50,000 pounds and the maximum expected gross weight is 73,000 pounds. The ROPS design must satisfy the OSHA ROPS regulations so the ROPS design engineer reads the regulations and finds that the ROPS must meet the requirements of SAE

Recommended Practice J395 (1969). Since his company's management is convinced that OSHA will update their regulations someday to reflect advances in SAE ROPS performance guidelines, he is told to consider the requirements found in SAE J1040c (1979) also.

The engineer consults Section 1926.1001 of Subpart W of Part 1926 of Title 29 of the Code of Federal Regulations. This section includes a graph and an equation that allows calculations of the side force required to demonstrate the horizontal static load capability of the ROPS. He also notes that the vertical static load capability is demonstrated by applying a downward force equal to the maximum gross weight of the machine. This top load test is conducted after the side force test is completed. A formula and graph are also provided to allow calculation of the energy that must be absorbed during the side force test.

The engineer calculates the side force, side energy, and top load requirements as follows:

- Side force

$$= \text{GVW} \times 0.59 \left(\frac{\text{GVW}}{10,000} \right)^{0.22}$$

$$= 73,000 \text{ lb} \times 0.59 \left(\frac{73,000}{10,000} \right)^{0.22}$$

$$= 73,000 \text{ lb} \times 0.91366$$

$$= \underline{66,697 \text{ lb}}$$
- Side energy

$$= 45,000 \left(\frac{\text{GVW}}{10,000} \right)^{1.23}$$

$$= 45,000 \left(\frac{73,000}{10,000} \right)^{1.23}$$

$$= 45,000 \times 11.5315$$

$$= \underline{518,918 \text{ in-lb}}$$
- Vertical top load = 1 x GVW

$$= 1 \times 73,000 \text{ lb}$$

$$= \underline{73,000 \text{ lb}}$$

The engineer then performs similar calculations to determine the side force, side energy, and top load requirements of SAE J1040c:

- Side force $= 6,090 \left(\frac{GVW}{10,000} \right)^{1.2}$

$= 6,090 \left(\frac{73,000}{10,000} \right)^{1.2}$

$= 6,090 \times 10.8639$

$= \underline{66,161 \text{ lb}}$
- Side energy $= 42,830 \left(\frac{GVW}{10,000} \right)^{1.25}$

$= 42,830 \left(\frac{73,000}{10,000} \right)^{1.25}$

$= 42,830 \times 11.992$

$= \underline{513,926 \text{ in-lb}}$
- Vertical top load $= 2 \times GVW$

$= 2 \times 73,000 \text{ lb}$

$= \underline{146,000 \text{ lb}}$

A tabulation of the calculation results reveals that the side force and side energy requirements for SAE J395 and SAE J1040c are similar but that the top load required to satisfy SAE J1040c is double that required by SAE J395:

	<u>SAE J395</u>	<u>SAE J1040c</u>
Side force	66,697 lb	66,161 lb
Side energy	518,918 in-lb	513,926 in-lb
Top load	73,000 lb	146,000 lb

The engineer reviews the above requirements and begins his design of the ROPS. Because of the high costs associated with conducting the static structural performance verification tests, he may be influenced to create a ROPS that will have a high probability of exceeding the minimum performance requirements. He may realize that by exceeding the minimum performance requirements, the resultant ROPS may use heavier, and therefore more costly,

steel components. This relatively minor inefficiency may be accepted to preclude the chance of a more optimally designed ROPS experiencing a structural failure during the verification tests. Better to be safe than sorry.

The above rather lengthy, and simplified, description of the steps leading up to a decision to "overdesign" ROPS is presented to illustrate a concern that has been expressed as to the perceived success of ROPS designed to meet SAE performance guidelines. If the field rollover accident data support the premise that ROPS are protecting machine operators, does that mean that the SAE ROPS performance criteria are adequate? Or does it mean that ROPS that are designed to exceed significantly the SAE criteria are successfully protecting machine operators? A concern has been expressed that during the several years that ROPS have been designed and manufactured for construction and mining equipment, the designs have been "overdesigned" to a significant margin. Perhaps this additional structural capability is necessary to provide adequate operator protection. This concern continues with the thought that ROPS designers are improving the capability to predict the results of static structural tests through the development of sophisticated finite element computer programs. The SAE recently published an Information Report entitled "Performance Prediction of Rollover Protective Structures (ROPS) Through Analytical Methods." This Information Report (its number is SAE J1215) discusses approaches to predicting ROPS structural performance. The correlation between predictions of ROPS performance with the actual results of ROPS static structural tests are very good. This ability to confidently design a ROPS that just exceeds the SAE performance criteria is new. The high percentage of ROPS that have been installed on mining and construction equipment were not designed using the new computer-aided design techniques.

In an attempt to qualify the extent of the "overdesign" that may exist in ROPS that are currently out in the field on equipment, Woodward Associates, Inc. asked several ROPS manufacturers and construction equipment manufacturers to provide the results of static structural tests that they have conducted on ROPS of their design. Nine different companies provided extensive sets of test results covering a total of 403 tests. These tests were compiled and analyzed. The results of the analyses are presented in the following section of this report.

4.1 ROPS PERFORMANCE VERIFICATION STATIC TESTS — DATA COMPILATION AND ANALYSIS

The ROPS static test information received from contributing companies was first compiled into tables similar to that given in the example shown in Table 4-1.

The column headings are defined as follows:

- Column 1 — The generic classification of the machine.
- Column 2 — Maximum Recommended Machine Mass: This represents the maximum machine mass that is anticipated by the ROPS designer in preparing the ROPS design for this specific model of machine. It does not include soil, mud, rocks, limbs, debris, etc., that commonly adhere to or lay on machines in actual use. It does anticipate the use of various optional attachments that may increase the mass of the "bare" machine.
- Column 3 — Minimum Possible Machine Mass: This represents the mass of a machine without optional attachments. It is usually the mass of a "bare" machine.
- Column 4 — Minimum Acceptable Side Force Requirement (Maximum GVW): This is the minimum side load that must be attained to satisfy the SAE ROPS criteria for the maximum recommended machine mass.
- Column 5 — Minimum Acceptable Side Force Requirement (Minimum GVW): This is the minimum side load that must be attained to satisfy the SAE ROPS criteria for the minimum possible machine mass.
- Column 6 — Maximum Side Force Attained in Static Test: This is the maximum side load experienced by the ROPS during the static test.

As can be seen in the example shown in Table 4-1, the design margins can be very small or quite large. During compilation of the 403 static test

TABLE 4-1. SAE ROPS Design Margin

Col. 1 Machine Type	Col. 2 Maximum Recommended Machine Mass	Col. 3 Minimum Possible Machine Mass	Col. 4 Minimum Acceptable Side Force Requirement, maximum GVW	Col. 5 Minimum Acceptable Side Force Requirement, minimum GVW	Col. 6 Maximum Side Force Attained in Static Test	Design Margins	
						Col. 6 Col. 4	Col. 6 Col. 5
Wheel loader	10,978	6,120	5,939	2,911	9,900	1.67	3.40
Wheel loader	17,270	15,660	10,322	9,160	15,100	1.46	1.65
Wheel loader	55,880	51,620	43,243	39,254	50,537	1.17	1.29
Scraper	27,150	19,400	17,926	11,896	40,430	2.26	3.40
Scraper	34,000	33,380	46,061	44,980	52,800	1.15	1.17
Crawler dozer	18,400	13,662	12,415	8,633	33,801	2.72	3.91
Crawler dozer	62,000	47,525	54,386	39,530	117,154	2.15	2.96
Crawler dozer	42,500	40,009	34,567	32,025	41,140	1.19	1.28

reports received, design margins as high as 400% over the required side force were noted. The compiled static test data were then reduced to cumulative histograms similar to the two examples shown in Figures 4-1 and 4-2.

These histograms were prepared for each set of static test data provided to Woodward Associates, Inc. It is recognized that this sample of 403 ROPS designs may not be a statistically accurate representative of all of the ROPS designs used on mining and construction equipment. It is the author's opinion that the information presented may understate the overdesign situation since this ROPS design sample was furnished by the largest and most technically advanced producers of ROPS. The smaller ROPS manufacturer might be expected to design ROPS with larger design margins since they have less test experience and limited access to the newer computer programs.

The separate histograms were reviewed and a simple aggregate analysis conducted and a composite cumulative histogram prepared (Figures 4-3 and 4-4). Examination of these histograms and the tabular presentation in Table 4-2 allow generalization with the following conclusions:

1. Assuming that all machines actually in use in the field had machine masses equal to the Maximum Recommended Machine Mass:
 - a. 70% of the ROPS designs exceeded the SAE side load requirement by at least 20%.
 - b. 50% of the ROPS designs exceeded the SAE side load requirement by at least 40%.
 - c. 15% of the ROPS designs exceeded the SAE side load requirement by at least 100%.

2. Assuming that all machines actually in use in the field had machine masses equal to the Minimum Possible Machine Mass:
 - a. 90% of the ROPS designs exceeded the SAE side load requirement by at least 20%.
 - b. 85% of the ROPS designs exceeded the SAE side load requirement by at least 40%.

COMMENTS:

1. About 50% of the ROPS are at least 30% "stronger" than required by the SAE Recommended Practice for the gross vehicle weight assumed as the maximum weight.
2. About 25% of the ROPS are at least 80% "stronger" than required by the SAE Recommended Practice for the gross vehicle weight assumed as the maximum weight.

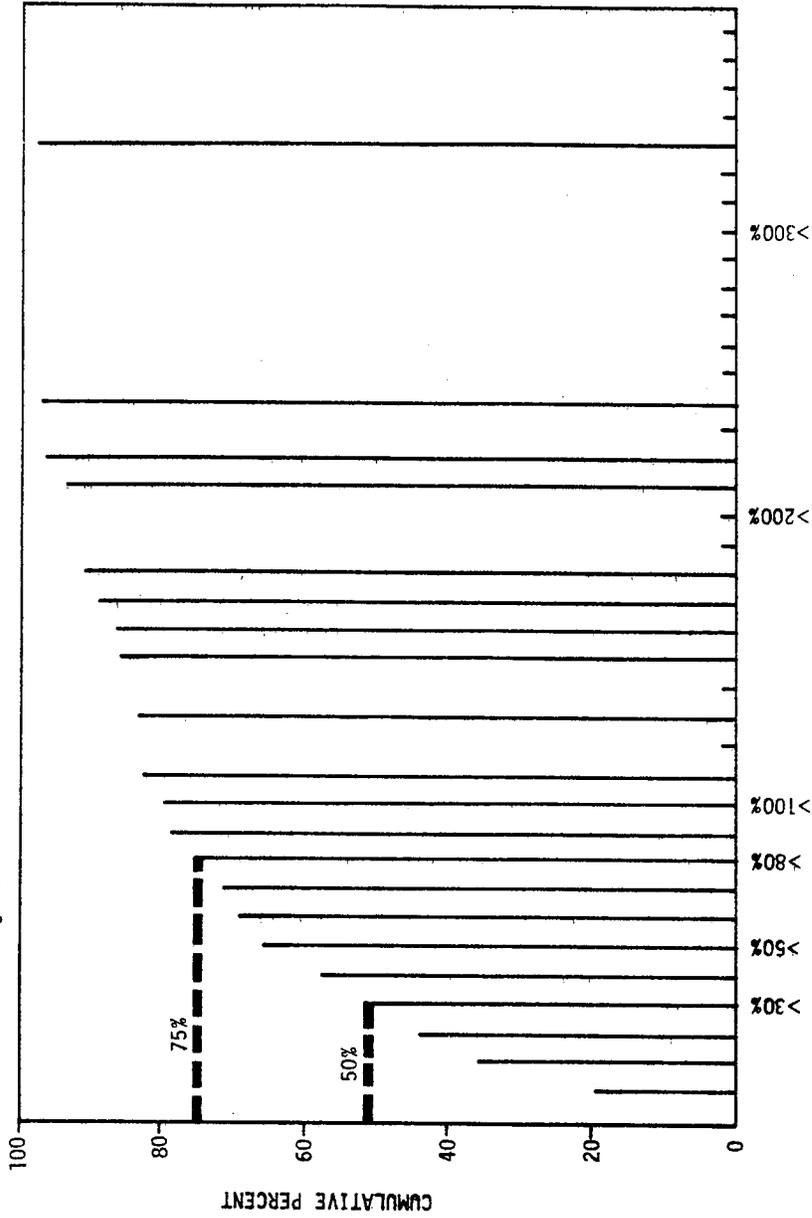


FIGURE 4-1. ROPS Design Margin — Percent Static Test Side Force Exceeds SAE Side Force Requirements (Maximum GVW Machine) (Example — Static Test Reports from One Source)

COMMENTS:

1. About 75% of the ROPS are at least 50% "stronger" than required by the SAE Recommended Practice if used on a minimum weight machine.
2. Over 50% of the ROPS are at least twice as "strong" as required by the SAE Recommended Practice if used on a minimum weight machine.

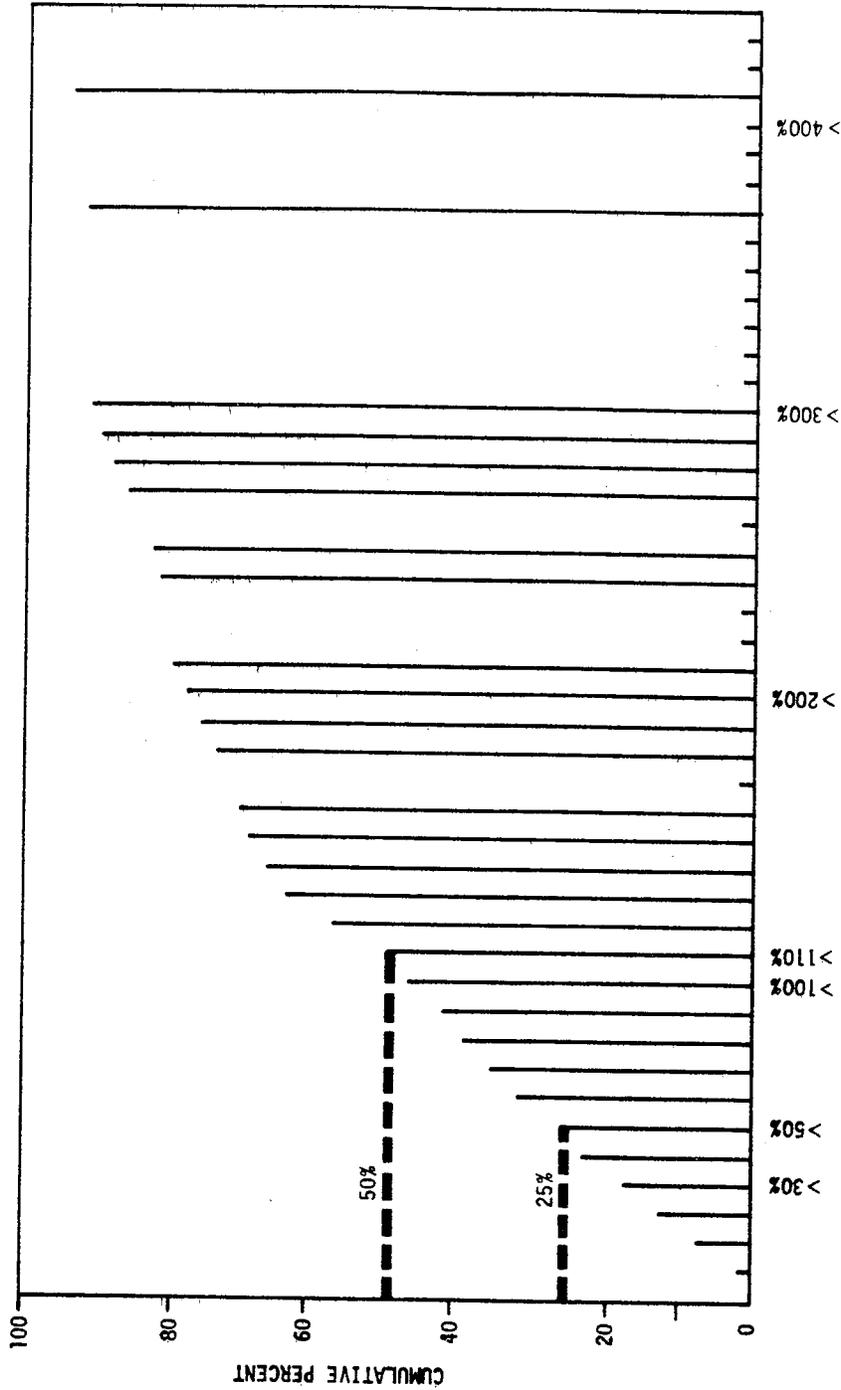


FIGURE 4-2. ROPS Design Margin - Percent Static Test Side Force Exceeds SAE Side Force Requirement (Minimum GVW Machine)
(Example - Static Test Reports from One Source)

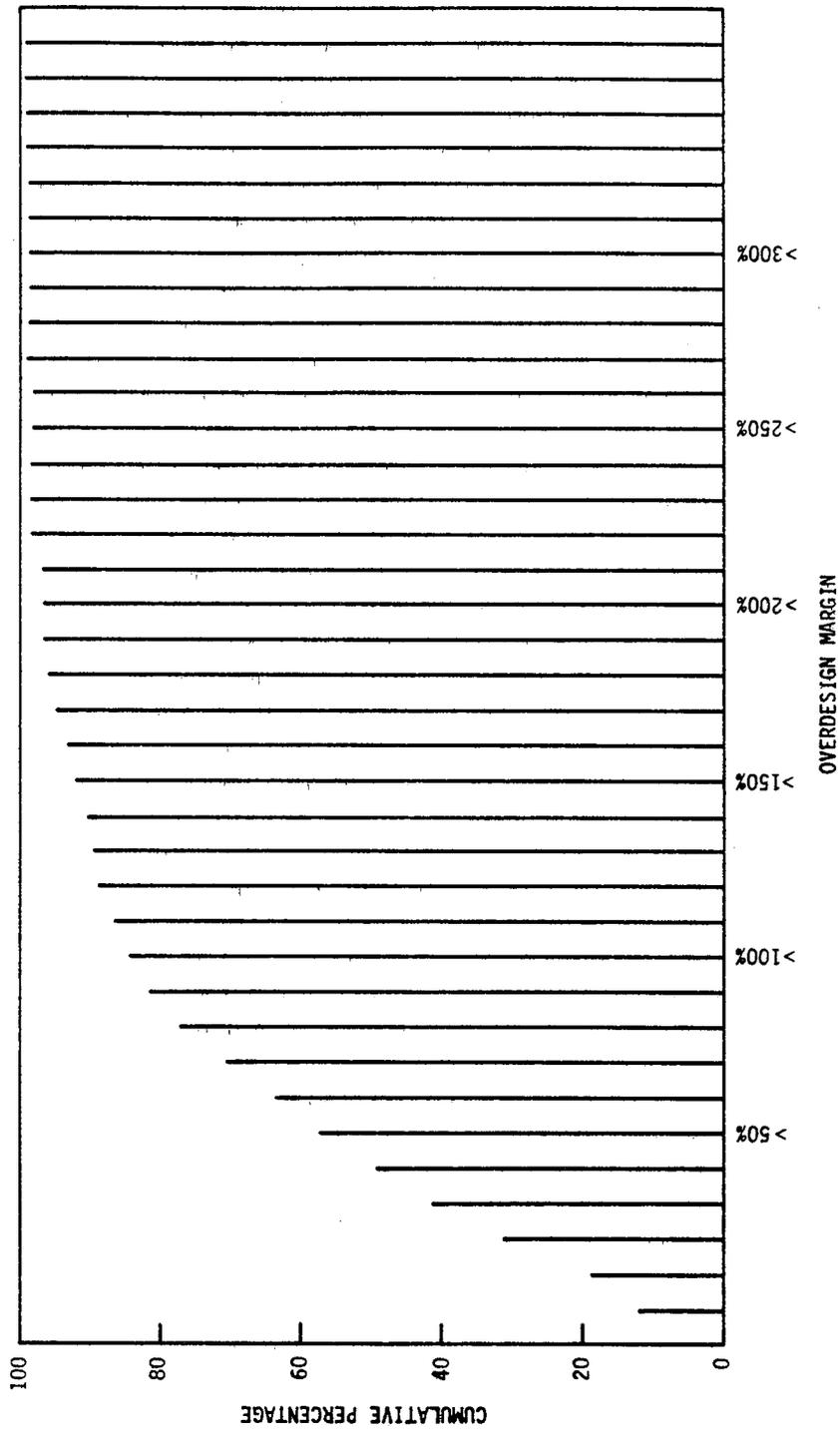


FIGURE 4-3. Overdesign of ROPS Meeting SAE Recommended Practices
 (assumes all machines are at Maximum Recommended Machine Mass)
 (403 Static Test Reports)

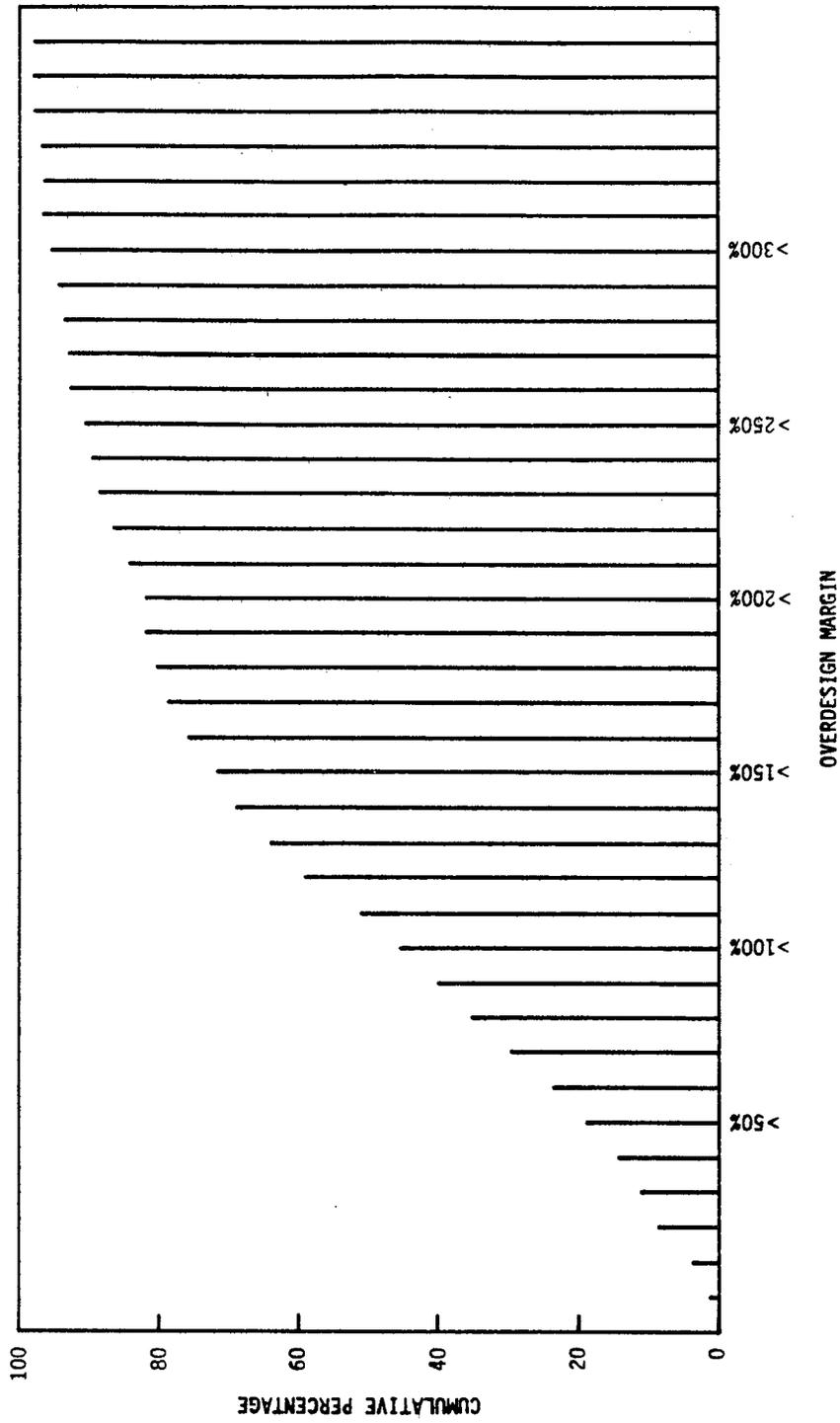


FIGURE 4-4. Overdesign of ROPS Meeting SAE Recommended Practices
 (assumes all machines are at Minimum Possible Machine Mass)
 (403 Static Test Reports)

TABLE 4-2. Overdesign of ROPS Meeting SAE Recommended Practices*

Overdesign Margin	Percentage of Machines if All Were Maximum Recommended Machine Mass	Percentage of Machines if All Were Minimum Possible Machine Mass
20%	68.3	93.6
30%	58.6	89.0
40%	50.6	85.4
50%	42.4	81.3
70%	29.5	70.7
100%	15.4	54.5
140%	9.9	31.3
200%	3.9	17.4

*Table prepared from 403 static test reports.

- c. 70% of the ROPS designs exceeded the SAE side load requirement by at least 70%.
- d. 50% of the ROPS designs exceeded the SAE side load requirement by at least 110%.
- e. 15% of the ROPS designs exceeded the SAE side load requirement by at least 210%.

The machines that are in use in construction and mining operations have masses that are somewhere between the two assumptions stated above. Some machines have very few attachments and approach the minimum mass. They are essentially "bare" machines. For example, a crawler dozer may be fitted with a bulldozer blade and no other attachments. If equipped with a bulldozer blade and a ripper it might approach the maximum recommended mass. It could be speculated that a reasonable expectation of the actual representation of the field situation is that perhaps 75% of the ROPS designs in the field exceed the SAE requirements for the machine on which they are mounted by at least 40%. And perhaps 50% of the ROPS in the field exceed the SAE requirements by at least 70%.

As the reader will recall from an earlier section of this report, the SAE recommended practices also require demonstration of the energy absorption capability of the ROPS. The energy to be absorbed is calculated from formulae similar to the side force formulae. The energy absorption requirement is a function of machine mass. The energy absorption requirement increases as the machine mass increases. As the side force is incrementally applied to the ROPS, the ROPS behaves as an elastic structure and deflects a given distance with each increment of side force. As portions of the structure begin to experience stresses beyond the yield stress of the steel, those areas begin to deform plastically. This plastic deformation will produce larger deflections for the same increments of side force. At some side force level, the structure may begin to experience plastic deformation in enough area to allow large deflections in the structure for small increments of added side force. The general shape of a force-deflection curve for a ROPS static test is illustrated in Figure 4-5. The static test is usually terminated when both the side force and energy absorption requirements

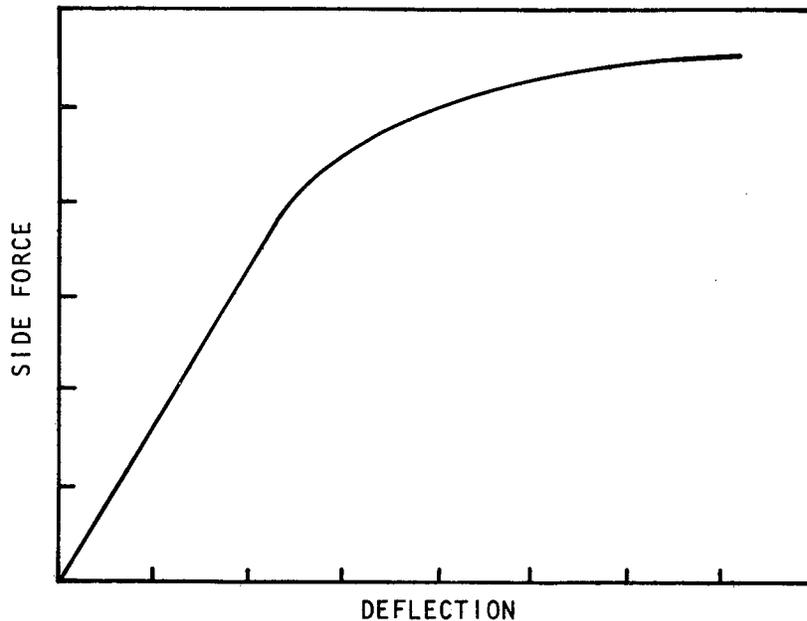


FIGURE 4-5. Typical Side Force-Deflection Curve for a ROPS Static Performance Test

are met. The side force requirement is almost always achieved prior to reaching the energy requirement.

It is industry practice to apply the side load until the required energy is attained (with perhaps 5% overtest) and then stop. In many tests the ROPS is still several inches from the Deflection Limiting Volume. It is also true that, in many static tests, the maximum side force attained is not the maximum side force that could be attained if the side loading was continued. As is evident in Figure 4-5 the side force is still rising at the termination of the test. This fact adds more margin to the ROPS design capabilities mentioned earlier.

4.2 CONCLUSIONS

This report presents two general conclusions. First, ROPS are saving lives and are not experiencing structural failure in rollovers. Second, the ROPS in use on machines have structural strength levels significantly in excess of the requirements given in SAE performance criteria for ROPS. The question remains, "Would ROPS that were designed to meet the minimum

performance requirements of SAE by performing as satisfactorily as the ROPS now in the field?" The Bureau of Mines is sponsoring contract research efforts that are attempting to develop ROPS performance criteria for the large wheel loaders that are used as mining shovels in surface mines. This program, entitled "Development of ROPS Performance Criteria for Large Mobile Mining Equipment" (USBM Contract No. HO292020), has developed some preliminary data that may have important implications to the development of improved ROPS standards. This program will conduct rollover tests on two models of large wheel loaders. Their gross vehicle weights are 280,000 pounds and 390,000 pounds.

As part of the preliminary work leading up to the field rollovers of these massive machines, a smaller wheel loader (52,000 pounds) was rolled to check out operation of the roll hill and to confirm the approaches to instrumenting the test machines. Two checkout rollovers were conducted on this smaller wheel loader. In both rollovers the production ROPS on the wheel loader maintained its structural integrity during the first revolution down the roll hill. In the first checkout roll test, the wheel loader ROPS also survived the second revolution, then impacted a roadway at the base of the roll hill and failed. If an operator had been in this machine, it is the opinion of the author that the operator would have been seriously injured or killed. In the second checkout roll test, the wheel loader's ROPS failed in the second revolution. The machine operator would probably have been killed. This ROPS exceeded the SAE performance requirements by a 27% margin. Though this ROPS exceeded the SAE requirements, it would not have provided satisfactory operator protection if this wheel loader had been involved in a rollover accident that was similar to the checkout roll tests.

In both of the checkout roll tests, the ROPS successfully completed a roll scenario very similar to the scenario given in the SAE recommended practices. As shown earlier in this report, appreciable numbers of wheel loaders experience rollovers where the ROPS impacts the slope two or more times. Also shown earlier was evidence that crawler dozers and scrapers experience even more multi-impact rollovers than wheel loaders.

Should ROPS provide operator protection in a higher percentage of rollovers? Should the ROPS performance criteria be developed to provide

the structural capability to withstand specific numbers of impacts on a standard roll hill? For example, ROPS for wheel loaders might be designed for survival on two impacts on the roll hill while ROPS for crawler dozers could be designed to survive additional impacts, say a total of four. Would this increase in ROPS structural capability result in the reduction in deaths and injuries due to ROPS failures? Probably not. This survey project was unable to document any incident where the structural failure of a ROPS designed to meet SAE criteria had failed and caused a death or injury. Doesn't this lack of evidence of SAE ROPS failures argue against changes in performance criteria? Why fool with success? Of course the earlier discussion on ROPS static test results suggests that the current success of ROPS may be due to the fact that many ROPS exceed the SAE requirements by large margins. This fact also suggests that an increase in side force requirements would not obsolete many of the current ROPS designs.

Another factor that may be playing an important role in the current success of ROPS has to do with the types of ROPS that are installed on machines in operation. An unknown, but no doubt significant, percentage of ROPS in the field are designed to meet Corps of Engineers performance criteria. These ROPS meet criteria requiring side load capability of at least 1.5 times the machine maximum gross weight. An older (1967) Corps of Engineers criteria required side load capability of 2 times the machine maximum gross weight. In prior studies for other clients, Woodward Associates, Inc. analyzed the structural capabilities of Corps of Engineers ROPS designs. The designs examined were all oversized by large margins, some as high as 300-400% over the requirements. Since the Corps of Engineers requirements were already much higher than SAE requirements, this overdesign produces a ROPS that exceeds SAE requirements by even larger margins. Perhaps the ROPS success is in part due to the fact that the ROPS population is composed of large numbers of Corps of Engineers ROPS and large numbers of oversized SAE ROPS. As the newer, and lower strength, SAE ROPS gain increased percentages of the total ROPS population, the frequency of ROPS failure may also increase.

If the existing ROPS structural performance standards need to be modified, what would be the requirements of new ROPS criteria? Are there

any existing data that would be useful in determining the levels of side force and the amount of energy needed to provide adequate operator protection? It would appear that the static test results examined during this project provide some clues toward defining the required side force levels. The test data already available from the two checkout rollovers previously conducted are helpful and test data to be gathered during 1981 will provide additional insight into ROPS performance requirements for wheel loaders. More test data are needed on rollovers of crawler dozers, scrapers, and haulage trucks. Rollover test data on motor graders and other types of equipment would be interesting but are not imperative for the development of satisfactory ROPS performance guidelines. Lacking sufficient rollover test data on crawler dozers, scrapers, and haulage trucks, the data resulting from the USBM research program on large wheel loader ROPS performance could be examined and through some type of analog analysis, be extrapolated to other types of machines.

The direction for future development of operator protective structures is not clear. The necessary test data is expensive to acquire and it is not clear if the responsibility for providing these data can be determined. The federal government agencies requiring ROPS are the Occupational Safety and Health Administration and the Mine Safety and Health Administration. Should they be responsible for doing the "homework" to support regulations? The Bureau of Mines has accepted the responsibility for specific studies related to mining machines; there is no comparable agency with interests in construction machines.

Though the direction and planning for improving machine operator protection structures is not clear, it is clear that the opportunity to increase the safety of machine operators exists.

APPENDIX A

ROPS REGULATIONS AND PERFORMANCE CRITERIA

REGULATIONS DEFINING ROPS REQUIREMENTS

Mine Safety and Health Administration

- CFR 30, Section 55.9-88 (Metal and Nonmetallic Open Pit Mines)
- CFR 30, Section 56.9-88 (Sand, Gravel, and Crushed Stone Operations)
- CFR 30, Section 57.9-88 (Surface areas of Metal and Nonmetallic Underground Mines)
- CFR 30, Section 77.403a (Surface Coal Mines and Surface areas of Underground Coal Mines)

Occupational Safety and Health Administration

- CFR 29, Part 1926, Subpart W

Corps of Engineers

- General Safety Requirements, EM-385-1-1 (March 1967) and EM-385-1-1, Change No. 1 (March 1972)

Bureau of Reclamation

- Safety and Health Regulations for Construction, Part II

ROPS PERFORMANCE CRITERIA PUBLISHED BY SAE

Minimum Performance Criteria for Roll-Over Protective Structure for Rubber-Tired, Self-Propelled Scrapers

- SAE J320 (1967), SAE J320a (1969), SAE J320b (1972)

Minimum Performance Criteria for Roll-Over Protective Structure for Rubber-Tired Dozers

- SAE J394 (1969), SAE J394a (1972)

Minimum Performance Criteria for Roll-Over Protective Structure for Crawler Tractors and Crawler-Type Loaders

- SAE J395 (1969), SAE J395a (1972)

Minimum Performance Criteria for Roll-Over Protective Structure for Motor Graders

- SAE J396 (1969), SAE J396a (1972)

Critical Zone -- Characteristics and Dimensions for Operators of Construction and Industrial Machinery

- SAE J397 (1969), SAE J397a (1972)

Performance Criteria for Rollover Protective Structures (ROPS) for Earthmoving, Construction, Logging, and Industrial Vehicles

- SAE J1040 (1974), SAE J1040a (1975), SAE J1040b (1977), SAE J1040c (1979)

Labeling of ROPS and FOPS

- SAE J1164 (1977)

Steel Products for Rollover Protective Structures (ROPS) and Falling Object Protective Structures (FOPS)

- SAE J1119 (1975)

Performance Prediction of Roll-Over Protective Structures (ROPS) through Analytical Methods

- SAE J1215 (1979)

Deflection Limiting Volume -- ROPS/FOPS Laboratory Evaluation

- SAE J397a (1973), SAE J397b (1979)

APPENDIX B

SAE ROPS PERFORMANCE STANDARDS

The Society of Automotive Engineers, Inc. has assumed the leadership in formulating the structural performance requirements for rollover protective structures. This activity began in 1966 and has resulted in a continuing evolution of improved performance standards. This appendix contains the minimum structural performance requirements; the side force, the side energy, and the vertical force specified in each of the SAE recommended practices.

SAE ROPS PERFORMANCE STANDARDS

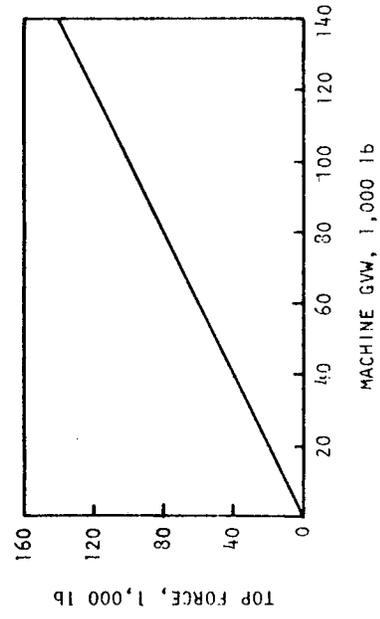
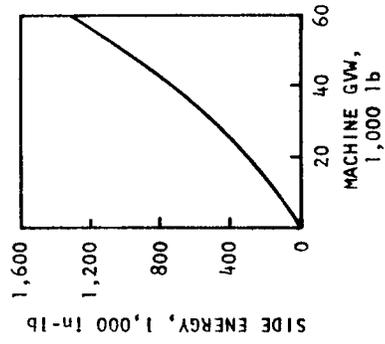
SAE J320 (Scrapers)

Side Force Equation:

None defined in recommended practice.

Side Energy Equation:

$$\text{Side energy} = 1.80 \times 10^{-4} (\text{GVW})^2 + 11.34 (\text{GVW})$$



Top Force Equation:

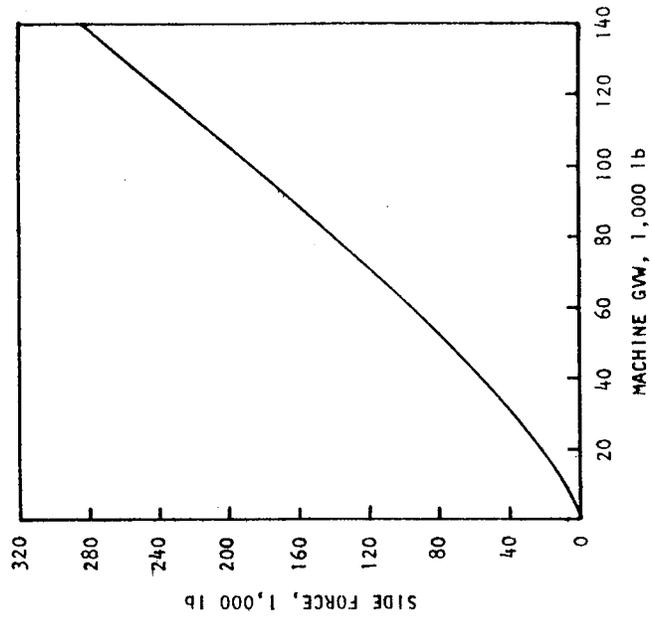
$$\text{Top force} = \text{GVW}$$

SAE ROPS PERFORMANCE STANDARDS

SAE J320a (Scrapers)

Side Force Equation:

$$\text{Side Force} = \text{GVW} \times 0.95 \left(\frac{\text{GVW}}{10,000} \right)^{0.29}$$

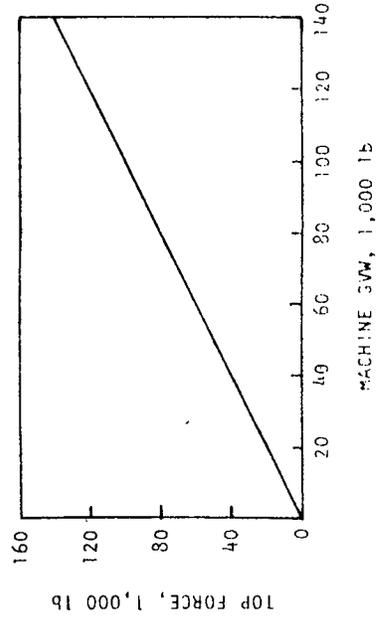
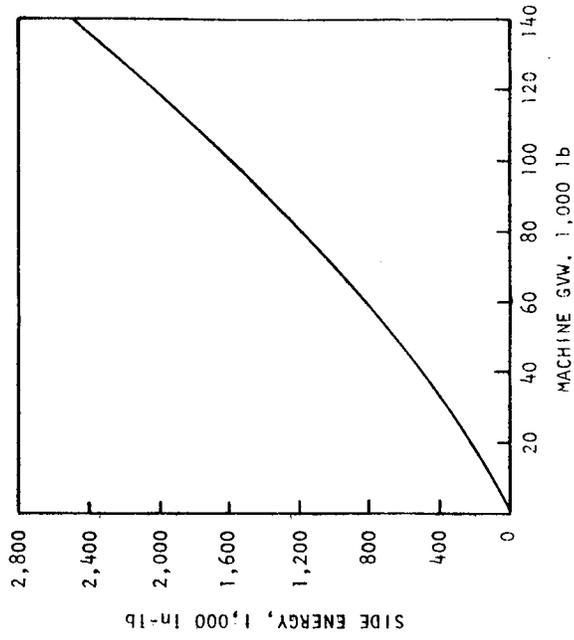


SAE ROPS PERFORMANCE STANDARDS

SAE J320a (Scrapers) (Cont)

Side Energy Equation:

$$\text{Side energy} = 80,000 \left(\frac{\text{GVW}}{10,000} \right)^{1.3}$$



Top Force Equation:

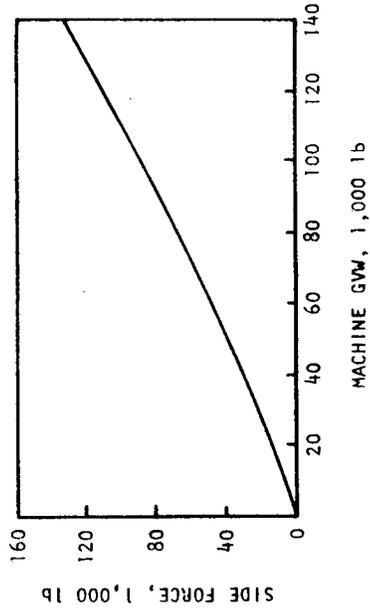
$$\text{Top force} = \text{GVW}$$

SAE ROPS PERFORMANCE STANDARDS

SAE J394 (Wheel Loaders)

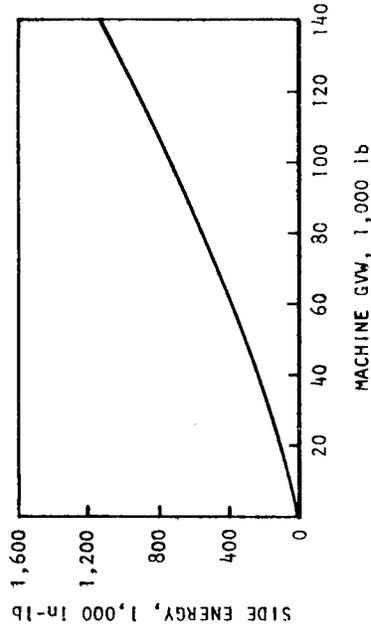
Side Force Equation:

$$\text{Side force} = \text{GVW} \times 0.53 \left(\frac{\text{GVW}}{10,000} \right)^{0.22}$$



Side Energy Equation:

$$\text{Side energy} = 42,000 \left(\frac{\text{GVW}}{10,000} \right)^{1.25}$$

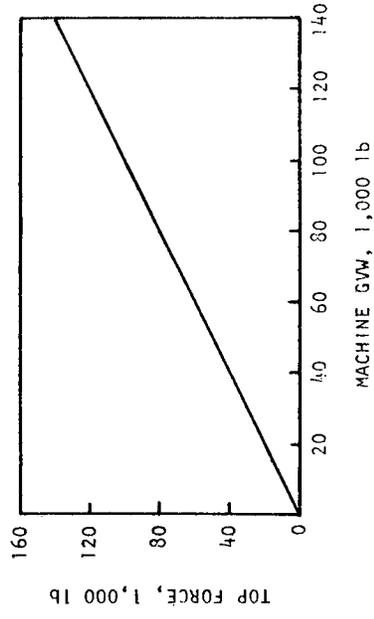


SAE ROPS PERFORMANCE STANDARDS

SAE J394 (Wheel Loaders) (Cont)

Top Force Equation:

$$\text{Top force} = \text{GVW}$$

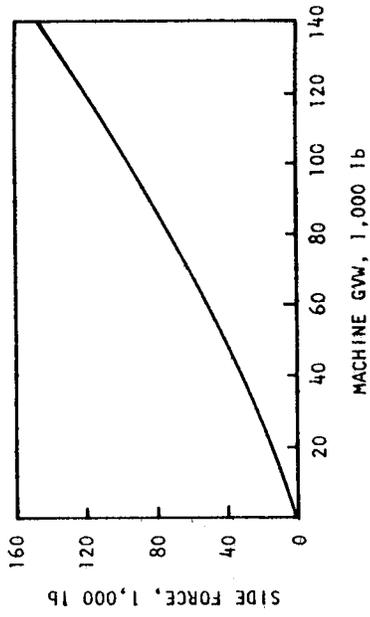


SAE ROPS PERFORMANCE STANDARDS

SAE J395 (Crawler Tractors)

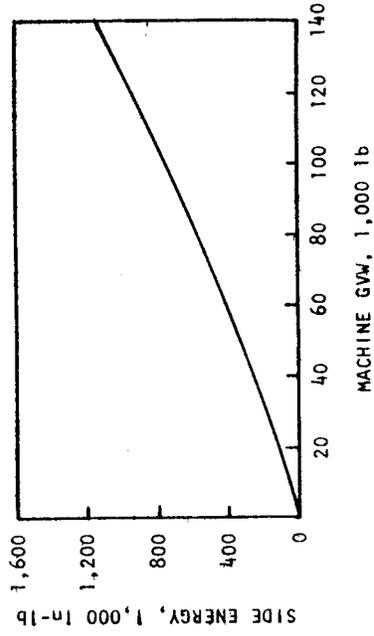
Side Force Equation:

$$\text{Side force} = \text{GVW} \times 0.59 \left(\frac{\text{GVW}}{10,000} \right)^{0.22}$$



Side Energy Equation:

$$\text{Side energy} = 45,000 \left(\frac{\text{GVW}}{10,000} \right)^{1.23}$$

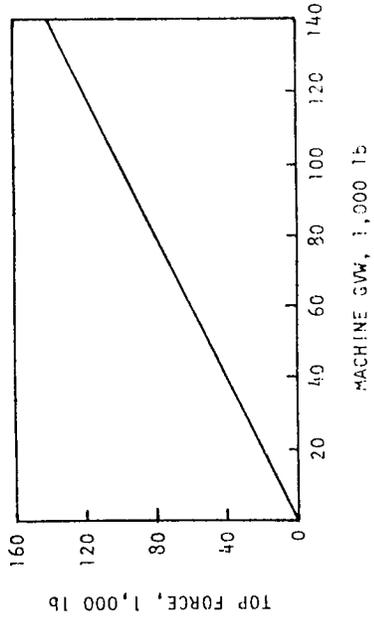


SAE ROPS PERFORMANCE STANDARDS

SAE J395 (Crawler Tractors) (Cont)

Top Force Equation:

$$\text{Top force} = \text{GVW}$$

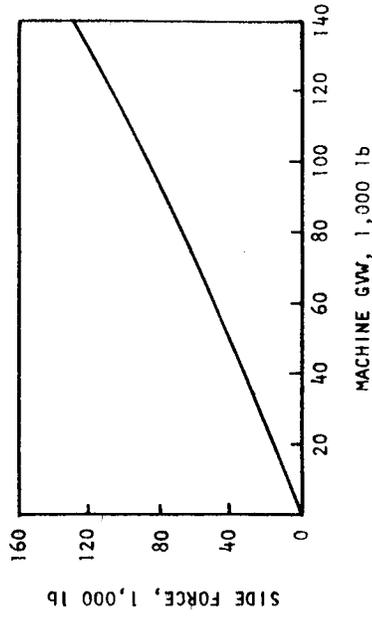


SAE ROPS PERFORMANCE STANDARDS

SAE J396 (Motor Graders)

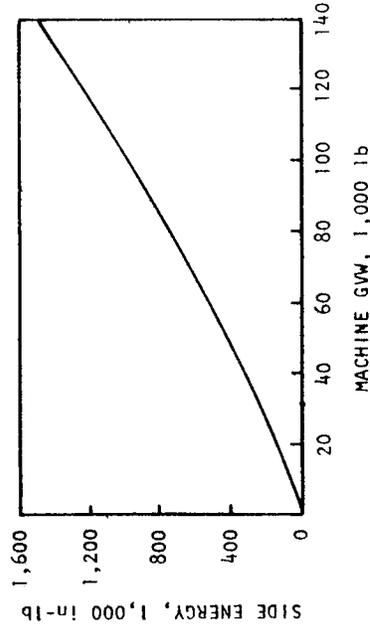
Side Force Equation:

$$\text{Side force} = \text{GVW} \times 0.70 \left(\frac{\text{GVW}}{10,000} \right)^{0.10}$$



Side Energy Equation:

$$\text{Side energy} = 55,000 \left(\frac{\text{GVW}}{10,000} \right)^{1.25}$$

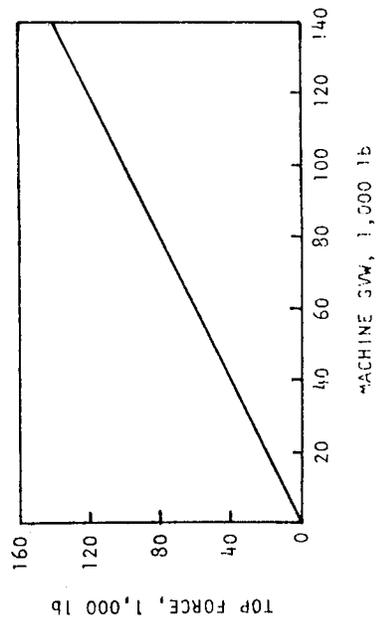


SAE ROPS PERFORMANCE STANDARDS

SAE J396 (Motor Graders) (Cont)

Top Force Equation:

$$\text{Top force} = \text{GVW}$$



SAE ROPS PERFORMANCE STANDARDS

SAE J1040-J1040a (Crawler Tractors)

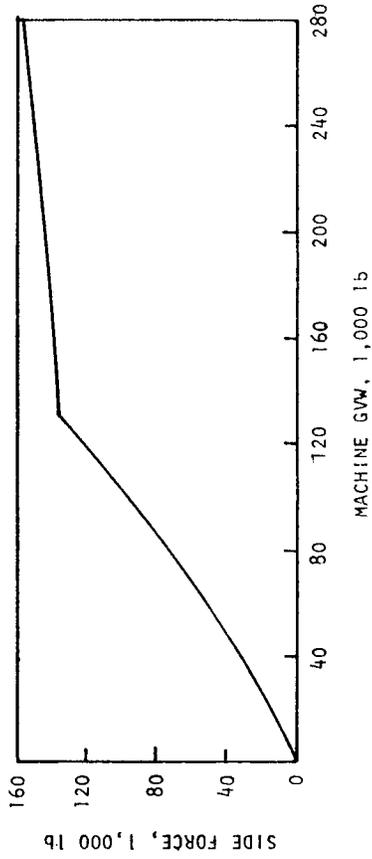
Side Force Equation:

For $GVW < 132,280 \text{ lb}$

$$\text{Side force} = 6,090 \left(\frac{GVW}{10,000} \right)^{1.20}$$

For $GVW > 132,280 \text{ lb}$

$$\text{Side force} = 80,610 \left(\frac{GVW}{10,000} \right)^{0.20}$$



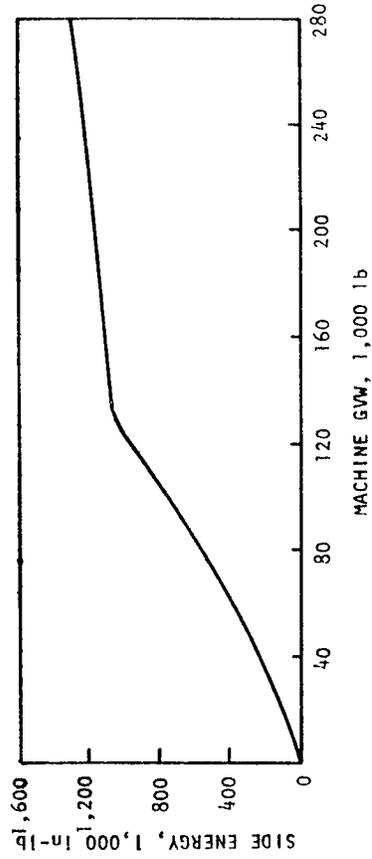
Side Energy Equation:

For $GVW < 132,280 \text{ lb}$

$$\text{Side energy} = 42,830 \left(\frac{GVW}{10,000} \right)^{1.25}$$

For $GVW > 132,280 \text{ lb}$

$$\text{Side energy} = 566,480 \left(\frac{GVW}{10,000} \right)^{0.25}$$

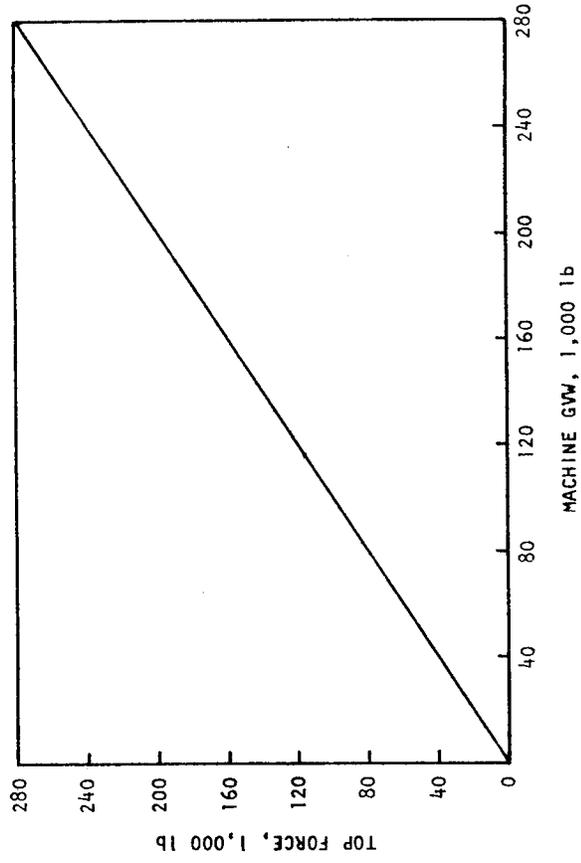


SAE ROPS PERFORMANCE STANDARDS

SAE J1040-J1040a (Crawler Tractors) (Cont)

Top Force Equation:

$$\text{Top force} = \text{GVW}$$



SAE ROPS PERFORMANCE STANDARDS

SAE J1040-J1040a (Motor Graders)

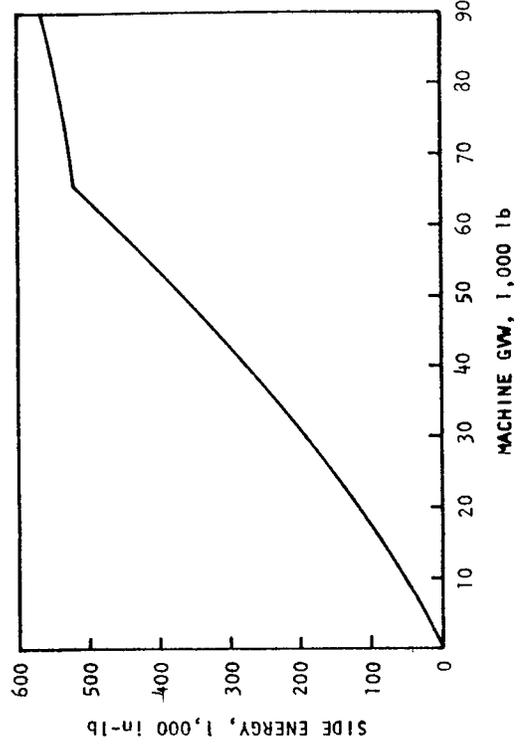
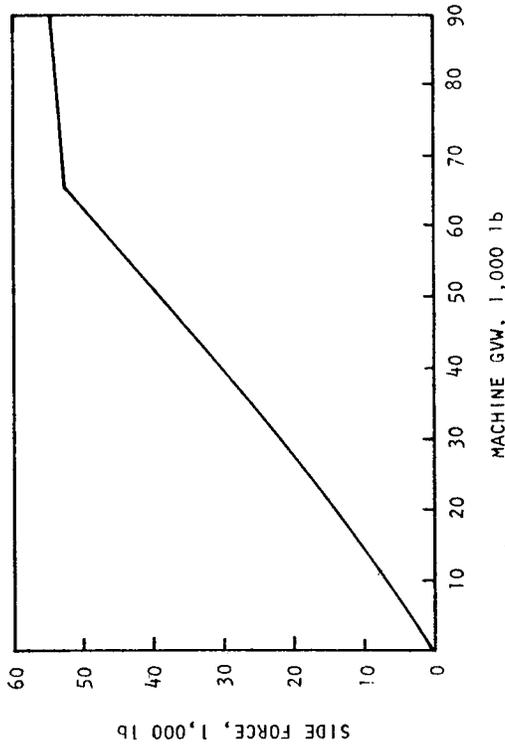
Side Force Equation:

For GVW < 66,140 lb

$$\text{Side force} = 6,600 \left(\frac{\text{GVW}}{10,000} \right)^{1.10}$$

For GVW > 66,140 lb

$$\text{Side force} = 43,620 \left(\frac{\text{GVW}}{10,000} \right)^{0.10}$$



Side Energy Equation:

For GVW < 66,140 lb

$$\text{Side energy} = 49,410 \left(\frac{\text{GVW}}{10,000} \right)^{1.25}$$

For GVW > 66,140 lb

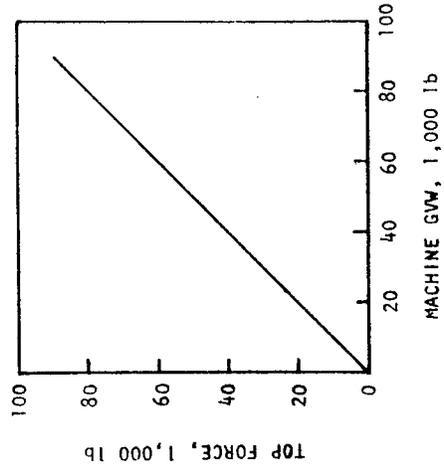
$$\text{Side energy} = 326,810 \left(\frac{\text{GVW}}{10,000} \right)^{0.25}$$

SAE ROPS PERFORMANCE STANDARDS

SAE J1040-J1040a (Motor Graders) (Cont)

Top Force Equation:

$$\text{Top force} = \text{GVW}$$



SAE ROPS PERFORMANCE STANDARDS

SAE J1040-J1040a (Wheel Loaders)

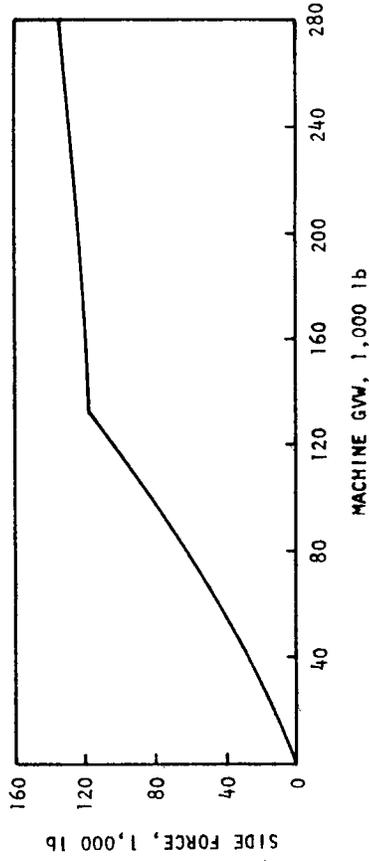
Side Force Equation:

For GVW < 132,280 lb

$$\text{Side force} = 5,220 \left(\frac{\text{GVW}}{10,000} \right)^{1.20}$$

For GVW > 132,280 lb

$$\text{Side force} = 69,100 \left(\frac{\text{GVW}}{10,000} \right)^{0.20}$$



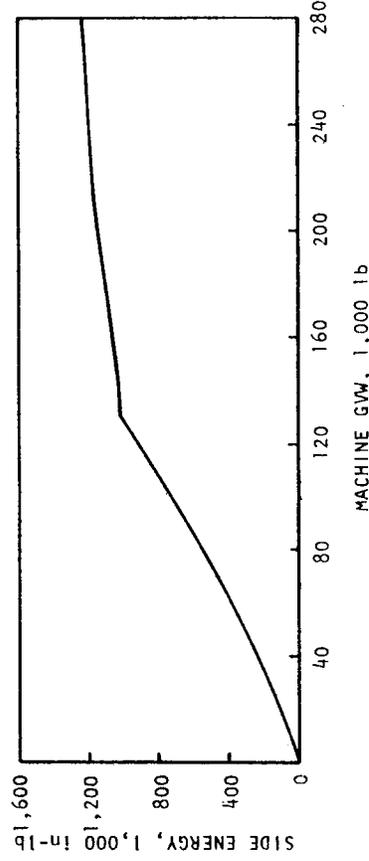
Side Energy Equation:

For GVW < 132,280 lb

$$\text{Side energy} = 41,180 \left(\frac{\text{GVW}}{10,000} \right)^{1.25}$$

For GVW > 132,280 lb

$$\text{Side energy} = 544,690 \left(\frac{\text{GVW}}{10,000} \right)^{0.25}$$

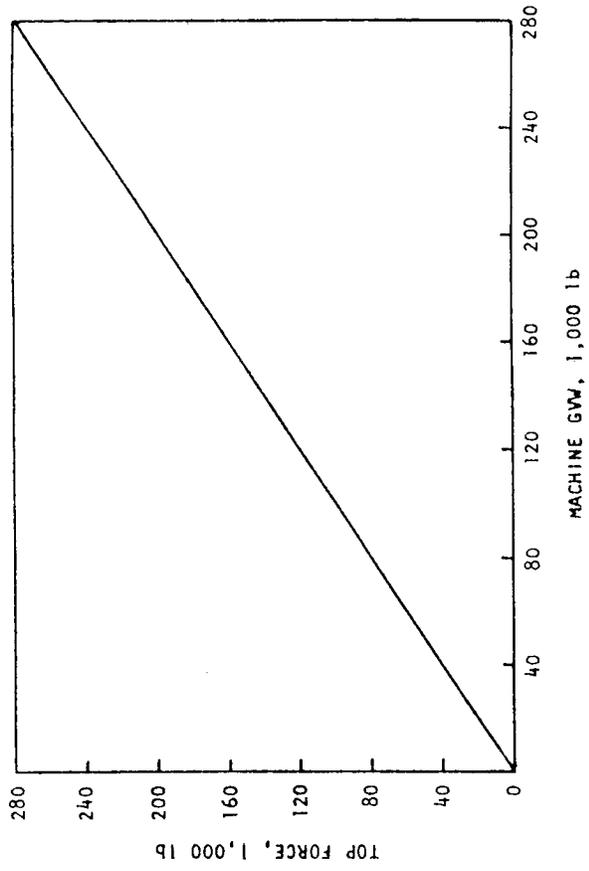


SAE ROPS PERFORMANCE STANDARDS

SAE J1040-J1040a (Wheel Loaders) (Cont)

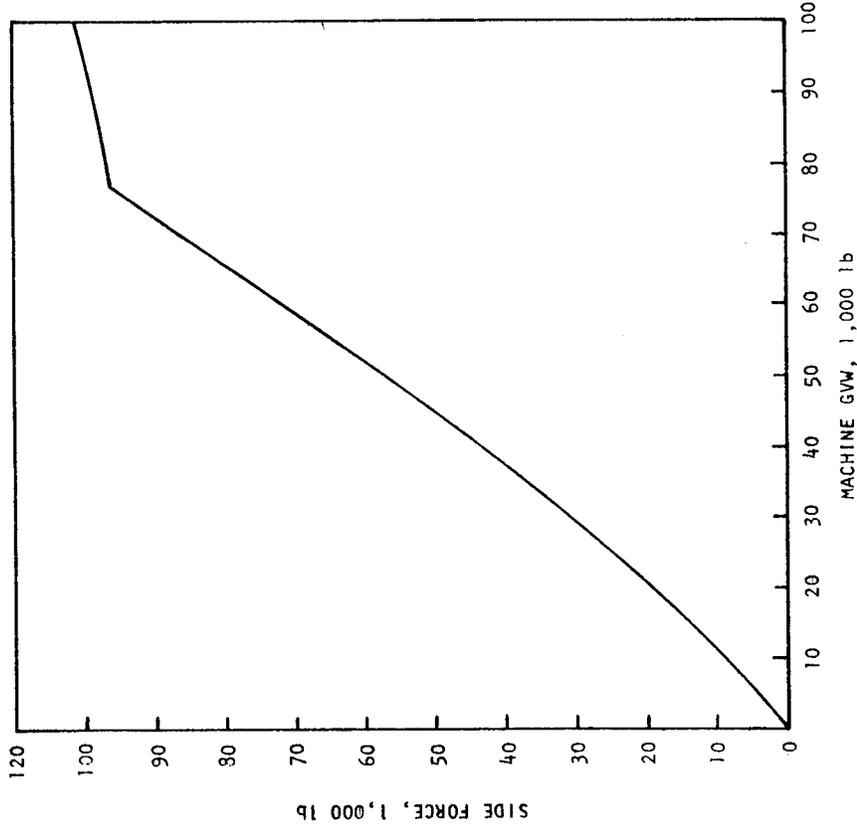
Top Force Equation:

$$\text{Top force} = \text{GVW}$$



SAE ROPS PERFORMANCE STANDARDS

SAE J1040-J1040a (Scrapers)



Side Force Equation:

For GVW < 77,160 lb

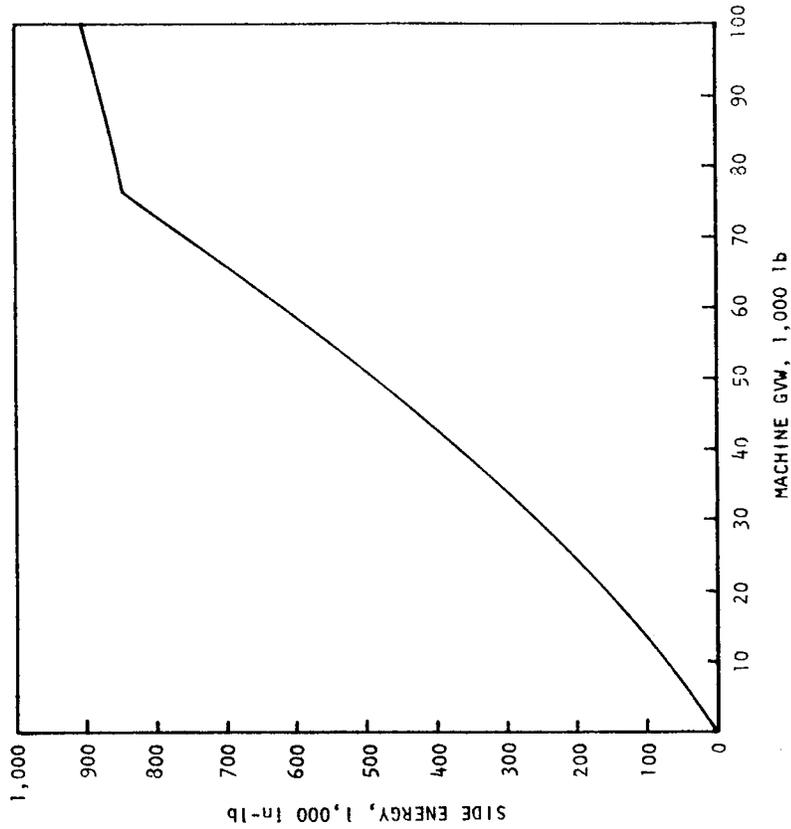
$$\text{Side force} = 8,270 \left(\frac{\text{GVW}}{10,000} \right)^{1.20}$$

For GVW > 77,160 lb

$$\text{Side force} = 63,820 \left(\frac{\text{GVW}}{10,000} \right)^{0.20}$$

SAE ROPS PERFORMANCE STANDARDS

SAE J1040-J1040a (Scrapers) (Cont)



Side Energy Equation:

For GVW < 77,160 lb

$$\text{Side energy} = 65,880 \left(\frac{\text{GVW}}{10,000} \right)^{1.20}$$

For GVW > 77,160 lb

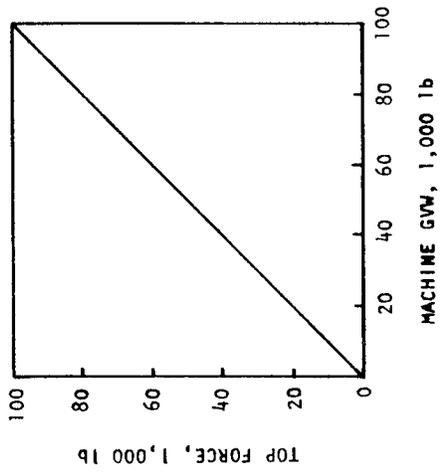
$$\text{Side energy} = 508,380 \left(\frac{\text{GVW}}{10,000} \right)^{0.25}$$

SAE ROPS PERFORMANCE STANDARDS

SAE J1040-J1040a (Scrapers) (Cont)

Top Force Equation:

$$\text{Top force} = \text{GVW}$$



SAE ROPS PERFORMANCE STANDARDS

SAE J1040-J1040a (Dumpers)

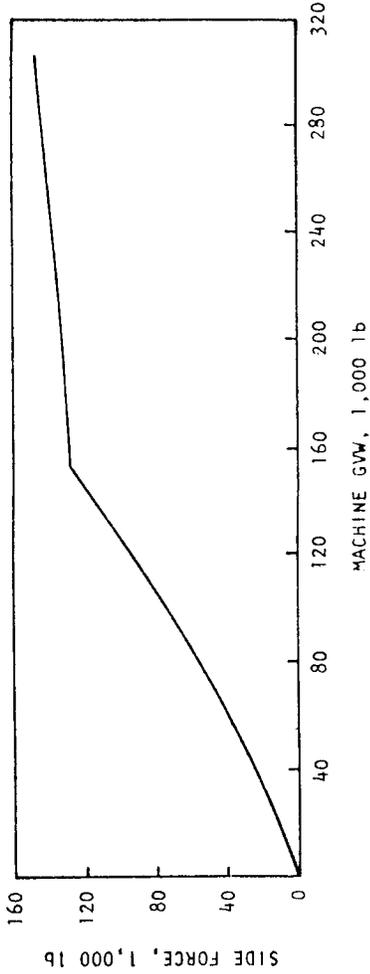
Side Force Equation:

For $GVW < 154,320$ lb

$$\text{Side force (ROPS)} = 4,790 \left(\frac{GVW}{10,000} \right)^{1.10}$$

For $GVW > 154,320$ lb

$$\text{Side force (ROPS)} = 73,890 \left(\frac{GVW}{10,000} \right)^{0.20}$$



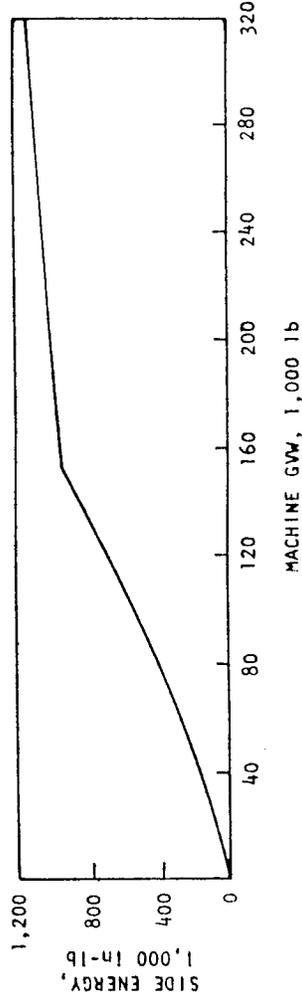
Side Energy Equation:

For $GVW < 154,320$ lb

$$\text{Side energy (ROPS)} = 31,300 \left(\frac{GVW}{10,000} \right)^{1.25}$$

For $GVW > 154,320$ lb

$$\text{Side energy (ROPS)} = 482,960 \left(\frac{GVW}{10,000} \right)^{0.25}$$



Top Force Equation:

Top force = $GVW - \text{body tare mass}$
(ROPS)

SAE ROPS PERFORMANCE STANDARDS

SAE J1040-J1040a (Dumpers)

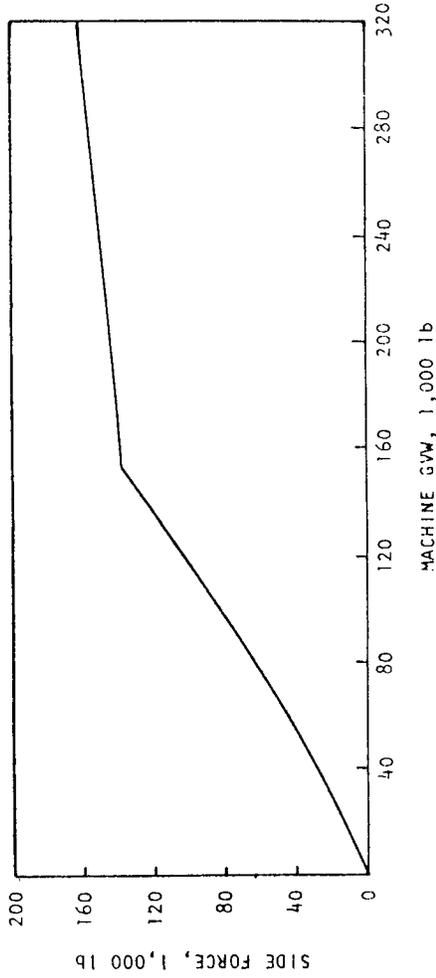
Side Force Equation:

For $GVW < 154,320$ lb

$$\text{Side force (Body)} = 5,220 \left(\frac{GVW}{10,000} \right)^{1.20}$$

For $GVW > 154,320$ lb

$$\text{Side force (Body)} = 80,610 \left(\frac{GVW}{10,000} \right)^{0.20}$$



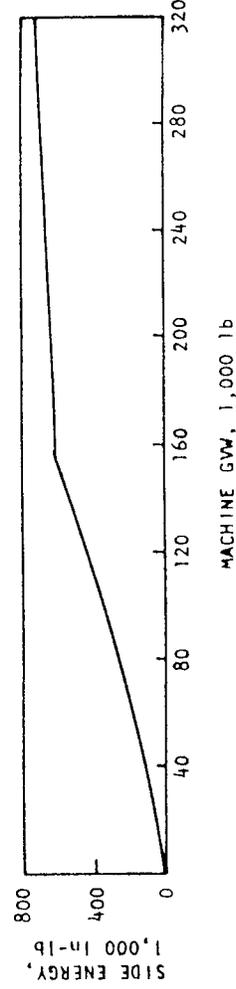
Side Energy Equation:

For $GVW < 154,320$ lb

$$\text{Side energy (Body)} = 19,770 \left(\frac{GVW}{10,000} \right)^{0.20}$$

For $GVW > 154,320$ lb

$$\text{Side energy (Body)} = 305,030 \left(\frac{GVW}{10,000} \right)^{0.25}$$

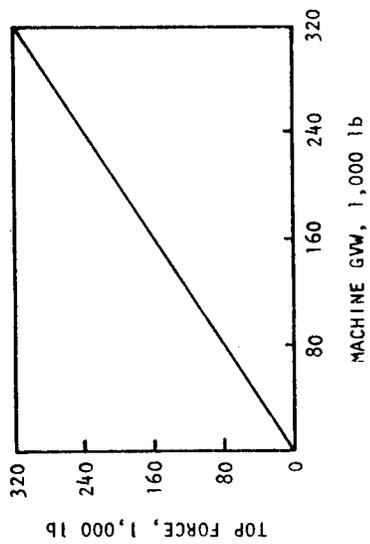


SAE ROPS PERFORMANCE STANDARDS

SAE J1040-J1040a (Dumpers) (Cont)

Top Force Equation:

$$\text{Top Force} = \text{GVW} \\ (\text{Body})$$



SAE ROPS PERFORMANCE STANDARDS

SAE J1040b (Crawler Tractors)

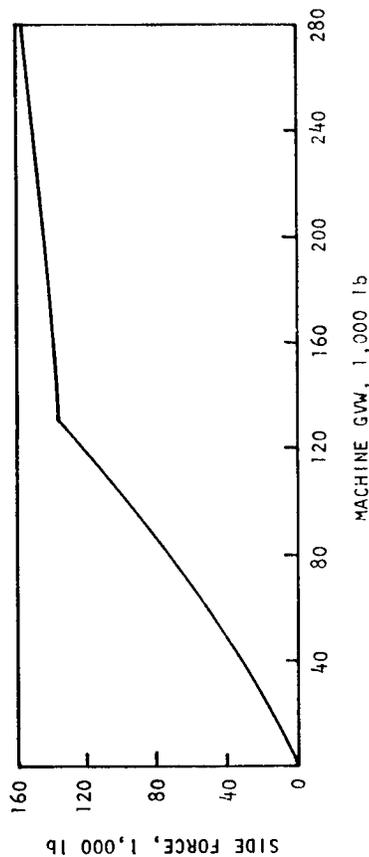
Side Force Equation:

For GVW < 132,280 lb

$$\text{Side force} = 6,090 \left(\frac{\text{GVW}}{10,000} \right)^{1.20}$$

For GVW > 132,280 lb

$$\text{Side force} = 80,610 \left(\frac{\text{GVW}}{10,000} \right)^{0.20}$$



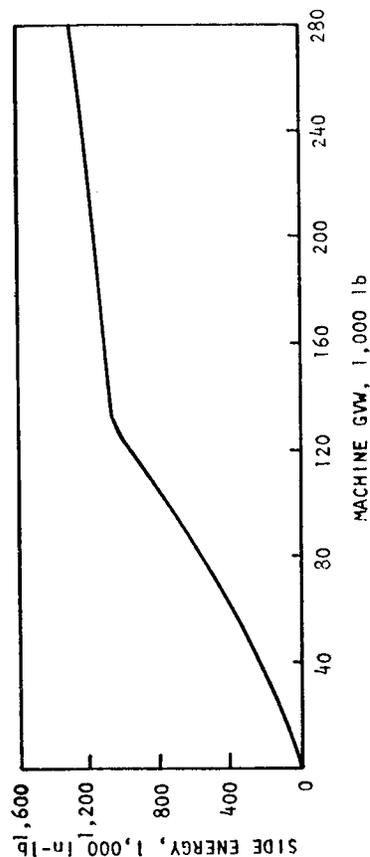
Side Energy Equation:

For GVW < 132,280 lb

$$\text{Side energy} = 42,830 \left(\frac{\text{GVW}}{10,000} \right)^{1.25}$$

For GVW > 132,280 lb

$$\text{Side energy} = 566,480 \left(\frac{\text{GVW}}{10,000} \right)^{0.25}$$

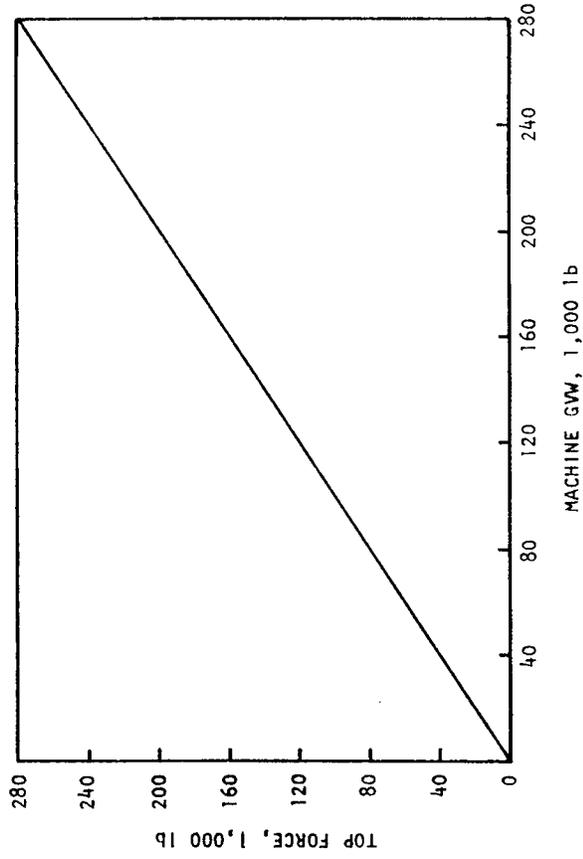


SAE ROPS PERFORMANCE STANDARDS

SAE J1040b (Crawler Tractors) (Cont)

Top Force Equation:

$$\text{Top force} = \text{GVW}$$

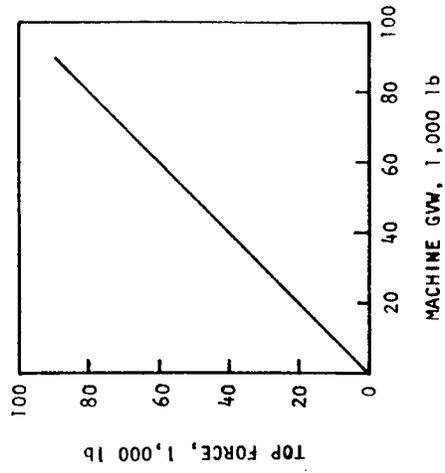


SAE ROPS PERFORMANCE STANDARDS

SAE J1040b (Motor Graders) (Cont)

Top Force Equation:

$$\text{Top force} = \text{GVW}$$



SAE ROPS PERFORMANCE STANDARDS

SAE J1040b (Wheel Loaders)

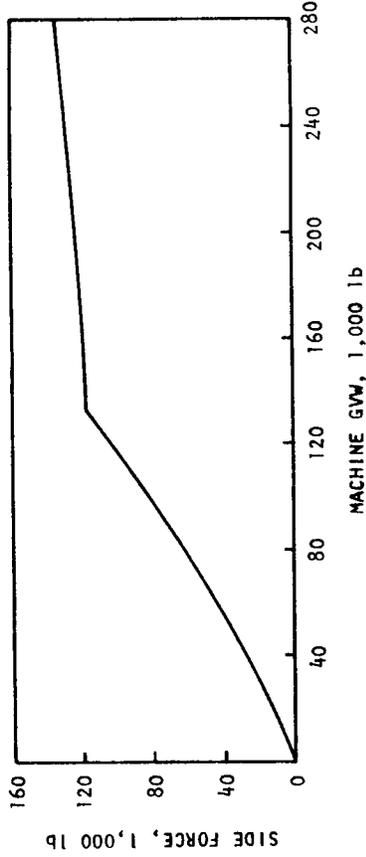
Side Force Equation:

For GVW < 132,280 lb

$$\text{Side force} = 5,220 \left(\frac{\text{GVW}}{10,000} \right)^{1.20}$$

For GVW > 132,280 lb

$$\text{Side force} = 69,100 \left(\frac{\text{GVW}}{10,000} \right)^{0.20}$$



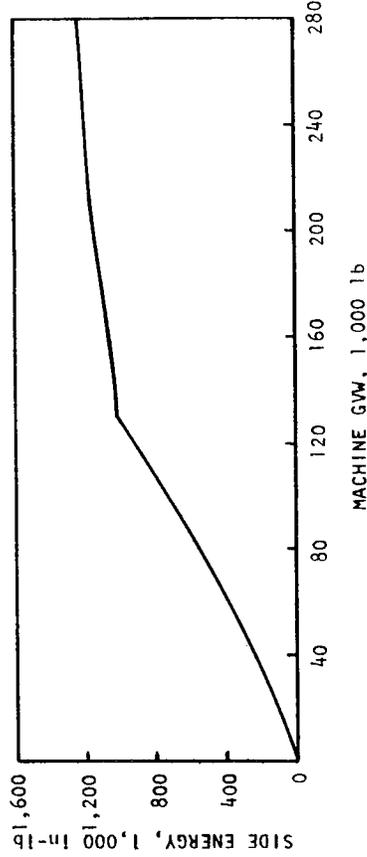
Side Energy Equation:

For GVW < 132,280 lb

$$\text{Side energy} = 41,180 \left(\frac{\text{GVW}}{10,000} \right)^{1.25}$$

For GVW > 132,280 lb

$$\text{Side energy} = 544,690 \left(\frac{\text{GVW}}{10,000} \right)^{0.25}$$

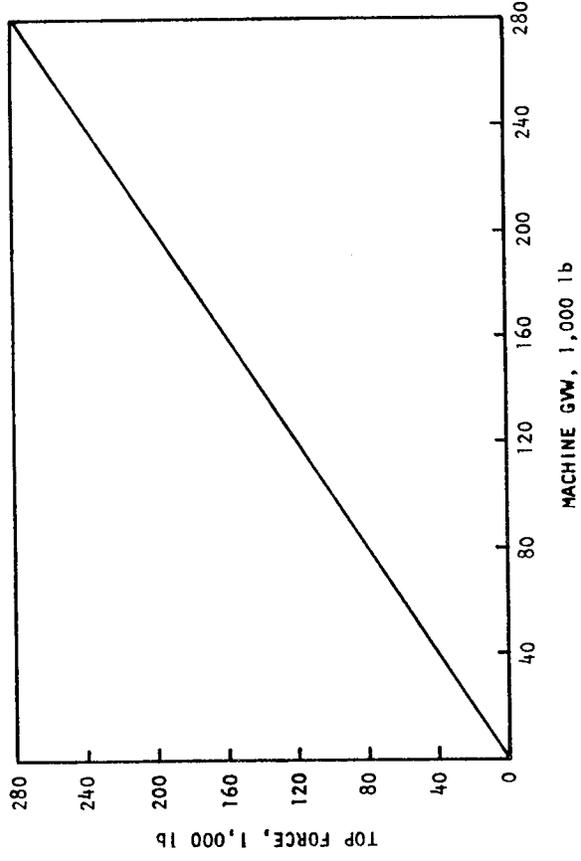


SAE ROPS PERFORMANCE STANDARDS

SAE J1040b (Wheel Loaders) (Cont)

Top Force Equation:

$$\text{Top force} = \text{GVW}$$



SAE ROPS PERFORMANCE STANDARDS

SAE J1040b (Scrapers)

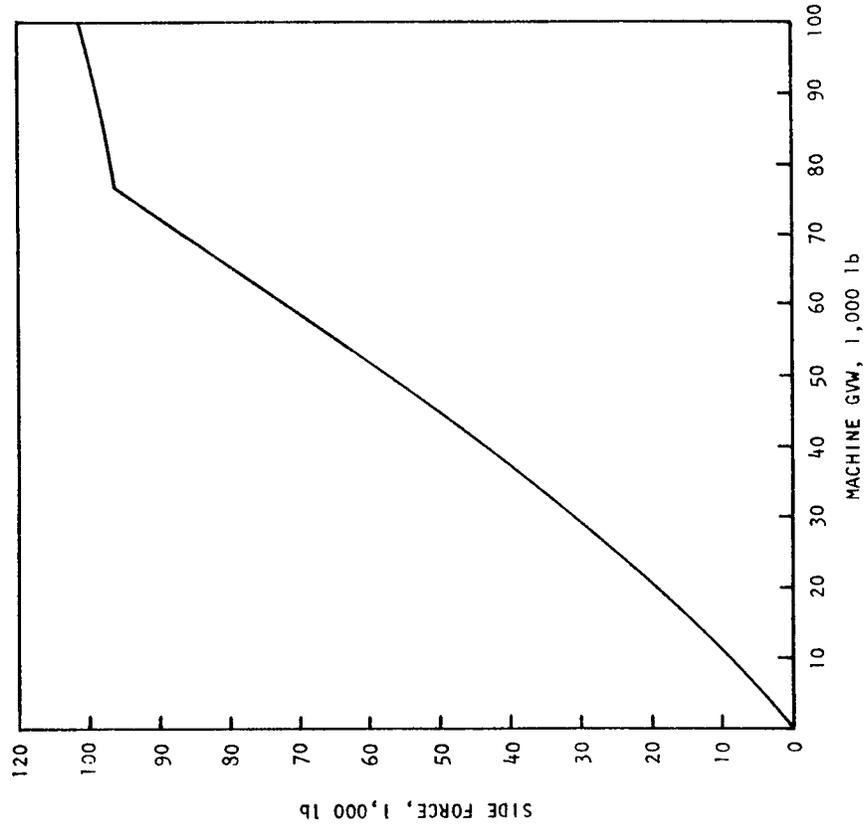
Side Force Equation:

For GVW < 77,160 lb

$$\text{Side force} = 8,270 \left(\frac{\text{GVW}}{10,000} \right)^{1.20}$$

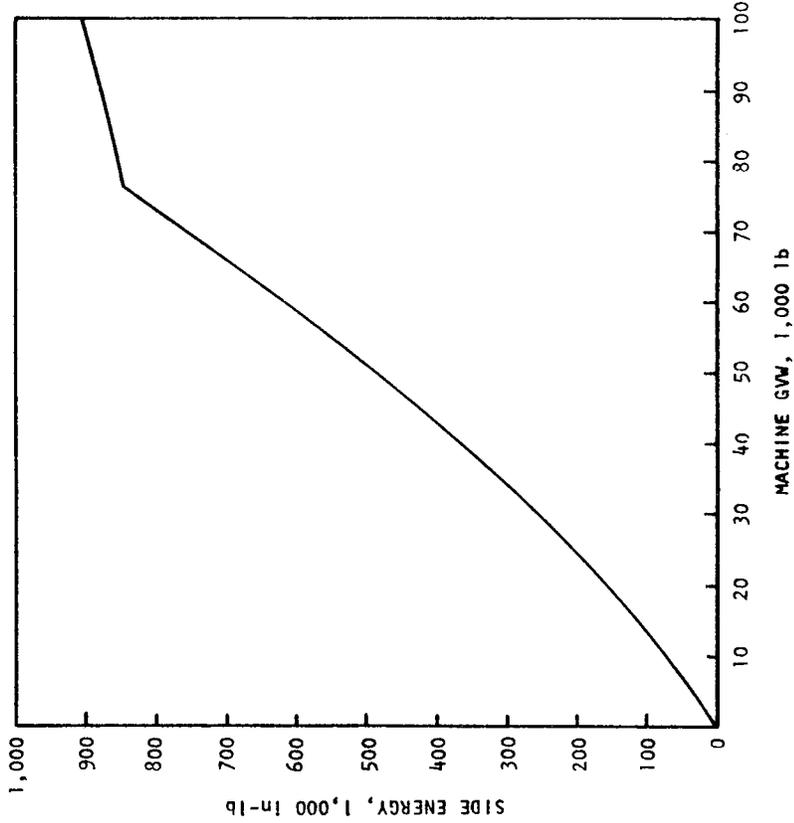
For GVW > 77,160 lb

$$\text{Side force} = 63,820 \left(\frac{\text{GVW}}{10,000} \right)^{0.20}$$



SAE ROPS PERFORMANCE STANDARDS

SAE J11040b (Scrapers) (Cont)



Side Energy Equation:

For GVW < 77,160 lb

$$\text{Side energy} = 65,880 \left(\frac{\text{GVW}}{10,000} \right)^{1.25}$$

For GVW > 77,160 lb

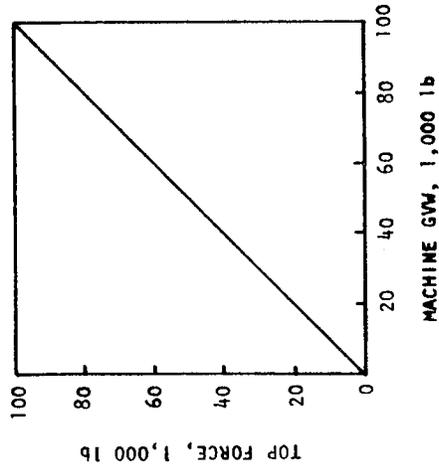
$$\text{Side energy} = 508,380 \left(\frac{\text{GVW}}{10,000} \right)^{0.25}$$

SAE ROPS PERFORMANCE STANDARDS

SAE J1040b (Scrapers) (Cont)

Top Force Equation:

$$\text{Top force} = \text{GW}$$



SAE ROPS PERFORMANCE STANDARDS

SAE J1040b (Dumpers)

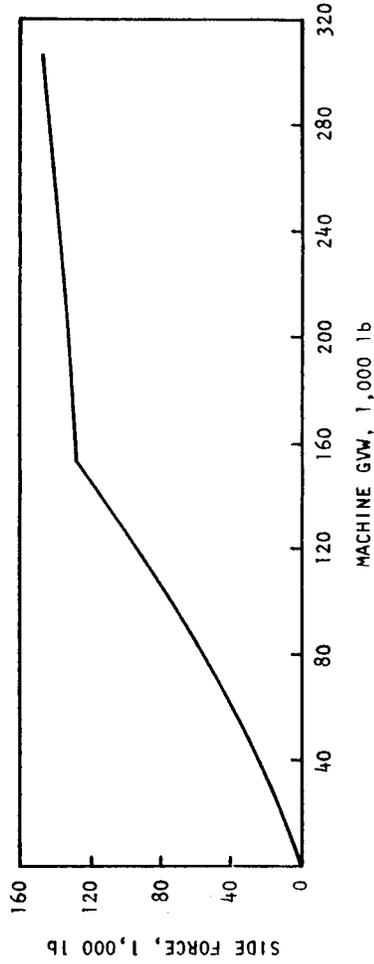
Side Force Equation:

For GVW < 154,320 lb

$$\text{Side force (ROPS)} = 4,790 \left(\frac{\text{GVW}}{10,000} \right)^{1.20}$$

For GVW > 154,320 lb

$$\text{Side force (ROPS)} = 73,890 \left(\frac{\text{GVW}}{10,000} \right)^{0.20}$$



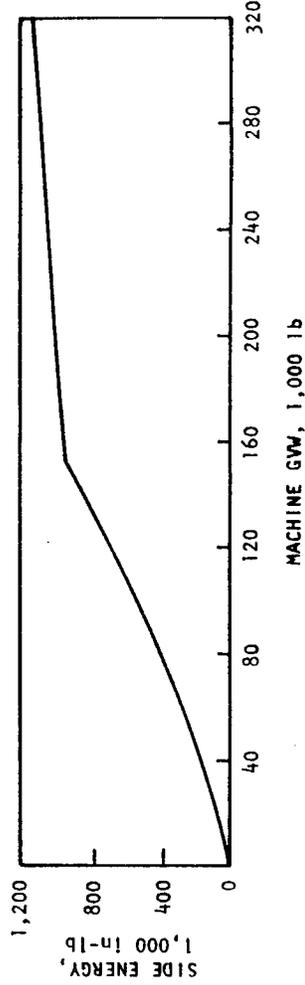
Side Energy Equation:

For GVW < 154,320 lb

$$\text{Side energy (ROPS)} = 31,300 \left(\frac{\text{GVW}}{10,000} \right)^{1.25}$$

For GVW > 154,320 lb

$$\text{Side energy (ROPS)} = 482,960 \left(\frac{\text{GVW}}{10,000} \right)^{0.25}$$



Top Force Equation:

$$\text{Top force (ROPS)} = \text{GVW} - \text{body tare mass}$$

SAE ROPS PERFORMANCE STANDARDS

SAE J1040b (Dumpers)

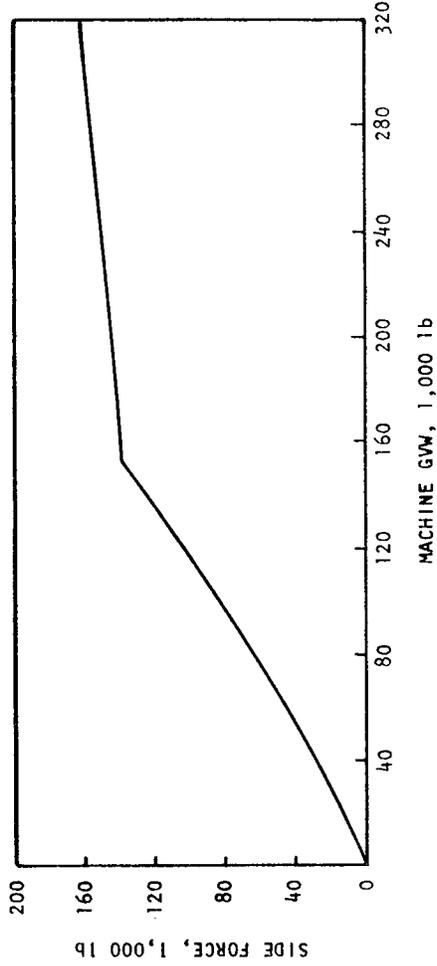
Side Force Equation:

For GW $<$ 154,320 lb

$$\text{Side force (Body)} = 5,220 \left(\frac{\text{GW}}{10,000} \right)^{1.20}$$

For GW $>$ 154,320 lb

$$\text{Side force (Body)} = 80,610 \left(\frac{\text{GW}}{10,000} \right)^{0.20}$$



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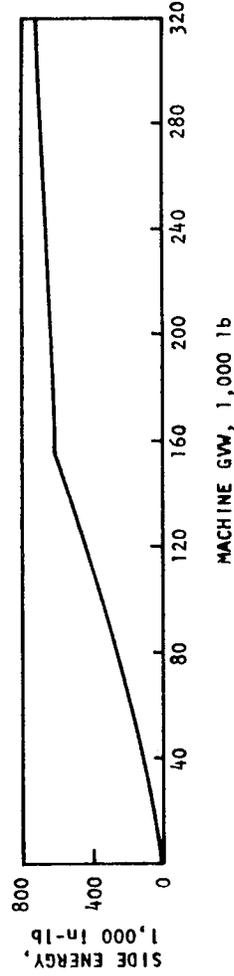
Side Energy Equation:

For GW $<$ 154,320 lb

$$\text{Side energy (Body)} = 19,770 \left(\frac{\text{GW}}{10,000} \right)^{1.25}$$

For GW $>$ 154,320 lb

$$\text{Side energy (Body)} = 305,030 \left(\frac{\text{GW}}{10,000} \right)^{0.25}$$

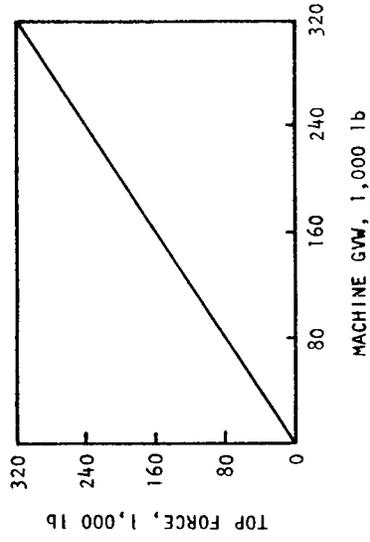


SAE ROPS PERFORMANCE STANDARDS

SAE J1040b (Dumpers) (Cont)

Top Force Equation:

$$\text{Top force} = \text{GWW} \\ \text{(Body)}$$



SAE ROPS PERFORMANCE STANDARDS

SAE J1040c (Crawler Tractors)

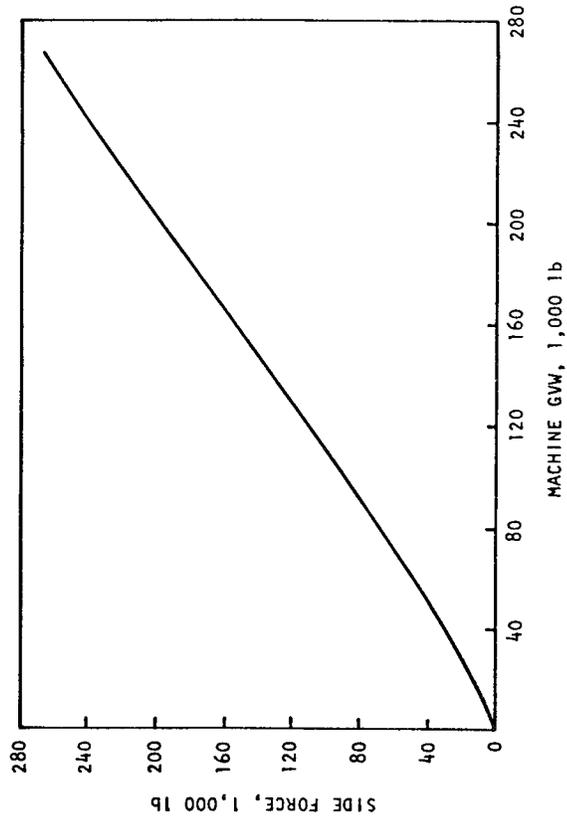
Side Force Equation:

For GW $<$ 131,173 lb

$$\text{Side force} = 6,090 \left(\frac{\text{GVW}}{10,000} \right)^{1.20}$$

For 131,173 lb $<$ GW $<$ 264,555 lb

Side force = 1.02 GW



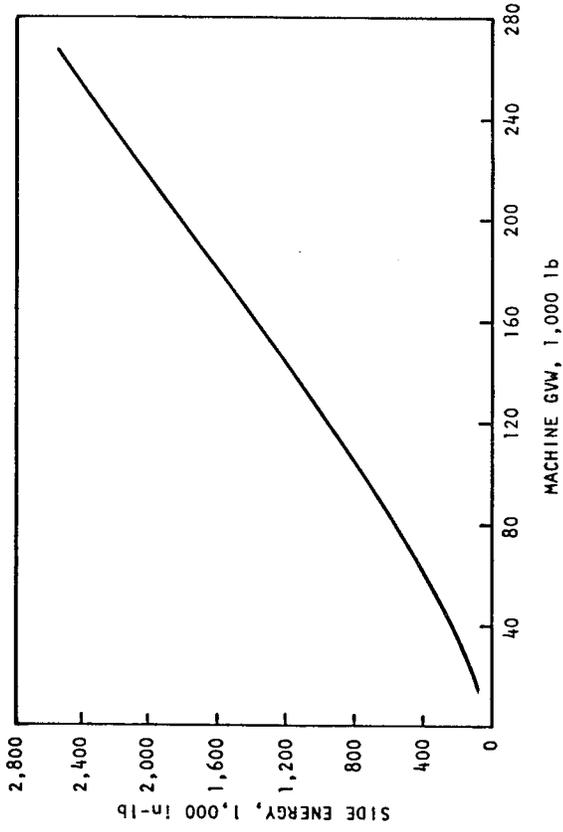
SAE ROPS PERFORMANCE STANDARDS

SAE J1040c (Crawler Tractors) (Cont)

Side Energy Equation:

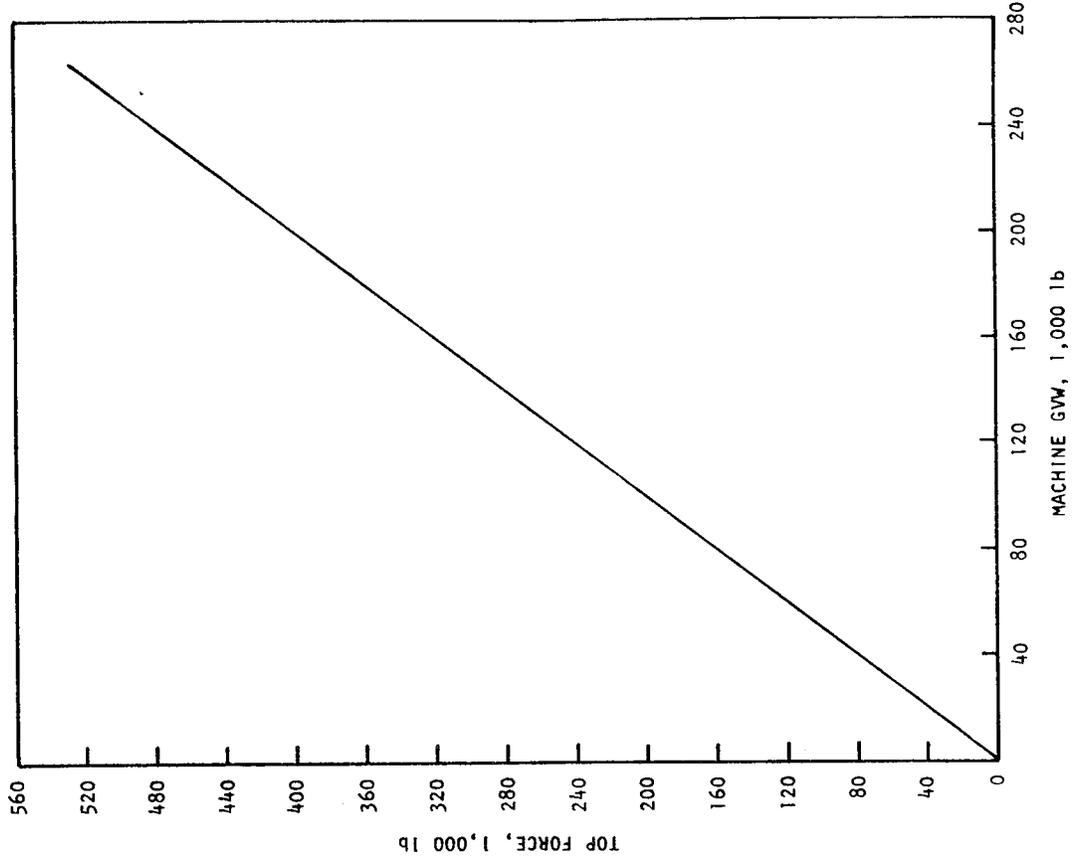
For GVW < 264,555 lb

$$\text{Side energy} = 42,830 \left(\frac{\text{GVW}}{10,000} \right)^{1.25}$$



SAE ROPS PERFORMANCE STANDARDS

SAE J1040c (Crawler Tractors) (Cont)



Top Force Equation:

For GVW < 264,555 lb

Top force = 2.0 GVW

SAE ROPS PERFORMANCE STANDARDS

SAE J1040c (Motor Graders)

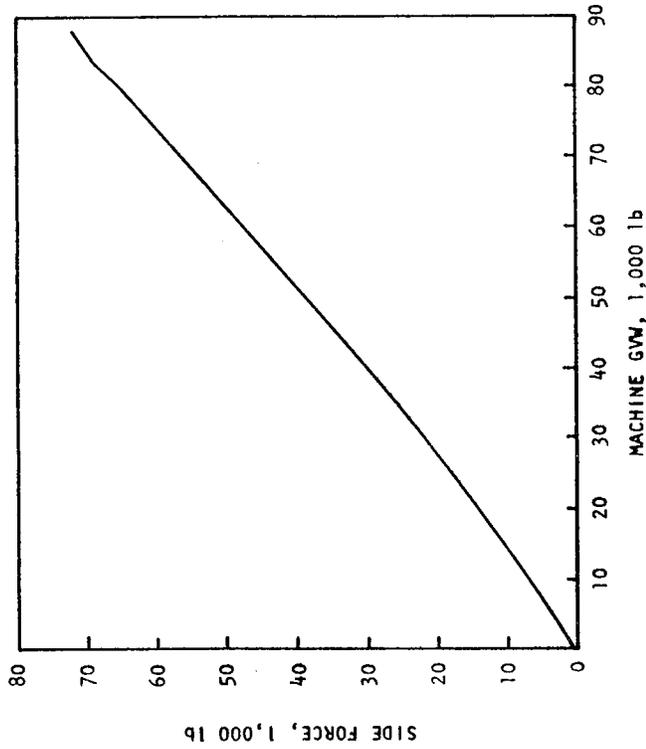
Side Force Equation:

For $GW < 83,800$ lb

$$\text{Side force} = 6,600 \left(\frac{GW}{10,000} \right)^{1.10}$$

For $83,800$ lb $< GW < 88,185$ lb

Side force = 0.82 GW



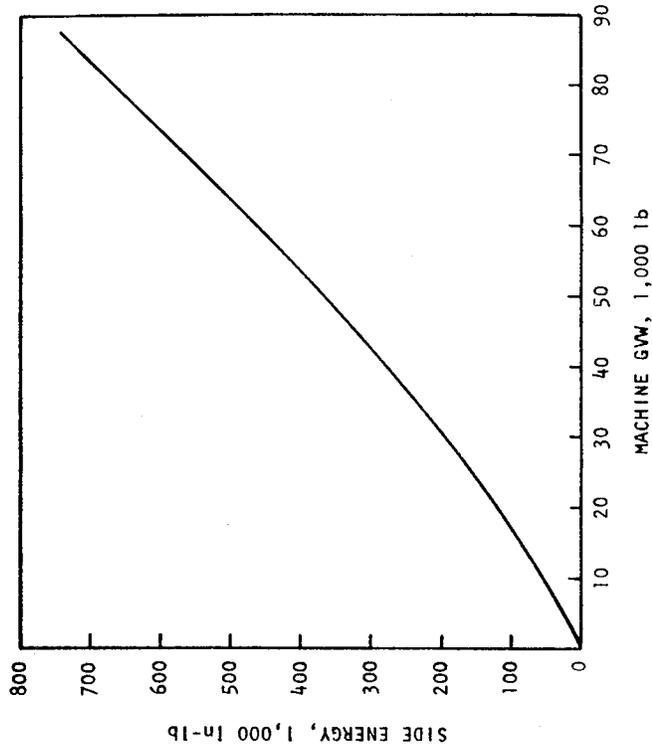
SAE ROPS PERFORMANCE STANDARDS

SAE J1040c (Motor Graders) (Cont)

Side Energy Equation:

For $GVW < 88,185 \text{ lb}$

$$\text{Side energy} = 49,410 \left(\frac{GVW}{10,000} \right)^{1.25}$$



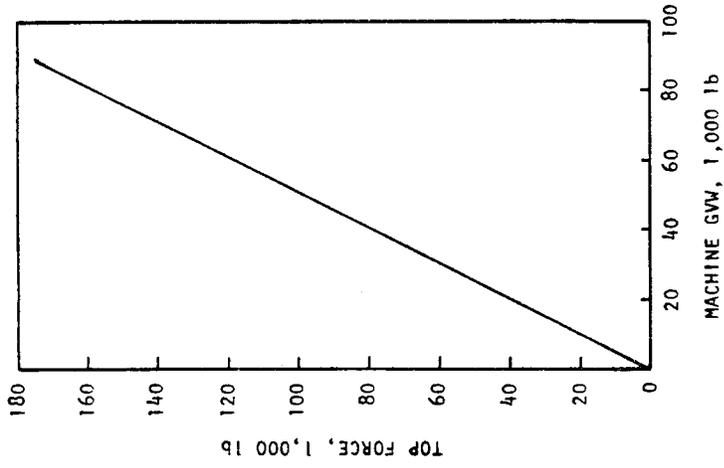
SAE ROPS PERFORMANCE STANDARDS

SAE J1040c (Motor Graders) (Cont)

Top Force Equation:

For $GW < 88,185 \text{ lb}$

Top force = 2.0 GW



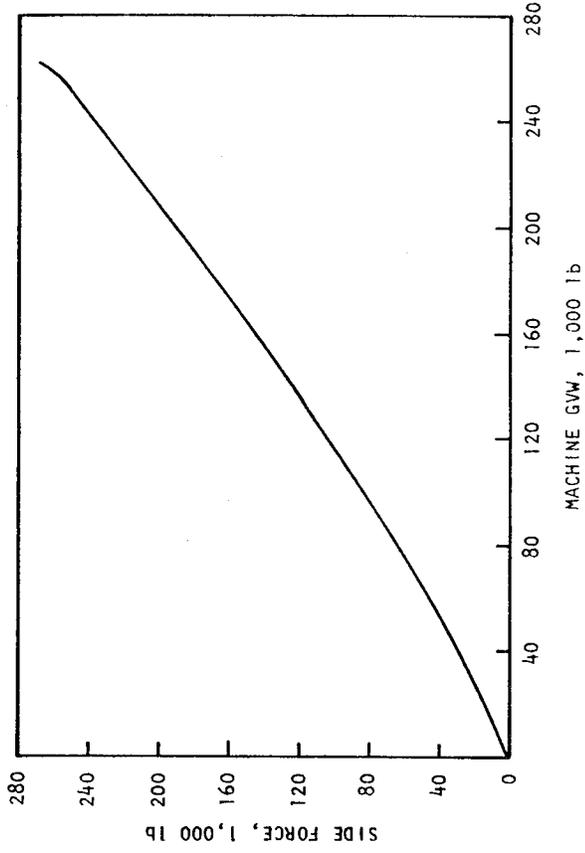
SAE ROPS PERFORMANCE STANDARDS

SAE J1040c (Wheel Loaders)

Side Force Equation:

For $GVW < 264,555 \text{ lb}$

$$\text{Side force} = 5,220 \left(\frac{GVW}{10,000} \right)^{1.20}$$



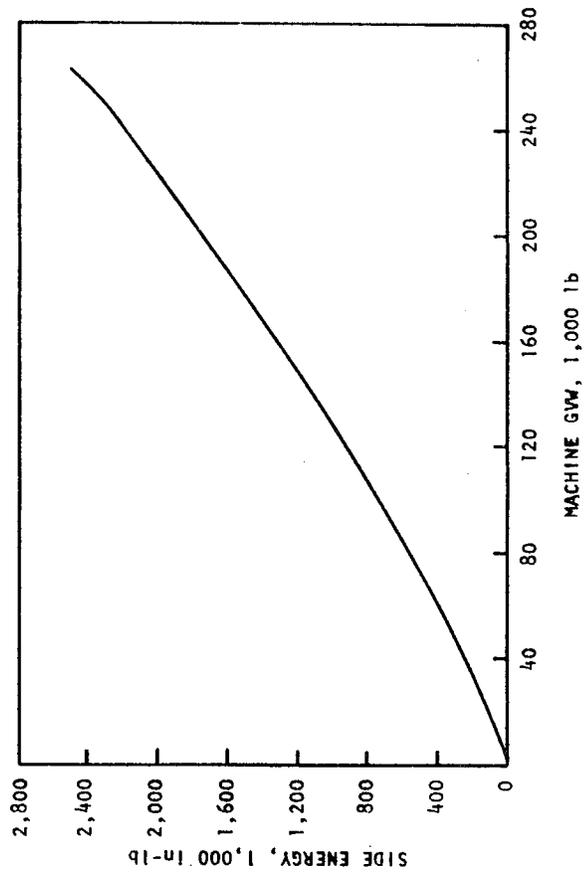
SAE ROPS PERFORMANCE STANDARDS

SAE J1040c (Wheel Loaders) (Cont)

Side Energy Equation:

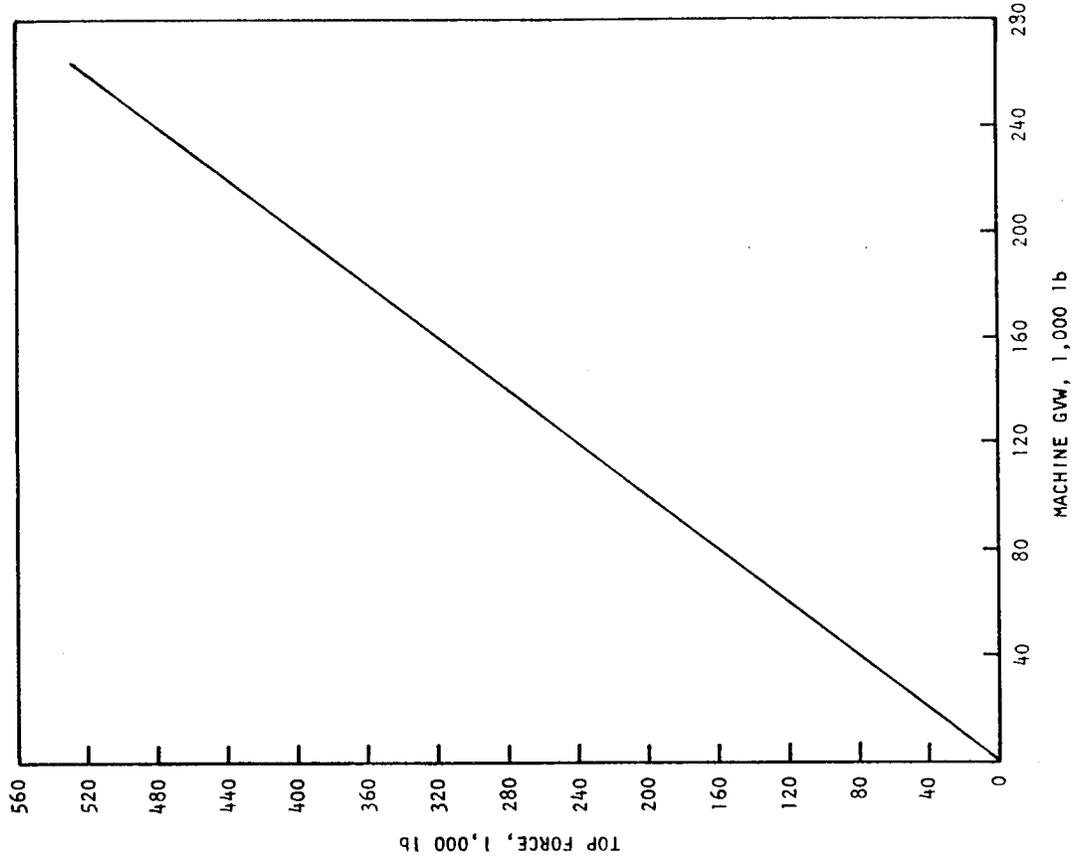
For $GW < 264,555 \text{ lb}$

$$\text{Side energy} = 41,180 \left(\frac{GW}{10,000} \right)^{1.25}$$



SAE ROPS PERFORMANCE STANDARDS

SAE J1040c (Wheel Loaders) (Cont)



Top Force Equation:

$$\text{Top force} = 2.0 \text{ GVW}$$

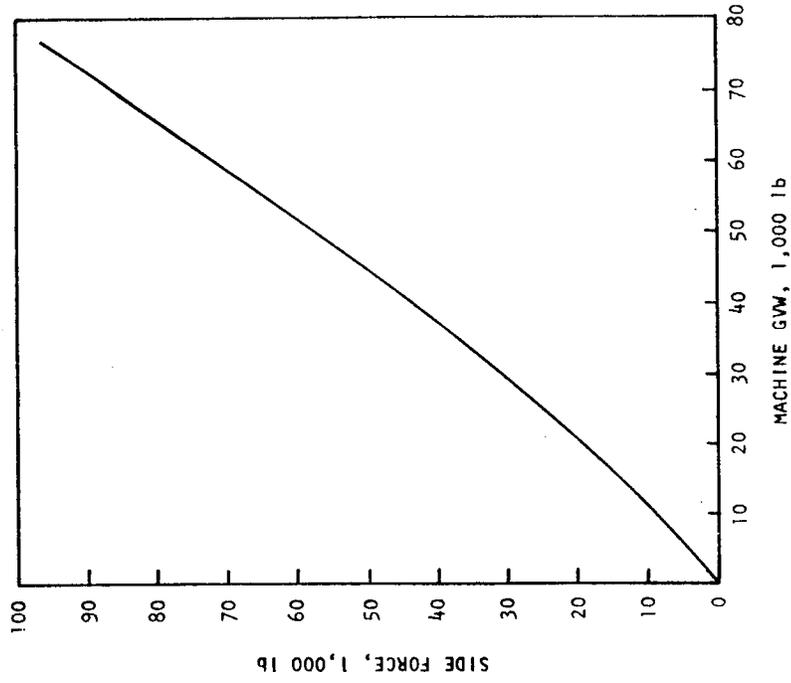
SAE ROPS PERFORMANCE STANDARDS

SAE J1040c (Scrapers)

Side Force Equation:

For GVW < 77,162 lb

$$\text{Side force} = 8,270 \left(\frac{\text{GVW}}{10,000} \right)^{1.20}$$



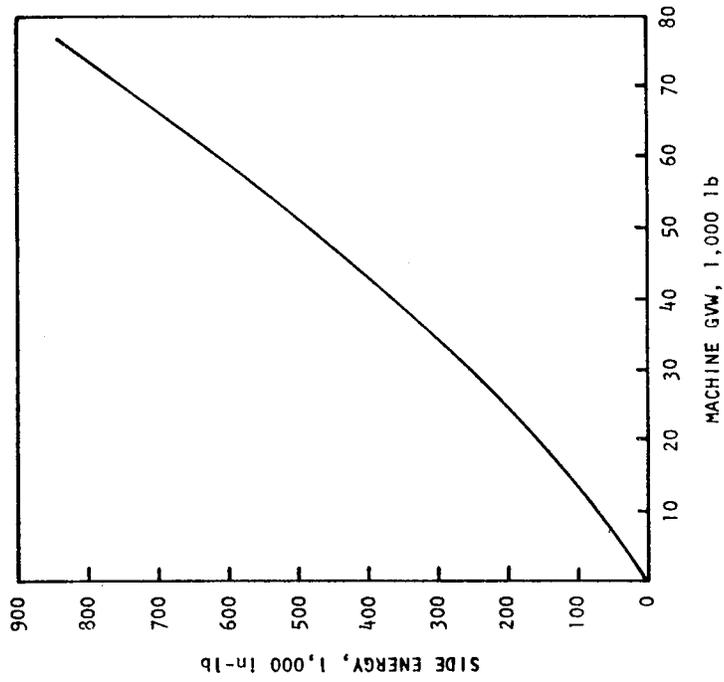
SAE ROPS PERFORMANCE STANDARDS

SAE J11040c (Scrapers) (Cont)

Side Energy Equation:

For GWW < 77,162 lb

$$\text{Side energy} = 65,880 \left(\frac{\text{GWW}}{10,000} \right)^{1.25}$$



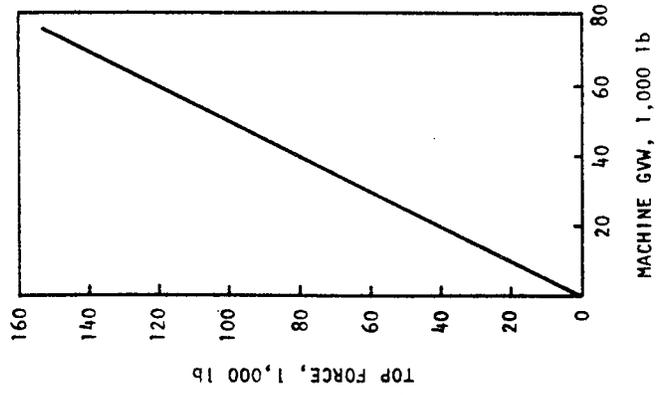
SAE ROPS PERFORMANCE STANDARDS

SAE J1040c (Scrapers) (Cont)

Top Force Equation:

For $GVW < 77,162 \text{ lb}$

Top force = 2.0 GVW



SAE ROPS PERFORMANCE STANDARDS

SAE J1040c (Dumpers)

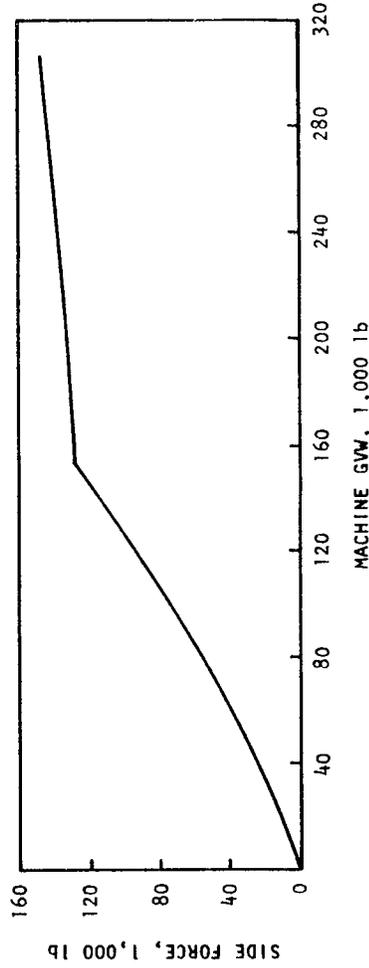
Side Force Equation:

For GVW < 154,324 lb

$$\text{Side force} = 4,790 \left(\frac{\text{GVW}}{10,000} \right)^{1.20} \text{ (ROPS)}$$

For GVW > 154,324 lb

$$\text{Side force} = 73,890 \left(\frac{\text{GVW}}{10,000} \right)^{0.20} \text{ (ROPS)}$$



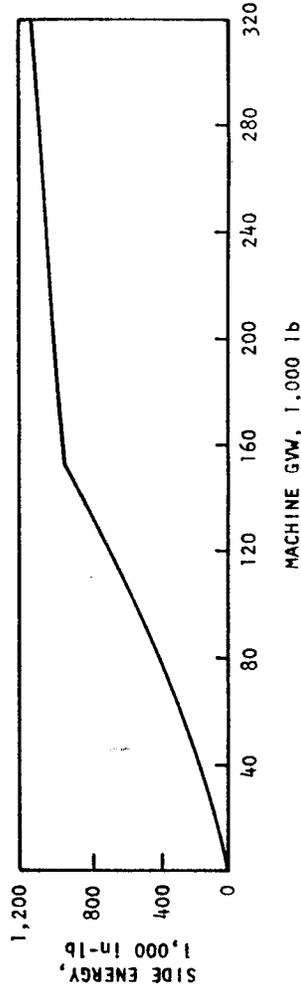
Side Energy Equation:

For GVW < 154,324 lb

$$\text{Side energy} = 31,300 \left(\frac{\text{GVW}}{10,000} \right)^{1.25} \text{ (ROPS)}$$

For GVW > 154,324 lb

$$\text{Side energy} = 482,960 \left(\frac{\text{GVW}}{10,000} \right)^{0.25} \text{ (ROPS)}$$

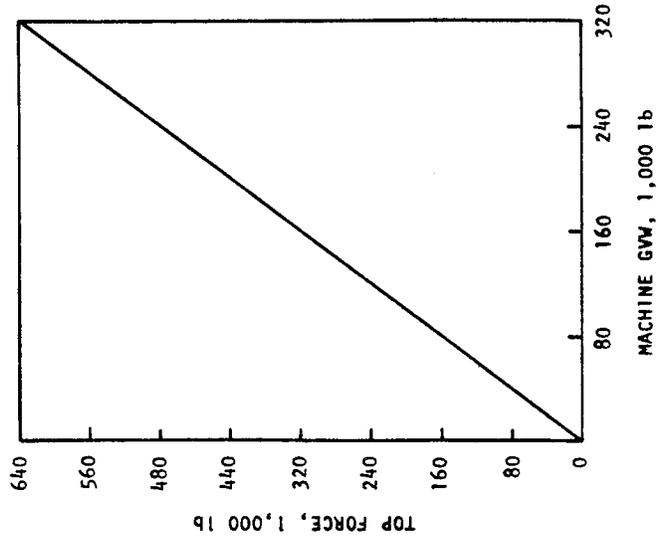


SAE ROPS PERFORMANCE STANDARDS

SAE J1040c (Dumpers) (Cont)

Top Force Equation:

Top force = 2.0 GWW
(ROPS)



SAE ROPS PERFORMANCE STANDARDS

SAE J1040c (Dumpers)

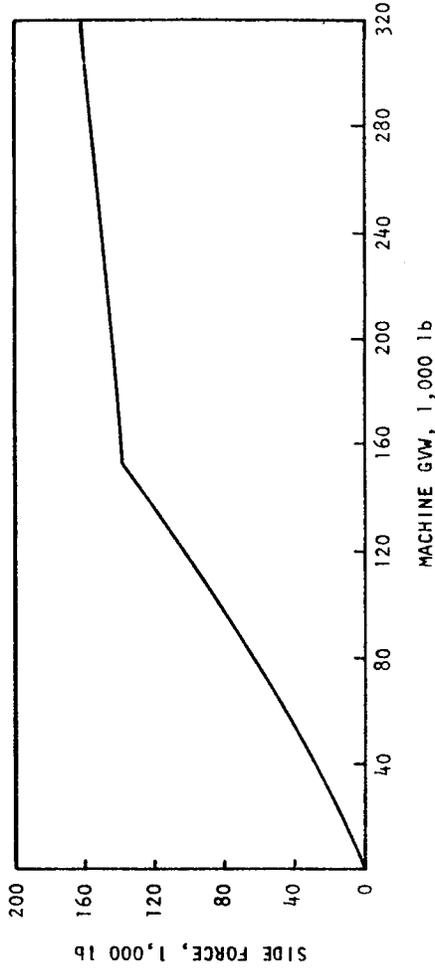
Side Force Equation:

For GW < 154,324 lb

$$\text{Side force (Body)} = 5,220 \left(\frac{\text{GVW}}{10,000} \right)^{1.20}$$

For GW > 154,324 lb

$$\text{Side force (Body)} = 80,610 \left(\frac{\text{GVW}}{10,000} \right)^{0.20}$$



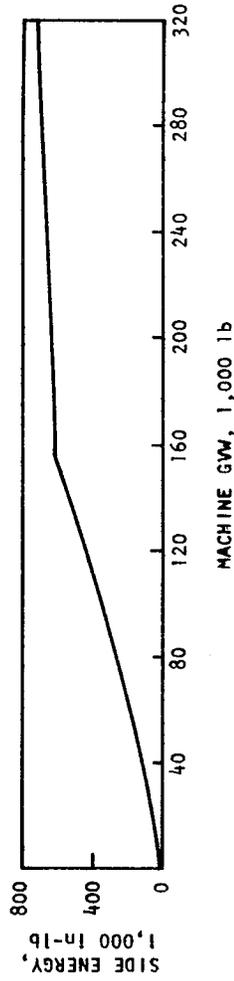
Side Energy Equation:

For GW < 154,324 lb

$$\text{Side energy (Body)} = 19,770 \left(\frac{\text{GVW}}{10,000} \right)^{1.25}$$

For GW > 154,324 lb

$$\text{Side energy (Body)} = 305,030 \left(\frac{\text{GVW}}{10,000} \right)^{0.25}$$

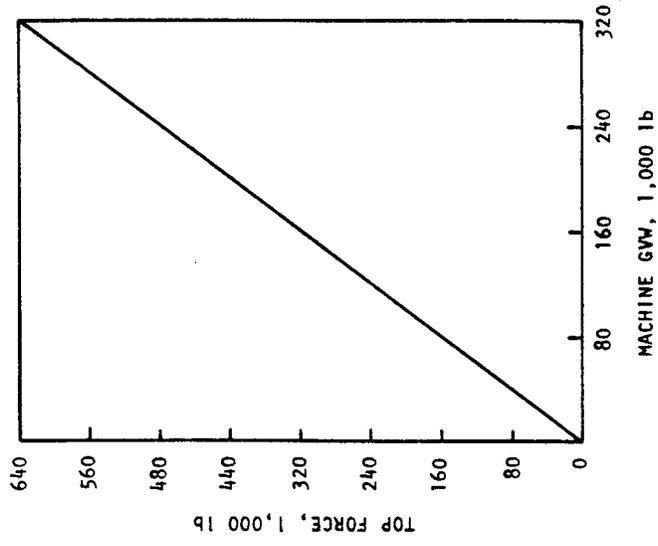


SAE ROPS PERFORMANCE STANDARDS

SAE J1040c (Dumpers) (Cont)

Top Force Equation:

$$\text{Top force} = 2.0 \text{ GWW} \\ \text{(Body)}$$



APPENDIX C

REFERENCES

1. Society of Automotive Engineers, Inc. Technical Paper 800679, "ROPS Field Performance - A Status Report."
2. SAE Recommended Practice J1040c, "Performance Criteria for Rollover Protective Structures (ROPS) for Construction, Earthmoving, Forestry, and Mining Machines."
3. Woodward Associates, Inc. Report 74-19F, "Study to Determine the Engineering and Economic Feasibility of Retrofitting ROPS on Pre-July 1, 1969 Construction Equipment." Final Report to Department of Labor under Contract No. JO357110, July 15, 1974.
4. Woodward Associates, Inc. Report 76-22F, "Design Criteria and Guidelines for Falling Object Protective Structures (FOPS)." Final Report to U.S. Bureau of Mines under Contract No. JO357110, February 20, 1976.
5. Woodward Associates, Inc. Report 78-25F, Volume I, "Coal Mine Equipment Population Characterization and Protective Structure Status." Final Report to U.S. Bureau of Mines under Contract No. JO366016, October 20, 1978.
6. Woodward Associates, Inc. Report 80-99F, "Service Life Analysis of Rollover Protective Structures (ROPS) on Surface Mining Machines." Final Report to the U.S. Bureau of Mines under Contract No. JO199139, October 31, 1980.