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CONSTRUCTION-SITE NOISE CONTROL COST-BENEFIT ESTIMATION TECHNIC--ETC(U)
JAN 78   F M KESSLER, P D SCHOMER, R C CHANAUD

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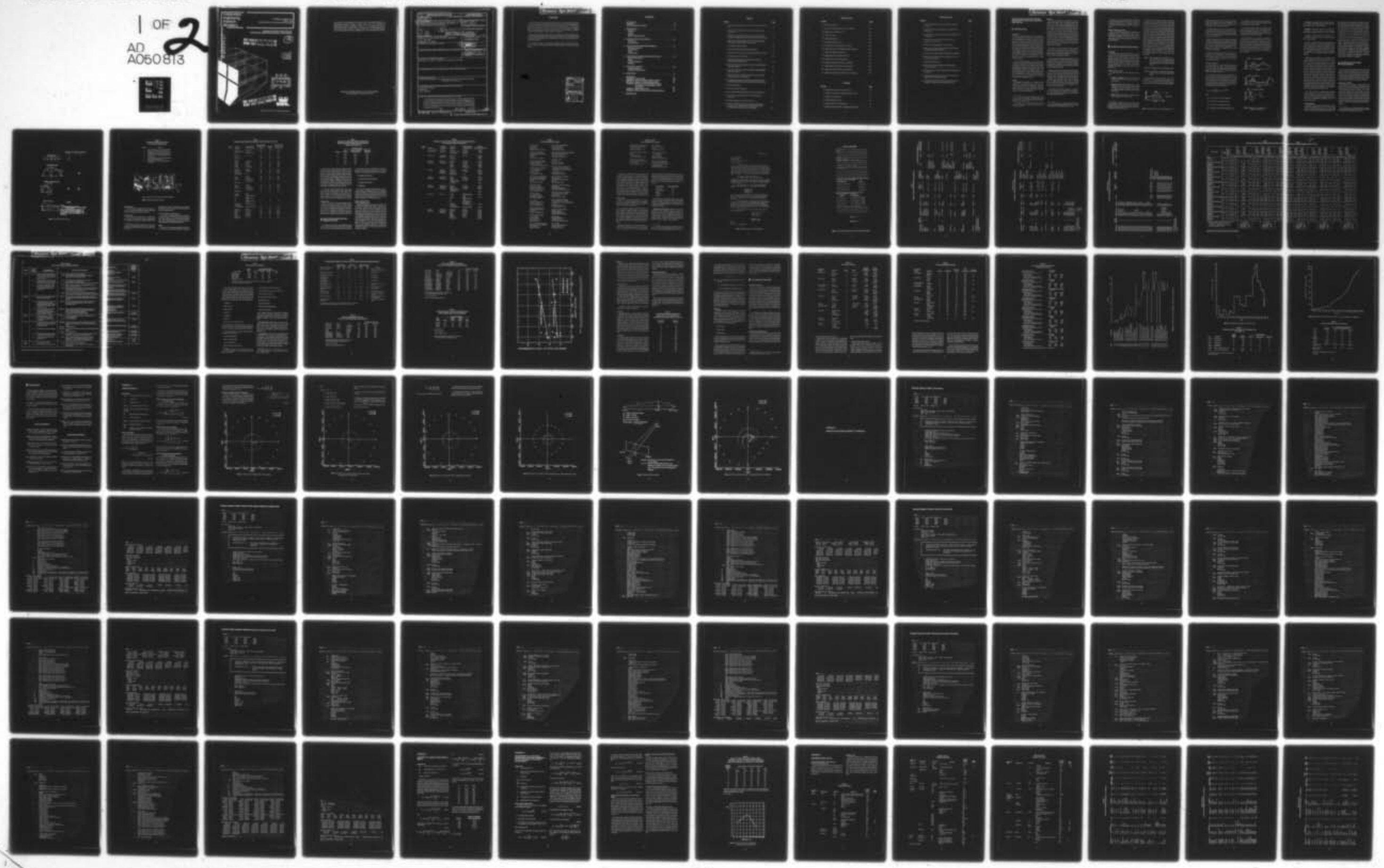

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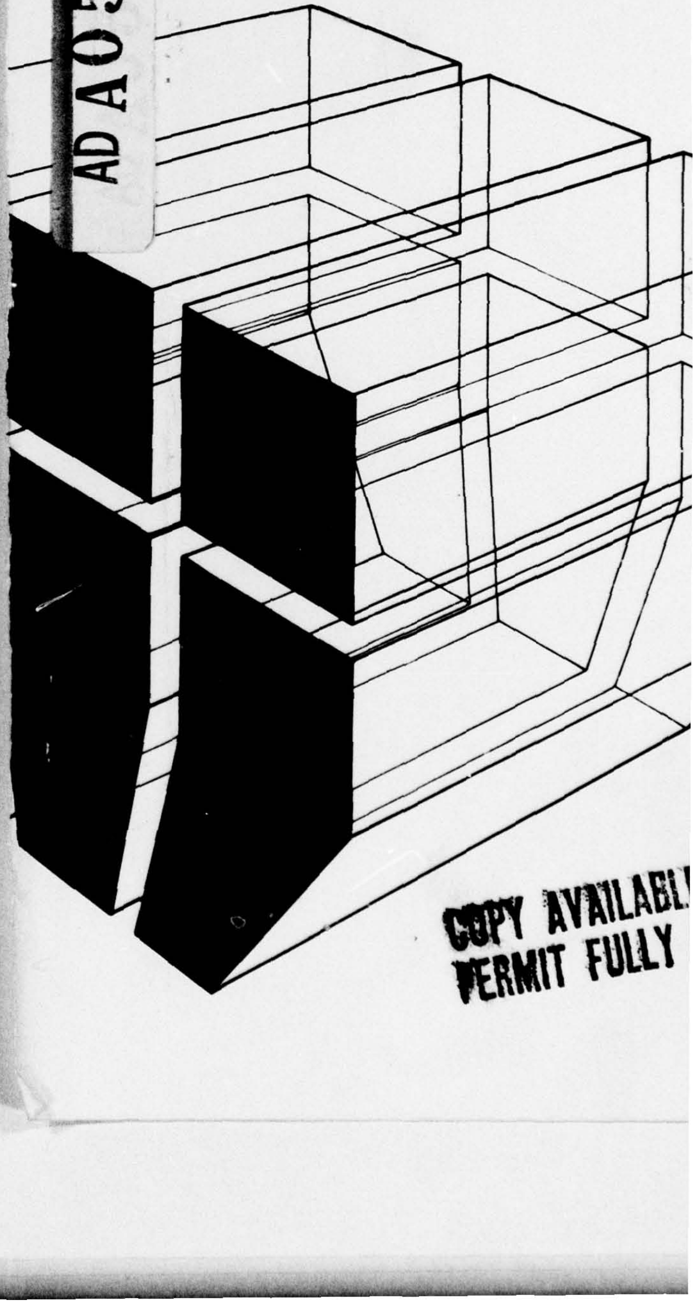

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This report provides rationale and data supporting a companion report, *Construction Site Noise Control–Cost-Benefit Estimating Procedures*, Interim Report N-36 (U.S. Army Construction Engineering Research Laboratory [CERL], January 1978). Presented are methods of estimating noise level at a construction site, methods of noise reduction and control at a construction site, and the associated costs for this reduction with the emphasis on equipment noise control.

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FOREWORD

The U.S. Army Construction Engineering Research Laboratory (CERL) conducted this study for the Directorate of Military Construction, Office of the Chief of Engineers (OCE), under Project A476720A968, "Pollution Control Technology"; Task 03, "Environmental Quality Technology for Operation and Construction of Military Facilities"; Work Unit 002, "Construction Site Noise: Specification and Control." The QCR number is 1.03.006. The OCE Technical Monitor was Mr. D. Spivey, DAEN-MCC-C.

OK

The report is the result of a joint effort by Dr. Fred Kessler of Dames and Moore (main contractor); Dr. Robert Chanaud of Engineering Dynamics, Inc.; Mr. Eugene Rosendahl of General Electric TEMPO; and Dr. Paul Schomer of CERL's Acoustics Team, Environmental Division (EN).

Dr. R. K. Jain is Chief of EN, and Dr. Paul Schomer is Leader of the Acoustics Team. COL J. E. Hays is Commander and Director of CERL, and Dr. L. R. Shaffer is Technical Director.

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CONSTRUCTION-SITE NOISE CONTROL COST-BENEFIT ESTIMATION TECHNICAL BACKGROUND

1 INTRODUCTION

Background

Noise is a pollutant generated by construction activity. This pollution may interfere with activities such as watching television, listening to radios or recorded music, or carrying on conversations. Noise can affect the ability to concentrate or to perform mental or intricate manual tasks. Although often of short duration, construction noise, because of its level and character, is more than simply a minor annoyance or irritation. Many Federal agencies such as the U. S. Environmental Protection Agency (EPA), the Federal Highway Administration (FHWA), and the General Services Administration (GSA), in addition to the Department of the Army and others, have recognized the need to reduce construction noise.

A recent CERL publication on construction noise proposed specifications for limiting noise emitted from construction activities.[1] These proposed specifications are applicable to all military construction. To comply with these specifications, it might be necessary to use unconventional construction methods, quieter construction equipment, or other noise-control measures. The implementation of necessary noise-control measures may require that the contractor incur additional material, labor, and equipment costs.

Purpose

The purpose of this report is to examine the cost-benefit(s) of construction site noise control and to provide the rationale and data in support of a companion interim report.[2] Users of the companion report may refer to this report for detailed data used in the development of the estimating procedures.

Approach

Two construction-site noise models have been developed for this study. The first method considers the construction activity noise as emanating from a relatively small area and radiating considerable distances. An alternative model was developed which computes the average noise level contours around the construction activity. The second model, developed by Dr. Chanaud and his associates, was used to check the first and simpler model. The results indicate that the simpler model is satisfactory for the noise-estimating procedures needed by contractors and cost-estimating prodecures needed both by contractors and cost estimators. Both models are discussed in Chapter 2. Details of the second model including computer programs are provided in Appendices A through D.

The basis for the noise-reduction benefit analyses are field noise measurements made by CERL at Fort Hood and Fort Carson. The Fort Hood noise data have been presented in CERL Interim Report N-3.[3] The Fort Carson results are discussed in Chapter 3.

Noise-control methods and their associated costs are discussed in Chapter 4, with an emphasis on equipment modifications. Some discussion of the use of barriers and equipment substitution is also included. Detailed discussions of process noise control have been reported in CERL Interim Report N-3.

Chapter 5 contains data which support the development of Table 6 of the companion manual. Detailed equipment and operating costs are provided for the scenarios used in the estimating manual. The chapter concludes with a discussion of the actual phases and cumulative costs observed at Fort Hood. A computation of feasible equipment noise control, if applied there, discloses that increased construction costs would amount to less than 1 percent for a 10-decibel reduction in construction-site noise.

Conclusions are provided in Chapter 6. A reference list is also included and contains all the documents used in developing this report plus some additional reports which may be of interest.

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[1] P. Schomer and B. Homans, *Construction Noise: Specification, Control and Mitigation*, Technical Report E-53/ADA010629 (U.S. Army Construction Engineering Research Laboratory [CERL], April 1975).

[2] F. M. Kessler, et al., *Construction-Site Noise Control–Cost-Benefit Estimating Procedures*, Interim Report N-36 (CERL, January 1978).

[3] P. D. Schomer, et al., *Cost Effectiveness of Alternative Noise Reduction Methods for Construction of Family Housing*, Interim Report N-3/ADA028922 (CERL, July 1976).

Appendix E contains equipment models, their noise levels, and other miscellaneous information. Appendix F presents an alternative cost estimating procedure; it is very detailed and is based on construction trade documents.

Mode of Technology Transfer

This report provides background information to a companion report, *Construction-Site Noise Control Cost-Benefit Estimating Procedures,* Interim Report N-36 (CERL, December 1977). Information in the companion report can be disseminated by OCE as a Technical Bulletin.

2 CONSTRUCTION-SITE NOISE MODELS

Basic Model

The model used in this study is similar to one developed for the U.S. Environmental Protection Agency (EPA). Use of the model yields an estimation of the average sound level, L_{eq}, emitted from a construction site. The model is simple to use and reasonably accurate. With the model, one may evaluate the noise emitted from construction sites as a result of construction equipment operating at present noise levels or future quieted levels.

Required Equipment Data

To apply the model, the following data must be known:

1. **Equipment Schedule**–A list of the types and numbers of equipment used during each construction scenario
2. **Equipment Noise Levels**–Noise levels for each equipment type used are needed. The maximum A-weighted sound level produced by the equipment and the distance at which the measurements were made
3. **Usage Factors***–The fraction of time the equipment is operated in its noisiest mode.

In the course of a typical work cycle, construction equipment spends part of its cycle idling or preparing to perform a task. During some part of its work cycle, the level of the noise the machine emits is higher than at any other time. Since L_{eq} is an average value representing the total sound energy emitted during the period of interest, the maximum sound level and the duration of maximum noise as a fraction of the total period must be known to determine the equivalent (energy average) sound level emitted by the machine during a total work period: for example, a typical work day. The fraction of this period that the equipment operates in its noisiest mode is designated as the Usage Factor (UF). The usage factor is considered to be the product of two component elements, an operating factor (F_1) and a utilization factor (F_2); UF = $F_1 \times F_2$. The operating factor is that portion of the typical work cycle during which the equipment emits its maximum noise. This factor is illustrated in Figure 1 where $F_1 = T_1/T_2$. Three possible time-varying modes of equipment noise emission are possible.

Mode 1: The equipment works cyclically; for example, a backhoe or front-end loader may generate maximum sound while trenching but significantly less sound while using its loader.

Mode 2: The equipment moves throughout the site.

Mode 3: An operation is performed sporadically, possibly only once during the observation period.

The utilization factor is that portion of the work period (e.g., 8-hr work day) that the equipment is on the site and is being used. Thus, the utilization factor considers the number of work cycles for the equipment

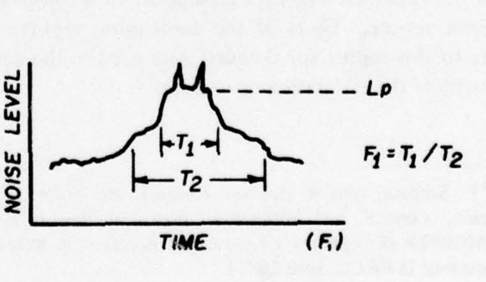

Figure 1. Operating factor (F_1) of determination of T_1.

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*For example, the usage factor relates to the time a backhoe is digging with its engine at full load and producing near-maximum noise levels. It does not relate only to the time of instantaneous high noise produced by extraneous noise sources such as blade-to-rock impact (Figure 1).

during typical operations over the work period. Figure 2 illustrates possible time histories applicable to each mode. The utilization factor is then multiplied by the operating factor to yield the usage factor.

Stationary equipment may not be operating, may be idling while other preparatory activities are in process, or may be operating at full load (and maximum noise level). These operations may be repeated often during a typical construction day.

Mobile equipment may be operating at maximum noise levels for a short duration; an example is a front-end loader while loading. The equipment (the loader) may travel a considerable distance to place this load. At a receiver, sound levels drop significantly as the loader leaves the scene even though the source noise level has not diminished.

Operating factors and utilization factors are best determined from measurements at a construction site where operations similar to those at the site under study are occurring. Data on usage factors for various construction sites are sparse.

Description of Model

Construction-site noise levels are estimated for each construction phase of activity. The construction-site noise is calculated by adding applicable construction equipment average noise levels and extrapolating these levels to the locations of interest.

If the major dimensions of the construction area are small compared to the distance from the site to the noise-sensitive land-use area considered (in a 1:5 ratio), the noise produced by the equipment can be assumed to be emanating from a point at the center of the site. The noise from all the equipment is normalized to a common distance and then summed as:

$$L_{eq} = 10 \log \sum_{i}^{n} UF_i \times N_i \times 10^{L_{Pi}/10}$$

where

L_{eq} = average noise level of all equipment

UF_i = usage factor of equipment type i

N_i = number of units of equipment type i

L_{Pi} = maximum sound level of equipment type i.

The resulting sound level is then extrapolated to the site boundary or various noise-sensitive land-use areas assuming hemispherical spreading.

For large sites which cannot be treated as point sources, the average noise level for each equipment unit must be individually extrapolated to the land-use area considered, and the resulting average sound levels (L_{eq}) are then added to obtain the total value.

These procedures are even further complicated if the equipment moves appreciable distances on the site, as is the case for dump trucks or earth-moving equipment which transfer material from one location to another. If the equipment path length is comparable to the distance from the noise source to the observer, then the construction operation cannot be considered stationary. Equipment movement can be classified into several categories.

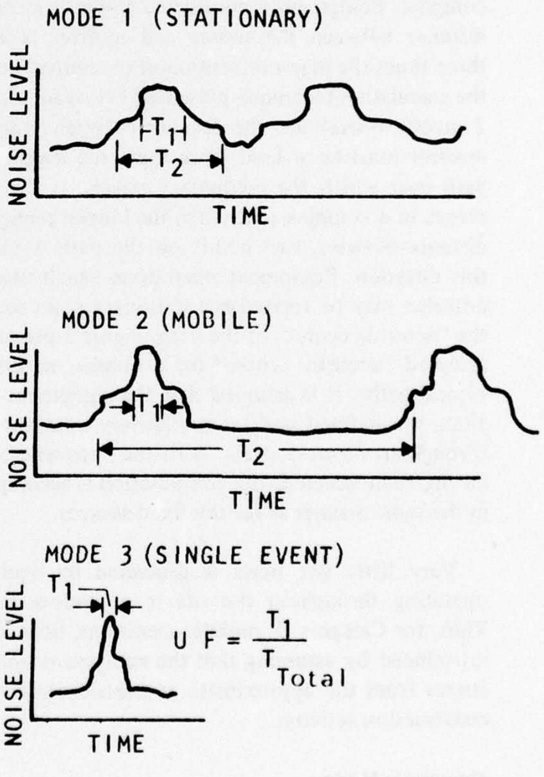

Figure 2. Usage factor—examples of the evaluation of F_1 and UF.

Category 1: Equipment moves from one point on a site to another. The transit time is short and the equipment spends most of its time stationary.

Category 2: Equipment moves in a simple, predictable pattern from one point on the site to another. The equipment spends the majority of its time moving.

Category 3: Equipment moves in a random or complex path, spending part of the time in motion and part of the time stationary.

The first category is dealt with by assuming that the equipment spends all of its time at different site locations. Transit time is ignored. The equipment is considered individually for each location at which it operates. The equipment usage factor is adjusted to reflect the operations at the separate locations. A separate usage factor is used for subsequent calculations for each location.

Calculations for Category 2 are somewhat more complex. Equipment is considered a point source if the distance between the source and receiver is at least three times the major dimension of the source. To apply the calculation technique presented below for Category 2 mobile operations, the distance between source and receiver must be at least three times the length of the path over which the equipment travels. If the source moves in a complex path, then the longest straight-line distance between two points on the path is used for this criterion. Equipment operations which meet this criterion may be treated as a stationary point source at the "acoustic center" of the path. Figure 3 presents the assumed "acoustic center" for a number of different typical paths. It is assumed that the equipment moves along the defined path at a relatively constant speed throughout its work cycle. With the "acoustic center" having been selected, the computation is accomplished in the same manner as for the fixed sources.

Very little site noise is generated by equipment operating throughout the site in a random manner. Thus, for Category 3, mobile operations, little error is introduced by assuming that the equipment noise emanates from the approximate geometric center of the construction activity.

Computer Models

Alternative construction-site noise models were developed. These models calculate noise contours of equal equivalent energy levels (L_{eq}) equal to 55 and 65 dB. There are five models, each based on progressively simpler equations and more assumptions. Model 1 is a base model where L_{eq} is expressed as a function of any number of vehicles and vehicular paths. Model 2 is a simplification of Model 1 in which the motion of each vehicle is represented by its mean position. Model 3 assumes that each vehicle is a point source radiating noise at the acoustical center of the site. Model 4 further simplifies construction noise by representing the time-varying characteristics of noise emitted from each vehicle by the maximum sound level and vehicle usage factor. This model is similar to the basic construction-site model discussed in Chapter 2. Model 5 is a modification of Model 1 which includes the effects of attenuation by barriers. These models and their governing equations are discussed in Appendix A. To simplify the computational procedure required of each model, computer programs were developed and are listed in Appendix B. The accuracy of replacing vehicle motions by single point sources is discussed in Appendix C. Equations used in the computation of barrier effects and their applicability are discussed in Appendix D.

3 CONSTRUCTION-SITE NOISE MEASUREMENTS

Much of the procedure presented in the companion manual is based on data acquired at construction sites located on two Army military bases: Fort Hood, TX, and Fort Carson, CO. Data relating to the construction of 1000 family housing units at Fort Hood can be found in CERL Interim Report N-3.[4] Data on the construction of barracks at Fort Carson are presented below.

Measurement Locations

Noise levels were measured at eight locations near different construction activities. The locations and the construction activities are presented in Table 1. A map of these locations is shown in Figure 4. A list of the construction equipment at each location and their noise data are presented in Table 2. Sound-level measurements at Fort Carson were chosen to minimize the number of measurements acquired while maximizing the information obtained. Each measurement location was at the boundary of a work area (or at a similar location) at which a particular construction phase was in progress.

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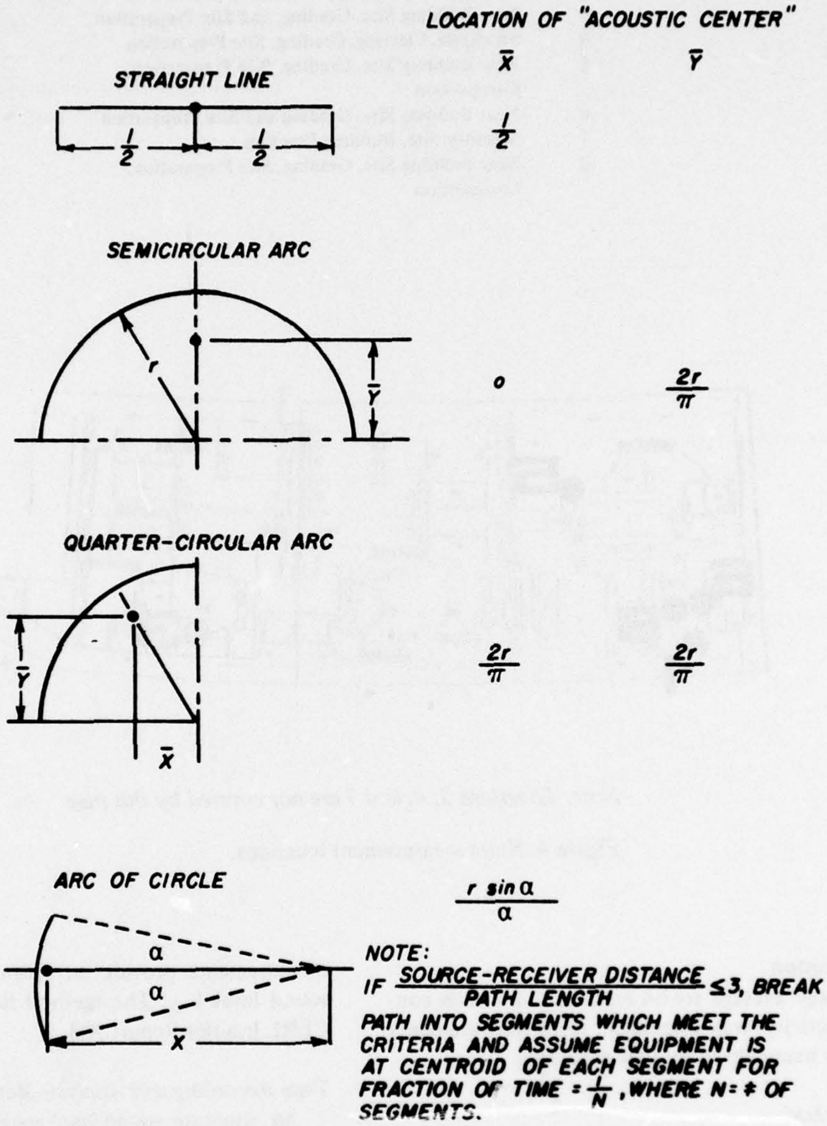
[4] P. D. Schomer, et al., *Cost Effectiveness of Alternative Noise Reduction Methods for Construction of Family Housing*, Interim Report N-3/ADA028992 (CERL, 1976).

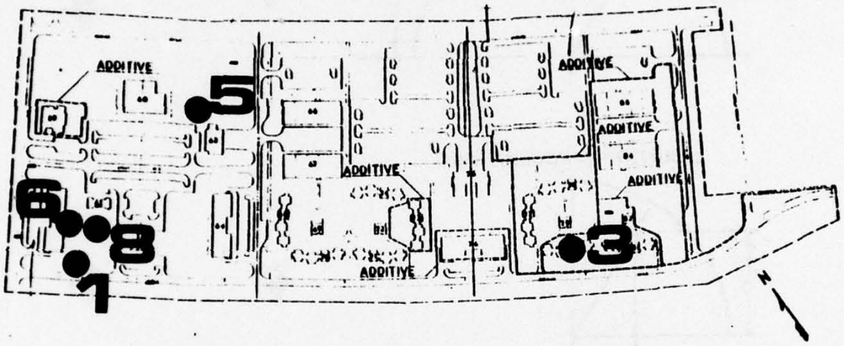


NOTE:
IF $\frac{\text{SOURCE-RECEIVER DISTANCE}}{\text{PATH LENGTH}} \leq 3$, BREAK PATH INTO SEGMENTS WHICH MEET THE CRITERIA AND ASSUME EQUIPMENT IS AT CENTROID OF EACH SEGMENT FOR FRACTION OF TIME = $\frac{1}{N}$, WHERE N = # OF SEGMENTS.

Figure 3. Location of acoustic center.

Table 1
Description of Measurement Locations at Fort Carson Construction Site

Location	Activity
1	Sewer Construction, Backfill, and Compaction
2	Parking Lot, Grading, and Site Preparation
3	Near Building Site, Grading, and Site Preparation
4	Stockpile, Clearing, Grading, Site Preparation
5	Near Building Site, Grading, Site Preparation, Compaction
6	Near Building Site, Grading and Site Preparation
7	Masonry Site, Building Erection
8	Near Building Site, Grading, Site Preparation, Compaction



Note: Locations 2, 4, and 7 are not covered by this map.

Figure 4. Noise measurement locations.

Data Acquisition

The energy average sound level, L_{eq}, for each construction activity was calculated from measurements made either manually or by tape recording.

Manual Method

The procedures for measurement of construction-site boundary sound levels were those recommended by the Society of Automotive Engineers (SAE).[5] The measurements provide an estimate of the equivalent sound level L_{eq}. The method is described in detail in CERL Interim Report N-3.

Tape Recording and Analysis Method

An alternate sound-level measurement and analysis procedure consists of recording the sound on magnetic tape. Such measurements were conducted simultaneously with the manual acquisition of data. This method is also described in CERL Interim Report N-3.

Results

A summary of the measured equivalent sound level at each work area is presented in Table 3. Comparison

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[5] *SAE Recommended Practice: Measurement Procedure for Determining a Representative Sound Level at a Construction Site Boundary Location,* Draft 6 (Society of Automotive Engineers, 1975).

Table 2
Estimated Energy Equivalent Sound Level at Various Locations–Fort Carson

Location No.	Type of Equipment	Equipment Model Name and/or No.	Maximum Sound Level dBA @ 50 ft (15 m)	Operating Factor	Equivalent Sound Level L_{eq} (dB) @ 50 ft (15 m)
1	Backhoe	Drott 50	84	.29	78.6
	Front-End Loader	CAT 988	88	.10	78.0
	Tamper	Koehring D1000	96	.55	93.0
2	Scraper (2)	CAT 633C	86	.35	84.0
	Grader		88	.32	83.0
	Water Truck		89	.19	82.0
3	Bulldozer	CAT D8H	83	.15	75.0
	Grader	CAT 120	84	.34	79.0
	Grader	CAT 12F	93	.29	88.0
	Scraper	JD 860A	76	.14	67.0
	Backhoe	Koehring 466	80	.21	73.0
4	Scraper (3)	JD 860A	89	.33	89.0
	Scraper (2)	CAT 633C	86	.35	81.0
	Water Truck		89	.19	82.0
	Pick-Up Truck	Ford	–	–	–
5	Scraper	JD 860A	88	.43	84.0
	Grader	CAT 12F	83	.19	76.0
	Dozer	CAT D8H (with sheepsfoot)	96	.12	87.0
	Water Truck		–	–	–
6	Grader	CAT 12F	83	.74	82.0
	Scraper (2)	CAT 633C	86	.19	82.0
	Dozer	CAT D8H (with sheepsfoot)	96	.70	94.0
	Water Truck		89	.04	75.0
7	Forklift	White	–	–	–
	Forklift	Warner and Swasey 1200	–	–	–
	Saw	Clipper Bricksaw-matic	–	–	–
	Saw	Cardinal Concrete Saw	82	.20	75.0
	Portable Air Compressor	Leroi Dresser 160	–	–	–
	Front-End Loader	Vermeer Dutchman	80	.28	74.0
8	Scraper (3)	JD 860A	88	.43	89.0
	Scraper (2)	CAT 6336	86	.19	82.0
	Grader	CAT 120	84	.90	84.0
	Grader	CAT 12F	83	.74	82.0
	Dozer	CAT D8H	96	.70	94.0
	Compactor	CAT 815	–	–	–
	Water Truck		89	.04	75.0

Table 3
Summary of Equivalent Sound Levels Calculated from Measured Sound Data at Representative Site Boundary Locations, Fort Carson, CO

	Calculated L_{eq} (dB)		
Location	**SAE Procedure**	**Computer Controlled Analysis Procedure**	**Construction Noise Model**
1	73.0	72.3	72.0
2	62.3	64.0	67.0
3	72.7	74.5	73.0
4	59.9	61.6	66.0
5	71.4	70.4	70.0
6	71.2	73.1	75.0
7	68.4	64.9	67.0
8	74.3	74.2	79.0

of results from the SAE and tape-recording measurement procedures reveals that most of the L_{eq} values obtained by both methods agree to within ±2 dB. At location 7, the agreement is within 4 dB. The discrepancies between the equivalent sound levels from the two methods are greatest when the construction activity produces noise which is impulsive in nature, such as hammering and sawing. The agreement between the L_{eq} calculated by the two procedures is best when the construction activities produce relatively constant sound levels, such as grading or earth removal.

The measured results compared with values calculated using the construction-site noise model. (The model is described in Chapter 2.) The results are presented in Table 3. The comparison indicates that L_{eq} values calculated from the construction-site model are within ±5 dB of the values obtained by tape recording.

Equipment Cost

The cost of specific construction equipment used at the eight Fort Carson sites is listed in Table 4. These costs were used as baseline information in the development of the cost-benefit estimating manual. They were estimated from information contained in the U.S. Army Corps of Engineers North Pacific Division's Equipment Ownership and Operating Expense Schedule.

4 NOISE-CONTROL METHODS AND ASSOCIATED COSTS

For construction activities near residential areas and other noise-sensitive land uses, construction noise should be kept to levels as low as possible. Construction noise can be reduced by either using quieter construction equipment or employing other noise-control methods. The most commonly used noise-control methods are:

1. Equipment Modification

2. Noise-Control Barrier Installation

3. Equipment Substitution

4. Scheduling.

Use of one of the above methods to limit construction-site noise is an additional cost to the construction project. The added cost for each noise-control method is almost proportional to the amount of noise reduction needed. The cost associated with each noise-control method is discussed in the following sections.

Equipment Noise Control

Survey of Manufacturers

Equipment manufacturers were contacted by letter (by Dames and Moore) and asked to provide noise-control and related cost data. Twenty-eight manufacturers were contacted for the 64 different pieces of equipment present at the Fort Hood and Fort Carson construction sites. Information on similar and easily interchangeable equipment was also requested. Requests for additional information were also sent to manufacturers contacted previously during the preparation of CERL Interim Report N-3. A list of the manufacturers is given in Table 5. A copy of the letter sent appears in Figure 5. An equipment noise-control cost data sheet was prepared to assist manufacturers in providing the requested information. A copy of the data sheet is presented in Figure 6.

Table 4
Measurement Locations, Phases of Construction, and Equipment Present at Fort Carson Housing Construction Site

Location No.	Description	Phase of Construction	Type of Equipment	Equipment Model Name and/or No.	Estimated Equipment Cost/Unit ($)
1	Sewer Construction by Building 58	Backfilling, Compaction	Backhoe	Drott 50	35,000
			Front-End Loader	CAT 988	175,000
			Hand Tamper	Koehring	1,200
2	Parking Area	Grading, Site Preparation	Scraper (2)	Cat 633C	235,000
			Grader		50,000
			Water Truck		129,400
3	Fill Site by Building 81	Grading, Site Preparation	Bulldozer	CAT D8H	130,000
			Grader	CAT 120	50,000
			Grader	CAT 12F	61,000
			Scraper	JD 860A	94,500
			Backhoe	Koehring 466	80,000
4	Stockpile	Clearing, Grading, Site Preparation	Scraper (3)	JD 860A	94,500
			Scraper (2)	CAT 633C	235,000
			Water Truck		129,400
			Pick-up Truck	Ford	5,000
5	Fill Site by Building 60	Grading, Site Preparation	Scraper	JD 860A	94,500
			Grader	CAT 12F	61,000
			Bulldozer (with sheepsfoot roller)	CAT D8H	130,000
			Water Truck		129,400
6	Fill Site by Building 58	Grading, Site Preparation, Compaction	Grader	CAT 12F	61,000
			Scraper (2)	CAT 633C	235,000
			Bulldozer (with sheepsfoot roller)	CAT D8H	130,000
			Water Truck		129,400
7	Masonry Site	Erection	Forklift	Warner and Swasey 1200	25,000
			Forklift	White	25,000
			Saw	Clipper Bricksaw-matic	
			Saw	Cardinal Concrete Saw M352E	
			Portable Air Compressor	Leroi Dresser 160	8,000
			Front-End Loader	Vermeer Dutchman	30,000
8	Fill Site by Building 58	Grading, Site Preparation, Compaction	Scraper (3)	JD 860A	94,000
			Scraper (2)	CAT 633C	235,000
			Grader	CAT 120	50,000
			Grader	CAT 12F	61,000
			Bulldozer	D8H	130,000
			Compactor	CAT 815	70,000
			Water Truck		129,400

Table 5
List of Manufacturers Contacted

Mr. W. E. Bueche
Allis-Chalmers
P.O. Box 512
Milwaukee, Wisconsin 53201

Mr. Ray C. Broce, President
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Dodge City, Kansas 67801

Mr. D. D. Lipson, Sales Manager
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Conshohocken, Pennsylvania 19428

Mr. David Abbott, Vice President
and General Manager
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Racine, Wisconsin 53404

Mr. D. P. Burks, General Manager
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163 Carlingview Drive
Rexdale, Ontario, Canada

Mr. L. H. Hobson, Customer Service Manager
Essick Manufacturing Company
1950 Santa Fe Avenue
Los Angeles, California 90021

Mr. Ralph E. Keidel
Euclid, Inc.
22221 St. Clair Avenue
Cleveland, Ohio 44117

Mr. Frank J. Strand, Assistant to the
President and Technical Director
FMC Corporation, Crane and Excavation
Division
1201 Sixth Street, S.W.
Cedar Rapids, Iowa 52406

Mr. Robert D. Strawser, President
Hyster Company
Construction Equipment Division
Box 289
Kewanee, Illinois 61443

Mr. Joseph A. Windel, Vice President
Ingersoll-Rand
200 Chestnut Ridge Road
Woodcliff Lake, New Jersey 07075

Mr. John W. Barnett, Vice President
Ingram Manufacturing Company
P.O. Box 2020
San Antonio, Texas 78297

Mr. J. L. Adams, Vice President
International Harvester Company
Pay Line Division, Construction Equipment
Sales
600 Woodfield Avenue
Schaumburg, Illinois 60172

Mr. Orville R. Mertz, President
Koehring Company
780 North Water Street
Milwaukee, Wisconsin 53201

Mr. Ken Handa
Komatsu-American Corp.
555 California Street
San Francisco, California 94104

Mr. G. E. Willis
The Lincoln Electric Company
22801 St. Clair Avenue
Cleveland, Ohio 44117

Table 5 (Cont'd)
List of Manufacturers Contacted

Mr. K. M. Ligare, Sales Manager
Miller Electric Manufacturing Co.
718 S. Bounds Street
Appelton, Wisconsin 54911

Mr. Frederick W. Dalton, President
Poclain
3401 Tidewater Trail
Fredericksburg, Virginia 22401

Mr. Alan J. Stone, President
Stone Construction Equipment, Inc.
32 E. Main Street
Honeoye, New York 14471

Mr. J. B. O'Keefe
Thomas Equipment, Ltd.
Box 130
Centerville, NB, Canada

Mr. Klaus Wacker, Executive
Vice President
Wacker Corporation
3808 West Elm Street
Milwaukee, Wisconsin 53209

Mr. R. N. Franz, Vice President
Worthington Compressors, Inc.
Construction Equipment Division
57 Appleton Street
Holyoke, Massachusetts 01040

These contacts were followed up by telephone calls to confirm data received and to request additional information. Approximately 75 percent of the manufacturers contacted responded to the requests. A summary of the responses, presented in Table 6, indicates that costs of noise control are not readily available from manufacturers. Most manufacturers produce noise-control features as standard equipment. The cost of these features on new machinery cannot be easily isolated from the cost of other improvements. In addition, only a limited number of equipment items are available with optional noise control features for which noise-control costs are directly related to the purchase price.

Published Data

Most of the construction equipment at Fort Hood and Fort Carson can be grouped into four categories: (1) trucks, (2) wheel and crawler tractors, (3) pneumatic impact tools, and (4) air compressors.

In its program to regulate construction noise, the EPA conducted extensive studies on the technology and economics of quieting construction equipment in these categories. As a result of these studies, data on noise control methods and their costs for these types of construction equipment were published. These data were based on literature searches, manufacturers surveys, inquiries, and other communications with the industry.

Trucks. This category of construction equipment includes diesel- and gasoline-powered heavy and medium trucks, concrete mixers, water trucks, and dump trucks. Studies conducted by International Harvester[6] have indicated that the primary noise sources of trucks are the cooling fan and the exhaust system. For a truck passby noise level of 88 dBA at 50 ft (15 m), the noise contribution from each noise-generating component is as follows:

Noise Sources	Noise Level (dBA)
Cooling fan	86
Exhaust system	83
Engine	78
Air intake	73
Others	71

The estimated costs of quieting trucks to meet levels of 81 dBA, 78 dBA, 76 dBA, and 73 dBA are presented in Table 7. The percent increase in truck prices required if gasoline and diesel trucks were to meet these levels is presented in Table 8.

Wheel and Crawler Tractors. The basic construction equipment in this machine category are dozers and loaders. These tractors, when equipped with different attachments such as dozer blades, loader buckets, leg clamps, backhoes, rippers, block tines, side booms, and forklifts, may be converted into dozers, loaders, graders, backhoes, scrapers, shovels, or other equipment.

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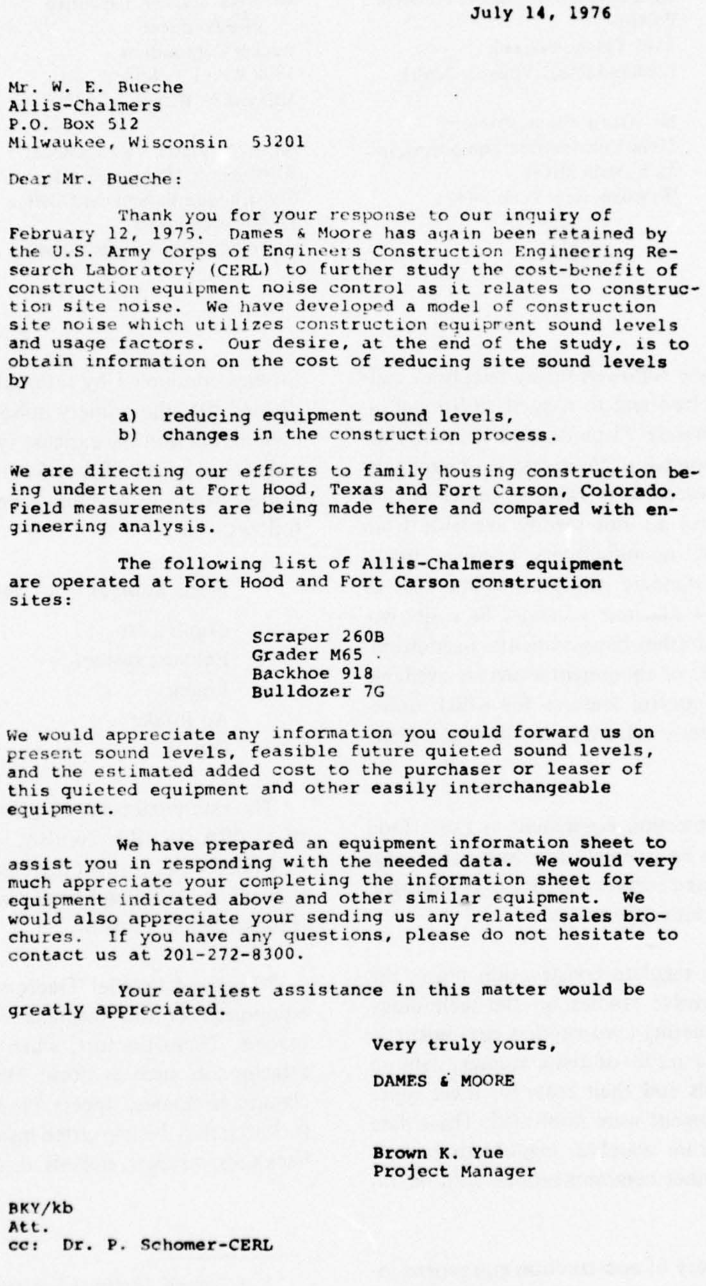
[6] E. E. Landis, *International Harvester's Approach to Diesel Truck Noise Reduction*, paper presented at the National Conference on Noise Control Engineering, October 15 to 17, 1973.



July 14, 1976

Mr. W. E. Bueche
Allis-Chalmers
P.O. Box 512
Milwaukee, Wisconsin 53201

Dear Mr. Bueche:

Thank you for your response to our inquiry of February 12, 1975. Dames & Moore has again been retained by the U.S. Army Corps of Engineers Construction Engineering Research Laboratory (CERL) to further study the cost-benefit of construction equipment noise control as it relates to construction site noise. We have developed a model of construction site noise which utilizes construction equipment sound levels and usage factors. Our desire, at the end of the study, is to obtain information on the cost of reducing site sound levels by

a) reducing equipment sound levels,
b) changes in the construction process.

We are directing our efforts to family housing construction being undertaken at Fort Hood, Texas and Fort Carson, Colorado. Field measurements are being made there and compared with engineering analysis.

The following list of Allis-Chalmers equipment are operated at Fort Hood and Fort Carson construction sites:

Scraper 260B
Grader M65
Backhoe 918
Bulldozer 7G

We would appreciate any information you could forward us on present sound levels, feasible future quieted sound levels, and the estimated added cost to the purchaser or leaser of this quieted equipment and other easily interchangeable equipment.

We have prepared an equipment information sheet to assist you in responding with the needed data. We would very much appreciate your completing the information sheet for equipment indicated above and other similar equipment. We would also appreciate your sending us any related sales brochures. If you have any questions, please do not hesitate to contact us at 201-272-8300.

Your earliest assistance in this matter would be greatly appreciated.

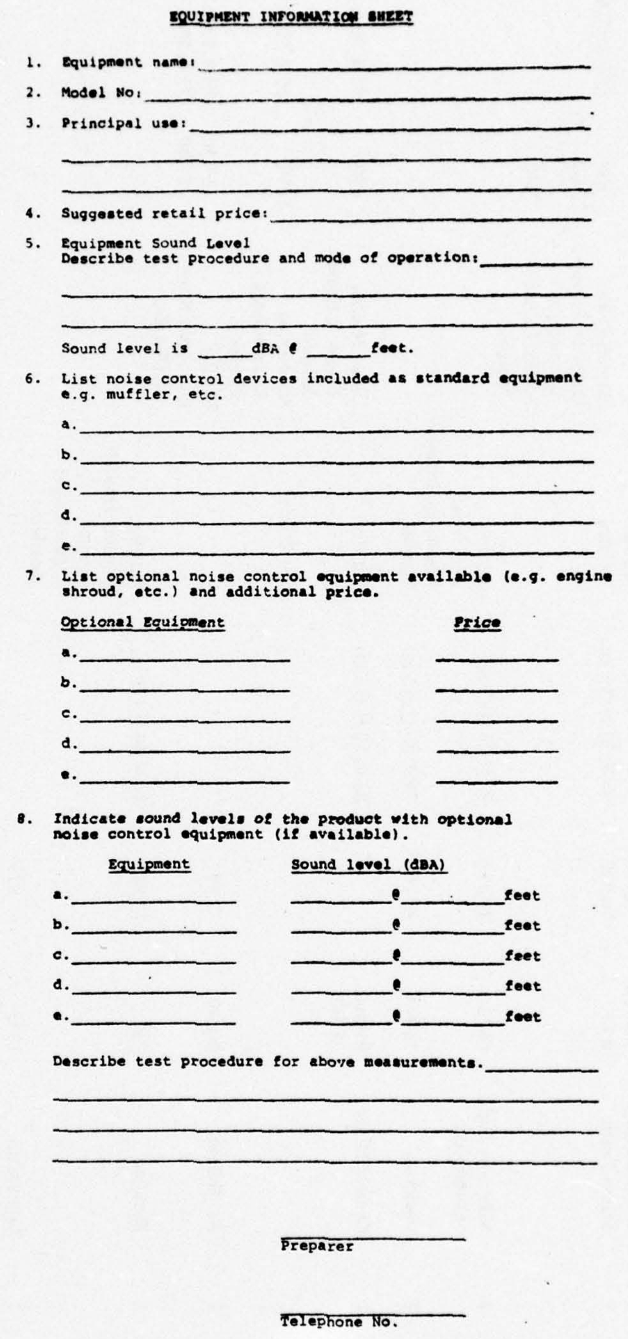
Very truly yours,

DAMES & MOORE

Brown K. Yue
Project Manager

BKY/kb
Att.
cc: Dr. P. Schomer-CERL

Figure 5. Sample of letter sent to manufacturer.



EQUIPMENT INFORMATION SHEET

1. Equipment name: ______________________
2. Model No: ______________________
3. Principal use: ______________________
____
____
4. Suggested retail price: ______________________
5. Equipment Sound Level
Describe test procedure and mode of operation: __________
____
____
Sound level is _____ dBA @ _____ feet.
6. List noise control devices included as standard equipment e.g. muffler, etc.
a. ______________________
b. ______________________
c. ______________________
d. ______________________
e. ______________________
7. List optional noise control equipment available (e.g. engine shroud, etc.) and additional price.

Optional Equipment	Price
a. __________	______
b. __________	______
c. __________	______
d. __________	______
e. __________	______

8. Indicate sound levels of the product with optional noise control equipment (if available).

Equipment	Sound level (dBA)
a. __________	______ @ ______ feet
b. __________	______ @ ______ feet
c. __________	______ @ ______ feet
d. __________	______ @ ______ feet
e. __________	______ @ ______ feet

Describe test procedure for above measurements. __________
____
____
____

____
Preparer

____
Telephone No.

Figure 6. Data response sheet provided to manufacturers surveyed.

Table 6
Summary of Responses From Manufacturers Survey

							Optional Noise Control Equipment		
Manufacturer	Type of Response*	Equipment Name	Model No.	Price ($)	Sound Level (dBA)	Standard Noise Control Devices	Type	Price ($)	Noise Level with Optional Equipment
Allis-Chalmers	1	Backhoe	918	28,500	81 @ 50 ft (15 m)	Muffler			
Broce	2	Broce Broom	D18	8, 450					
Cardinal	2	Concrete Saw	M352E						
Essick	3	Tamper Roller	VR30W	3,795		Muffler			
Euclid	1	Dump Truck	R22	79,800	84 @ 50 ft (15 m)	Muffler	Thermatic Fan	900	<80 @ 50 ft (15 m)
							Insulated Engine Enclosure	2,100	
							Special Exhaust System	500	
Hyster	3	Vibratory Soils Compactor	C610A	27,370	92 @ 23 ft (7 m)	Muffler Air Cleaner Engine Enclosure			
International Harvester	1	Backhoe	3600A	29,780	79 @ 50 ft (15 m)	Muffler			
International Harvester	1	Cement Mixer	Paystar 5000		86 @ 50 ft (15 m)	Muffler	Larger Muffler, Engine & Chassis Shields	450	83 @ 50 ft (15 m)
						Air Cleaner	Above plus - Encapsulated Engine	2,150	80 @ 50 ft (15 m)
Miller Electric	1	Arc Welder	Big 40	2,592			Muffler	14.30	80 @ 50 ft (15 m)
							Low Level Noise Muffler Kit	57.60	73 @ 50 ft (15 m)
Poclain	2	Backhoe	100	73,310	85 @ 50 ft (15 m)	Muffler Housing around Engine Engine Sound Insulated			
Stone	2	Compactor	1845	829					
Ingersoll-Rand	1	Portable Air Compressor	DRRF160	11,180	99 @ 3 ft (.9 m)	Muffler	Silencing Kit	560	92 @ 3 ft (.9 m) 83 @ 23 ft (7 m)
					87 @ 23 ft (7 m)	Side Doors	Residential Muffler	Included	
							Pan & Muffler on blowdown valve	Included	
Worthington	1	Air Compressor	160 Diesel	10, 395	102 @ 4 ft (1 m)	Shrouding Muffler Acoustical Lining Acoustical Wrap	Kit	578	93 @ 3 ft (.9 m)

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*1–Returned Questionnaire
2–Equipment Specification
3–Both

Table 6 (Cont'd)
Summary of Responses From Manufacturers Survey

							Optional Noise Control Equipment		
Manufacturer	Type of Response*	Equipment Name	Model No.	Price ($)	Sound Level (dBA)	Standard Noise Control Devices	Type	Price ($)	Noise Level with Optional Equipment
Worthington	1	Air Compressor	160 Gas	8,155	100 @ 4 ft (1 m)	Shrouding Muffler Acoustical Lining Acoustical Wrap	Kit Kit	578 1,161	93 @ 3 ft (.9 m) 85 @ 3 ft (.9 m)
Fiat-Allis	3	Scraper	260B	118,000	80 @ 50 ft (15 m)	Muffler	Cab Sound Kit	1,155	88 @ 50 ft (15 m)
Fiat-Allis	3	Grader	M65	23,000	80 @ 23 ft (7 m)	Muffler			
Fiat-Allis	3	Loader	76						
Fiat-Allis	3	Backhoe	981						
Challenge-Cook	3	Truck Mixer	M6002	14,075					
Ingram	3	Flat Roller	12-ton 3-wheel	23,500	77 @ 50 ft (15 m)^{a†} 74 @ 50 ft (15 m)^{b}	Muffler Air Cleaner Engine Enclosure			
Ingram	3	Roller	9-2800P	13,500	83 @ 50 ft (15 m)^{c} 79 @ 50 ft (15 m)^{d}	Muffler Air Cleaner Engine Enclosure			
Le Roi Dresser	3	Air Compressor	160RG1E	7,200	101.2 @ 1 m	Muffler Housing Fan Shroud	Residential Muffler	189	95.6 @ 3 ft (.9 m)
Koehring	3	Hand Tamper	T100D	1,198	88 @ 50 ft (15 m)	Exhaust Deflector	Muffler Kit	50	83 @ 50 ft (15 m)
Koehring	3	Backhoe	466D		86 @ 50 ft (15 m)	Exhaust System Air Intake Engine Assembly Insulation			
Koehring	3	Backhoe	666D		83 @ 50 ft (15 m)	Exhaust System Air Intake Engine Assembly Insulation			
Koehring	3	Trencher	77						
John Deere	2	Loader	JD755						
John Deere	2	Bulldozer	JD750						
John Deere	2	Backhoe Loader	JD310-A						
John Deere	2	Backhoe Loader	JD410						
John Deere	2	Backhoe Loader	JD510						
John Deere	2	Backhoe Loader	JD500-C						
John Deere	2	Utility Tractor	JD301-A						

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*1–Returned Questionnaire
2–Equipment Specification
3–Both

†a–8 mph
b–3 mph
c–15 mph
d–5 mph

Table 6 (Cont'd)
Summary of Responses From Manufacturers Survey

							Optional Noise Control Equipment		
Manufacturer	Type of Response*	Equipment Name	Model No.	Price ($)	Sound Level (dBA)	Standard Noise Control Devices	Type	Price ($)	Noise Level with Optional Equipment
John Deere	2	Utility Tractor	JD300B						
John Deere	2	Utility Tractor	JD302						
John Deere	2	Utility Tractor	JD302-A						
John Deere	2	Utility Tractor	JD401B						
John Deere	2	Utility Tractor	JD401C						
John Deere	2	Forklift	JD380						
John Deere	2	Forklift	JD480B						
John Deere	2	Loader	JD544B						
John Deere	2	Loader	JD644B						
John Deere	2	Excavator	JD690B						
John Deere	2	Scraper	JD762						
John Deere	2	Scraper	JD860A						
John Deere	2	Motor Grader	JD570A						
John Deere	2	Motor Grader	JD670						
John Deere	2	Motor Grader	JD770						
John Deere	2	Crawler	JD350C						
John Deere	2	Crawler	JD450C						
John Deere	2	Bulldozer	JD550						
John Deere	2	Loader	JD555						
John Deere	2	Loader	JD14						
John Deere	2	Loader	JD24						
John Deere	2	Compactor	JD646B						
John Deere	2	Bulldozer	JD350C						
Caterpillar	3	Grader	12G	61,000	85.5 @ 50 ft (15 m)	Quieted Power Train			
Caterpillar	3	Grader	14G	83,000	81.5 @ 50 ft (15 m)	Low Speed Engine Fan Muffler Rubber Mounted Hydraulic Pump			
Caterpillar	3	Dozer	977L	82,000	83.5 @ 50 ft (15 m)	Hood, Side Door			
Caterpillar	3	Dozer	D-6C	66,000	84 @ 50 ft (15 m)	Muffler			
Caterpillar	3	Dozer	D-8K	130,000	88.5 @ 50 ft (15 m)	Muffler			
Caterpillar	3	Front End Loader	930	45,000	86.5 @ 50 ft (15 m)	Muffler			
Caterpillar	3	Front End Loader	950	61,000	86 @ 50 ft (15 m)	Muffler			
Caterpillar	3	Front End Loader	966C	78,000	86 @ 50 ft (15 m)	Muffler			
Caterpillar	3	Front End Loader	988B	175,000	85 @ 50 ft (15 m)	Muffler			
Caterpillar	3	Backhoe	235	135,000	80 @ 50 ft (15 m)	Muffler			
Caterpillar	3	Scraper	6330	235,000	86.5 @ 50 ft (15 m)	Muffler			
Caterpillar	3	Compactor	815	70,000	87 @ 50 ft (15 m)	Muffler			
Caterpillar	3	Grader	120G	50,000	83.5 @ 50 ft (15 m)	Muffler			

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*1–Returned Questionnaire
2–Equipment Specification
3–Both

Table 7
Estimated Increase in Prices for Quieted Medium and Heavy Truc

ENGINE MODEL	TRUCK TYPE	Percentage of Total Truck Population	Engine 77 dBA Fan 73 dBA Exhaust 73 dBA Air Intake 72 dBA All Others 70 dBA TOTAL 80.6 dBA						Engine 73 dBA 74 dBA Fan 70 dBA 70 dBA Exhaust 69 dBA OR 69 dBA Air Intake 69 dBA 65 dBA All Others 70 dBA 70 dBA TOTAL 77.5 dBA 77.5 dBA						Engine Fan Exhaust Air Intake All Others TOTAL	
			Fan	Exhaust	Engine	Cab	Air Intake	TOTAL	Fan	Exhaust	Engine	Cab	Air Intake	TOTAL	Fan	Exhaust
Gasoline (1) Medium duty 75-77 dBA (2)	Medium	55.1%	a1 $10	b1 $25	–	–	–	$35	a2 $25	b2 $50	–	d1 $100	– $5	$180	a3 $50	b2 $50
	Heavy	10.2%	a1 $110	b1 $25	–	–	–	$135	a2 $125	b2 $50	–	d1 $100	e1 $5	$280	a3 $200	b2 $50
Diesel–2 stroke, naturally aspirated Heavy duty Manufacturer A 78-79 dBA	Heavy	12.0%	a1 $110	b1 $80	–	d1 $100	–	$290	a2 $125	b2 $155	–	d2 $400	e1 $5	$685	a3 $200	b2 $155
Diesel–4 stroke, naturally aspirated Medium duty Manufacturer B 83-85 dBA	Medium	0.79%	a1 $10	b1 $55	–	d2 $500	–	$565	a2 $25	b2 $105	–	d3 $850	e2 $30	$1010	a3 $50	b2 $105
	Heavy	5.21%	a1 $110	b1 $55	–	d2 $500	–	$665	a2 $125	b2 $105	–	d3 $850	e2 $30	$1110	a3 $125	b2 $105
Diesel–4 stroke, turbocharged Heavy duty Manufacturer B 81-83 dBA	Heavy	6.0%	a1 $110	b1 $55	–	d2 $400	–	$565	a2 $125	b2 $105	–	d2 $500	e2 $30	$760	a3 $125	b2 105
Diesel–4 stroke, turbocharged Heavy duty Manufacturer C 76-78 dBA	Heavy	4.8%	a1 $110	b1 $30	–	d1 $100	–	$240	a2 $125	b2 $55	–	d1 $200	e2 $30	$410	a3 $200	b2 $55
Diesel–4 stroke, naturally aspirated Medium duty Manufacturer D 80 dBA	Medium	0.29%	a1 $10	b1 $55	–	d1 $100	–	$165	a2 $25	b2 $105	–	d2 $500	e1 $5	$635	a3 $50	b2 $105
	Heavy	1.91%	a1 $110	b1 $55	–	d1 $100	–	$265	a2 $125	b2 $105	–	d2 $500	e1 $5	$735	a3 $200	b2 $105
Diesel–4 stroke, turbocharged Heavy duty Manufacturer D 76-78 dBA	Heavy	1.5%	a1 $110	b1 $55	–	d1 $100	–	$265	a2 $125	b2 $105	–	d1 $200	e2 $30	$460	a3 $200	b2 $105
Diesel–2 stroke, 12 cylinder Heavy duty Manufacturer A 79-81 dBA	Heavy	0.9%	a1 $110	b1 $80	–	d1 $200	–	$390	a2 $125	b2 $155	–	d2 $500	e1 $5	$785	a3 $200	b2 $155
Diesel–4 stroke, naturally aspirated Medium duty Manufacturer E 78-79 dBA	Medium	0.10%	a1 $10	b1 $30	–	d1 $100	–	$140	a2 $25	b2 $55	c1 $175	d1 $200	e1 $5	$460	a3 $50	b2 $55
	Heavy	0.67%	a1 $110	b1 $30	–	d1 $100	–	$240	a2 $125	b2 $55	c1 $175	d1 $200	e1 $5	$560	a3 $200	b2 $55
Diesel–4 stroke, naturally aspirated Heavy duty Manufacturer C 78-79 dBA	Heavy	0.47%	a1 $110	b1 $30	–	d1 $100	–	$240	a2 $125	b2 $55	c1 $175	d1 $200	e1 $5	$560	a3 $200	b2 $55
Diesel–4 stroke, naturally aspirated Heavy duty Manufacturer F 78-79 dBA	Heavy	0.225%	a1 $110	b1 $55	–	d1 $100	–	$265	a2 $125	b2 $105	c1 $200	d1 $200	e1 $5	$635	a3 $200	b2 $105
Diesel–4 stroke, naturally aspirated *Medium Duty* Manufacturer G 78-79 dBA	Medium	0.02%	a1 $10	b1 $55	–	d1 $100	–	$165	a2 $25	b2 $105	c1 $150	d1 $200	e1 $5	$485	a3 $50	b2 $105
	Heavy	0.15%	a1 $110	b1 $55	–	d1 $100	–	$265	a2 $125	b2 $105	c1 $150	d1 $200	e1 $5	$585	a3 $200	b2 $105
Diesel–4 stroke, turbocharged Heavy duty Manufacturer H 75 dBA	Heavy	0.015%	a1 $110	b1 $30	–	–	–	$140	a2 $125	b2 $55	–	d1 $100	e1 $5	$285	a3 $200	b2 $55

(1) Medium Duty and Heavy Duty refer to the severity of service for the engine, not to the weight class of the truck.

(2) Engine levels are for engines inside the truck as measured according to SAE J366b test procedure.

AVERAGES

Medium Gasoline = $35
Heavy Gasoline = 135
Medium Diesel = 426
Heavy Diesel = 387

AVERAGES

Medium Gasoline = 180
Heavy Gasoline = 280
Medium Diesel = 865
Heavy Diesel = 715

**Background Document for Medium and Heavy Truck Noise Emission Regulations*, EPA-550/9-76-008 (U.S. Environmental Protection Agency [EPA], March 1976).

2 1

Table 7

ease in Prices for Quieted Medium and Heavy Trucks*

<table>
<tr><td colspan="6">Engine 73 dBA 74 dBA
Fan 70 dBA 70 dBA
Exhaust 69 dBA OR 69 dBA
Air Intake 69 dBA 65 dBA
All Others 70 dBA 70 dBA
TOTAL 77.5 dBA 77.5 dBA</td><td colspan="6">Engine 71 dBA 72 dBA
Fan 64 dBA 64 dBA
Exhaust 69 dBA 69 dBA
Air Intake 65 dBA 65 dBA
All Others 70 dBA 65 dBA
TOTAL 75.6 dBA 75.1 dBA</td><td colspan="6">Engine 68 dBA
Fan 64 dBA
Exhaust 65 dBA
Air Intake 65 dBA
All Others 65 dBA
TOTAL 72.6 dBA</td></tr>
<tr><td></td><td>Exhaust</td><td>Engine</td><td>Cab</td><td>Air Intake</td><td>TOTAL</td><td>Fan</td><td>Exhaust</td><td>Engine</td><td>Cab</td><td>Air Intake</td><td>TOTAL</td><td>Fan</td><td>Exhaust</td><td>Engine</td><td>Cab</td><td>Air Intake</td><td>TOTAL</td></tr>
<tr><td>2
25</td><td>b2
$50</td><td>–</td><td>d1
$100</td><td>–
$5</td><td>$180</td><td>a3
$50</td><td>b2
$50</td><td>c1
$100</td><td>d1
$100</td><td>e2
$30</td><td>$330</td><td>a3
$50</td><td>b3
$260</td><td>–</td><td>d2
$325</td><td>e2
$30</td><td>$665</td></tr>
<tr><td>2
125</td><td>b2
$50</td><td>–</td><td>d1
$100</td><td>e1
$5</td><td>$280</td><td>a3
$200</td><td>b2
$50</td><td>c1
$100</td><td>d1
$100</td><td>e2
$30</td><td>$480</td><td>a3
$2000</td><td>b3
$260</td><td>–</td><td>d2
$325</td><td>e2
$30</td><td>$815</td></tr>
<tr><td>2
125</td><td>b2
$155</td><td>–</td><td>d2
$400</td><td>e1
$5</td><td>$685</td><td>a3
$200</td><td>b2
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$125</td><td>b3
$365</td><td>–</td><td>d3
$850</td><td>e2
$30</td><td>$1370</td></tr>
<tr><td>2
25</td><td>b2
$105</td><td>–</td><td>d3
$850</td><td>e2
$30</td><td>$1010</td><td>a3
$50</td><td>b2
$105</td><td>–</td><td>d4
$1075</td><td>e2
$30</td><td>$1260</td><td>a3
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$315</td><td>c1
$275</td><td>d4
$1075</td><td>e2
$30</td><td>$1745</td></tr>
<tr><td>2
125</td><td>b2
$105</td><td>–</td><td>d3
$850</td><td>e2
$30</td><td>$1110</td><td>a3
$125</td><td>b2
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$125</td><td>b3
$315</td><td>c1
$275</td><td>d4
$1075</td><td>e2
$30</td><td>$1820</td></tr>
<tr><td>a2
125</td><td>b2
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$500</td><td>e2
$30</td><td>$760</td><td>a3
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$125</td><td>b3
$315</td><td>–</td><td>d4
$1075</td><td>e2
$30</td><td>$1545</td></tr>
<tr><td>a2
125</td><td>b2
$55</td><td>–</td><td>d1
$200</td><td>e2
$30</td><td>$410</td><td>a3
$200</td><td>b2
$55</td><td>–</td><td>d2
$500</td><td>e2
$30</td><td>$785</td><td>e3
$125</td><td>b3
$265</td><td>–</td><td>d3
$850</td><td>e2
$30</td><td>$1270</td></tr>
<tr><td>a2
25</td><td>b2
$105</td><td>–</td><td>d2
$500</td><td>e1
$5</td><td>$635</td><td>a3
$50</td><td>b2
$105</td><td>–</td><td>d2
$500</td><td>e2
$30</td><td>$685</td><td>a3
$50</td><td>b3
$315</td><td>–</td><td>d4
$1075</td><td>e2
$30</td><td>$1470</td></tr>
<tr><td>a2
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$500</td><td>e1
$5</td><td>$735</td><td>a3
$200</td><td>b2
$105</td><td>–</td><td>d2
$500</td><td>e2
$30</td><td>$835</td><td>a3
$125</td><td>b3
$315</td><td>–</td><td>d4
$1075</td><td>e2
$30</td><td>$1545</td></tr>
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$200</td><td>e2
$30</td><td>$460</td><td>a3
$200</td><td>b2
$105</td><td>–</td><td>d2
$500</td><td>e2
$30</td><td>$835</td><td>a3
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$850</td><td>e2
$30</td><td>$1320</td></tr>
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$500</td><td>e1
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$200</td><td>b2
$155</td><td>c1
$200</td><td>d2
$500</td><td>e2
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$50</td><td>b2
$55</td><td>–</td><td>d2
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$265</td><td>–</td><td>d3
$850</td><td>e2
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$200</td><td>e1
$5</td><td>$560</td><td>a3
$200</td><td>b2
$55</td><td>–</td><td>d2
$500</td><td>e2
$30</td><td>$785</td><td>a3
$125</td><td>b3
$265</td><td>–</td><td>d3
$850</td><td>e2
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$200</td><td>b2
$105</td><td>–</td><td>d2
$500</td><td>e2
$30</td><td>$835</td><td>a3
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$105</td><td>–</td><td>d2
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$315</td><td>–</td><td>d3
$850</td><td>e2
$30</td><td>$1320</td></tr>
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$5</td><td>$285</td><td>a3
$200</td><td>b2
$55</td><td>–</td><td>d1
$200</td><td>e2
$30</td><td>$485</td><td>a3
$200</td><td>b3
$265</td><td>–</td><td>d2
$500</td><td>e2
$30</td><td>$995</td></tr>
</table>

AVERAGES

Medium Gasoline ≈ 180
Heavy Gasoline ≈ 280
Medium Diesel ≈ 865
Heavy Diesel ≈ 715

AVERAGES

Medium Gasoline = 330
Heavy Gasoline = 480
Medium Diesel = 1059
Heavy Diesel = 976

AVERAGES

Medium Gasoline = 665
Heavy Gasoline = 815
Medium Diesel = 1624
Heavy Diesel = 1454

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Table 7 (Cont'd)
Key to Noise Treatments and Costs for Table 7*

SYSTEM	Code for Noise Treatment	Description of Noise Control Treatment	Increase in Truck Purchase Price
Fan	a1	Improved fan and fan shroud design. Thermostatically controlled fan clutch on heavy trucks to allow removal of radiator shutters.	$ 10 - Design substitutes for similar equipment. $110 - Design substitutes ($10) plus net increase for replacing radiator shutters with fan clutch ($100).
	a2	Advanced system with improved fan design, fan shroud and radiator design. Includes fan clutch on heavy trucks.	$ 25 - Net price increase for replacing radiator, fan and fan shroud with ones of improved design. $125 - Improved radiator, fan and fan shroud ($25) and fan clutch ($100).
	a3	Best system possible using available technology; includes larger radiator which requires redesigned cab on heavy trucks.	$ 50 - Radiator, fan and fan shroud of improved design ($25) and larger fan and radiator ($25). $125 - Radiator, larger fan and fan shroud of improved design ($25), and fan clutch ($100). Costs for larger radiator and redesigned cab are included in cab treatment d3 or d4. $200 - Radiator, fan and fan shroud of improved design ($25), larger fan and radiator ($25), redesigned cab ($50) and fan clutch ($100).
Exhaust	b1	Best of presently available mufflers and seals for exhaust leaks.	$25-75 - Net price increase for replacing existing mufflers. Depends on unmuffled noise level; on 4-stroke engines $25-50 and on 2-stroke engines $75.
	b2	Advanced mufflers better than presently available on 4-stroke engines; manifold muffler and best of available mufflers on 2-stroke engines. Seals for exhaust leaks.	$50-150 - On 4-stroke engines; net increase for advanced mufflers, twice increased for best available mufflers ($25-75), depends on unmuffled noise level.
	b3	Best system possible using available technology; includes advanced mufflers, exhaust seals, double-wall piping and muffler wrapping.	$260-360 - Advanced mufflers ($50-150) depending on unmuffled noise level), manifold muffler ($150), muffler jackets ($30) and insulated double-wall exhaust piping ($30). For diesel trucks, add $5 for exhaust gas seals.
Engine	c1	Engine quieting kits - close fitting covers and isolated or damped exterior parts - supplied by engine manufacturer.	$150-275 - For Diesel engines, estimates based on engine manufacturers' prices for available kits. $100 - For Gasoline engines.
Cab	d1	Underhood treatment, such as acoustic absorbing material, side shields and recirculating panels.	$100-200 - For Diesel trucks; based on truck manufacturers' estimates. Depends on needed noise reduction; 2-3 dBA ($100) and 4 dBA ($200). $50-100 - For Gasoline trucks.
	d2	Underhood treatment and underpan.	$400-500 - For Diesel trucks; underhood treatment ($100-200) plus underpan ($300). $275-325 - For Gasoline trucks.
	d3	Partial (open front and back) engine enclosure and special engine mounts.	$850 - Partial engine enclosure ($775) and special engine mounts ($75). Includes costs for larger radiator and redesigned cab.
	d4	Full engine enclosure and special engine mounts.	$1075 - Average of truck manufacturers' estimates for full engine enclosure ($775-1300) and special engine mounts ($75). Includes costs for larger radiator and redesigned cab.
Air Intake	e1	Improve air intake design.	$ 5 - Design substitute for similar equipment.
	e2	Air intake silencer and improved air.	$ 30 - Air intake silencer ($25) and design substitute for similar equipment ($5).

*_Background Document for Medium and Heavy Truck Noise Emission Regulations_, EPA-550/19-76-008 (EPA, March 1976).

1

2

ck Purchase Price	Design Source Level of Noise Reduction
r equipment. s net increase for replacing atch ($100).	73 dBA
ing radiator, fan and fan ed design. fan shroud ($25) and fan clutch ($100).	70 dBA
d of improved design ($25) and). shroud of improved design ($25), and r larger radiator and redesigned cab nt d3 or d4. d of improved design ($25), larger signed cab ($50) and fan clutch ($100).	64 dBA
cing existing mufflers. Depends on -stroke engines $25-50 and on 2-stroke	73 dBA
crease for advanced mufflers, twice mufflers ($25-75), depends on	69 dBA
0) depending on unmuffled noise 150), muffler jackets ($30) and ust piping ($30). r exhaust gas seals.	65 dBA
es based on engine manufacturers'	2-3 dBA Noise Reduction
a truck manufacturers' estimates. reduction; 2-3 dBA ($100) and 4 dBA	2-4 dBA
od treatment ($100-200) plus underpan	5-9 dBA Noise Reduction
775) and special engine mounts ($75). diator and redesigned cab.	10-11 dBA Noise Reduction
turers' estimates for full engine l special engine mounts ($75). diator and redesigned cab.	12-15 dBA Noise Reduction
r equipment.	69 dBA
nd design substitute for similar	65 dBA

h 1976).

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Table 8
Percent Increase in Truck Prices*

Type of Truck	Average Truck Price	Percent Increase in Price Associated with Given Truck Level			
		81 dBA	78 dBA	76 dBA	73 dBA
Medium gasoline	$ 5,836	0.6	3.1	5.6	11.4
Heavy gasoline	11,613	1.2	2.4	4.1	
Medium diesel	7,360	5.8	11.8	14.4	
Heavy diesel	25,608	1.5	2.8	3.8	
Average for all trucks	–	1.0	3.0	4.9	9.2

**Background Document for Medium and Heavy Truck Noise Emission Regulations*, EPA-550/9-76-008 (EPA, March 1976).

In general, wheel and crawler tractors are powered by diesel engines. Many of the engine-related noise sources for such equipment are very similar to those of a diesel-engine truck. Primary differences are associated with the location of the noise sources and the shielding provided by the vehicle body. Also characteristic of the noise emission is noise from tracks and operational attachments. The major noise sources are identified as:

- Cooling fan
- Engine casing
- Exhaust system
- Air intake
- Transmission
- Hydraulics
- Track (for crawler-type machines).

The contributions of these noise sources to the total vehicle noise level as a function of engine horsepower are shown in detail in a forthcoming EPA publication.[7]

The techniques used to achieve an overall reduction in equipment noise include:

- Partially enclose engine
- Improve exhaust muffler
- Add air intake silencer
- Install muffler on hydraulic lines
- Install flexible hose on hydraulic lines
- Enclose hydraulic pumps, lines, and valves
- Isolate engine from frame
- Isolate panel covers from frame
- Damp panel covers
- Enclose transmission
- Replace noisy hydraulic pumps
- Improve cooling air fan

The estimated material costs and labor associated with these noise abatement techniques for different equipment horsepower classes are presented in Table 9. Details are available in the forthcoming EPA publication.[8]

Pneumatic Impact Tools. Such equipment includes paving breakers, rock drills, tampers, and sheet pile drivers. Data relating to equipment sound level, purchase price, and cost of noise control from a manufacturers survey are available in EPA documents to be published soon.

Air Compressors. The U.S. has measured and studied air-compressor noise extensively in its development of air-compressor noise regulations. Measurements made on standard and silenced air compressors are presented in Tables 10 and 11, respectively. A summary is presented in Figure 7. The estimated increases in list prices for air compressors to meet levels of 76 dBA, 75 dBA, 74 dBA, and 73 dBA are presented in Table 12.

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[7] *Background Document for Wheel and Crawler Tractor Noise Emission Regulation*, U.S. Environmental Protection Agency (in preparation).

[8] *Background Document for Wheel and Crawler Tractor Noise Emission Regulation*, U.S. Environmental Protection Agency (in preparation).

Table 9
Estimated Initial Capital Cost of Retrofit Noise Control on Diesel-Powered Mining Equipment*

Method for Noise Reduction	Less than 100 hp Material Costs	Less than 100 hp Labor Hours	100-200 hp Material Costs	100-200 hp Labor Hours	Greater than 200 hp Material Costs	Greater than 200 hp Labor Hours	Comments
Partial Engine Enclosure	$150	40	$180	60	$220	80	Manufacturer's estimate and similar construction for trucks
Install muffler(s) with sealed connectors on exhaust	$ 75	8	$100	12	$150	16	Advertised prices
Install silencer(s) on air intake	$ 35	2	$ 55	4	$ 65	5	Advertised prices
Install muffler(s) on hydraulic lines	$ 15	3	$ 35	6	$ 45	12	Advertised prices
Install flexible hose on hydraulic lines	$ 10	2	$ 20	4	$ 30	6	Advertised prices
Enclose hydraulic pumps, lines, and valves	$ 15	4	$ 45	12	$ 65	16	From similar construction for tractors
Isolate engine from frame	$ 50	6	$ 60	12	$ 80	16	Manufacturer's estimate
Isolate panel covers from frame	$ 20	8	$ 30	12	$ 40	16	Product literature
Damp panel covers	$ 75	8	$100	12	$125	16	At $2.00/sq ft ($22.00/m²)
Enclose transmission	$100	35	$115	50	$135	60	From similar construction for tractors
Replace noisy hydraulic	$ 45	3	$150	8	$200	12	Advertised replacement price over original price
Improve cooling air fan performance	$ 30	24	$ 40	32	$ 45	40	From similar construction for trucks

*W. N. Patterson, et al., *Noise Control of Underground Mining Equipment*, Publication PB 243-896 (National Technical Information Service [NTIS], January 1975).

Table 10
Noise Levels of Standard Compressors Using the CAGI/PNEUROP Measurement Method*

Manufacturer	Model	S/N	Cfm†	Average Noise Level (dBA) 4ft (1m)	Average Noise Level (dBA) 23ft (7m)⁺
Atlas Copco	VT85Dd	ARP203149	85	94.8	81.4
Atlas Copco	ST-48	51-232751	160	96.6	83.3
Atlas Copco	ST-95	51-274977	330	91.9	80.2
Jaeger	E	RC32032	85	92.5	81.5
Jaeger	A	RS32189	175	98.9	88.2
Ingersoll-Rand	DXL750	77380	750	98.6	87.7
Ingersoll-Rand	DXL900	75847	900	97.9	89.9
Ingersoll-Rand	DXLCU1050	75613	1050	100.8	90.2
Ingersoll-Rand	DXL1200	74430	1200	103.0	92.6

******Background Document for Portable Air Compressors,* **EPA-550/9-76-004 (EPA, December 1975).**

†1 cfm = 35.31 m³/min

⁺Includes overhead measurement point

Table 11
Noise Levels of Silenced Compressors Using the CAGI/PNEUROP Measurement Method[*]

Manufacturer	Models	S/N	Cfm[†]	Average Noise Level (dBA) 4ft (1m)	 23ft (7m)[+]
Atlas Copco	VS85	ARP203903	85	89.0	75.5
Atlas Copco	STS35Dd	ARP550924	125	85.5	73.5
Atlas Copco	VSS125Dd	51-345060	125	81.0	70.1
Atlas Copco	VSS170Dd	51-235072	170	83.9	70.2
Worthington	160G/2QT	821478	160	84.5	74.2
Gardner-Denver	SPHGC	629717	185	87.0	77.1
Gardner-Denver	SPQDA/2	608227	750	86.1	78.2
Worthington	750QTEX	848-019	750	84.0	74.7
Ingersoll-Rand	DXL900S	73693	900	82.4	76.0
Ingersoll-Rand	DXL900S	74050	900	82.0	75.1
Ingersoll-Rand	DXL900S	74051	900	83.1	75.3
Ingersoll-Rand	DXL900S	740471	900	82.4	75.0
Gardner-Denver	SPWDA/2	635851	1200	84.1	73.7

[*] *Background Document for Portable Air Compressors,* EPA-550/9-76-004 (EPA, December 1975).

[†] 1 cfm = 35.31 m^3/min

[+] Includes overhead measurement point

Table 12
Estimated Portable Air Compressor List Price Increases by Major Engine/Capacity Class and All Models[*]

SPL Target (at 7 m)	Percent Increase in Price Gasoline	 Diesel Below 251 cfm[†]	 Diesel Above 250 cfm[†]	 All Models
76 dBA[*]	8.5%	7.0%	11.4%	10.0%
75 dBA[+]	10.3	8.2	12.1	11.1
74 dBA[*]	12.1	9.6	13.0	12.3
73 dBA[+]	14.2	10.9	13.9	13.6

[*] 2 dBA tolerance

[+] 3 dBA tolerance

[†] 1 cfm = 35.31 m^3/min

[*] *Background Document for Portable Air Compressors,* EPA-550/9-76-004 (EPA, December 1975).

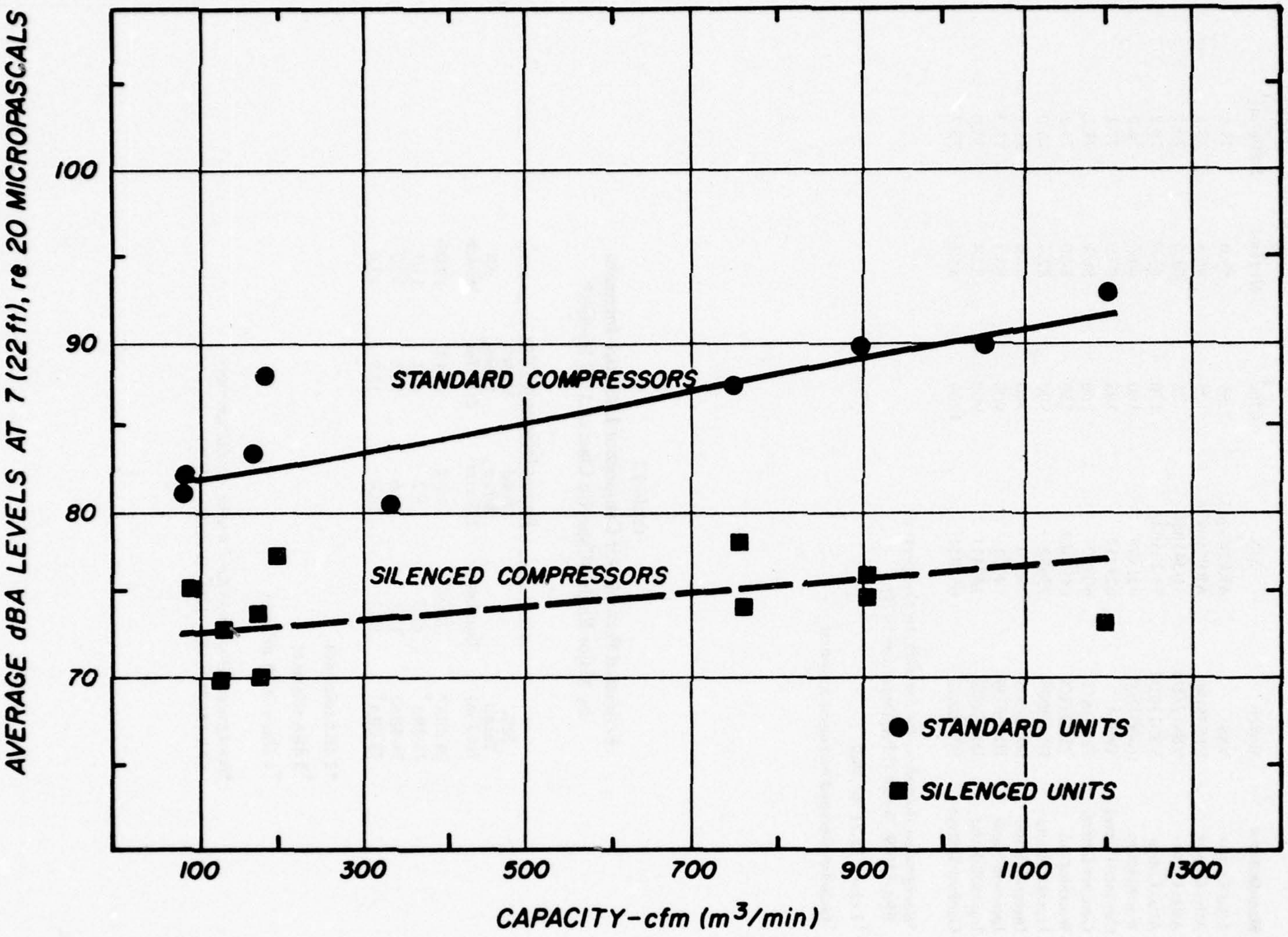

Figure 7. Noise of standard and silenced compressors as a function of capacity. (Source: *Background Document for Portable Air Compressors*, EPA-550/9-76-004 [EPA], December 1975.)

Barriers

An effective site noise-control technique is the use of barriers. Barriers shield an observer from a noise source in much the same manner as they shield an observer from a light source. The placement of a barrier between a source and an observer increases the minimum distance the sound has to travel to reach the observer (around the barrier). It is assumed that the contribution over the top of the barrier (and not through or around it) controls the noise levels reaching the observer. Noise attenuation from barriers is discussed in detail in CERL Interim Report N-3.

Plywood Barriers

Solid fences of plywood are commonly constructed around the perimeter of a construction site to prevent unwanted entry, to shield neighbors from flying debris, and to reduce noise. To be effective as a noise barrier, the fence should be made of plywood at least 3/8 in. (10 mm) thick and properly constructed to avoid leaks or cracks. Plywood is usually found on a construction site, so its cost as an additional material is nominal. Other sturdy material such as wood planking or sheet metal reinforced by wood lathing can be used in its place when these materials are more readily available.

A barrier of plywood construction costs approximately \$650 per 100 m^2 (1000 sq ft).

Stockpile

Material stockpiles on a construction site can be used as shielding either by proper placement of materials around noise or by placing machinery behind material storage area. Any material can be used and can, if needed, be covered or draped with sound-absorbing material (matting) to reduce reflectivity and increase sound absorption. Lumber can be placed to provide shielding, if necessary, or can be used to plug gaps in other types of shielding. This method is simple, mobile, and effective. The cost is nominal, since the material will be eventually used on-site in the construction process.

Earth Berms

At most home construction sites, earth is moved, the site is physically changed, and the earth is redistributed. The removed fill can be used on-site to form an earth fence or berm which can reduce noise emissions from the site. Earth from road excavation, foundation excavation, or high-spot excavation can be placed on the perimeter of the site or between noise-sensitive areas and the construction activity. The earth should be piled as high or higher than a fence or other site enclosure: 3.0 to 4.5 m (10 to 16 ft), if possible. The earth berm can be used as the foundation for a plywood barrier, thus increasing its effective height and reducing the amount of plywood needed. Planning beforehand is essential.

Equipment Substitution

The selection of processes or equipment to perform various tasks, based upon their noise emissions, is one method of achieving noise reduction. A single, large piece of equipment used in place of several small units may do the job and result in reduction of the average site noise level. One type of equipment can be selected in preference to others to perform a task because of its lower noise emissions and/or higher efficiency. For example, a scraper can be used instead of a loader for earth removal, since scrapers have large capacities and are usually quieter than loaders. Wheeled vehicles can be used in place of track vehicles because of their lower noise.

The cost associated with this noise control option is variable. A method of selecting substitution scenarios is outlined below. A procedure for estimating the cost associated with a given equipment mix is presented in Appendix F.

Table 13
Average Minimum Sound Level Difference Required Between the Permissible Total Site Sound Level and Each Vehicle's Sound Level

Total Number of Vehicles	Sound Level Difference
1	0
2	3.0
3	4.8
4	6.0
5	7.0
6	7.8
7	8.5
8	9.0
9	9.5
10	10.0
11	10.4
12	10.8
13	11.1
14	11.5
15	11.8
16	12.0
17	12.3
18	12.6
19	12.8
20	13.0

The total site sound level at 15 m (50 ft) which will comply with the regulation at the nearest land use is calculated. Table 13 is used to determine the average minimum sound level difference between the total site sound level and each vehicle's sound level. The permissible sound level for each vehicle is then calculated as

$$L_v = L_s - \Delta$$

where L_v = permissible sound level of vehicle at 15 m (50 ft)

L_s = permissible site sound level at 15 m (50 ft)

Δ = average minimum sound level difference.

The difference between L_v and the actual sound level produced by the equipment unit is the noise reduction for each equipment unit necessary to bring the site into compliance. Those equipment units requiring noise reduction (as calculated above) should be replaced by equipment having lower noise levels. Since some equipment may produce lower maximum noise levels but have higher usage factors, it is important to compare average noise levels (L_{eq}).

Scheduling

An effective noise control method is the proper scheduling of noisy activities. *Scheduling as a noise control measure will not decrease the total noise energy emitted during the duration of construction activity*; however, it may reduce annoyance to people at nearby noise-sensitive land-use areas. The most commonly applied scheduling methods involve allocating construction activities over the following periods:

1. Time of day
2. Day of week
3. Season of year

Other scheduling methods include controlling the duration of construction activities and conducting noisy operations simultaneously. These methods are discussed in detail in CERL Report N-3.

The cost associated with scheduling methods cannot be designated on a general basis. It is very site specific and even project specific. Construction schedules generating the least annoyance are usually not the quickest way to complete an operation. In situations where an operation has to be completed in a timely manner, this method cannot be applied or the incurred cost will be exorbitant. However, in other situations—for example, road construction in a business district—construction activity scheduled during nighttime or a weekend period will not only reduce annoyance but will increase efficiency as well.

5 COST-BENEFIT ANALYSIS

Construction Scenarios

This cost-benefit analysis is based on construction activities at Fort Carson and Fort Hood. Measurements at these two sites indicate that the grading, backfilling, trenching, and foundation phases of construction emit the most noise. Several construction scenarios relating to these activities have been selected for this study. Construction scenarios and the equipment used for each scenario are listed in Table 14. This table also includes the estimated cost for unquieted equipment. Equipment noise levels and site noise level (L_{eq}) for each scenario are presented in Table 15. The noise data and cost data in Tables 14 and 15, respectively, are used as baseline information for this cost-benefit analysis.

Costs relating to quieting construction site noise levels by 3 dB, 6 dB, and 10 dB are summarized in Table 16. These costs are estimated from the cost information on equipment noise control presented in Chapter 4. The cost of noise control is presented as a percentage increase in equipment cost as well as a percentage increase in construction cost. The relationships between equipment cost and construction cost are based on average cost data published in *Building Construction Cost Data.*[9]

Cost-Benefit Analysis Example

This example is based on actual construction of military barracks at Fort Carson, Colorado, and costs related to those construction activities. The cost of construction with noise abatement is estimated by determining the present cost of construction without noise abatement and then estimating the added cost for noise control.

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[9] *Building Construction Cost Data*, 33rd Annual Edition (Robert Snow Means Company, Inc., 1974).

Table 14
Construction Scenarios

Construction Scenario	Equipment	Quantity	Model	Estimated Purchase Price/Unit ($)	Total Purchase Price ($)
Road Grading	Grader	1	CAT 120	50,000	50,000
	Water Truck	1		129,400	129,400
	Scraper	2	CAT 633C	235,000	470,000
					649,400
Site Grading	Scraper	1	JD860A	94,500	94,500
	Grader	1	CAT 120	50,000	50,000
	Tractor	1	CAT D8H	130,000	130,000
					274,500
Street Grading and Compacting	Grader	1	CAT 120	50,000	50,000
	Flat Roller	1	Ingram	30,000	30,000
					80,000
Rough Backfill	Scraper	1	CAT 633C	235,000	235,000
	Scraper	3	JD860A	94,500	283,500
	Water Truck	1		129,400	129,400
					647,900
Site Backfill	Loader	1	CAT D8H	130,000	130,000
	Scraper	2	CAT 633C	235,000	470,000
	Grader	1	CAT 12F	61,000	61,000
	Water Truck	1		129,400	129,400
					790,400
Ditching	Backhoe	2	Koehring 466	80,000	160,000
Filling the Trench	Loader	1	CAT 988	175,000	175,000
	Backhoe	1	Drott 50	35,000	35,000
					210,000
Sheet Piles	Sheet Pile Driver	2		1,200	2,400
	Truck	1		20,000	20,000
	Mobile Crane	1		100,000	100,000
	Air Compressor	1		7,000	7,000
					129,400
Concrete Preparation	Batch Plant	1		–	–
	Loader	1		130,000	130,000
	Concrete Truck	2		37,000	74,000
Concrete Footings	Concrete Truck	1		37,000	37,000
	Concrete Vibrator	1		1,200	1,200
	Air Compressor	1		7,000	7,000
					45,200

Construction Without Noise Control

Construction cost data in the form of a computer analysis of time and cost schedules are available from Corps of Engineers site engineers. A chart showing construction activity by tasks from August 1975 to April 1976 is presented in Figure 8. This chart indicates that most of the earth work took place during the latter part of 1975, when the CERL acoustics team conducted field noise measurements. Construction costs in terms of cost per day and the cumulative costs for the same period are presented in Figures 9 and 10, respectively.

Construction With Noise Control

Construction activity during November 1975 to February 1976 (12th to 25th week) was selected to illustrate the cost of site noise control. During this period, numerous activities occurred on the site including installation of sewers, demolition, filling and grading, and fabrication and delivery of electrical equip-

Table 15
Construction Scenario Noise Data

Construction Scenario	Equipment	Quantity	L_p at 15m (50ft)*	Operating Factor*	Total L_{eq} at 15m (50 ft)	Site L_{eq} at 15m (50ft)
Road Grading	Grader	1	88	.32	83.1	
	Water Truck	1	89	.19	81.8	
	Scraper	2	86	.35	84.5	88.0
Site Grading	Scraper	1	88	.43	84.3	
	Grader	1	83	.19	75.8	
	Tractor	1	96	.12	86.8	90.0
Street Grading and Compacting	Grader	1	88	.32	83.1	
	Flat Roller	1	84	.6	81.8	85.5
Rough Backfill	Scraper	1	86	.35	81.4	
	Scraper	3	89	.33	84.2	
	Water Truck	1	89	.19	81.8	87.4
Site Backfill	Loader	1	96	.12	86.8	
	Scraper	2	86	.19	81.9	
	Grader	1	83	.74	81.7	
	Water Truck	1	89	.19	81.8	89.7
Ditching	Backhoe	2	80	.21	76.2	76.2
Filling the Trench	Loader	1	88	.10	78.0	
	Backhoe	1	84	.29	78.6	81.3
Sheet Piles	Sheet Pile Driver	2	88	.2	84.0	
	Truck	1	83	.03	67.8	
	Mobile Crane	1	88	.03	72.8	
	Air Compressor	1	82	1.0	82.0	86.4
Concrete Preparation	Batch Plant	1	95	1.0	95.0	
	Loader	1	89	.4	85.0	
	Concrete Truck	2	81	1.0	84.0	95.7
Concrete Footings	Concrete Truck	1	81	1.0	81.0	
	Concrete Vibrator	1	88	.5	85.0	
	Air Compressor	1	82	1.0	82.0	87.8

***Based on actual measurements**

ment and material. The cost data relating to these construction activities are presented in Table 17. The total construction cost incurred during that period is estimated to be $551,000, which includes approximately $159,000 for labor costs, $198,000 for equipment, $105,000 for material, and the contractor's overhead costs and profit. This cost does not include the fabrication and delivery of electrical equipment and material, which took place primarily off site.

The application of site noise abatement will increase construction cost (Table 18). It is estimated that for site noise levels to be reduced by 3 dB, 6 dB, and 10 dB, total construction cost for the period would increase by approximately $1,000, $1,700, and $4,700, respectively. These costs represent increases in construction cost of approximately .18 percent, .31 percent, and .85 percent, respectively.

The above analysis assumes that site noise levels are reduced by using quieted equipment. It is anticipated that the use of plywood barriers to achieve similar site noise reduction would be more costly because of the dispersed nature of the construction activities.

Table 16
Costs Associated With Noise Reduction of Construction Scenarios

Construction Scenario:	**Road Grading**		
Total Equipment Cost ($)	649,400		
Equipment Cost/Construction Cost* (%)	.75		
Noise Reduction	3 dB	6 dB	10 dB
Cost to Quiet ($)	2,455	4,705	12,660
Percentage of Equipment Cost (%)	.38	.73	1.95
Percentage of Construction Cost* (%)	.29	.54	1.46
Construction Scenario:	**Site Grading**		
Total Equipment Cost ($)	274,500		
Equipment Cost/Construction Cost* (%)	.60		
Noise Reduction	3 dB	6 dB	10 dB
Cost to Quiet ($)	1,810	3,445	9,300
Percentage of Equipment Cost (%)	.66	1.26	3.39
Percentage of Construction Cost* (%)	.39	.75	2.03
Construction Scenario:	**Street Grading and Compacting**		
Total Equipment Cost ($)	80,000		
Equipment Cost/Construction Cost* (%)	0.5		
Noise Reduction	3 dB	6 dB	10 dB
Cost to Quiet ($)	910	1,570	4,430
Percentage of Equipment Cost (%)	1.13	1.96	5.53
Percentage of Construction Cost* (%)	.55	.98	2.76
Construction Scenario:	**Rough Backfill**		
Total Equipment Cost ($)	647,900		
Equipment Cost/Construction Cost* (%)	0.7		
Noise Reduction	3 dB	6 dB	10 dB
Cost to Quiet ($)	3,225	6,300	16,800
Percentage of Equipment Cost (%)	.50	.97	2.60
Percentage of Construction Cost* (%)	.35	.68	1.82
Construction Scenario:	**Site Backfill**		
Total Equipment Cost ($)	790,400		
Equipment Cost/Construction Cost* (%)	.65		
Noise Reduction	3 dB	6 dB	10 dB
Cost to Quiet ($)	3,100	5,965	16,020
Percentage of Equipment Cost (%)	.39	.75	2.03
Percentage of Construction Cost* (%)	.25	.49	1.32
Construction Scenario:	**Ditching**		
Total Equipment Cost ($)	160,000		
Equipment Cost/Construction Cost* (%)	.65		
Noise Reduction	3 dB	6 dB	10 dB
Cost to Quiet ($)	1,040	1,850	5,160
Percentage of Equipment Cost (%)	.65	1.16	3.23
Percentage of Construction Cost* (%)	.42	.75	2.10
Construction Scenario:	**Filling the Trench**		
Total Equipment Cost ($)	210,000		
Equipment Cost/Construction Cost* (%)	.6		
Noise Reduction	3 dB	6 dB	10 dB
Cost to Quiet ($)	1,165	2,185	5,940
Percentage of Equipment Cost (%)	.55	1.04	2.83
Percentage of Construction Cost* (%)	.33	.62	1.70
Construction Scenario:	**Sheet Piles**		
Total Equipment Cost ($)	129,400		
Noise Reduction	3 dB	6 dB	10 dB
Cost to Quiet ($)	200	1,000	1,760
Percentage of Equipment Cost* (%)	.15	.77	1.36
Construction Scenario:	**Concrete Footings**		
Total Equipment Cost ($)	45,200		
Noise Reduction	3 dB	6 dB	10 dB
Cost to Quiet ($)	745	2,160	4,500
Percentage of Equipment Cost* (%)	1.65	4.78	9.96

*Excluding Material Cost, such as pipe, concrete, wood, gravel, etc.

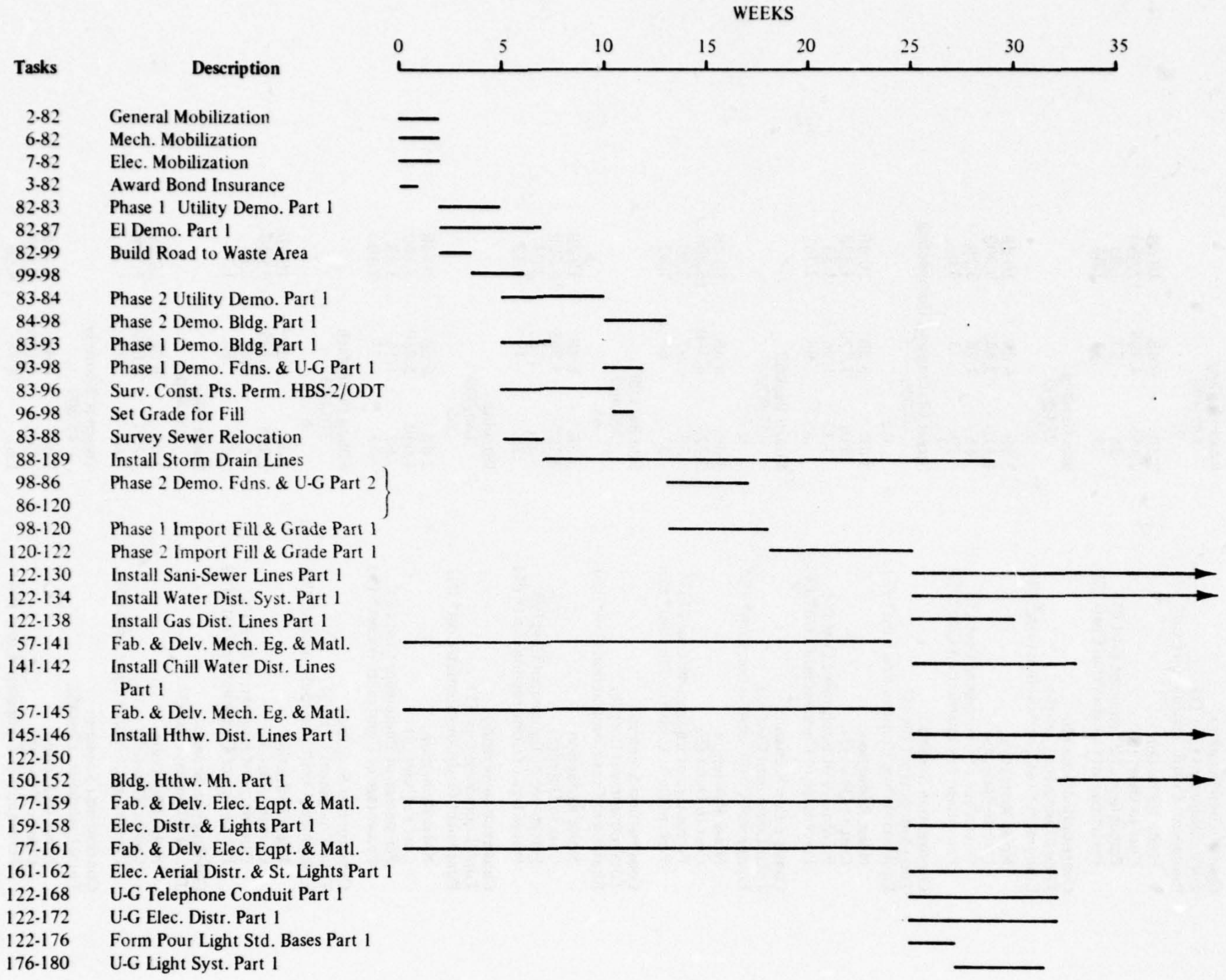

Figure 8. Construction activity from August to April 1976, Fort Carson, CO.

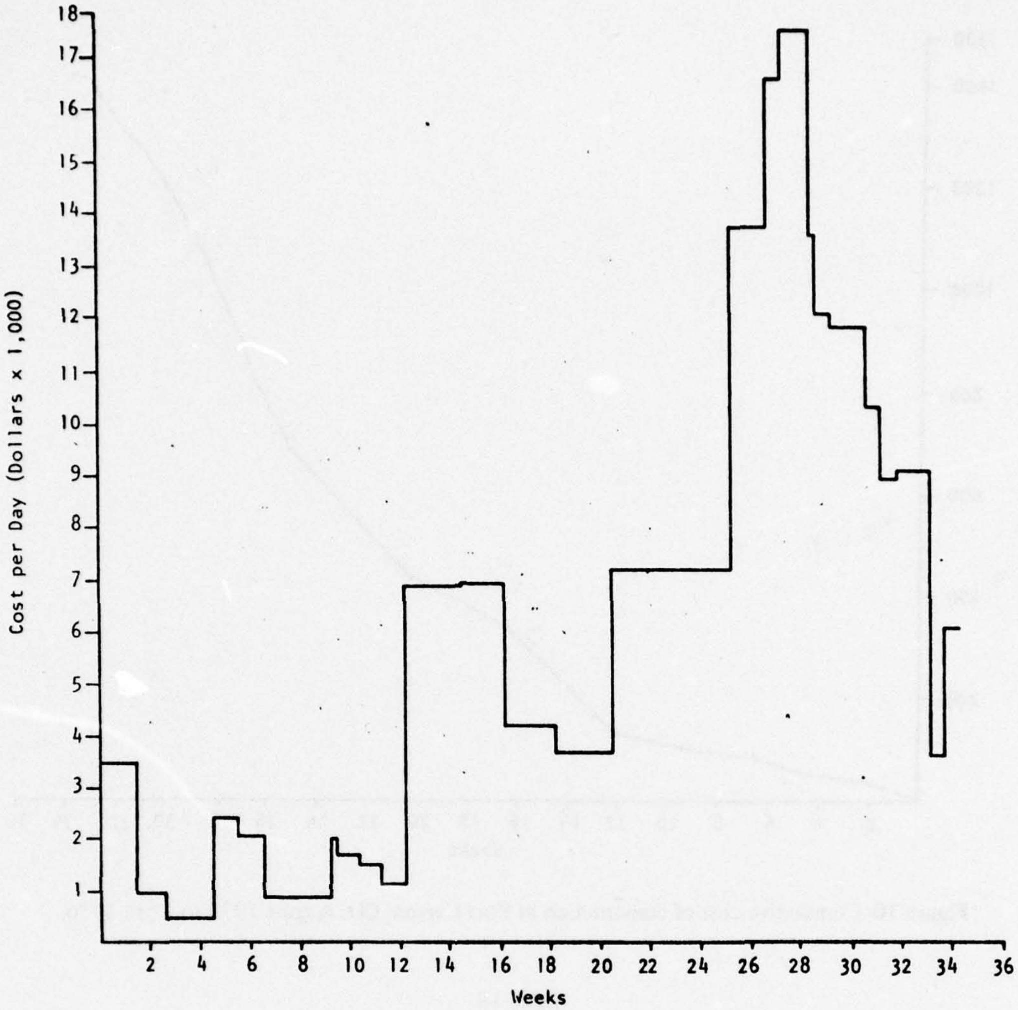

Figure 9. Construction cost per day at Fort Carson, CO.

Table 17
Construction Cost Data, November 1975 to February 1976, Fort Carson, CO

Task	Description	Task Duration (Days)	Cost Per Day ($)	Cost Breakdown*		
				Labor (%)	Equipment (%)	Material (%)
94-189	Install Drainage	33	3,893	3	10	76
92-94	Install Sewer	42	286	34	4	44
90-92	Install Sewer	16	229	34	4	44
98-86 86-120	Demolition Demolition	28	2,750	53	25	0
98-120	Phase 1 Import Fill & Grade	42	3,929	33	50	0
120-122	Phase 1 Import Fill & Grade	49	3,367	33	50	0

*Percentages do not sum to unity due to contractor's overhead and profit.

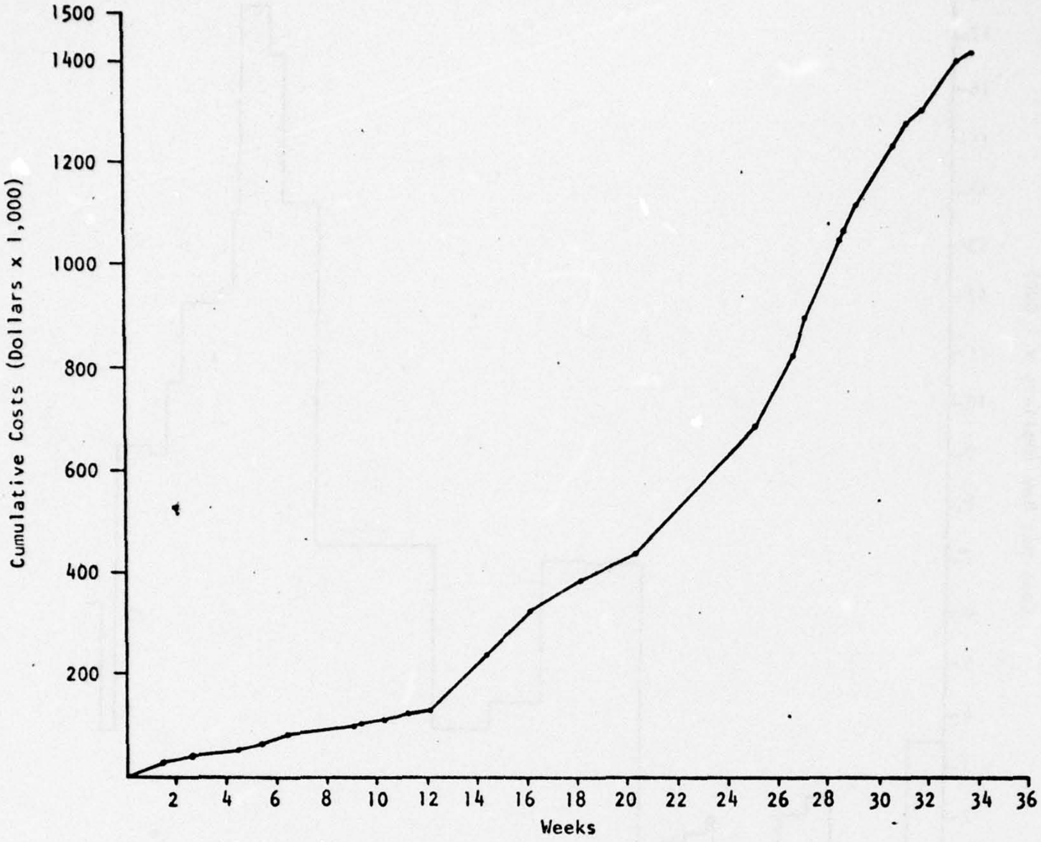

Figure 10. Cumulative cost of construction at Fort Carson, CO, August 1975 to April 1976.

Table 18
Increase in Equipment Cost for Noise Control

Task*	Equipment Cost ($)	Percentage Increases in Equipment Cost from Site Noise Reduction		
		3 dB (%)	6 dB (%)	10 dB (%)
94-189	12,847	.55	1.04	2.83
92-94	480	.55	1.04	2.83
90-92	147	.55	1.04	2.83
98-86[+] 86-120[+]	19,250	1.0	1.80	5.0
98-120	82,509	.39	.75	2.03
120-122	82,492	.39	.75	2.03
Total Equipment Cost ($)	197,725	198,635	199,449	202,418
Increase in Equipment Cost ($)		∿1,000	∿1,700	∿4,700

*See Table 17 for explanation of Task numbers

[+] Estimated

6 CONCLUSIONS

Modest reductions (5 dB) in construction-site noise are both technically feasible and economically reasonable for the types of construction studied at Fort Carson and Fort Hood. In general, these reductions will result in an increase of less than 1/2 percent in overall construction costs.

A variety of noise-reduction techniques are available, with one particular method normally preferred in a given situation

This report furnishes supporting rationale and data for the companion manual, *Construction-Site Noise Control–Cost-Benefit Estimating Procedures,* Interim Report N-36 (CERL, January 1978), which offers a means to estimate costs and select the preferred reduction technique.

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Patterson, W. N., et al., *Noise Control of Underground Mining Equipment,* Publication PB-243-896 (National Technical Information Service [NTIS], 1975).

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APPENDIX A:

COMPUTER MODELS

Nomenclature

L_{eq}	energy average equivalent sound level
t_n	time count
m	equipment count
X_o, Y_o	coordinates at observer position
$X_m(t_n)$, $Y_m(t_n)$	position of m^{th} equipment at time t_n
M	–total number of equipment units
N	–total units of time
X_a, Y_a	–acoustic center of vehicle movements
L_{max}	–maximum sound level
UF	–fraction of time equipment operates at maximum sound level

Model 1: Base Model

The base model accepts both location and pseudo sound power data for several equal interval points in time for any given number of vehicles. Pseudo sound power is the sound power of a monopole giving the sound levels observed. The L_{eq} values are calculated by the following, discrete summation equation:

$$L_{eq} = 10 \log_{10} \left[\frac{1}{N} \sum_{t_n=1}^{N} \sum_{m=1}^{M} \frac{10^{L'_m(t_n)/10}}{(X_o - X_m(t_n))^2 + (Y_o - Y_m(t_n))^2} \right] \quad \text{[Eq A1]}$$

where (X_o, Y_o) is the observer position, ($X_{m(t_n)}$), ($Y_{m(t_n)}$) is the position of vehicle m at time t_n, and $L'_m(t_n)$ is the pseudo sound power of vehicle m at time t_n.

The computer examines the L_{eq} for several points along several rays extending from the origin (0,0) until it locates the points on each ray which equal 55 and 65 dB. It then plots the L_{eq} = 55 and 65 dB contours, and the vehicles' movements.

Figure A1 is a printout based on the contours of three vehicles' movements. The vehicle movements and levels utilized for this computer run were based on data collected at Fort Hood, TX.

Model 2: Motion of Each Vehicle is Represented by its Mean Position

The base equation of Model 1 is simplified by representing the motion of each vehicle by a single point (X_m, Y_m), using the following equation:

$$L_{eq} = 10 \log_{10} \left[\sum_{m=1}^{M} \frac{\frac{1}{N} \sum_{t_n=1} 10^{L'_m(t_n)/10}}{(X_o - X_m)^2 + (Y_o - Y_m)^2} \right] \quad \text{[Eq A2]}$$

The effect of this assumption on the results of modeling the three vehicles depicted by Figure A1 is illustrated in Figure A2.

Model 3: Single-Point-Source Model

This model involves the assumption that the movements of all the vehicles can be replaced by a single point (X_a, Y_a) located at the acoustic center of the site. The model is based on this equation:

$$L_{eq} = 10 \log_{10} \left[\frac{\frac{1}{N} \sum_{m=1}^{M} \sum_{t_n=1}^{N} 10^{L'_m(t_n)/10}}{(X_o - X_a)^2 + (Y_o - Y_a)^2} \right] \quad \text{[Eq A3]}$$

Figure A3 depicts the effect that this assumption has on the same three-vehicle site modeled by the two previous procedures.

Model 4: Single-Point-Source and Acoustical Utilization-Factor Model

Model 3 is further simplified such that for each vehicle the changes in sound level as a function of time are replaced by each vehicle's maximum sound level (L_{max_m}) times the fraction of time the vehicle emits this maximum level (UF_m). The equation embodying this further simplification is:

$$L_{eq} = 10 \log_{10} \left[\frac{\sum_{m=1}^{M} UF_m \, 10^{L'_{max_m}/10}}{(X_o - X_a)^2 + (Y_o - Y_a)^2} \right] \quad \text{[Eq A4]}$$

Figure A4 illustrates the effect of this simplification on the three-vehicle site. Note that this figure is half scale as compared to Figures A1 to A3.

Model 5: Base Model Plus Barrier Attenuation

Model 1, the base equation, is expanded to include the ability to calculate the impact of a single, thin barrier on the L_{eq} = 55 and 65 dB contours. The amount of attenuation is calculated for each vehicle position over time with respect to each observer point under consideration. The equation for Model 5 is:

$$L_{eq} = 10 \log_{10}\left[\frac{1}{N}\sum_{n=1}^{N}\sum_{m=1}^{M}\frac{\frac{.0514}{\delta m(t_n)}\,10^{L'_m(t_n)/10}}{(X_o - X_m(t_n))^2 + (Y_o - Y_m(t_n))^2}\right] \qquad \text{[Eq A5]}$$

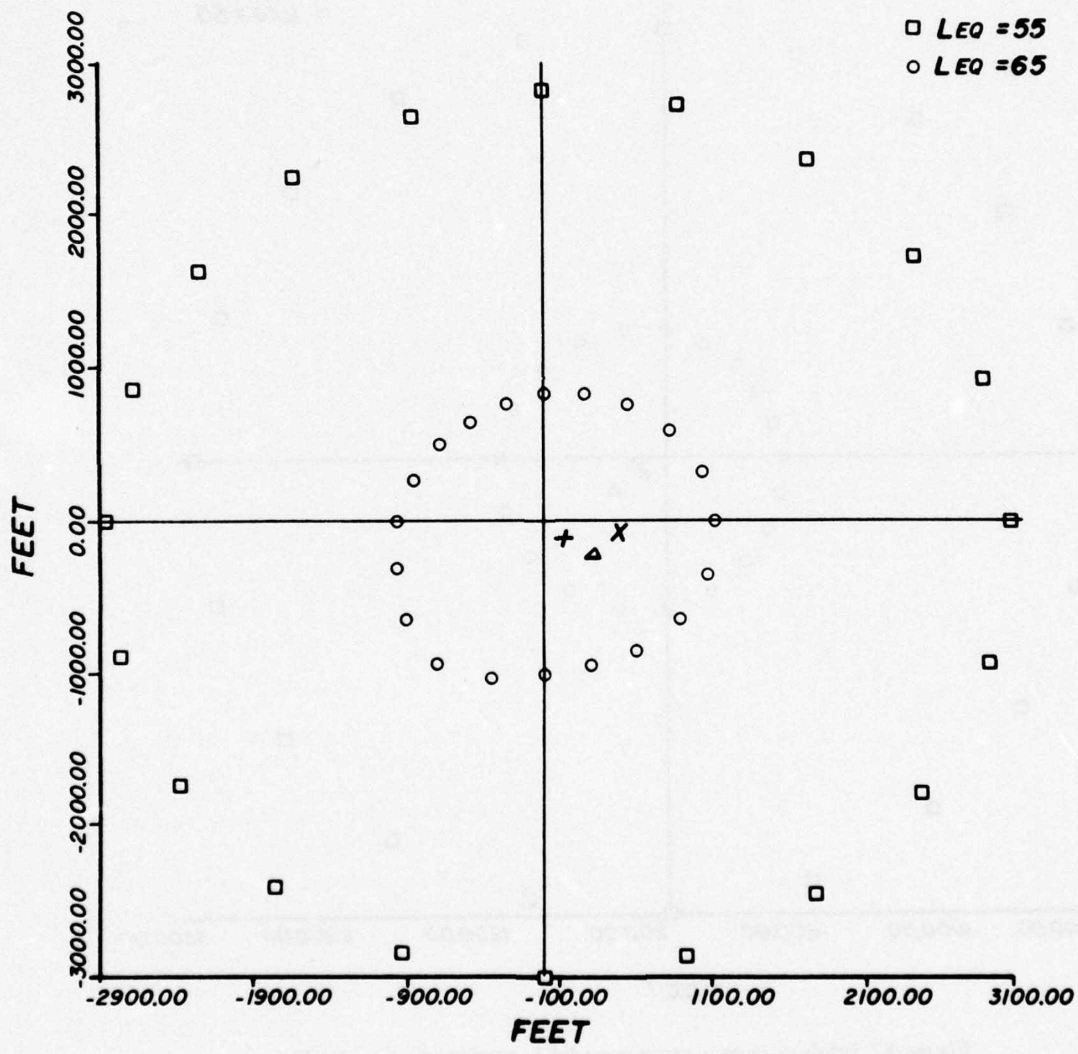


Figure A1. Printout from computer model 1: base equation.

where

$$\delta m(t_n) = a + b - c$$

$$a = \sqrt{(h_b - h_m)^2 + d^2}$$

$$b = \sqrt{(h_m - h_o)^2 + e^2}$$

$$c = \sqrt{(h_m - h_o)^2 + (d + e)^2}$$

$$d = \sqrt{(Y_i - Y_m(t_n))^2 + (X_i - X_m(t_n))^2}$$

$$e = \sqrt{(Y_i - Y_o)^2 + (X_i - X_o)^2}$$

(Refer to Figure A5 for the definition of these variables.)

Derivation of the barrier effect is discussed in Appendix D.

Particularly relevant to the equation form of Model 5 is Eq D10 of Appendix D, where if variable L_A is replaced by the expression for L_{eq} of Model 1 and if the term $10 \log_{10} \frac{0.0514}{\sigma}$ is altered to represent the variables of vehicle and time:

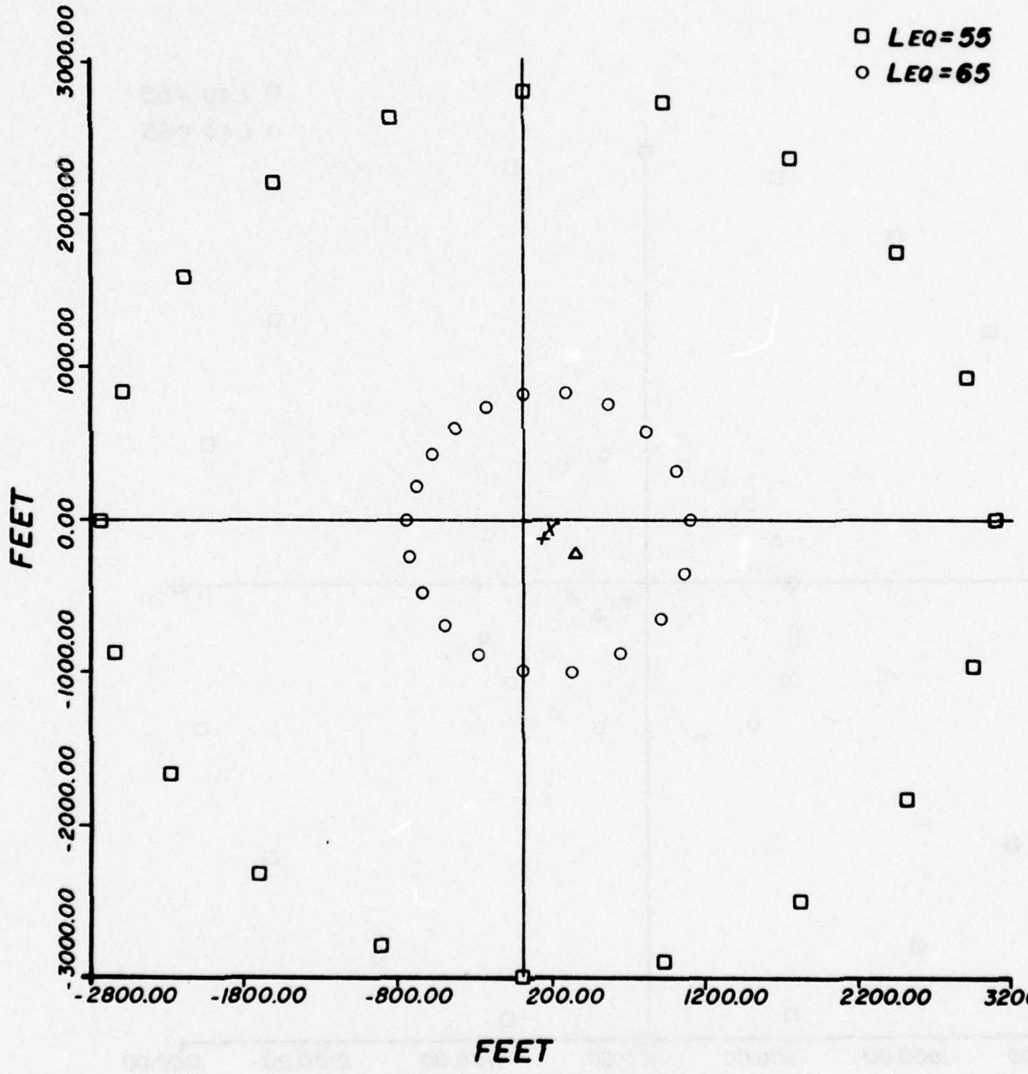


Figure A2. Printout from computer model 2: motion of each vehicle is represented by its mean position.

$$10 \log_{10} \sum_{t_n=1}^{N} \sum_{m=1}^{M} \frac{0.0514}{\sigma_m(t_n)}$$

then the equation for Model 5 can be derived.

Figure A6 shows the effect of a 16-ft (5-m) high and 600-ft (183-m) long barrier on the three-vehicle site.

The programs and definition of their variables are provided for Models 1 through 5 in Appendix B. These programs are written in Fortran IV.

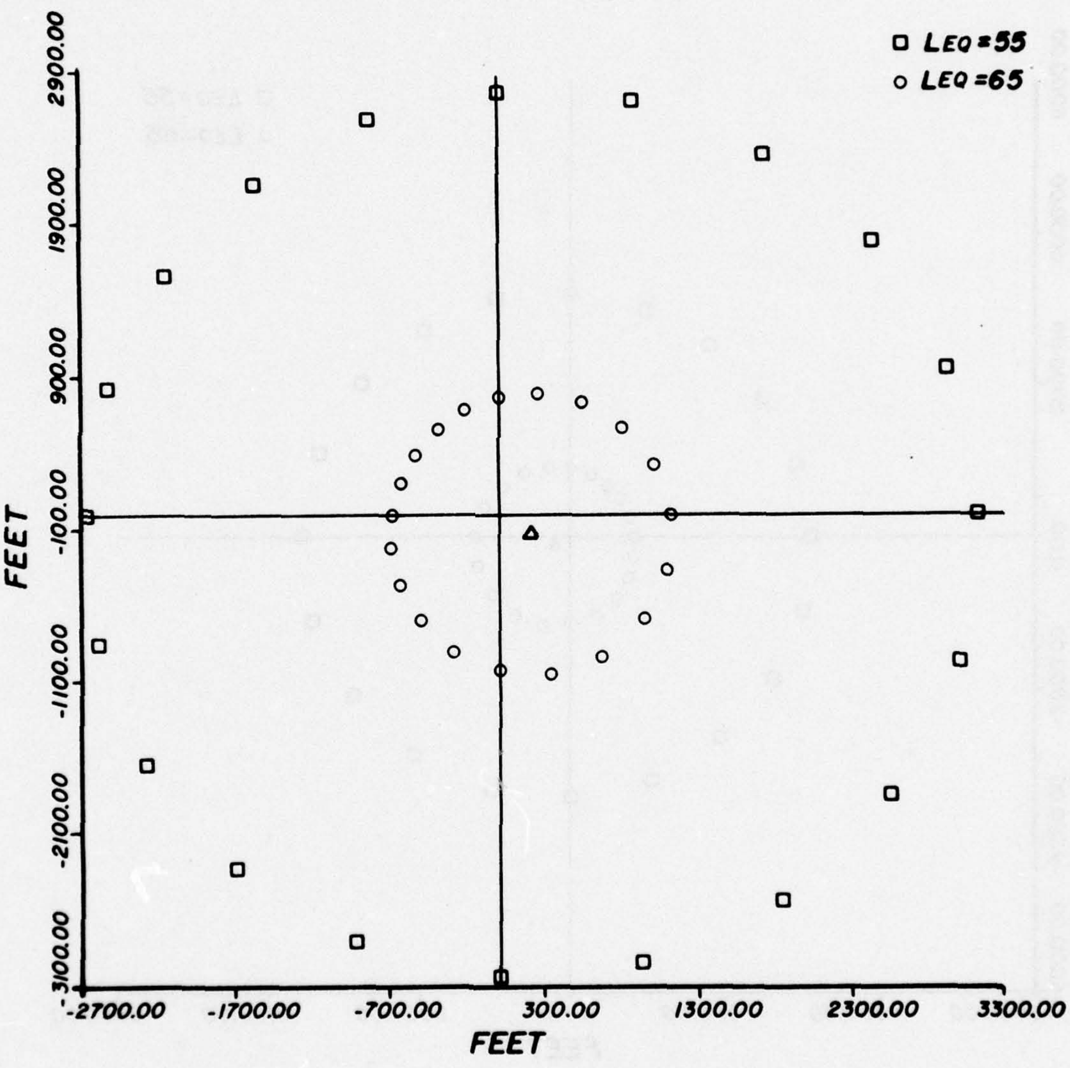


Figure A3. Printout from computer model 3: single-point-source model.

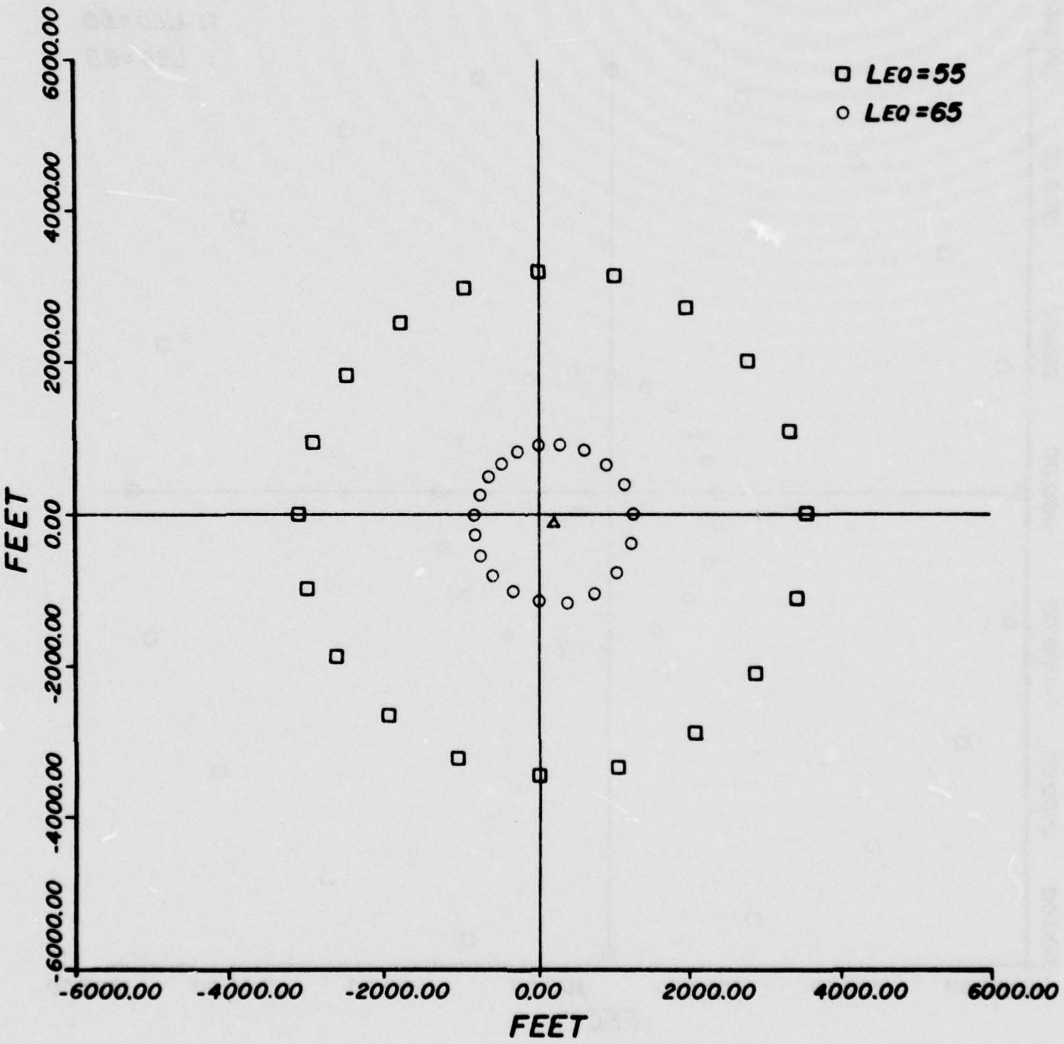
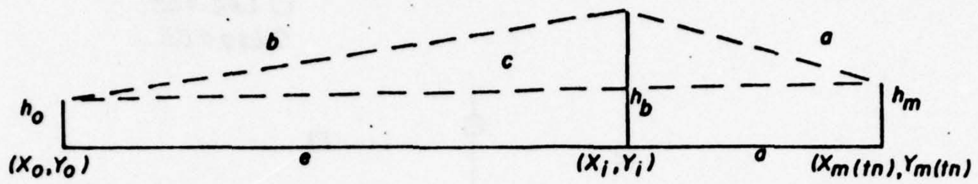


Figure A4. Printout from computer model 4: single-point-source and utilization-factor model.



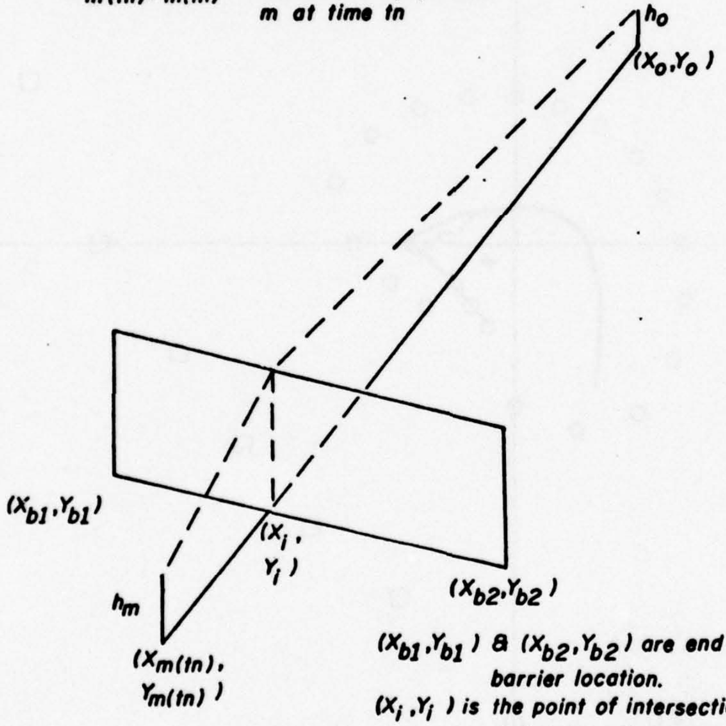
h_m = height of equipment exhaust

h_b = height of barrier

h_o = height of observer

(X_o, Y_o) = observer location

$(X_{m(tn)}, Y_{m(tn)})$ = location of equipment m at time tn



(X_{b1}, Y_{b1}) & (X_{b2}, Y_{b2}) are end points defining the barrier location.

(X_i, Y_i) is the point of intersection between a line defined by the points (X_o, Y_o) and $(X_{m(tn)}, Y_{m(tn)})$ and a line defined by the points (X_{b1}, Y_{b1}) & (X_{b2}, Y_{b2}).

Figure A5. Barrier equation variables.

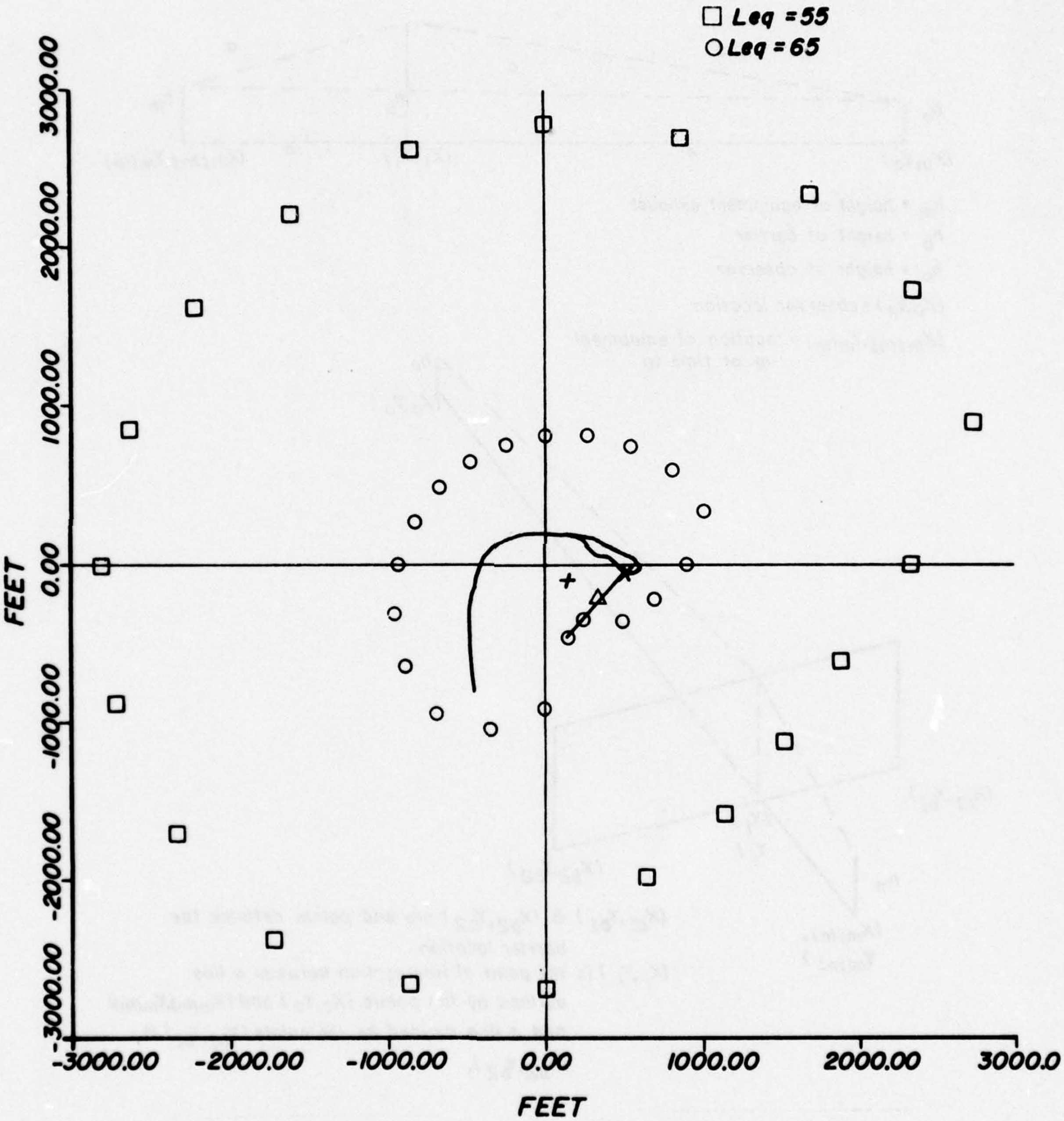
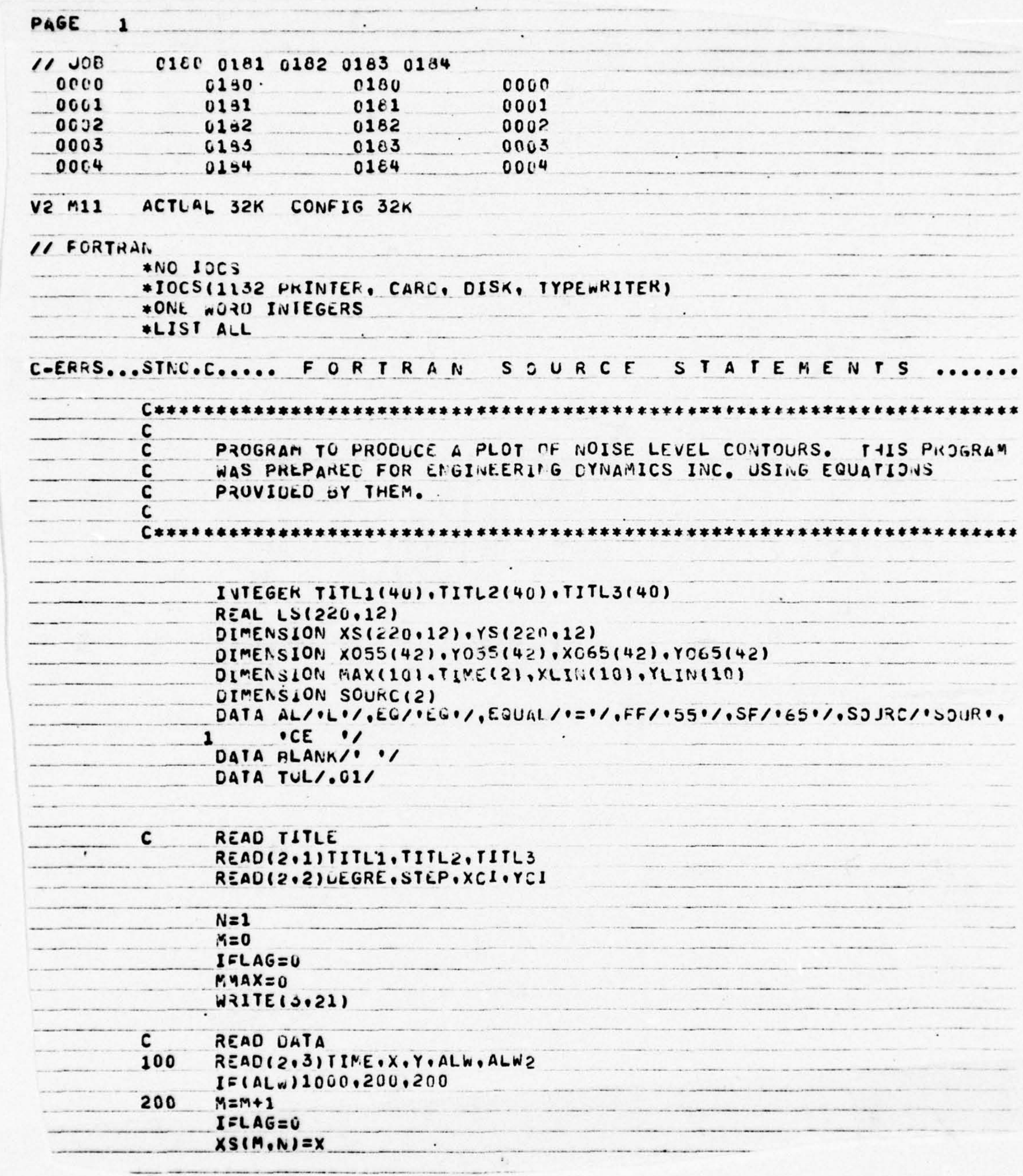


Figure A6. Computer printout of model 5: base equation plus barrier attenuation.

APPENDIX B:

COMPUTER PROGRAMS FOR MODELS 1 THROUGH 5

Computer Program for Model 1: Base Equation



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PAGE   1

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  0001          0181          0181          0001
  0002          0182          0182          0002
  0003          0183          0183          0003
  0004          0184          0184          0004

V2 M11   ACTUAL 32K  CONFIG 32K

// FORTRAN
          *NO IOCS
          *IOCS(1132 PRINTER, CARD, DISK, TYPEWRITER)
          *ONE WORD INTEGERS
          *LIST ALL

C-ERRS...STNC.C..... F O R T R A N   S O U R C E   S T A T E M E N T S .......

          C***********************************************************************
          C
          C      PROGRAM TO PRODUCE A PLOT OF NOISE LEVEL CONTOURS.  THIS PROGRAM
          C      WAS PREPARED FOR ENGINEERING DYNAMICS INC. USING EQUATIONS
          C      PROVIDED BY THEM.
          C
          C***********************************************************************


                 INTEGER TITL1(40),TITL2(40),TITL3(40)
                 REAL LS(220,12)
                 DIMENSION XS(220,12),YS(220,12)
                 DIMENSION X055(42),Y055(42),X065(42),Y065(42)
                 DIMENSION MAX(10),TIME(2),XLIN(10),YLIN(10)
                 DIMENSION SOURC(2)
                 DATA AL/'L'/,EG/'EG'/,EQUAL/'='/,FF/'55'/,SF/'65'/,SOURC/'SOUR',
               1     'CE  '/
                 DATA BLANK/' '/
                 DATA TOL/.01/


          C      READ TITLE
                 READ(2,1)TITL1,TITL2,TITL3
                 READ(2,2)DEGRE,STEP,XCI,YCI

                 N=1
                 M=0
                 IFLAG=0
                 MMAX=0
                 WRITE(3,21)

          C      READ DATA
          100    READ(2,3)TIME,X,Y,ALW,ALW2
                 IF(ALW)1000,200,200
          200    M=M+1
                 IFLAG=0
                 XS(M,N)=X
```

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PAGE   2

C-ERRS...STNO.C..... F O R T R A N   S O U R C E   S T A T E M E N T S .......

                  YS(M,N)=Y
                  LS(M,N)=ALW
                  WRITE(3,20)TIME,X,Y,ALW,ALW2
                  GO TO 100

            C     END OF DATA SET
            1000  IF(IFLAG)1100,1100,1200
            1100  IFLAG=1
                  WRITE(3,21)
                  MAX(N)=M
                  IF(M-498)1104,1104,1103
            1103  WRITE(3,22)M
                  CALL EXIT
            1104  IF(M-MMAX)1110,1110,1105
            1105  MMAX=M
            1110  M=0
            C     N=N+1
                  GO TO 100

            C     END OF ALL DATA SETS
            1200  NCONT=N-1
                  IF(NCONT-5)1210,1210,1205
            1205  WRITE(3,23)
                  CALL EXIT
            1210  MCONT=MMAX

            C     BEGIN COMPUTATIONS OF CONTOURS
                  ISTEP=360./DEGRE
                  IX55=0
                  IY55=0
                  IX65=0
                  IY65=0

                  DO 5000 IRAD=1,ISTEP
                  XC=XCI
                  YC=YCI
                  ANG=(IRAD-1)*DEGRE
                  ANG = ANG *.017453293
                  XINC=COS(ANG)*STEP
                  YINC=SIN(ANG)*STEP
                  ILEG=1

            C     LOOP TO COMPUTE ENERGY AT A GIVEN POINT
            1250  SUML=0.0
                  DO 1300 N=1,NCONT
                  MX=MAX(N)
                  AMX=MX
                  DO 1300 MM=1,MCONT
                  AM=MM
                  TEMP1=AM/AMX
                  TEMP2=MM/MX
```

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PAGE    3

C-ERRS...STNC.C.....  F O R T R A N   S O U R C E   S T A T E M E N T S  .......

                M=(TEMP1-TEMP2)*AMX
                IF(M)1260,1260,1275
          1260  M=MX
          1275  SUML=SUML+10.**(LS(M,N)/10.)/((XC-XS(M,N))**2+(YC-YS(M,N))**2)
           1300 CONTINUE
                SUML=10.0*ALOG(SUML/MCONT)/ALOG(10.)

          C     BRANCH TO CORRECT SECTIONS BASED ON OBSERVER POSITION
                GO TO(1400,1700,1800,2000,3000,4100,4100,1575),ILEG

          C     ILEG=1 OBSERVER AT ORGIN
          1400  IF(SUML-55.)1550,1500,1600
          1500  IX55=IX55+1
                IY55=IY55+1
                XO55(IX55)=XC
                YO55(IY55)=YC
                ILEG=2
                GO TO 4900

          1550  ILEG=8
                GO TO 4900

          1575  IF(SUML-55.)1580,1500,2020
          1580  IF(SUML-SUMA)5000,5000,4900

          1600  IF(SUML-65.)1660,1650,1670
          1650  IX65=IX65+1
                IY65=IY65+1
                XO65(IX65)=XC
                YO65(IY65)=YC
                ILEG=3
                GO TO 4900

          1660  ILEG=4
                GO TO 4900

          1670  ILEG=5
                GO TO 4900
          C     ILEG=2 OBSERVER AT 55 LEVEL
          1700  IF(SUML-55.)5000,1500,1720
          1720  ILEG=4
                GO TO 4900

          C     ILEG=3 OBSERVER AT 65 LEVEL
          1800  IF(SUML-65.)1840,1650,1820
          1820  ILEG=5
                GO TO 4900

          1840  ILEG=4
                GO TO 4900
```

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C-ERRS...STNO.C.....  F O R T R A N   S O U R C E   S T A T E M E N T S  .......

           C      ILEG=4 OBSERVER BETWEEN 55 AND 65 LEVEL
           2000   IF(SUML-55.)2020,1500,2040
           2020   TARGT=55.
                  ILEG=6
                  GO TO 4000

           2040   IF(SUML-65.)4900,1650,2050
           2050   TARGT=65.
                  ILEG=7
                  GO TO 4000

           C      ILEG=5 OVSERVER AT LEVEL GREATER THAN 65
           3000   IF(SUML-65.)2050,1650,4900

           C      ITERATE AROUND TARGET POINT
           4000   XB=XC
                  YB=YC
                  SUMB=SUML
           4010   XC=(XB+XA)/2.
                  YC=(YB+YA)/2.
                  GO TO 1250

           C      ILEG=6 OP 7  ITERATING AROUND TARGET LEVEL
           4100   IF(ABS(SUML-TARGT)-TOL)4500,4500,4120
           4120   IF(SUML-TARGT)4130,4130,4140
           4130   IF(SUMB-TARGT)4000,4137,4137
           4137   XA=XC
                  YA=YC
                  SUMA=SUML
                  GO TO 4010

           4140   IF(SUMB-TARGT)4137,4137,4000

           C      CONTOUR POINT FOUND
           4500   ILEG=ILEG-5
                  GO TO(1500,1650),ILEG

           C      STEP OUT ON RADIUS
           4900   XA=XC
                  YA=YC
                  SUMA=SUML
                  XC=XC+XINC
                  YC=YC+YINC
                  GO TO 1250

           5000   CONTINUE

                  WRITE(3,6)
                  WRITE(3,4)(X055(I),Y055(I),I=1,IX55)
                  WRITE(3,7)
                  WRITE(3,4)(X065(I),Y065(I),I=1,IX65)
```
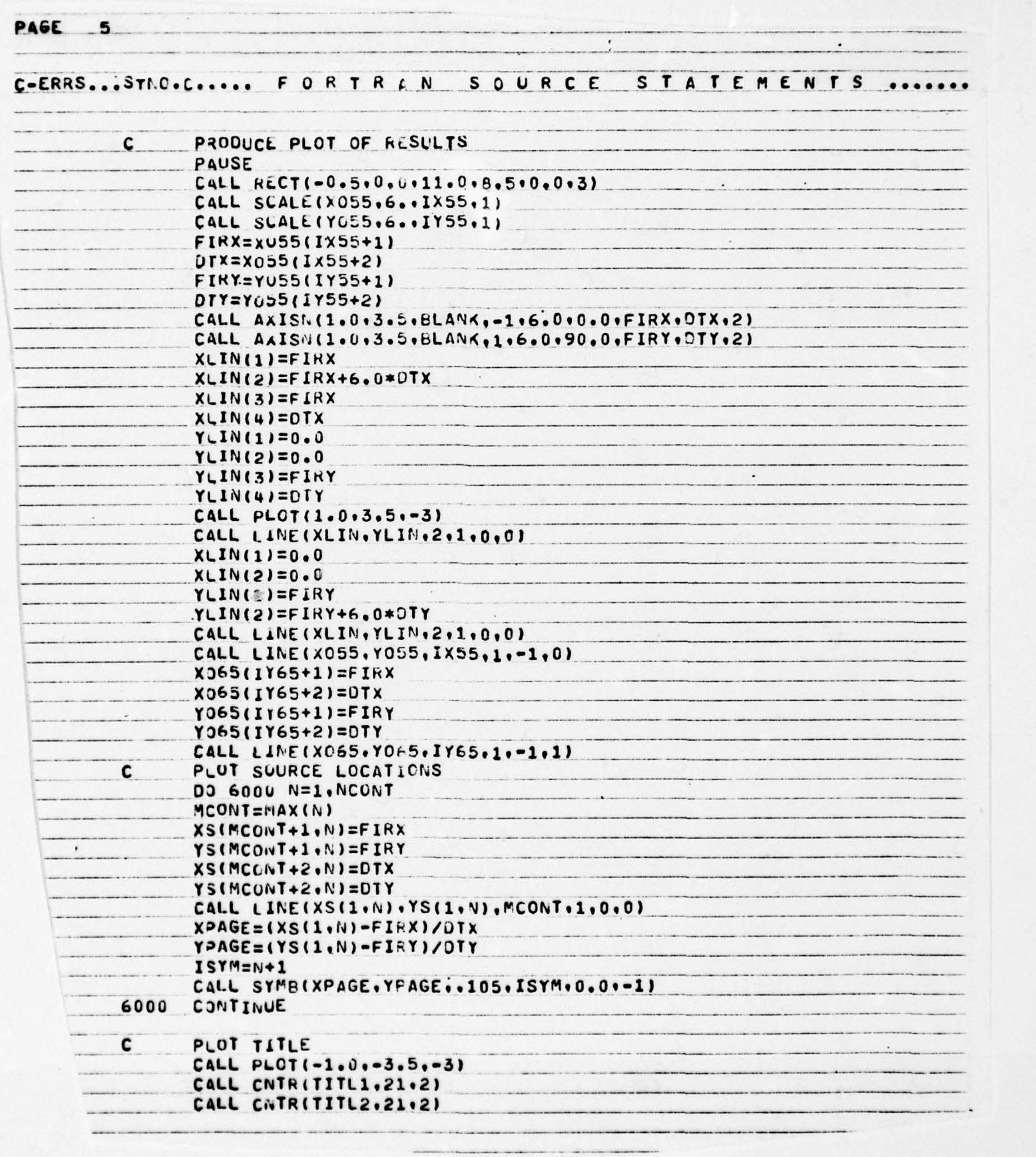



```
PAGE   5

C-ERRS...STNO.C.....  F O R T R A N   S O U R C E   S T A T E M E N T S  .......

         C      PRODUCE PLOT OF RESULTS
                PAUSE
                CALL RECT(-0.5,0.0,11.0,8.5,0.0,3)
                CALL SCALE(X055,6.,IX55,1)
                CALL SCALE(Y055,6.,IY55,1)
                FIRX=X055(IX55+1)
                DTX=X055(IX55+2)
                FIRY=Y055(IY55+1)
                DTY=Y055(IY55+2)
                CALL AXISN(1.0,3.5,BLANK,-1,6.0,0.0,FIRX,DTX,2)
                CALL AXISN(1.0,3.5,BLANK,1,6.0,90.0,FIRY,DTY,2)
                XLIN(1)=FIRX
                XLIN(2)=FIRX+6.0*DTX
                XLIN(3)=FIRX
                XLIN(4)=DTX
                YLIN(1)=0.0
                YLIN(2)=0.0
                YLIN(3)=FIRY
                YLIN(4)=DTY
                CALL PLOT(1.0,3.5,-3)
                CALL LINE(XLIN,YLIN,2,1,0,0)
                XLIN(1)=0.0
                XLIN(2)=0.0
                YLIN(1)=FIRY
                YLIN(2)=FIRY+6.0*DTY
                CALL LINE(XLIN,YLIN,2,1,0,0)
                CALL LINE(X055,Y055,IX55,1,-1,0)
                X065(IY65+1)=FIRX
                X065(IY65+2)=DTX
                Y065(IY65+1)=FIRY
                Y065(IY65+2)=DTY
                CALL LINE(X065,Y065,IY65,1,-1,1)
         C      PLOT SOURCE LOCATIONS
                DO 6000 N=1,NCONT
                MCONT=MAX(N)
                XS(MCONT+1,N)=FIRX
                YS(MCONT+1,N)=FIRY
                XS(MCONT+2,N)=DTX
                YS(MCONT+2,N)=DTY
                CALL LINE(XS(1,N),YS(1,N),MCONT,1,0,0)
                XPAGE=(XS(1,N)-FIRX)/DTX
                YPAGE=(YS(1,N)-FIRY)/DTY
                ISYM=N+1
                CALL SYMB(XPAGE,YPAGE,.105,ISYM,0.0,-1)
         6000   CONTINUE

         C      PLOT TITLE
                CALL PLOT(-1.0,-3.5,-3)
                CALL CNTR(TITL1,21,2)
                CALL CNTR(TITL2,21,2)
```

```
PAGE    6

C-ERRS...STNO.C..... F O R T R A N   S O U R C E   S T A T E M E N T S .......

                 CALL CNTR(TITL3,21,2)
                 CALL SYMB(1.06,2.75,.14,TITL1,0.0,3042)
                 CALL SYMB(1.06,2.47,.14,TITL2,0.0,3042)
                 CALL SYMB(1.06,2.19,.14,TITL3,0.0,3042)
                 CALL SYMB(1.13,1.76,.105,0,0.0,-1)
                 CALL SYMB(1.34,1.69,.14,AL,0.0,1)
                 CALL SYMB(1.48,1.69,.07,EQ,0.0,2)
                 CALL SYMB(1.76,1.69,.14,EQUAL,0.0,1)
                 CALL SYMB(2.04,1.69,.14,FF,0.0,2)

                 CALL SYMB(1.13,1.48,.105,1,0.0,-1)
                 CALL SYMB(1.34,1.41,.14,AL,0.0,1)
                 CALL SYMB(1.48,1.41,.070,EQ,0.0,2)
                 CALL SYMB(1.76,1.41,.14,EQUAL,0.0,1)
                 CALL SYMB(2.04,1.41,.14,SF,0.0,2)

                 DO 7000 N=1,NCONT
                 AN=N
                 ISYM=N+1
                 YPAGE=1.69-.1575*(N-1)
                 CALL SYMB(5.635,YPAGE,.105,SOURC,0.0,6)
                 CALL NUMB(6.37,YPAGE,.105,AN,0.0,-1)
                 CALL SYMB(6.9475,YPAGE+.0525,.105,ISYM,0.0,-1)
          7000   CONTINUE
                 CALL PLOT(15.,0.0,999)
                 CALL EXIT
          1      FORMAT(40A2)
          2      FORMAT(8F10.0)
          3      FORMAT(2A4,6F12.0)
          4      FORMAT(4(F9.2,2X,F9.2,6X))
          6      FORMAT(' COORDINATES OF LEQ = 55 LEVEL')
          7      FORMAT(///' COORDINATES OF LEQ = 65 LEVEL')
          20     FORMAT(1X,2A4,4F10.2)
          21     FORMAT(1H1)
          22     FORMAT(1X,14('****ERROR')/' DATA SET TO LARGE'/I5,' POINTS'//////
          23     FORMAT(1X,14('****ERROR')/' TOO MANY DATA SETS'//////////////////
                 END
VARIABLE ALLOCATIONS
    XS(R )=149E-0000     YS(R )=293E-14A0  X055(R )=2992-2940  Y055(R )=29E6-2994
  TIME(R )=2A92-2A90   XLIN(R )=2AA6-2A94  YLIN(R )=2ABA-2AA8 SOURC(R )=2ABE-2ABC
  STEP(R )=3F62         XCI(R )=3F64        YCI(R )=3F66          X(R )=3F68
  ALW2(R )=3F6E          XC(R )=3F70         YC(R )=3F72        ANG(R )=3F74
  SUML(R )=3F7A         AMX(R )=3F7C         AM(R )=3F7E      TEMP1(R )=3F80
 TARGT(R )=3F86          XB(R )=3F88         YB(R )=3F8A       SUMB(R )=3F8C
   TOL(R )=3F92        FIRX(R )=3F94        DTX(R )=3F96       FIRY(R )=3F98
 XPAGE(R )=3F9E       YPAGE(R )=3FA0         AL(R )=3FA2         EQ(R )=3FA4
    SF(R )=3FAA          AN(R )=3FAC        MAX(I )=3FBF-3FB6 TITL1(I )=3FE7-3FC0
     N(I )=4038           M(I )=4039      IFLAG(I )=403A       MMAX(I )=403B
 ISTEP(I )=403E        IX55(I )=403F       IY55(I )=4040       IX65(I )=4041
  ILEG(I )=4044          MX(I )=4045         MM(I )=4046          I(I )=4047
```

```
PAGE   7

STATEMENT ALLOCATIONS
     1=409F       2=40A2       3=40A5       4=40AA       6=40B1       7=40C2      20=4
   100=416D     200=4180    1000=4182    1100=4186    1103=41CD    1104=41D4    1105=4
  1210=41F5    1250=423D    1260=4277    1275=427B    1300=42A5    1400=42DB    1500=4
  1600=431D    1650=4326    1660=434A    1670=4350    1700=4356    1720=435F    1800=4
  2020=4383    2040=438D    2050=4396    3000=43A0    4000=43AB    4010=43B7    4100=4
  4140=43F3    4500=43FC    4900=4408    5000=4422    6000=45DA    7000=45BA

FEATURES SUPPORTED
 ONE WORD INTEGERS
 STANDARD PRECISION
 IOCS-
   1132 PRINTER
   DISK
   TYPEWRITER
   CARD

CALLED SUBPROGRAMS
 FCOS     FSIN     FALOG    FABS     RECT     SCALE    AXISN    PLOT     LINE     SYMB
 FSUBX    FMPY     FDIV     FLD      FLDX     FSTO     FSTOX    FSBR     FDVR     FAXI
 SRED     SWRT     SCOMP    SFIO     SICAI    SIOAF    SIOFX    SIOF     SIOI     SUBSC

REAL CONSTANTS
  .360000E 03=404E     .174532E-01=4050     .000000E 00=4052     .100000E 02=4054
  .200000E 01=405A     .500000E 00=405C     .110000E 02=405E     .850000E 01=4060
  .350000E 01=4066     .900000E 02=4068     .105000E 00=406A     .106000E 01=406C
  .247000E 01=4072     .219000E 01=4074     .113000E 01=4076     .176000E 01=4078
  .148000E 01=407E     .700000E-01=4080     .204000E 01=4082     .141000E 01=4084
  .637000E 01=408A     .694750E 01=408C     .525000E-01=408E     .150000E 02=4090

INTEGER CONSTANTS
     2=4092       1=4093       0=4094       3=4095     498=4096       5=4097       8=4
    21=409C    3042=409D     999=409E

CORE REQUIREMENTS FOR -
 COMMON-      0,   VARIABLES AND TEMPORARIES- 16462,   CONSTANTS AND PROGRAM-  16

END OF SUCCESSFUL COMPILATION
```

Computer Program for Model 2: Motion of Each Vehicle is Presented by its Mean Position

```
PAGE    1

// JOB     0180 0181 0182 0183 0184
  0000           0180           0180          0000
  0001           0181           0181          0001
  0002           0182           0182          0002
  0003           0183           0183          0003
  0004           0184           0184          0004

V2 M11    ACTUAL 32K   CONFIG 32K

// FORTRAN
        *NO IOCS
        *IOCS(1132 PRINTER, CARD, DISK, TYPEWRITER)
        *ONE WORD INTEGERS
        *LIST ALL

C-ERRS...STNO.C.....  F O R T R A N   S O U R C E   S T A T E M E N T S  .......

        C***********************************************************************
        C
        C      PROGRAM TO PRODUCE A PLOT OF NOISE LEVEL CONTOURS.  THIS PROGRAM
        C      WAS PREPARED FOR ENGINEERING DYNAMICS INC. USING EQUATIONS
        C      PROVIDED BY THEM.
        C
        C      SIMPLIFICATION 3A  -  THE SOURCE POSITIONS AS A FUNCTION OF
        C                            TIME CAN BE REPLACED BY THEIR MEAN
        C                            POSITION.
        C
        C***********************************************************************


               INTEGER TITL1(40),TITL2(40),TITL3(40)
               REAL LS(500,5)
               DIMENSION XS(5),YS(5)
               DIMENSION X055(42),Y055(42),X065(42),Y065(42)
               DIMENSION MAX(10),TIME(2),XLIN(10),YLIN(10)
               DIMENSION SOURC(2)
               DATA AL/'L'/,EQ/'EQ'/,EQUAL/'='/,FF/'55'/,SF/'65'/,SOURC/'SOUR',
             1      'CE  '/
               DATA BLANK/'  '/
               DATA TOL/.01/


        C      READ TITLE
               READ(2,1)TITL1,TITL2,TITL3
               READ(2,2)DEGRE,STEP,XCI,YCI

               N=1
               M=0
               IFLAG=0
               MMAX=0
               XSUM =0.0
               YSUM= 0.0
               WRITE(3,21)
```

```
PAGE    2

C-ERRS...STNO.C.....  F O R T R A N   S O U R C E   S T A T E M E N T S  .......

        C       READ DATA
        100     READ(2,3)TIME,X,Y,ALW
                IF(ALW)1000,200,200
        200     M=M+1
                IFLAG=0
                XSUM=XSUM+X
                YSUM=YSUM+Y
                LS(M,N)=ALW
                WRITE(3,20)TIME,X,Y,ALW
                GO TO 100

        C       END OF DATA SET
        1000    IF(IFLAG)1100,1100,1200
        1100    IFLAG=1
                WRITE(3,21)
                XS(N) = XSUM/M
                YS(N) = YSUM/M
                MAX(N)=M
                IF(M-498)1104,1104,1103
        1103    WRITE(3,22)M
                CALL EXIT
        1104    IF(M-MMAX)1110,1110,1105
        1105    MMAX=M
        1110    M=0
                N=N+1
                XSUM = 0.0
                YSUM = 0.0
                GO TO 100

        C       END OF ALL DATA SETS
        1200    NCONT=N-1
                IF(NCONT-5)1210,1210,1205
        1205    WRITE(3,23)
                CALL EXIT
        1210    MCONT=MMAX

        C       BEGIN COMPUTATIONS OF CONTOURS
                ISTEP=360./DEGRE
                IX55=0
                IY55=0
                IX65=0
                IY65=0

                DO 5000 IRAD=1,ISTEP
                XC=XCI
                YC=YCI
                ANG=(IRAD-1)*DEGRE
                ANG = ANG *.017453293
                XINC=COS(ANG)*STEP
                YINC=SIN(ANG)*STEP
                ILEG=1
```

```
C-ERRS...STNO.C..... F O R T R A N   S O U R C E   S T A T E M E N T S .......

        C      LOOP TO COMPUTE ENERGY AT A GIVEN POINT
        1250   SUML=0.0
               DO 1300 N=1,NCONT
               MX=MAX(N)
               AMX=MX
               DO 1300 MM=1,MCONT
               AM=MM
               TEMP1=AM/AMX
               TEMP2=MM/MX
               M=(TEMP1-TEMP2)*AMX
               IF(M)1260,1260,1275
        1260   M=MX
        1275   SUML=SUML+10.**(LS(M,N)/10.)/((XC-XS(   N))**2+(YC-YS(   N))**2)
         1300  CONTINUE
               SUML=10.0*ALOG(SUML/MCONT)/ALOG(10.)

        C      BRANCH TO CORRECT SECTIONS BASED ON OBSERVER POSITION
               GO TO(1400,1700,1600,2000,3000,4100,4100,1575),ILEG

        C      ILEG=1 OBSERVER AT ORGIN
        1400   IF(SUML-55.)1550,1500,1600
        1500   IX55=IX55+1
               IY55=IY55+1
               XO55(IX55)=XC
               YO55(IY55)=YC
               ILEG=2
               GO TO 4900

        1550   ILEG=8
               GO TO 4900

        1575   IF(SUML-55.)1580,1500,2020
        1580   IF(SUML-SUMA)5000,5000,4900

        1600   IF(SUML-65.)1660,1650,1670
        1650   IX65=IX65+1
               IY65=IY65+1
               XO65(IX65)=XC
               YO65(IY65)=YC
               ILEG=3
               GO TO 4900

        1660   ILEG=4
               GO TO 4900

        1670   ILEG=5
               GO TO 4900
        C      ILEG=2 OBSERVER AT 55 LEVEL
        1700   IF(SUML-55.)5000,1500,1720
        1720   ILEG=4
```

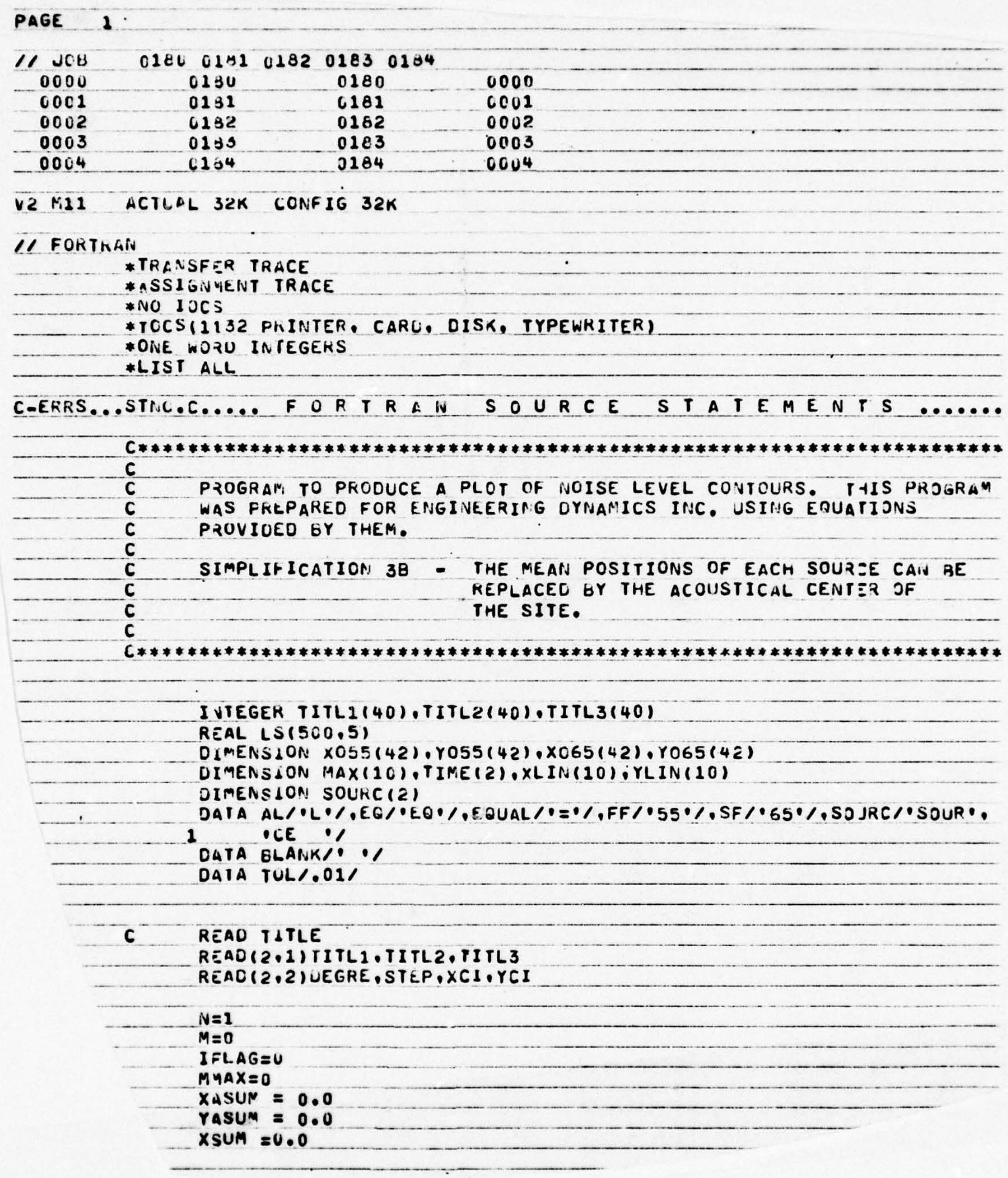
```
C-ERRS...STNC.C.....  FORTRAN  SOURCE  STATEMENTS .......
              GO TO 4900

        C     ILEG=3 OBSERVER AT 65 LEVEL
        1800  IF(SUML-65.)1840,1650,1820
        1820  ILEG=5
              GO TO 4900

        1840  ILEG=4
              GO TO 4900

        C     ILEG=4 OBSERVER BETWEEN 55 AND 65 LEVEL
        2000  IF(SUML-55.)2020,1500,2040
        2020  TARGT=55.
              ILEG=6
              GO TO 4000

        2040  IF(SUML-65.)4900,1650,2050
        2050  TARGT=65.
              ILEG=7
              GO TO 4000

        C     ILEG=5 OVSERVER AT LEVEL GREATER THAN 65
        3000  IF(SUML-65.)2050,1650,4900

        C     ITERATE AROUND TARGET POINT
        4000  XB=XC
              YB=YC
              SUMB=SUML
        4010  XC=(XB+XA)/2.
              YC=(YB+YA)/2.
              GO TO 1250

        C     ILEG=6 OR 7  ITERATING AROUND TARGET LEVEL
        4100  IF(ABS(SUML-TARGT)-TOL)4500,4500,4120
        4120  IF(SUML-TARGT)4130,4130,4140
        4130  IF(SUMB-TARGT)4000,4137,4137
        4137  XA=XC
              YA=YC
              SUMA=SUML
              GO TO 4010

        4140  IF(SUMB-TARGT)4137,4137,4000

        C     CONTOUR POINT FOUND
        4500  ILEG=ILEG-5
              GO TO(1500,1650),ILEG

        C     STEP OUT ON RADIUS
        4900  XA=XC
              YA=YC
              SUMA=SUML
```

```
C-ERRS...STNO.C..... FORTRAN SOURCE STATEMENTS .......

                 XC=XC+XINC
                 YC=YC+YINC
                 GO TO 1250

           5000  CONTINUE

                 WRITE(3,6)
                 WRITE(3,4)(X055(I),Y055(I),I=1,IX55)
                 WRITE(3,7)
                 WRITE(3,4)(X065(I),Y065(I),I=1,IX65)

           C     PRODUCE PLOT OF RESULTS
                 PAUSE
                 CALL RECT(-0.5,0.0,11.0,8.5,0.0,3)
                 CALL SCALE(X055,6.,IX55,1)
                 CALL SCALE(Y055,6.,IY55,1)
                 FIRX=X055(IX55+1)
                 DTX=X055(IX55+2)
                 FIRY=Y055(IY55+1)
                 DTY=Y055(IY55+2)
                 CALL AXISN(1.0,3.5,BLANK,-1,6.0,0.0,FIRX,DTX,2)
                 CALL AXISN(1.0,3.5,BLANK,1,6.0,90.0,FIRY,DTY,2)
                 XLIN(1)=FIRX
                 XLIN(2)=FIRX+6.0*DTX
                 XLIN(3)=FIRX
                 XLIN(4)=DTX
                 YLIN(1)=0.0
                 YLIN(2)=0.0
                 YLIN(3)=FIRY
                 YLIN(4)=DTY
                 CALL PLOT(1.0,3.5,-3)
                 CALL LINE(XLIN,YLIN,2,1,0,0)
                 XLIN(1)=0.0
                 XLIN(2)=0.0
                 YLIN(1)=FIRY
                 YLIN(2)=FIRY+6.0*DTY
                 CALL LINE(XLIN,YLIN,2,1,0,0)
                 CALL LINE(X055,Y055,IX55,1,-1,0)
                 X065(IY65+1)=FIRX
                 X065(IY65+2)=DTX
                 Y065(IY65+1)=FIRY
                 Y065(IY65+2)=DTY
                 CALL LINE(X065,Y065,IY65,1,-1,1)
           C     PLOT SOURCE LOCATIONS
                 DO 6000 N=1,NCONT
                 XPAGE=(XS(   N)-FIRX)/DTX
                 YPAGE=(YS(   N)-FIRY)/DTY
                 ISYM=N+1
                 CALL SYMB(XPAGE,YPAGE,.105,ISYM,0.0,-1)
           6000  CONTINUE
```

```
C-ERRS...STNO.C..... F O R T R A N   S O U R C E   S T A T E M E N T S .......

            C      PLOT TITLE
                   CALL PLOT(-1.0,-3.5,-3)
                   CALL CNTR(TITL1,21,2)
                   CALL CNTR(TITL2,21,2)
                   CALL CNTR(TITL3,21,2)
                   CALL SYMB(1.06,2.75,.14,TITL1,0.0,3042)
                   CALL SYMB(1.06,2.47,.14,TITL2,0.0,3042)
                   CALL SYMB(1.06,2.19,.14,TITL3,0.0,3042)
                   CALL SYMB(1.13,1.76,.105,0,0.0,-1)
                   CALL SYMB(1.34,1.69,.14,AL,0.0,1)
                   CALL SYMB(1.48,1.69,.07,EQ,0.0,2)
                   CALL SYMB(1.76,1.69,.14,EQUAL,0.0,1)
                   CALL SYMB(2.04,1.69,.14,FF,0.0,2)

                   CALL SYMB(1.13,1.48,.105,1,0.0,-1)
                   CALL SYMB(1.34,1.41,.14,AL,0.0,1)
                   CALL SYMB(1.46,1.41,.070,EQ,0.0,2)
                   CALL SYMB(1.76,1.41,.14,EQUAL,0.0,1)
                   CALL SYMB(2.04,1.41,.14,SF,0.0,2)

                   DO 7000 N=1,NCONT
                   AN=N
                   ISYM=N+1
                   YPAGE=1.69-.1575*(N-1)
                   CALL SYMB(5.635,YPAGE,.105,SOURC,0.0,6)
                   CALL NUMB(6.37,YPAGE,.105,AN,0.0,-1)
                   CALL SYMB(6.9475,YPAGE+.0525,.105,ISYM,0.0,-1)
            7000   CONTINUE
                   CALL PLOT(15.,0.0,999)
                   CALL EXIT
            1      FORMAT(40A2)
            2      FORMAT(8F10.0)
            3      FORMAT(2A4,6F12.0)
            4      FORMAT(4(F9.2,2X,F9.2,6X))
            6      FORMAT(' COORDINATES OF LEQ = 55 LEVEL')
            7      FORMAT(///' COORDINATES OF LEQ = 65 LEVEL')
            20     FORMAT(1X,2A4,3F10.2)
            21     FORMAT(1H1)
            22     FORMAT(1X,14('****ERROR')/' DATA SET TO LARGE'/I5,' POINTS'//////
            23     FORMAT(1X,14('****ERROR')/' TOO MANY DATA SETS'//////////////////
                   END
VARIABLE ALLOCATIONS
     XS(R )=0008-0000      YS(R )=0012-000A   XO55(R )=0066-0014   YO55(R )=00BA-0068
   TIME(R )=0166-0164    XLIN(R )=017A-0168   YLIN(R )=018E-017C  SOURC(R )=0192-0190
   STEP(R )=151E          XCI(R )=1520         YCI(R )=1522        XSUM(R )=1524
      Y(R )=152A          ALW(R )=152C          XC(R )=152E          YC(R )=1530
   YINC(R )=1536         SUML(R )=1538         AMX(R )=153A          AM(R )=153C
   SUMA(R )=1542        TARGT(R )=1544          XB(R )=1546          YB(R )=1548
     YA(R )=154E          TOL(R )=1550        FIRX(R )=1552         DTX(R )=1554
  BLANK(R )=155A        XPAGE(R )=155C       YPAGE(R )=155E          AL(R )=1560
     FF(R )=1566           SF(R )=1568          AN(R )=156A         MAX(I )=1570-1574
```

```
PAGE   7

 TITL3(I )=15F5-15CE       N(I )=15F6           M(I )=15F7       IFLAG(I )=15F8
 MCONT(I )=15FB       ISTEP(I )=15FC        IX55(I )=15FD        IY55(I )=15FE
  IRAD(I )=1601        ILEG(I )=1602          MX(I )=1603          MM(I )=1604

STATEMENT ALLOCATIONS
     1=165D       2=1660       3=1663       4=1668       6=166F       7=1680      20=1
   100=1733     200=1744    1000=1774    1100=1778    1103=17A4    1104=17A8    1105=1
  1210=170A    1250=1822    1260=185C    1275=1860    1300=188F    1400=19C2    1500=1
  1600=1907    1650=1910    1660=1934    1670=193A    1700=1940    1720=1949    1800=1
  2020=196D    2040=1977    2050=1980    3000=198A    4000=1995    4010=19A1    4100=1
  4140=19DD    4500=19E6    4900=19F2    5000=1A0C    6000=1879    7000=1C59

FEATURES SUPPORTED
 ONE WORD INTEGERS
 STANDARD PRECISION
 IOCS-
   1132 PRINTER
   DISK
   TYPEWRITER
   CARD

CALLED SUBPROGRAMS
 FCOS     FSIN     FALOG    FABS     RECT     SCALE    AXISN    PLOT     LINE     SYMB
 FSUBX    FMPY     FDIV     FLD      FLDX     FSTO     FSTOX    FSBR     FDVR     FAXI
 SRED     SWRT     SCOMP    SFIO     SIOAI    SIOAF    SIOFX    SIOF     SIOI     SUBSC

REAL CONSTANTS
  .000000E 00=160C      .360000E 03=160E      .174532E-01=1610      .100000E 02=1612
  .200000E 01=1618      .500000E 00=161A      .110000E 02=161C      .850000E 01=161E
  .350000E 01=1624      .900000E 02=1626      .105000E 00=1628      .106000E 01=162A
  .247000E 01=1630      .219000E 01=1632      .113000E 01=1634      .176000E 01=1636
  .148000E 01=163C      .700000E-01=163E      .204000E 01=1640      .141000E 01=1642
  .637000E 01=1648      .694750E 01=164A      .525000E-01=164C      .150000E 02=164E

INTEGER CONSTANTS
     2=1650       1=1651       0=1652       3=1653     498=1654       5=1655       8=1
    21=165A    3042=165B     999=165C

CORE REQUIREMENTS FOR -
 COMMON-      0,   VARIABLES AND TEMPORARIES-  5644,   CONSTANTS AND PROGRAM-  16

END OF SUCCESSFUL COMPILATION
```

Computer Program for Model 3: Single Point Source Model



```
PAGE    1

// JOB     0180 0181 0182 0183 0184
  0000          0180          0180          0000
  0001          0181          0181          0001
  0002          0182          0182          0002
  0003          0183          0183          0003
  0004          0184          0184          0004

V2 M11   ACTUAL 32K  CONFIG 32K

// FORTRAN
         *TRANSFER TRACE
         *ASSIGNMENT TRACE
         *NO IOCS
         *IOCS(1132 PRINTER, CARD, DISK, TYPEWRITER)
         *ONE WORD INTEGERS
         *LIST ALL

C-ERRS...STNC.C.....  F O R T R A N   S O U R C E   S T A T E M E N T S  .......

         C**********************************************************************
         C
         C      PROGRAM TO PRODUCE A PLOT OF NOISE LEVEL CONTOURS.  THIS PROGRAM
         C      WAS PREPARED FOR ENGINEERING DYNAMICS INC. USING EQUATIONS
         C      PROVIDED BY THEM.
         C
         C      SIMPLIFICATION 3B  -  THE MEAN POSITIONS OF EACH SOURCE CAN BE
         C                            REPLACED BY THE ACOUSTICAL CENTER OF
         C                            THE SITE.
         C
         C**********************************************************************


                INTEGER TITL1(40),TITL2(40),TITL3(40)
                REAL LS(500,5)
                DIMENSION XO55(42),YO55(42),XO65(42),YO65(42)
                DIMENSION MAX(10),TIME(2),XLIN(10),YLIN(10)
                DIMENSION SOURC(2)
                DATA AL/'L'/,EG/'EQ'/,EQUAL/'='/,FF/'55'/,SF/'65'/,SOURC/'SOUR',
               1     'CE  '/
                DATA BLANK/' '/
                DATA TOL/.01/

         C      READ TITLE
                READ(2,1)TITL1,TITL2,TITL3
                READ(2,2)DEGRE,STEP,XCI,YCI

                N=1
                M=0
                IFLAG=0
                MMAX=0
                XASUM = 0.0
                YASUM = 0.0
                XSUM =0.0
```

```
PAGE    2

C-ERRS...STNO.C..... F O R T R A N   S O U R C E   S T A T E M E N T S .......

                YSUM= 0.0
                WRITE(3,21)

          C     READ DATA
          100   READ(2,3)TIME,X,Y,ALW
                IF(ALW)1000,200,200
          200   M=M+1
                IFLAG=0
                XSUM=XSUM+X
                YSUM=YSUM+Y
                LS(M,N)=ALW
                WRITE(3,20)TIME,X,Y,ALW
                GO TO 100

          C     END OF DATA SET
          1000  IF(IFLAG)1100,1100,1200
          1100  IFLAG=1
                WRITE(3,21)
                YSUM = YSUM/M
                XSUM = XSUM/M
                MAX(N)=M
                IF(M-498)1104,1104,1103
          1103  WRITE(3,22)M
                CALL EXIT
          1104  IF(M-MMAX)1110,1110,1105
          1105  MMAX=M
          1110  M=0
                N=N+1
                XASUM = XASUM + XSUM
                YASUM = YASUM + YSUM
                XSUM = 0.0
                YSUM = 0.0
                GO TO 100

          C     END OF ALL DATA SETS
          1200  NCONT=N-1
                XAC    = XASUM / NCONT
                YAC    = YASUM / NCONT
                IF(NCONT-5)1210,1210,1205
          1205  WRITE(3,23)
                CALL EXIT
          1210  MCONT=MMAX

          C     BEGIN COMPUTATIONS OF CONTOURS
                ISTEP=360./DEGRE
                IX55=0
                IY55=0
                IX65=0
                IY65=0

                DO 5000 IRAC=1,ISTEP
```

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PAGE   3

C-ERRS...STNC.C..... FORTRAN SOURCE STATEMENTS .......

             XC=XCI
             YC=YCI
             ANG=(IRAD-1)*DEGRE
             ANG = ANG *.017453293
             XINC=COS(ANG)*STEP
             YINC=SIN(ANG)*STEP
             ILEG=1

       C     LOOP TO COMPUTE ENERGY AT A GIVEN POINT
       1250  SUML=0.0
             DO 1300 N=1,NCONT
             MX=MAX(N)
             AMX=MX
             DO 1300 MM=1,MCONT
             AM=MM
             TEMP1=AM/AMX
             TEMP2=MM/MX
             M=(TEMP1-TEMP2)*AMX
             IF(M)1260,1260,1275
       1260  M=MX
       1275  SUML=SUML+10.**(LS(M,N)/10.)
        1300 CONTINUE
             SUML = SUML/MCONT/((XC-XAC)**2+(YC-YAC)**2)
             SUML = 10.0 * ALOG(SUML)/ALOG(10.0)

       C     BRANCH TO CORRECT SECTIONS BASED ON OBSERVER POSITION
             GO TO(1400,1700,1800,2000,3000,4100.4100,1575),ILEG

       C     ILEG=1 OBSERVER AT ORGIN
       1400  IF(SUML-55.)1550,1500,1600
       1500  IX55=IX55+1
             IY55=IY55+1
             XO55(IX55)=XC
             YO55(IY55)=YC
             ILEG=2
             GO TO 4900

       1550  ILEG=8
             GO TO 4900

       1575  IF(SUML-55.)1580,1500,2020
       1580  IF(SUML-SUMA)5000,5000,4900

       1600  IF(SUML-65.)1660,1650,1670
       1650  IX65=IX65+1
             IY65=IY65+1
             XO65(IX65)=XC
             YO65(IY65)=YC
             ILEG=3
             GO TO 4900
```

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PAGE    4

C-ERRS...STNO.C.....  F O R T R A N   S O U R C E   S T A T E M E N T S .......

          1660  ILEG=4
                GO TO 4900

          1670  ILEG=5
                GO TO 4900
          C     ILEG=2 OBSERVER AT 55 LEVEL
          1700  IF(SUML-55.)5000,1500,1720
          1720  ILEG=4
                GO TO 4900

          C     ILEG=3 OBSERVER AT 65 LEVEL
          1800  IF(SUML-65.)1840,1650,1820
          1820  ILEG=5
                GO TO 4900

          1840  ILEG=4
                GO TO 4900

          C     ILEG=4 OBSERVER BETWEEN 55 AND 65 LEVEL
          2000  IF(SUML-55.)2020,1500,2040
          2020  TARGT=55.
                ILEG=6
                GO TO 4000

          2040  IF(SUML-65.)4900,1650,2050
          2050  TARGT=65.
                ILEG=7
                GO TO 4000

          C     ILEG=5 OVSERVER AT LEVEL GREATER THAN 65
          3000  IF(SUML-65.)2050,1650,4900

          C     ITERATE AROUND TARGET POINT
          4000  XB=XC
                YB=YC
                SUMB=SUML
          4010  XC=(XB+XA)/2.
                YC=(YB+YA)/2.
                GO TO 1250

          C     ILEG=6 OR 7  ITERATING AROUND TARGET LEVEL
          4100  IF(ABS(SUML-TARGT)-TOL)4500,4500,4120
          4120  IF(SUML-TARGT)4130,4130,4140
          4130  IF(SUMB-TARGT)4000,4137,4137
          4137  XA=XC
                YA=YC
                SUMA=SUML
                GO TO 4010

          4140  IF(SUMB-TARGT)4137,4137,4000
```

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PAGE   5

C-ERRS...STNO.C.....  F O R T R A N   S O U R C E   S T A T E M E N T S  .......

          C      CONTOUR POINT FOUND
          4500   ILEG=ILEG-5
                 GO TO(1500,1650),ILEG

          C      STEP OUT ON RADIUS
          4900   XA=XC
                 YA=YC
                 SUMA=SUML
                 XC=XC+XINC
                 YC=YC+YINC
                 GO TO 1250

          5000   CONTINUE

                 WRITE(3,6)
                 WRITE(3,4)(X055(I),Y055(I),I=1,IX55)
                 WRITE(3,7)
                 WRITE(3,4)(X065(I),Y065(I),I=1,IX65)

          C      PRODUCE PLOT OF RESULTS
                 PAUSE
                 CALL RECT(-0.5,0.0,11.0,8.5,0.0,3)
                 CALL SCALE(X055,6.,IX55,1)
                 CALL SCALE(Y055,6.,IY55,1)
                 FIRX=X055(IX55+1)
                 DTX=X055(IX55+2)
                 FIRY=Y055(IY55+1)
                 DTY=Y055(IY55+2)
                 CALL AXISN(1.0,3.5,BLANK,-1,6.0,0.0,FIRX,DTX,2)
                 CALL AXISN(1.0,3.5,BLANK,1,6.0,90.0,FIRY,DTY,2)
                 XLIN(1)=FIRX
                 XLIN(2)=FIRX+6.0*DTX
                 XLIN(3)=FIRX
                 XLIN(4)=DTX
                 YLIN(1)=0.0
                 YLIN(2)=0.0
                 YLIN(3)=FIRY
                 YLIN(4)=DTY
                 CALL PLOT(1.0,3.5,-3)
                 CALL LINE(XLIN,YLIN,2,1,0,0)
                 XLIN(1)=0.0
                 XLIN(2)=0.0
                 YLIN(1)=FIRY
                 YLIN(2)=FIRY+6.0*DTY
                 CALL LINE(XLIN,YLIN,2,1,0,0)
                 CALL LINE(X055,Y055,IX55,1,-1,0)
                 X065(IY65+1)=FIRX
                 X065(IY65+2)=DTX
                 Y065(IY65+1)=FIRY
                 Y065(IY65+2)=DTY
                 CALL LINE(X065,Y065,IY65,1,-1,1)
```

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PAGE   6

C-ERRS...STMC.C.....  F O R T R A N   S O U R C E   S T A T E M E N T S  .......

         C       PLOT SOURCE LOCATIONS
                 XPAGE = (XAC-FIRX)/DTX
                 YPAGE = (YAC-FIRY)/DTY
                 ISYM = 2
                 CALL SYMB(XPAGE,YPAGE,.105,ISYM,0.0,-1)

         C       PLOT TITLE
                 CALL PLOT(-1.0,-3.5,-3)
                 CALL CNTR(TITL1,21,2)
                 CALL CNTR(TITL2,21,2)
                 CALL CNTR(TITL3,21,2)
                 CALL SYMB(1.06,2.75,.14,TITL1,0.0,3042)
                 CALL SYMB(1.06,2.47,.14,TITL2,0.0,3042)
                 CALL SYMB(1.06,2.19,.14,TITL3,0.0,3042)
                 CALL SYMB(1.13,1.76,.105,0,0.0,-1)
                 CALL SYMB(1.34,1.69,.14,AL,0.0,1)
                 CALL SYMB(1.48,1.69,.07,EQ,0.0,2)
                 CALL SYMB(1.76,1.69,.14,EQUAL,0.0,1)
                 CALL SYMB(2.04,1.69,.14,FF,0.0,2)

                 CALL SYMB(1.13,1.48,.105,1,0.0,-1)
                 CALL SYMB(1.34,1.41,.14,AL,0.0,1)
                 CALL SYMB(1.48,1.41,.070,EQ,0.0,2)
                 CALL SYMB(1.76,1.41,.14,EQUAL,0.0,1)
                 CALL SYMB(2.04,1.41,.14,SF,0.0,2)

                 N=1
                 YPAGE=1.69-.1575*(N-1)
                 CALL SYMB(5.95 ,YPAGE,.105,SOURC,0.0,6)
                 CALL SYMB(6.9475,YPAGE+.0525,.105,ISYM,0.0,-1)
                 CALL PLOT(15.,0.0,999)
                 CALL EXIT
         1       FORMAT(40A2)
         2       FORMAT(8F10.0)
         3       FORMAT(2A4,6F12.0)
         4       FORMAT(4(F9.2,2X,F9.2,6X))
         6       FORMAT(' COORDINATES OF LEQ = 55 LEVEL')
         7       FORMAT(///' COORDINATES OF LEQ = 65 LEVEL')
         20      FORMAT(1X,2A4,3F10.2)
         21      FORMAT(1H1)
         22      FORMAT(1X,14('****ERROR')/' DATA SET TO LARGE'/I5,' POINTS'//////
         23      FORMAT(1X,14('****ERROR')/' TOO MANY DATA SETS'///////////////////
                 END
VARIABLE ALLOCATIONS
  X055(R )=0052-0000  Y055(R )=00A6-0054  X065(R )=00FA-00A8  Y065(R )=014E-00FC
  YLIN(R )=017A-0168 SOURC(R )=017E-017C    LS(R )=1506-0180 DEGRE(R )=1508
   YCI(R )=150E       XASUM(R )=1510     YASUM(R )=1512        XSUM(R )=1514
     Y(R )=151A         ALW(R )=151C       XAC(R )=151E         YAC(R )=1520
   ANG(R )=1526        XINC(R )=1528      YINC(R )=152A        SUML(R )=152C
 TEMP1(R )=1532       TEMP2(R )=1534      SUMA(R )=1536       TARGT(R )=1538
  SUMB(R )=153E          XA(R )=1540        YA(R )=1542         TOL(R )=1544
```

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PAGE   7

  FIRY(R )=154A        DTY(R )=154C      BLANK(R )=154E       XPAGE(R )=1550
    EQ(R )=1556      EQUAL(R )=1558         FF(R )=155A          SF(R )=155C
 TITL2(I )=158F-1598 TITL3(I )=15B7-15C0     N(I )=15E8           M(I )=15E9
 NCONT(I )=15EC      MCONT(I )=15ED      ISTEP(I )=15EE        IX55(I )=15EF
  IY65(I )=15F2       IRAD(I )=15F3       ILEG(I )=15F4          MX(I )=15F5
  ISYM(I )=15F6

STATEMENT ALLOCATIONS
      1=164D       2=1650       3=1653       4=1658       6=165F       7=1670      20=1
    100=172B     200=173C    1000=176C    1100=1771    1103=1797    1104=179E    1105=1
   1210=17E9    1250=1851    1260=186C    1275=1870    1300=1886    1400=18CC    1500=1
   1600=1911    1650=191A    1660=193E    1670=1944    1700=194A    1720=1953    1800=1
   2020=1977    2040=1981    2050=198A    3000=1994    4000=199F    4010=19A3    4100=1
   4140=19E7    4500=19F0    4900=19FB    5000=1A15

FEATURES SUPPORTED
 TRANSFER TRACE
 ASSIGNMENT TRACE
 ONE WORD INTEGERS
 STANDARD PRECISION
 IOCS-
   1132 PRINTER
   DISK
   TYPEWRITER
   CARD

CALLED SUBPROGRAMS
 FCOS     FSIN     FALOG    FABS     RECT     SCALE    AXISN    PLOT     LINE     SYMB
 FDIV     FLD      FLDX     FSTO     FSBR     FDVR     FAXI     SFAR     SFARX    SIAR
 SFIF     SGOTO    CARDZ    PRNTZ    SRED     SWRT     SCOMP    SFIO     SIOAI    SIOAF
 SNR      SDFIO

REAL CONSTANTS
  .000000E 00=15FE     .360000E 03=1600     .174532E-01=1602     .100000E 02=1604
  .200000E 01=160A     .500000E 00=160C     .110000E 02=160E     .850000E 01=1610
  .350000E 01=1616     .900000E 02=1618     .105000E 00=161A     .106000E 01=161C
  .247000E 01=1622     .219000E 01=1624     .113000E 01=1626     .175000E 01=1628
  .148000E 01=162E     .700000E-01=1630     .204000E 01=1632     .141000E 01=1634
  .694750E 01=163A     .525000E-01=163C     .150000E 02=163E

INTEGER CONSTANTS
      2=1640       1=1641       0=1642       3=1643     498=1644       5=1645       8=1
     21=164A    3042=164B     999=164C

CORE REQUIREMENTS FOR -
 COMMON-      0,   VARIABLES AND TEMPORARIES-  5630,   CONSTANTS AND PROGRAM-  15

END OF SUCCESSFUL COMPILATION
```

Computer Program for Model 4: Single-Point-Source and Utilization-Factor Model

```
PAGE   1

// JOB     0180 0181 0182 0183 0184
  0000          0180          0180          0000
  0001          0181          0181          0001
  0002          0182          0182          0002
  0003          0183          0183          0003
  0004          0184          0184          0004

V2 M11    ACTUAL 32K  CONFIG 32K

// FORTRAN
          *NO IOCS
          *IOCS(1132 PRINTER, CARD, DISK, TYPEWRITER)
          *ONE WORD INTEGERS
          *LIST ALL

C-ERRS...STNO.C.....  F O R T R A N   S O U R C E   S T A T E M E N T S  .......

          C**********************************************************************
          C
          C      PROGRAM TO PRODUCE A PLOT OF NOISE LEVEL CONTOURS.  THIS PROGRAM
          C      WAS PREPARED FOR ENGINEERING DYNAMICS INC. USING EQUATIONS
          C      PROVIDED BY THEM.
          C
          C      SIMPLIFICATION 4A  -  REPLACE THE ACTUAL SAMPLED TIME HISTORY
          C                            BY A RECTANGULAR TIME HISTORY FOR EACH
          C                            SOURCE
          C
          C**********************************************************************


                 INTEGER TITL1(40),TITL2(40),TITL3(40)
                 REAL LS(6)
                 DIMENSION U(6)
                 DIMENSION X055(42),Y055(42),X065(42),Y065(42)
                 DIMENSION MAX(10),TIME(2),XLIN(10),YLIN(10)
                 DIMENSION SOURC(2)
                 DATA AL/'L'/,EQ/'EQ'/,EQUAL/'='/,FF/'55'/,SF/'65'/,SOURC/'SOUR',
                1     'CE  '/
                 DATA BLANK/' '/
                 DATA TOL/.01/


          C      READ TITLE
                 READ(2,1)TITL1,TITL2,TITL3
                 READ(2,2)DEGRE,STEP,XCI,YCI

                 N=1
                 M=0
                 IFLAG=0
                 MMAX=0
                 XASUM = 0.0
                 YASUM = 0.0
                 XSUM =0.0
                 YSUM= 0.0
```

```
PAGE   2

C-ERRS...STNO.C.....  F O R T R A N   S O U R C E   S T A T E M E N T S  .......

          C      READ DATA
          99     READ(2,2)U(N),LS(N)
                 WRITE(3,24)U(N),LS(N)
          100    READ(2,3)TIME,X,Y,ALW
                 IF(ALW)1000,200,200
          200    M=M+1
                 IFLAG=0
                 XSUM=XSUM+X
                 YSUM=YSUM+Y
                 WRITE(3,20)TIME,X,Y,ALW
                 GO TO 100

          C      END OF DATA SET
          1000   IF(IFLAG)1100,1100,1200
          1100   IFLAG=1
                 YSUM = YSUM/M
                 XSUM = XSUM/M
                 MAX(N)=M
                 IF(M-498)1104,1104,1103
          1103   WRITE(3,22)M
                 CALL EXIT
          1104   IF(M-MMAX)1110,1110,1105
          1105   MMAX=M
          1110   M=0
                 N=N+1
                 XASUM = XASUM + XSUM
                 YASUM = YASUM + YSUM
                 XSUM = 0.0
                 YSUM = 0.0
                 GO TO 99

          C      END OF ALL DATA SETS
          1200   NCONT=N-1
                 XAC   = XASUM / NCONT
                 YAC   = YASUM / NCONT
                 WRITE(3,25)XAC,YAC
                 IF(NCONT-5)1210,1210,1205
          1205   WRITE(3,23)
                 CALL EXIT
          1210   MCONT=MMAX

          C      BEGIN COMPUTATIONS OF CONTOURS
                 ISTEP=360./DEGRE
                 AL10=10.0/ALOG(10.0)
                 IX55=0
                 IY55=0
                 IX65=0
                 IY65=0

                 DO 5000 IRAD=1,ISTEP
```

```
C-EPRS...STNC.C.....  F O R T R A N   S O U R C E   S T A T E M E N T S .......

              XC=XCI
              YC=YCI
              ANG=(IRAD-1)*DEGRE
              ANG = ANG *.017453293
              XINC=COS(ANG)*STEP
              YINC=SIN(ANG)*STEP
              ILEG=1

        C     LOOP TO COMPUTE ENERGY AT A GIVEN POINT
        1250  SUML=0.0
              DO 1300 N=1,NCONT
              SUML=SUML+U(N)*10.0**(LS(N)/10.0)
        1300  CONTINUE
              SUML=SUML/((XC-XAC)**2+(YC-YAC)**2)
              SUML=ALOG(SUML)*AL10

        C     BRANCH TO CORRECT SECTIONS BASED ON OBSERVER POSITION
              GO TO(1400,1700,1800,2000,3000,4100.4100,1575),ILEG

        C     ILEG=1 OBSERVER AT ORGIN
        1400  IF(SUML-55.)1550,1500,1600
        1500  IX55=IX55+1
              IY55=IY55+1
              XO55(IX55)=XC
              YO55(IY55)=YC
              ILEG=2
              GO TO 4900

        1550  ILEG=8
              GO TO 4900

        1575  IF(SUML-55.)1580,1500,2020
        1580  IF(SUML-SUMA)5000,5000,4900

        1600  IF(SUML-65.)1660,1650,1670
        1650  IX65=IX65+1
              IY65=IY65+1
              XO65(IX65)=XC
              YO65(IY65)=YC
              ILEG=3
              GO TO 4900

        1660  ILEG=4
              GO TO 4900

        1670  ILEG=5
              GO TO 4900
        C     ILEG=2 OBSERVER AT 55 LEVEL
        1700  IF(SUML-55.)5000,1500,1720
        1720  ILEG=4
              GO TO 4900
```

```
PAGE    4

C-ERRS...STNO.C.....  F O R T R A N   S O U R C E   S T A T E M E N T S .......

          C      ILEG=3 OBSERVER AT 65 LEVEL
          1800   IF(SUML-65.)1840,1650,1820
          1820   ILEG=5
                 GO TO 4900

          1840   ILEG=4
                 GO TO 4900

          C      ILEG=4 OBSERVER BETWEEN 55 AND 65 LEVEL
          2000   IF(SUML-55.)2020,1500,2040
          2020   TARGT=55.
                 ILEG=6
                 GO TO 4000

          2040   IF(SUML-65.)4900,1650,2050
          2050   TARGT=65.
                 ILEG=7
                 GO TO 4000

          C      ILEG=5 OVSERVER AT LEVEL GREATER THAN 65
          3000   IF(SUML-65.)2050,1650,4900

          C      ITERATE AROUND TARGET POINT
          4000   XB=XC
                 YB=YC
                 SUMB=SUML
          4010   XC=(XB+XA)/2.
                 YC=(YB+YA)/2.
                 GO TO 1250

          C      ILEG=6 OR 7  ITERATING AROUND TARGET LEVEL
          4100   IF(ABS(SUML-TARGT)-TOL)4500,4500,4120
          4120   IF(SUML-TARGT)4130,4130,4140
          4130   IF(SUMB-TARGT)4000,4137,4137
          4137   XA=XC
                 YA=YC
                 SUMA=SUML
                 GO TO 4010

          4140   IF(SUMB-TARGT)4137,4137,4000

          C      CONTOUR POINT FOUND
          4500   ILEG=ILEG-5
                 GO TO(1500,1650),ILEG

          C      STEP OUT ON RADIUS
          4900   XA=XC
                 YA=YC
                 SUMA=SUML
                 XC=XC+XINC
```

```
PAGE   5

C-ERRS...STNC.C.....  F O R T R A N   S O U R C E   S T A T E M E N T S  .......

            YC=YC+YINC
            GO TO 1250

      5000  CONTINUE

            WRITE(3,6)
            WRITE(3,4)(X055(I),Y055(I),I=1,IX55)
            WRITE(3,7)
            WRITE(3,4)(X065(I),Y065(I),I=1,IX65)

      C     PRODUCE PLOT OF RESULTS
            PAUSE
            CALL RECT(-0.5,0.0,11.0,8.5,0.0,3)
            CALL SCALE(X055,6.,IX55,1)
            CALL SCALE(Y055,6.,IY55,1)
            FIRX=X055(IX55+1)
            DTX=X055(IX55+2)
            FIRY=Y055(IY55+1)
            DTY=Y055(IY55+2)
            CALL AXISN(1.0,3.5,BLANK,-1,6.0,0.0,FIRX,DTX,2)
            CALL AXISN(1.0,3.5,BLANK,1,6.0,90.0,FIRY,DTY,2)
            XLIN(1)=FIRX
            XLIN(2)=FIRX+6.0*DTX
            XLIN(3)=FIRX
            XLIN(4)=DTX
            YLIN(1)=0.0
            YLIN(2)=0.0
            YLIN(3)=FIRY
            YLIN(4)=DTY
            CALL PLOT(1.0,3.5,-3)
            CALL LINE(XLIN,YLIN,2,1,0,0)
            XLIN(1)=0.0
            XLIN(2)=0.0
            YLIN(1)=FIRY
            YLIN(2)=FIRY+6.0*DTY
            CALL LINE(XLIN,YLIN,2,1,0,0)
            CALL LINE(X055,Y055,IX55,1,-1,0)
            X065(IY65+1)=FIRX
            X065(IY65+2)=DTX
            Y065(IY65+1)=FIRY
            Y065(IY65+2)=DTY
            CALL LINE(X065,Y065,IY65,1,-1,1)
      C     PLOT SOURCE LOCATIONS
            XPAGE = (XAC-FIRX)/DTX
            YPAGE = (YAC-FIRY)/DTY
            ISYM = 2
            CALL SYMB(XPAGE,YPAGE,.105,ISYM,0.0,-1)

      C     PLOT TITLE
            CALL PLOT(-1.0,-3.5,-3)
            CALL CNTR(TITL1,21,2)
```

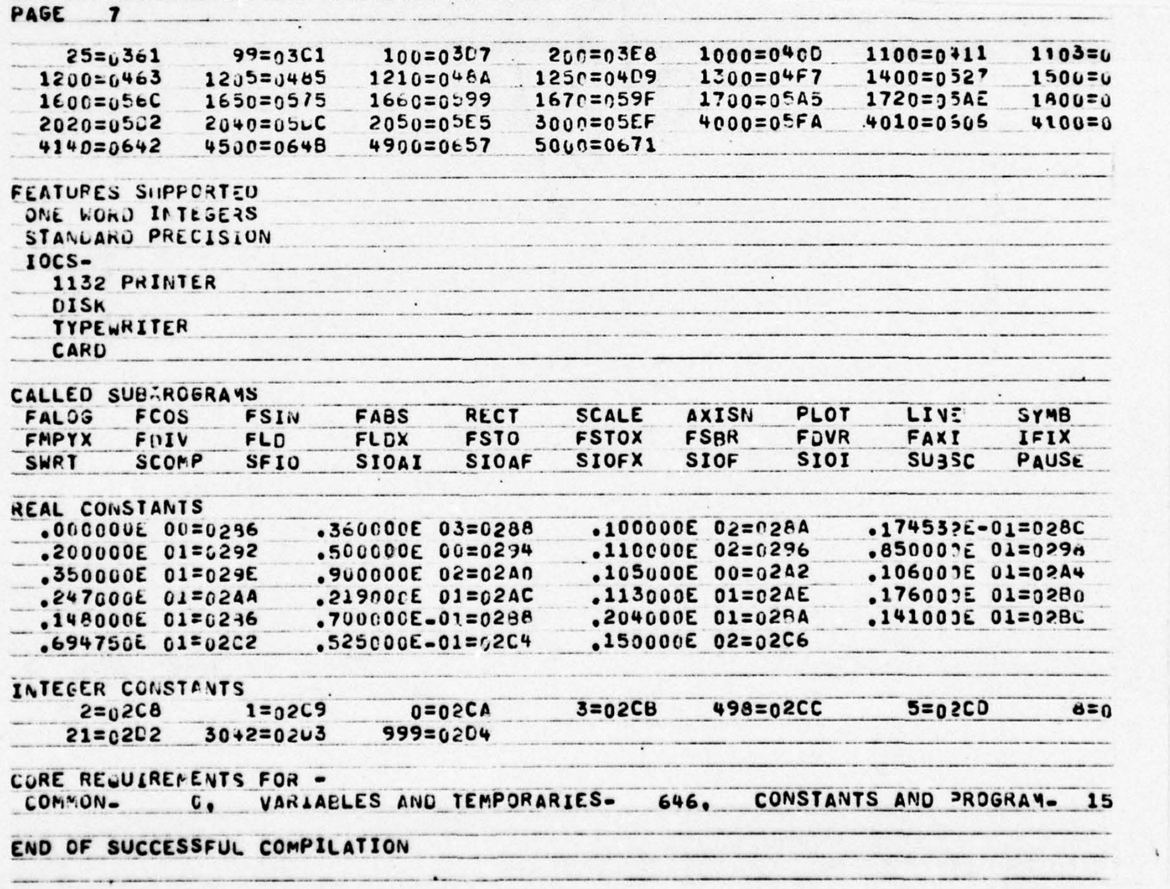
```
PAGE   6

C-ERRS...STNO.C.....  F O R T R A N   S O U R C E   S T A T E M E N T S  .......
                      CALL CNTR(TITL2,21,2)
                      CALL CNTR(TITL3,21,2)
                      CALL SYMB(1.06,2.75,.14,TITL1,0.0,3042)
                      CALL SYMB(1.06,2.47,.14,TITL2,0.0,3042)
                      CALL SYMB(1.06,2.19,.14,TITL3,0.0,3042)
                      CALL SYMB(1.13,1.76,.105,0,0.0,-1)
                      CALL SYMB(1.34,1.69,.14,AL,0.0,1)
                      CALL SYMB(1.48,1.69,.07,EQ,0.0,2)
                      CALL SYMB(1.76,1.69,.14,EQUAL,0.0,1)
                      CALL SYMB(2.04,1.69,.14,FF,0.0,2)

                      CALL SYMB(1.13,1.48,.105,1,0.0,-1)
                      CALL SYMB(1.34,1.41,.14,AL,0.0,1)
                      CALL SYMB(1.48,1.41,.070,EQ,0.0,2)
                      CALL SYMB(1.76,1.41,.14,EQUAL,0.0,1)
                      CALL SYMB(2.04,1.41,.14,SF,0.0,2)

                      N=1
                      YPAGE=1.69-.1575*(N-1)
                      CALL SYMB(5.95 ,YPAGE,.105,SOURC,0.0,6)
                      CALL SYMB(6.9475,YPAGE+.0525,.105,ISYM,0.0,-1)
                      CALL PLOT(15.,0.0,999)
                      CALL EXIT
               1      FORMAT(40A2)
               2      FORMAT(8F10.0)
               3      FORMAT(2A4,6F12.0)
               4      FORMAT(4(F9.2,2X,F9.2,6X))
               6      FORMAT(' COORDINATES OF LEQ = 55 LEVEL')
               7      FORMAT(///' COORDINATES OF LEQ = 65 LEVEL')
               20     FORMAT(1X,2A4,3F10.2)
               22     FORMAT(1X,14('****ERROR')/' DATA SET TO LARGE'/I5,' POINTS'//////
               23     FORMAT(1X,14('****ERROR')/' TOO MANY DATA SETS'///////////////////
               24     FORMAT(1H1,2F10.4)
               25     FORMAT('  SOURCE LOCATED AT',F10.3,',',F10.3)
                      END
VARIABLE ALLOCATIONS
     U(R )=000A-0000  X055(R )=005E-000C  Y055(R )=0082-0060  X065(R )=0106-0034
  XLIN(R )=0172-0160  YLIN(R )=0186-0174 SOURC(R )=018A-0188     LS(R )=0196-018C
   XCI(R )=019C          YCI(R )=019E        XASUM(R )=01A0       YASUM(R )=01A2
     X(R )=01A8            Y(R )=01AA          ALW(R )=01AC         XAC(R )=01AE
    XC(R )=01B4           YC(R )=01B6          ANG(R )=01B8        XINC(R )=01BA
  SUMA(R )=01C0        TARGT(R )=01C2           XB(R )=01C4          YB(R )=01C6
    YA(R )=01CC          TCL(R )=01CE         FIRX(R )=01D0         DTX(R )=01D2
 BLANK(R )=01D8        XPAGE(R )=01DA        YPAGE(R )=01DC          AL(R )=01DE
    FF(R )=01E4           SF(R )=01E6          MAX(I )=01F9-01F0 TITL1(I )=0221-01FA
     N(I )=0272            M(I )=0273        IFLAG(I )=0274        MMAX(I )=0275
 ISTEP(I )=0278         IX55(I )=0279         IY55(I )=027A        IX65(I )=027B
  ILEG(I )=027E            I(I )=027F         ISYM(I )=0280

STATEMENT ALLOCATIONS
     1=0205        2=0208        3=020B        4=02E0        6=02E7        7=02F8       20=0
```



```
PAGE   7

   25=0361      99=03C1      100=03D7     200=03E8    1000=040D    1100=0411    1103=0
 1200=0463    1205=0485     1210=048A    1250=04D9    1300=04F7    1400=0527    1500=0
 1600=056C    1650=0575     1660=0599    1670=059F    1700=05A5    1720=05AE    1800=0
 2020=05D2    2040=05DC     2050=05E5    3000=05EF    4000=05FA    4010=0606    4100=0
 4140=0642    4500=064B     4900=0657    5000=0671

FEATURES SUPPORTED
 ONE WORD INTEGERS
 STANDARD PRECISION
 IOCS-
   1132 PRINTER
   DISK
   TYPEWRITER
   CARD

CALLED SUBPROGRAMS
 FALOG    FCOS     FSIN     FABS     RECT     SCALE    AXISN    PLOT     LINE     SYMB
 FMPYX    FDIV     FLD      FLDX     FSTO     FSTOX    FSBR     FDVR     FAXI     IFIX
 SWRT     SCOMP    SFIO     SIOAI    SIOAF    SIOFX    SIOF     SIOI     SUBSC    PAUSE

REAL CONSTANTS
 .000000E 00=0286     .360000E 03=0288      .100000E 02=028A     .174532E-01=028C
 .200000E 01=0292     .500000E 00=0294      .110000E 02=0296     .850000E 01=0298
 .350000E 01=029E     .900000E 02=02A0      .105000E 00=02A2     .106000E 01=02A4
 .247000E 01=02AA     .219000E 01=02AC      .113000E 01=02AE     .176000E 01=02B0
 .148000E 01=02B6     .700000E-01=02B8      .204000E 01=02BA     .141000E 01=02BC
 .694750E 01=02C2     .525000E-01=02C4      .150000E 02=02C6

INTEGER CONSTANTS
     2=02C8       1=02C9        0=02CA       3=02CB     498=02CC        5=02CD        8=0
    21=02D2    3042=02D3      999=02D4

CORE REQUIREMENTS FOR -
 COMMON-      0,   VARIABLES AND TEMPORARIES-    646,    CONSTANTS AND PROGRAM-  15

END OF SUCCESSFUL COMPILATION
```

Computer Program for Model 5: Base Equation Plus Barrier Attenuation

```
PAGE   1

// JOB     0180 0181 0182 0183 0184
  0000          0180          0180          0000
  0001          0181          0181          0001
  0002          0182          0182          0002
  0003          0183          0183          0003
  0004          0184          0184          0004

V2 M11   ACTUAL 32K  CONFIG 32K

// FORTRAN
          *NO IOCS
          *IOCS(1132 PRINTER, CARD, DISK, TYPEWRITER)
          *ONE WORD INTEGERS
          *LIST ALL

C-ERRS...STNO.C..... F O R T R A N   S O U R C E   S T A T E M E N T S .......

          C***********************************************************************
          C
          C      PROGRAM TO PRODUCE A PLOT OF NOISE LEVEL CONTOURS.  THIS PROGRAM
          C      WAS PREPARED FOR ENGINEERING DYNAMICS INC. USING EQUATIONS
          C      PROVIDED BY THEM.
          C
          C***********************************************************************


                 INTEGER TITL1(40),TITL2(40),TITL3(40)
                 REAL LS(500,5)
                 DIMENSION XS(500,5),YS(500,5)
                 DIMENSION X055(42),Y055(42),X065(42),Y065(42)
                 DIMENSION MAX(10),TIME(2),XLIN(10),YLIN(10)
                 DIMENSION SOURC(2)
                 DATA AL/'L'/,EQ/'EQ'/,EQUAL/'='/,FF/'55'/,SF/'65'/,SOURC/'SOUR',
               1      'CE  '/
                 DATA BLANK/' '/
                 DATA TOL/.01/


          C      READ TITLE
                 READ(2,1)TITL1,TITL2,TITL3
                 READ(2,2)STANG
                 READ(2,2)DEGRE,STEP,XCI,YCI
                 READ(2,2)XB1,YB1,XB2,YB2,H1,H2,H3

                 N=1
                 M=0
                 IFLAG=0
                 MMAX=0
                 WRITE(3,21)

          C      READ DATA
          100    READ(2,3)TIME,X,Y,ALW
                 IF(ALW)1000,200,200
          200    M=M+1
```

```
PAGE   2

C-ERRS...STNO.C..... F O R T R A N   S O U R C E   S T A T E M E N T S .......
                IFLAG=0
                XS(M,N)=X
                YS(M,N)=Y
                LS(M,N)=ALW
                WRITE(3,20)TIME,X,Y,ALW
                GO TO 100

          C     END OF DATA SET
          1000  IF(IFLAG)1100,1100,1200
          1100  IFLAG=1
                WRITE(3,21)
                MAX(N)=M
                IF(M-498)1104,1104,1103
          1103  WRITE(3,22)M
                CALL EXIT
          1104  IF(M-MMAX)1110,1110,1105
          1105  MMAX=M
          1110  M=0
                N=N+1
                GO TO 100

          C     END OF ALL DATA SETS
          1200  NCONT=N-1
                IF(NCONT-5)1210,1210,1205
          1205  WRITE(3,23)
                CALL EXIT
          1210  MCONT=MMAX

          C     BEGIN COMPUTATIONS OF CONTOURS
                ISTEP=360./DEGRE
                IX55=0
                IY55=0
                IX65=0
                IY65=0
                ITCNT = 0

          C     DEFINE SLOPE OF BARRIER
                IF(XB1-XB2)1220,1225,1220
          1220  ISB=1
                SBAR=(YB1-YB2)/(XB1-XB2)
                GOTO 1230
          1225  ISB=0
                SBAR=0
          1230  CONTINUE

                DO 5000 IRAD=1,ISTEP
                XC=XCI
                YC=YCI
                ANG=(IRAD-1)*DEGRE
                ANG=ANG+STANG
                WRITE(1,12)ANG
```

```
PAGE   3

C-ERRS...STNO.C..... FORTRAN  SOURCE  STATEMENTS .......

        12      FORMAT('ANGLE ='F10.2)
                ANG = ANG *.017453293
                XINC=COS(ANG)*STEP
                YINC=SIN(ANG)*STEP
                ILEG=1

        C       LOOP TO COMPUTE ENERGY AT A GIVEN POINT
        1250    SUML=0.0
                DO 1300 N=1,NCONT
                MX=MAX(N)
                AMX=MX
                DO 1300 MM=1,MCONT
                AM=MM
                TEMP1=AM/AMX
                TEMP2=MM/MX
                M=(TEMP1-TEMP2)*AMX
                IF(M)1260,1260,1275
        1260    M=MX
        1275    XSC=XS(M,N)
                YSC=YS(M,N)
                IF(XSC-XC)1278,1279,1278
        1278    ISL=1
                SLIN=(YSC-YC)/(XSC-XC)
                GOTO 1280
        1279    SLIN=0
                ISL=0
        1280    IF(SBAR-SLIN)1282,1281,1282
        1281    FAC=1.0
                GOTO 1299
        1282    IF(ISB)1284,1283,1284
        C       SBAR = INF
        1283    XI=XB1
                YI=SLIN*(XI-XC)+YC
                GO TO 1287

        1284    IF(ISL)1286,1285,1286
        C        SLIN = INF
        1285    XI=XC
                YI=SBAR*(XI-XB1)+YB1
                GOTO 1287

        1286    XI=(SLIN*XC - SBAR*XB1 - YC + YB1)/(SLIN-SBAR)
                YI=SBAR*XI - SBAR*XB1 + YB1
        1287    CALL SEG(XB1,XB2,XI,ID)
                GO TO(1288,1281),ID
        1288    CALL SEG(XC,XSC,XI,ID)
                GOTO (1290,1281),ID

        C       DEFINE PARAMETERS FOR BARRIER CONDITION
        1290    EMT=((YI-YC)**2 + (XI-XC)**2)**.5
                DMT = ((YI-YSC)**2 + (XI-XSC)**2)**.5
```

```
PAGE    4

C-ERRS...STNO.C.....  F O R T R A N   S O U R C E   S T A T E M E N T S  .......

                CMT = ((H1-H3)**2 + (EMT+DMT)**2)**.5
                BMT = ((H2-H3)**2 + EMT**2)**.5
                AMT = ((H2-H1)**2 + DMT**2)**.5
                GAMMA = AMT + BMT - CMT
                IF(GAMMA-.0514)1297,1298,1298
          1297  GAMMA=.0514
          1298  FAC = .0514/GAMMA
          1299  SUML = SUML+FAC*10.0**(LS(M,N)/10.0)/((XC-XSC)**2 + (YC-YSC)**2)
           1300 CONTINUE
                SUML=10.0*ALOG(SUML/MCONT)/ALOG(10.)
                WRITE(3,30)SUML,XC,YC
          30    FORMAT(3F12.4)

          C     BRANCH TO CORRECT SECTIONS BASED ON OBSERVER POSITION
                GO TO(1400,1700,1800,2000,3000,4100,4100,1575),ILEG

          C     ILEG=1 OBSERVER AT ORGIN
          1400  IF(SUML-55.)1550,1500,1600
          1500  IX55=IX55+1
                IY55=IY55+1
                XO55(IX55)=XC
                YO55(IY55)=YC
                ILEG=2
                GO TO 4900

          1550  ILEG=8
                GO TO 4900

          1575  IF(SUML-55.)1580,1500,2020
          1580  IF(SUML-SUMA)5000,5000,4900

          1600  IF(SUML-65.)1660,1650,1670
          1650  IX65=IX65+1
                IY65=IY65+1
                XO65(IX65)=XC
                YO65(IY65)=YC
                ILEG=3
                GO TO 4900

          1660  ILEG=4
                GO TO 4900

          1670  ILEG=5
                GO TO 4900
          C     ILEG=2 OBSERVER AT 55 LEVEL
          1700  IF(SUML-55.)5000,1500,1720
          1720  ILEG=4
                GO TO 4900

          C     ILEG=3 OBSERVER AT 65 LEVEL
          1800  IF(SUML-65.)1640,1650,1820
```

```
PAGE   5

C-ERRS...STNC.C.....  FORTRAN  SOURCE  STATEMENTS .......

          1820  ILEG=5
                GO TO 4900

          1840  ILEG=4
                GO TO 4900

          C     ILEG=4 OBSERVER BETWEEN 55 AND 65 LEVEL
          2000  IF(SUML-55.)2020,1500,2040
          2020  TARGT=55.
                ILEG=6
                GO TO 4000

          2040  IF(SUML-65.)4900,1650,2050
          2050  TARGT=65.
                ILEG=7
                GO TO 4000

          C     ILEG=5 OVSERVER AT LEVEL GREATER THAN 65
          3000  IF(SUML-65.)2050,1650,4900

          C     ITERATE AROUND TARGET POINT
          4000  XB=XC
                YB=YC
                SUMB=SUML
          4010  XC=(XB+XA)/2.
                YC=(YB+YA)/2.
                WRITE(1,10)TARGT
          10    FORMAT('START OF ITERATION',F10.2)
                GO TO 1250

          C     ILEG=6 OR 7  ITERATING AROUND TARGET LEVEL
          4100  ITCNT = ITCNT +1
                IF(ITCNT-15)4105,4105,4500
          4105  IF(ABS(SUML-TARGT)-TOL)4500,4500,4120
          4120  IF(SUML-TARGT)4130,4130,4140
          4130  IF(SUMB-TARGT)4000,4137,4137
          4137  XA=XC
                YA=YC
                SUMA=SUML
                GO TO 4010

          4140  IF(SUMB-TARGT)4137,4137,4000

          C     CONTOUR POINT FOUND
          4500  ILEG=ILEG-5
                ITCNT = 0
                WRITE(1,11)
          11    FORMAT('END OF ITERATION')
                GO TO(1500,1650),ILEG

          C     STEP OUT ON RADIUS
```

```
C-ERRS...STNC.C.....  F O R T R A N   S O U R C E   S T A T E M E N T S  .......

          4900  XA=XC
                YA=YC
                SUMA=SUML
                XC=XC+XINC
                YC=YC+YINC
                GO TO 1250

          5000  CONTINUE

                WRITE(3,6)
                WRITE(3,4)(X055(I),Y055(I),I=1,IX55)
                WRITE(3,7)
                WRITE(3,4)(X065(I),Y065(I),I=1,IX65)

          C     PRODUCE PLOT OF RESULTS
                PAUSE
                CALL RECT(-0.5,0.0,11.0,8.5,0.0,3)
                CALL SCALE(X055,6.,IX55,1)
                CALL SCALE(Y055,6.,IY55,1)
                FIRX=X055(IX55+1)
                DTX=X055(IX55+2)
                FIRY=Y055(IY55+1)
                DTY=Y055(IY55+2)
                CALL AXISN(1.0,3.5,BLANK,-1,6.0,0.0,FIRX,DTX,2)
                XLIN(1)=FIRX
                CALL AXISN(1.0,3.5,BLANK,1,6.0,90.0,FIRY,DTY,2)
                XLIN(2)=FIRX+6.0*DTX
                XLIN(3)=FIRX
                XLIN(4)=DTX
                YLIN(1)=0.0
                YLIN(2)=0.0
                YLIN(3)=FIRY
                YLIN(4)=DTY
                CALL PLOT(1.0,3.5,-3)
                CALL LINE(XLIN,YLIN,2,1,0,0)
                XLIN(1)=0.0
                XLIN(2)=0.0
                YLIN(1)=FIRY
                YLIN(2)=FIRY+6.0*DTY
                CALL LINE(XLIN,YLIN,2,1,0,0)
                CALL LINE(X055,Y055,IX55,1,-1,0)
                X065(IY65+1)=FIRX
                X065(IY65+2)=DTX
                Y065(IY65+1)=FIRY
                Y065(IY65+2)=DTY
                CALL LINE(X065,Y065,IY65,1,-1,1)

          C     PLOT SOURCE LOCATIONS
                DO 6000 N=1,NCONT
                MCONT=MAX(N)
                XS(MCONT+1,N)=FIRX
```

```
C-ERRS...STNO.C..... F O R T R A N   S O U R C E   S T A T E M E N T S .......

              YS(MCONT+1,N)=FIRY
              XS(MCONT+2,N)=DTX
              YS(MCONT+2,N)=DTY
              CALL LINE(XS(1,N),YS(1,N),MCONT,1,0,0)
              XPAGE=(XS(1,N)-FIRX)/DTX
              YPAGE=(YS(1,N)-FIRY)/DTY
              ISYM=N+1
              CALL SYMB(XPAGE,YPAGE,.105,ISYM,0.0,-1)
        6000  CONTINUE

        C     PLOT BARRIER POSITION
              ISGN=(YB1-YB2)/ABS(YB1-YB2)
              IF(ISB)5200,5100,5200
        5100  YB1=YB1+ISGN*H2
              YB2=YB2-ISGN*H2
              GO TO 5300
        5200  ISGNX=(XB1-XB2)/ABS(XB1-XB2)
              YDIF=ABS(YB1-YB2)/(EMT+DMT)*H2
              XDIF=ABS(XB1-XB2)/(EMT+DMT)*H2
              YB1=YB1+ISGN*YDIF
              YB2=YB2-ISGN*YDIF
              XB1=XB1+ISGNX*XDIF
              XB2=XB2-ISGNX*XDIF
        5300  XPAGE=(XB1-FIRX)/DTX
              YPAGE=(YB1-FIRY)/DTY
              CALL PLOT(XPAGE,YPAGE,3)
              XPAGE=(XB2-FIRX)/DTX
              YPAGE=(YB2-FIRY)/DTY
              CALL PLOT(XPAGE,YPAGE,2)

        C     PLOT TITLE
              CALL PLOT(-1.0,-3.5,-3)
              CALL CNTR(TITL1,21,2)
              CALL CNTR(TITL2,21,2)
              CALL CNTR(TITL3,21,2)
              CALL SYMB(1.06,2.75,.14,TITL1,0.0,3042)
              CALL SYMB(1.06,2.47,.14,TITL2,0.0,3042)
              CALL SYMB(1.06,2.19,.14,TITL3,0.0,3042)
              CALL SYMB(1.13,1.76,.105,0,0.0,-1)
              CALL SYMB(1.34,1.69,.14,AL,0.0,1)
              CALL SYMB(1.48,1.69,.07,EQ,0.0,2)
              CALL SYMB(1.76,1.69,.14,EQUAL,0.0,1)
              CALL SYMB(2.04,1.69,.14,FF,0.0,2)

              CALL SYMB(1.13,1.48,.105,1,0.0,-1)
              CALL SYMB(1.34,1.41,.14,AL,0.0,1)
              CALL SYMB(1.48,1.41,.070,EQ,0.0,2)
              CALL SYMB(1.76,1.41,.14,EQUAL,0.0,1)
              CALL SYMB(2.04,1.41,.14,SF,0.0,2)

              DO 7000 N=1,NCONT
```

```
PAGE   8

C-ERRS...STNO.C..... F O R T R A N   S O U R C E   S T A T E M E N T S .......

             AN=N
             ISYM=N+1
             YPAGE=1.69-.1575*(N-1)
             CALL SYMB(5.635,YPAGE,.105,SOURC,0.0,6)
             CALL NUMB(6.37,YPAGE,.105,AN,0.0,-1)
             CALL SYMB(6.9475,YPAGE+.0525,.105,ISYM,0.0,-1)
        7000 CONTINUE
             CALL PLOT(15.,0.0,999)
             CALL EXIT
           1 FORMAT(40A2)
           2 FORMAT(8F10.0)
           3 FORMAT(2A4,6F12.0)
           4 FORMAT(4(F9.2,2X,F9.2,6X))
           6 FORMAT(' COORDINATES OF LEQ = 55 LEVEL')
           7 FORMAT(///' COORDINATES OF LEQ = 65 LEVEL')
          20 FORMAT(1X,2A4,3F10.2)
          21 FORMAT(1H1)
          22 FORMAT(1X,14('****ERROR')/' DATA SET TO LARGE'/I5,' POINTS'//////
          23 FORMAT(1X,14('****ERROR')/' TOO MANY DATA SETS'///////////////////
             END
VARIABLE ALLOCATIONS
    XS(R )=1386-0000     YS(R )=270E-1388  X055(R )=2762-2710  Y055(R )=2786-2764
  TIME(R )=2862-2860   XLIN(R )=2876-2864  YLIN(R )=288A-2878 SOURC(R )=288E-288C
 DEGRE(R )=3C1A          STEP(R )=3C1C        XCI(R )=3C1E         YCI(R )=3C20
   XB2(R )=3C26           YB2(R )=3C28         H1(R )=3C2A          H2(R )=3C2C
     Y(R )=3C32           ALW(R )=3C34       SBAR(R )=3C36          XC(R )=3C38
  XINC(R )=3C3E          YINC(R )=3C40       SUML(R )=3C42         AMX(R )=3C44
 TEMP2(R )=3C4A           XSC(R )=3C4C        YSC(R )=3C4E        SLIN(R )=3C50
    YI(R )=3C56           EMT(R )=3C58        DMT(R )=3C5A         CMT(R )=3C5C
 GAMMA(R )=3C62          SUMA(R )=3C64      TARGT(R )=3C66          XB(R )=3C68
    XA(R )=3C6E            YA(R )=3C70        TOL(R )=3C72        FIRX(R )=3C74
   DTY(R )=3C7A         BLANK(R )=3C7C      XPAGE(R )=3C7E       YPAGE(R )=3C80
    AL(R )=3C86            EQ(R )=3C88      EQUAL(R )=3C8A          FF(R )=3C8C
   MAX(I )=3CA3-3C9A TITL1(I )=3CC6-3CA4 TITL2(I )=3CF3-3CCC TITL3(I )=3D13-3CF4
 IFLAG(I )=3D1E          MMAX(I )=3D1F      NCONT(I )=3D20       MCONT(I )=3D21
  IY55(I )=3D24          IX65(I )=3D25       IY65(I )=3D26       ITCNT(I )=3D27
  ILEG(I )=3D2A            MX(I )=3D28         MM(I )=3D2C         ISL(I )=3D2D
  ISYM(I )=3D30          ISGN(I )=3D31      ISGNX(I )=3D32

STATEMENT ALLOCATIONS
   12=3D8C     30=3D93     10=3D96     11=3DA2      1=3DAC      2=3DAF      3=3
   20=3DE3     21=3DE9     22=3DEC     23=3E0E    100=3E90    200=3EA1   1000=3
 1105=3EF9   1110=3EFD   1200=3F09   1205=3F15   1210=3F1A   1220=3F40   1225=3
 1275=3FD4   1278=3FEC   1279=4000   1280=4009   1281=4010   1282=4016   1285=4
 1287=4068   1288=4074   1290=4080   1297=40F4   1298=40F8   1299=40FE   1300=4
 1575=419A   1580=41A3   1600=41AC   1650=4185   1660=4109   1670=410F   1700=4
 1840=4203   2000=4209   2020=4212   2040=421C   2050=4225   3000=422F   4000=4
 4120=4278   4130=427F   4137=4286   4140=4294   4500=429D   4900=4231   5000=4
 5300=451A   7000=461B

FEATURES SUPPORTED
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PAGE   9

 ONE WORD INTEGERS
 STANDARD PRECISION
 IOCS-
    1132 PRINTER
    DISK
    TYPEWRITER
    CARD

CALLED SUBPROGRAMS
 FCOS      FSIN      SEG       FALOG     FABS      RECT      SCALE     AXISN     PLOT      LINE
 FSUB      FMPY      FDIV      FLD       FLDX      FSTO      FSTOX     FSBR      FDVR      FAXI
 SRED      SWRT      SCOMP     SFIO      SIOAI     SIOAF     SIOFX     SIOF      SIOI      SUBSC

REAL CONSTANTS
  .360000E 03=3D38      .174532E-01=3D3A      .000000E 00=3D3C      .100000E 01=3D3E
  .100000E 02=3D44      .550000E 02=3D46      .650000E 02=3D48      .200000E 01=3D4A
  .600000E 01=3D50      .350000E 01=3D52      .900000E 02=3D54      .105000E 00=3D56
  .140000E 00=3D5C      .247000E 01=3D5E      .219000E 01=3D60      .113000E 01=3D62
  .169000E 01=3D68      .148000E 01=3D6A      .700000E-01=3D6C      .204000E 01=3D6E
  .563500E 01=3D74      .637000E 01=3076      .694750E 01=3D78      .525000E-01=3D7A

INTEGER CONSTANTS
     2=3D7E        1=3D7F        0=3D80        3=3D81      498=3D82        5=3D83        8=3
    15=3D88       21=3D89     3042=3D8A      999=3D8B

CORE REQUIREMENTS FOR -
 COMMON-      0,   VARIABLES AND TEMPORARIES- 15672.   CONSTANTS AND PROGRAM-  22

END OF SUCCESSFUL COMPILATION
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APPENDIX C:

ACCURACY OF A SINGLE-POINT-SOURCE MODEL

Nomenclature

L_{or}	–sound level of noise source at distance D_r
L_{sr}	–sound level of source at 50 ft (15 m)
D_r	–distance to noise source
D_1, D_2	–distances

Estimation of the degree of accuracy sacrificed by adoption of a point-source model as a function of the amount of vehicle motion perpendicular to an observer point may be calculated by assuming an arbitrary reference sound level (L_{or}) at an observer point located an arbitrary reference distance (D_r) from the source which produces a reference sound level (L_{sr}) at 50 ft (15 m). Given these variable definitions, the following relationship is true:

$$L_{or} = 10 \log_{10} \frac{50^2 \times 10^{L_{sr}/10}}{D_r^2} \qquad \text{(Eq C1)}$$

The question may then be asked: at what distance D_1/D_r or D_2/D_r will the sound level at the observer point be less than or greater than L_{or} by X amount?

$$X = L_{or} - 10 \log_{10} \frac{50^2 \times 10^{L_{sr}/10}}{D_1^2} \qquad \text{(Eq C2)}$$

and

$$X = 10 \log_{10} \left[\frac{50^2 \times 10^{L_{sr}/10}}{D_2^2} \right] - L_{or} \qquad \text{(Eq C3)}$$

Substituting the equality set forth for L_{or} in Eqs C2 and C3 gives:

(Eq C4)

$$X = 10 \log_{10} \left[\frac{50^2 \times 10^{L_{sr}/10}}{D_r^2} \right] - 10 \log_{10} \left[\frac{50^2 \times 10^{L_{sr}/10}}{D_1^2} \right]$$

and (Eq C5)

$$X = 10 \log_{10} \left[\frac{50^2 \times 10^{L_{sr}/10}}{D_2^2} \right] - 10 \log_{10} \left[\frac{50^2 \times 10^{L_{sr}/10}}{D_r^2} \right]$$

From Eqs C4 and C5, the following relationships can be derived:

$$D_1 = D_r \sqrt{10^{X/10}} \qquad \text{(Eq C6)}$$

$$D_2 = D_r / \sqrt{10^{X/10}} \qquad \text{(Eq C7)}$$

If values of X are substituted into Eqs C6 and C7, the following relationships of D_1 and D_2 to D_r may be derived:

X	D_1/D_r	D_2/D_r
1.0	1.122	.891
1.5	1.189	.841
2.0	1.259	.794
2.5	1.334	.750
3.0	1.413	.708
3.5	1.496	.668
4.0	1.585	.631
4.5	1.679	.596
5.0	1.778	.562
5.5	1.884	.531

From these relationships, the degree of accuracy sacrificed by the point-source model may be provided as a function of the amount of movement relative to a given distance to observer position (D_r) in feet.*

Accuracy	Movement Acceptable Around Center Point
± 1 dB	.347 D_r
2 dB	.583 D_r
3 dB	.827 D_r
4 dB	1.082 D_r
5 dB	1.352 D_r

---

*1 ft = .3048 m

APPENDIX D:

DEVELOPMENT OF A SIMPLIFIED BARRIER EQUATION AND ASSESSMENT OF ITS APPLICABILITY TO A POINT-SOURCE MODEL

Nomenclature

α	–constant equal to 20
δ	difference in sound path distance with and without barrier
λ	–wavelength
L_{BA}	–barrier attenuation
FR_f	–frequency f
L_B	–A-weighted sound level at observer position with barrier
L_A	–A-weighted sound level at observer position without barrier
A_f	–A-weighting correction for frequency f
L_f	–sound pressure level at frequency f

Barrier Equation Development

A barrier equation was derived from a simplified form of Makawa's equation:

$$L_{BA} = 10 \log_{10}\left(\frac{\alpha 2\delta}{\lambda}\right) \qquad \text{[Eq D1]}$$

α = a constant which equals 20

λ = (1130 ft/sec [344 m/sec])/FR

δ = the difference in sound path distance travel with and without the barrier (Figure A5), $\delta = a+b-c$.

FR = frequency in Hz

Given the above definitions, the equation can be rewritten as:

$$L_{BA} = 10 \log_{10} \frac{FR_f}{28.25} + 10 \log_{10} \delta \qquad \text{[Eq D2]}$$

If L_A and L_B are the A-weighted sound levels at the observer position without and with a barrier, respectively, and A_f equals the A-weighting correction for each frequency f, then the following relationship is true:

$$L_A = 10 \log_{10} \sum_{f=1}^{F} 10^{(L_f - A_f - L_{BA})/10} \qquad \text{[Eq D3]}$$

Substituting the equality presented for L_{BA} in Eq D2 into Eq D3 gives:

$$L_A = 10 \log_{10}\left[\sum_{f=1}^{F} \frac{10^{(L_f - A_f)/10}}{FR_f} \times \frac{28.25}{\delta}\right] \qquad \text{[Eq D4]}$$

Eq D4 can be rewritten as:

$$L_A = 10 \log_{10}\left[\frac{28.25}{\delta} \sum_{f=1}^{F} \frac{10^{(L_f - A_f)/10}}{FR_f}\right] \qquad \text{[Eq D5]}$$

At this point the assumption is made that all construction vehicles have a frequency spectrum which is similar enough to allow acceptance of a single representative spectrum (which can be weighted to yield the total sound level measured for each vehicle). Given this assumption, a new variable (FS_f) is defined as that value which when added to the total A-weighted sound level (L_A), will yield the quantity of the sound level (L_f) of frequency f minus the A-weighting component (A_f):

$$L_A + FS_f = L_f - A_f \qquad \text{[Eq D6]}$$

Substituting this relationship into Eq D5:

$$L_B = 10 \log_{10}\left[\frac{28.25}{\delta} \sum_{f=1}^{F} \frac{10^{(L_A + FS_f)/10}}{FR_f}\right] \qquad \text{[Eq D7]}$$

from which Eq D8 can be derived:

[Eq D8]

$$L_B = 10 \log_{10}\left[\frac{28.25}{\delta} \times 10^{L_A/10} \sum_{f=1}^{F} \frac{10^{FS_f/10}}{FR_f}\right]$$

Since it has been assumed that the same relative spectrum applies to all construction vehicles, then the quantity

$$\sum_{f=1}^{F} \frac{10^{FS_f/10}}{FR_f}$$

is a constant, which is calculated to equal 0.001 when the spectrum depicted by Figure D1 is selected as representative. Substituting this value into Eq D8 we have:

$$L_B = 10 \log_{10} \frac{0.3 \times 10^{L_A/10}}{\delta} \qquad \text{[Eq D9]}$$

Eq D9 can be rewritten as:

$$L_B = L_A + 10 \log_{10} \frac{0.0514}{\delta} \qquad \text{[Eq D10]}$$

Given that the difference in the A-weighted sound levels at the observer with and without the barrier equals the excess attenuation due to the barrier L_{BA}, then:

$$L_{BA} = L_A - L_B \qquad \text{[Eq D11]}$$

Replacing the term L_B in Eq D11 with the equality presented in Eq D10 gives:

$$L_{BA} = 10 \log_{10} (\delta/0.0514) \qquad \text{[Eq D12]}$$

Application of Barrier Equation to a Point-Source Model

A procedure was developed for applying this barrier Eq D12 to a point-source construction-site model. A series of simple hypothetical situations was postulated where a vehicle was moved in discrete, equally spaced steps behind a barrier. The variables investigated were the distance from the observer to the barrier, the closest vehicle approach to barrier, the farthest distance from the barrier to the vehicle, the median distance of the vehicle to the barrier, and the total distance of vehicle movement.

The results of the analyses of these hypothetical situations indicate that a fixed-point-source model located at the median position of vehicle travel behind a barrier will estimate the barrier-attenuated sound level to within approximately 1 dB given that the quotient of the total distance of vehicle movement divided by the distance from the observer to the barrier is 2 greater than the quotient of the nearest approach of the vehicle to the barrier divided by the distance from the observer to the barrier.

Derivation of a Simple Table of Barrier Attenuation Levels

In order to derive a simple table of barrier attenuation levels, a program was developed to calculate the excess attenuation resulting from several combinations of barrier and vehicle heights, for various distances from barriers to vehicle and to observer, for various fractions of vehicle path shielding, and for two conditions of vehicle noise levels. From these scenarios (2400 in all), three tendencies were observed:

Difference Between Barrier and Vehicle Heights

The first trend which became apparent was the excess attenuation only ranged a maximum of 1.1 dB for any given difference between barrier and vehicle heights, regardless of the actual barrier and vehicle heights. The relationship held for all barrier-to-vehicle and barrier-to-observer distances modeled.

Distance Between Barrier and Observer

Another relationship investigated was excess attenuation as a function of the distance between barrier and observer for a constant barrier-to-vehicle distance. For any given barrier to vehicle distance, excess attenuation was found to be relatively constant (within 1.2 dB) for barrier to observer distances of 2500 ft (762 m) and beyond. Excess attentuation increases as the distance from barrier to observer decreases from 2500 ft (762 m). No simplifying relationship was found for these shorter distances.

Percentage of Vehicle Path Shielded by Barrier

The third relationship investigated is excess attenuation as a function of the percentage of the vehicle path shielded by the barrier. It was determined that for every 25 percent decrease in the percentage of the vehicle path shielded by the barrier, the excess attenuation values provided in Table D1 should be halved. This procedure is accurate within 1 dB for all conditions investigated (vehicle distance from 50 to 400 ft (15 to 122 m) behind the barrier and barrier-vehicle height differences ranging from 0 to 13 ft (0 to 4 m)), except when the vehicle was 50 ft (15 m) behind the barrier and the barrier-vehicle height was greater than 10 ft (3 m). In these cases, when this procedure is used, the excess attenuation is overestimated by as much as 1.9 dB.

Table D1

Number of Decibels Attenuation Provided by Barrier Shielding as a Function of (1) Distance between Vehicle and Barrier and (2) Difference between Barrier and Vehicle Heights*

Barrier Ht Minus Vehicle Ht (ft)$^+$	Median Distance between Vehicle and Barrier (ft)$^+$				
	50	100	150	200	400
0-2	0.0dB	0.0dB	0.0dB	0.0dB	0.0dB
3	0.0	0.0	0.0	0.0	0.0
4	3.0	0.0	0.0	0.0	0.0
5	5.0	2.0	0.0	0.0	0.0
6	6.5	4.0	2.0	1.0	0.0
7	8.0	5.0	3.5	2.0	0.0
8	9.0	6.0	4.5	3.5	1.0
9	10.0	7.0	5.5	4.5	1.5
10	11.0	8.0	6.5	5.0	2.0
11	12.0	9.0	7.0	6.0	3.0
12	12.5	9.5	8.0	7.0	4.0
13	13.0	10.0	9.5	7.5	4.5

***This table is most accurate when applied to points 2,500 ft (762 m) or more behind the barrier. For points closer to the barrier than 2500 ft (762 m), more attenuation than indicated by the table will be obtained.**

$^+$1 ft = .3048 m

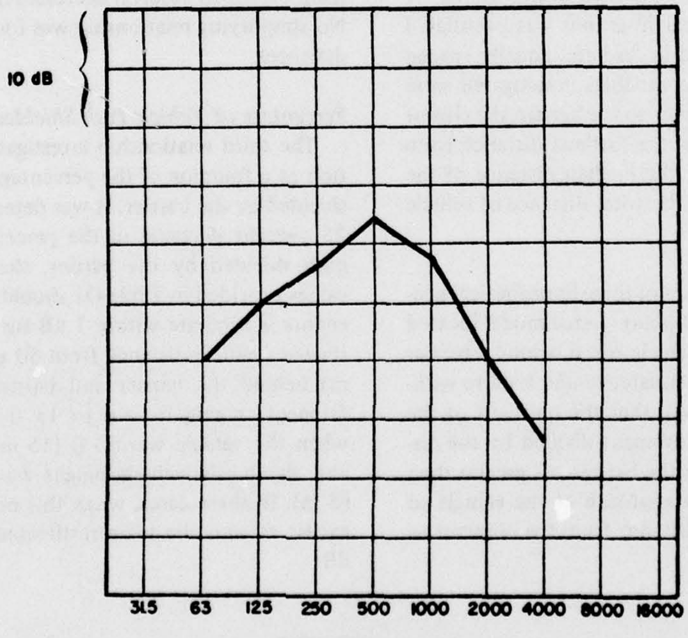

Figure D1. Relative spectrum for typical engine powered construction equipment.

APPENDIX E:

EQUIPMENT NOISE LEVELS

Construction Equipment at Fort Hood and Fort Carson Construction Sites

Noise measurements of construction equipment were made at Fort Hood and Fort Carson construction sites. Table E1 summarizes data relating to these pieces of equipment, such as equipment types, manufacturers, model numbers, modes of operation, noise levels, and usage factors.

Donaldson Tests

Donaldson Company, Inc., of Minneapolis, MN, has conducted numerous noise level tests on construction equipment. More than 90 noise-level measurements of construction equipment with varying machine sizes and noise control features were made. A summary of the test results is presented in Table E2. Linear regressions of the maximum sound level versus engine horsepower ($L_p = 80.8 + .01$ hp) and sound level versus the logarithm of the engine horsepowers ($L_p = 64.1 + 9.05 \log_{10}$ hp) are presented in Figures E1 and E2 respectively.

Table E1
Equipment Noise Data

Equipment Type	Manufacturer	Model No.	Operation	L_p (dBA) at 15 m (50 ft)	Usage Factor
Backhoe	Case	530	Used as trencher–filling in telephone trench	80	
		580B	Filling in plumbing trench using front loader	66	
			Idling	59-70	
			Setting up in sandy soil	68	
			Ditching and emptying shovel	69-71	
			Ditching with faster idle	72-74	
	John Deere	410	Digging trench for sewer line	82	
Bulldozer	Case	450	Moving light sand	80	
			Idling	68	
			Backing	74	
	Caterpillar	D3		82.5	
		D4D		81.5	
		D5		83.5	
		D6	Moving forward and backward	88	
			Passby with moderate load	84	
		D6C	Backing	84	
			Forward scraping	85	
		D76		85.5	
		D8H	With sheepsfoot attachment	99.1	.06
			Forward	88.1	.31
			Backward	89	.23
		D8K	Digging furrows	88	
			Backing up	89	
			Passby	79	
		D9H		88.8	
	International Harvester	TD-15C		87	
		TD-20E		87	
		TD-25C		89	
	John Deere	350-B	Forward	81	.10
			Backward	79	
		450-B		82.5	

Table E1 (Cont'd)
Equipment Noise Data

Equipment Type	Manufacturer	Model No.	Operation	L_p (dBA) at 15 m (50 ft)	Usage Factor
Compactor	Caterpillar	DW20	Road preparation	81-82	
		815		91	.10
Compressor	Ingersoll-Rand	DRAF 160 cfm*	Testing plumbing for leaks	82	
	Unidentified		Idling	69-70	
			Rear	75-86	
			Right side	67-68	
Concrete Batch Plant			Loading truck	95.5	
Concrete Mixer (small)			Mixing mortar for brick facade	67-68	
Concrete truck				69-79	
Crane	Skyhook	5-section telescope	Raising framed trusses to second story	75-78	
Forklift	John Deere	480	Passby–no load	81	
Front-End Loader	Caterpillar	910		80.5	
		920		85.5	
		930	Removing piles of hard dirt	87	
			Forward	79-88	
			Leaving site	83	
			Scooping dirt from pile–near idle	84	
			Backing	79-83	
			Scooping dirt from pile, then leaving	81	
			Dumping dirt into dump truck	81	
		930C	Picking up dirt	73	
				82	
		931		81.8	
		941B		82.3	
		950		81.5-82.5	.1
			Handling 4-ft. tile sections	78	
			Backing–no load	80	
			Picking up tile	82	
			Backing	74	
		951C		82.3	
		955L		85	
		966C		86	
		977L		83.5-85.9	.1
		980B		89	
		988		90.5	
		992B		89.5	
	Clarke	M610	Picking up sand	73-75	
			Forward	73	
			Passby	72	
	John Deere	644B	Removing piles of hard dirt–lifting	89	
			- lifting	85	
			- backwards while scraping	82-89	
			- leaving site	73	
Excavator	Caterpillar	235		84.8	.10
Grader	Allis Chalmers	M65	Forward–road preparation	71-72	
			Backward–road preparation	70-76	
	Caterpillar	12F	Grading–road preparation	85	
			Road grading–moderate load	80-82	
			Backing	79-81	.8

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*1 cfm = 35.31 m^3/min

Table E1 (Cont'd)
Equipment Noise Data

Equipment Type	Manufacturer	Model No.	Operation	L_p (dBA) at 15 m (50 ft)	Usage Factor
			Forward	88.4	.04
			Backwards	95.5	.03
		12G	Forward–leveling sandy soil	75	
			Backwards	86	
			Idling	67-74	
			Road grading–finishing	82	
		14E	Leveling sandy soil	73	
				80	
				65	
			Grading roadway	80	
			Slow	79	
			Idling	78	
		120		80	.33
Hy Hoes	Caterpillar	235	Trenching in hard clay	80	
			Steady	76	
			Digging, clanking	81	
			Idling	65	
	John Deere	690A	Digging plumbing trench–scooping	73	
			Impulsive	87	
			Moving	79	
			Scraping	85	
Hydraulic Hammer	BMC		Tamping fill over sewer line–peak	99-105	
Self Propelled Roller	Ingram Flat		Passby upgrade	86	
			Passby downgrade	72	
			Finishing roadbed–slow	77	
			Finishing roadbed	84	
	Ingram Pneumatic		Passby	80	
			Downhill 5° grade	75	
			Uphill	71	
			Uphill–revving engine	81	
			Downhill	78	
			Uphill full speed	80	
Scraper	Allis Chalmers	260B	Fully loaded traveling down 10° slope	83	
			Unloaded traveling up 10° slope	89	
			Backing	78	
			Idle	72	
			Starting up	87	
			Dumping dirt for roadbed	87	
	Caterpillar	633C	Unloaded	89.2	.09
			Loaded	86.5	.13
			Digging	90.7	.24
	John Deere	760A		82	
		860A	Unloaded	87.3	.12
			Loaded	82.8	.21
			Digging	88.6	.44
			Dumping	88.6	.37
Hand Tamper	Wacker	51005	Side	87	
			Front	88	
			Shielded	85	
Trenchers	Ditchwitch	R65	Trenching for telephone cable–hard clay subsoil	81-83	
			Continuous	81	1.0
				85	1
			Rock	83	

Table E2
Summary of Donaldson Company, Inc., Test Results

EQUIPMENT				ENGINE				WORK CYCLE		Sound Level @ 15 m (50 ft)	Passby Loaded	Muffler Orientation	Usage Factor %
Manufacturer	Type	Model	Year	Manufacturer	Model	HP	RPM	Hrs/Day	Hrs/Week				
Caterpillar	FEL	992B	75	Caterpillar	12-cyl. turbo D-348	550	2000	10	50	89	89	H	50
Caterpillar	Crawler-Tractor	D9H	72	Caterpillar	D353E	385	1330	10	50	86	86	V	60
Caterpillar	Road Grader	12F	70	Caterpillar	2904 Series F D333	125	2000	10	50	85	85	V	65
Terex	Scraper	524	67	Detroit Diesel	12V71	432	2100	10	50	93	93	H	50
Terex	Scraper	524	–	DD	12V71 MA	432	2100	10	50	93	93	H	65
Ingersoll-Rand	Compressor	160 Gyro	73	Ford	2711E	74	2500	10	50	78	–	V	98
Unit Rig	Truck	Mark 30	74	Detroit Diesel	DD12V149T1	1200	1900	8	40	88	–	X	50
Euclid	Truck	R-170	74	Detroit Diesel	DD16V149T1	1492	1900	8	40	91	–	X	50
Unit Rig	Truck	Mark 36	74	Detroit Diesel	DD16V149T1	1492	1900	8	40	93	–	X	50
Caterpillar	Tractor	D9G	67	Caterpillar	D353	385	1330	8	40	95	–	X	60
Drott	Excavator	40	74	DD	4-cyl. DD 4-53	123	2500	8	40	83	–	V	70
Caterpillar	Grader	14G	74	–	3305	180	2000?	8	40	80	80	V	35
Caterpillar	FEL	988	67	Caterpillar	6-cyl. turbo D343	325	2060	8	40	95	–	X	50
Caterpillar	Scraper	651	64-69	Caterpillar	D346	500	1900	8	40	91	–	X	60
Kenworth	Mixer	C525	72	Cummins	V555	–	–	8	40	82	82	V	50
Diamond Rio	Truck	–	–	–	–	–	–	–	–	82	82	H	50
Caterpillar	Scraper	651B	74	Caterpillar	V8 turbo D546	500	1900	8	40	87	–	V	60
Caterpillar	Grader	14E	70	CAT 72C-933	D333	125	2000	8	40	85	–	V	35
Caterpillar	FEL	C920	73-75	Caterpillar	3304	80	2200	8	40	79	–	V	40
Peterbilt	Truck	–	–	Cummins	555	–	–	–	–	84	82	V	–
White	Concrete Mixer	4564WD Western Star	–	Cummins	V8210	188	3000	8	40	83	83	V	50
P&H	Shovel	1400	56	Caterpillar	D397	427	1000	8	40	95.5	–	X	–
Caterpillar	FEL	980B	71	Caterpillar	D333-TA	–	–	8-10	–	86	–	V	–
Kenworth	Concrete Mixer	C923	–	Cummins	C190	–	–	8	40	85	85	V	50
Peterbilt	Concrete Mixer	–	–	Cummins	V555	202	3000	8	40	84	84	V	50
I-H	Truck	65,200 lb. Dump Body F85 OM	73	Caterpillar	1160	206	2800	8	40	82	81	V	50
I-H	Truck Tractor	559646	–	–	8 cyl. V7087-7093	301	2100	8	40	84	84	V	50
I-H	Mixer	4200	72	Cummins	V903	299	2600	8	40	78	78	V	50
I-H	Mixer	F4270	74	Detroit Diesel	81-71?	300	2100	8	40	83	83	V	50
John Deere	Grader	JD570	70	John Deere	M63VA	83	2300	8	40	79	–	V	40
Caterpillar	Scraper	623B	74	Caterpillar	6-cyl. turbo 3H06	330	1900	8	40	81	–	H	–

Table E2 (Cont'd)
Summary of Donaldson Company, Inc., Test Results

EQUIPMENT				ENGINE				WORK CYCLE		Sound Level @ 15 m (50 ft)	Passby Loaded	Muffler Orien- tation	Usage Factor %
Manufacturer	Type	Model	Year	Manufacturer	Model	HP	RPM	Hrs/Day	Hrs/Week				
WABCO	Truck	120C	75	GM-DD	12V149T	1000	1900	20	140	91	91	X	50
WABCO	Truck	120B	71	GM-DD	12V149T	1000	1900	20	140	93.5	93.5	X	50
WABCO	Truck	120B	71	Caterpillar	D348	960	2000	20	140	86.5	86.5	X	50
Unit Rig	Truck	M100	68	Caterpillar	D348	950	2100	20	140	86	86	X	50
K.W. Dart	Truck	65-ton D4655	65	Cummins	VTA1710C	650	–	20	140	79	79	X	50
Caterpillar	Grader (#77)	D16G	70	Caterpillar	D343	225	1900	16	80	77.5	77.5	V	50
Caterpillar	Grader	16G	68	Caterpillar	D343	225	1900	16	80	88	88	X	50
Caterpillar	Grader	D16G	75	Caterpillar	3406	250	2000	16	80	86	86	V	40
BLH Austin-W. Stern	Crane	410 Senior	–	G11-DD	4–53N	–	–	16	80	87	77	H	50
Grove	Crane	RT75S	75	Caterpillar	320B	185	2600	16	80	85	85	V	50
Caterpillar	Tractor	D8	57	Caterpillar	–	–	–	8	40	82	–	X	90
Caterpillar	Crawler-Tractor	D9G	74	Caterpillar	D353	385	1330	16	80	81	81	V	30
Caterpillar	Crawler-Tractor	D8H	69	Caterpillar	D342	270	1280	16	80	87	87	X	20
Caterpillar	Dozer	955K	70	Caterpillar	330	130	2185	8	40	86	–	V	–
Allis Blake	Crawler-Tractor	HD41	72	Cummins	VT1710-C	524	2100	16	80	96	96	X	30
Joy	Compressor	RPQ-1200D 5M61	–	Caterpillar	D343-TA	380	2000	8	40	90	–	H	50-100
Gardner-Denver	Compressor	ROTA SCRON 900	–	Caterpillar	D343A	282	1800	8	40	102	–	X	60
Gardner-Denver	Compressor	SP600F/1	65	Detroit Diesel	6-71	202	2100	8	40-80	82	–	H	60
Caterpillar	Generator	D336	65	Caterpillar	D336	235	2200	8	40	87.5	–	X	100
Caterpillar	Gen Set	SRCR	74	Caterpillar	3304	74	1800	8	40	81.5	–	V	100
Case	FEL	580B	72	Case	188	188	2100	8	40	78	–	V	–
Caterpillar	FEL	920	71	Caterpillar	330	130	2185	3	15	80	–	V	–
Trojan	Wheel FEL	304A	63-65	GM Detroit Diesel	GV53N	185	2500	8	40	84	–	H	20
Trojan Eaton	Wheel FEL	6000	71	Cummins	NT855C335	335	2100	8-16	40-80	86	84	H	60
Caterpillar	Wheel FEL	988	71	Caterpillar	D343	325	2060	8	40	86	–	V	30
R. G. Letoveneau	Wheel FEL	L-700	74	Detroit Diesel	16V71T	700	2100	16	80	85	85	H	50
Trojan Eaton	WFEL	8000	–	Detroit Diesel	12V71N	456	2100	8-16	40-80	91	–	H	70-80
Caterpillar	WFEL	950	65-72	Caterpillar	D330	130	2150	8	40	86	–	V	–
Caterpillar	WFEL	980	67	Caterpillar	D336	235	2200	8	40	88	84	X	60-80
Michigan	WFEL	175-111A	67	GM Detroit Diesel	8V71N	290	2100	8	40	85	–	H	20
Trojan Eaton	WFEL	404	63-68	GM Detroit Diesel	8V71N	318	2100	8	40	88	–	H	20

Table E2 (Cont'd)
Summary of Donaldson Company, Inc., Test Results

EQUIPMENT				ENGINE				WORK CYCLE		Sound Level @ 15 m (50 ft)	Passby Loaded	Muffler Orien-tation	Usage Factor %
Manufacturer	Type	Model	Year	Manufacturer	Model	HP	RPM	Hrs/Day	Hrs/Week				
Hyster	Roller	C530A	–	GM 4-cylinder	GM230-G	–	2800	8	40	82	–	V	–
Ingersoll-Rand	Steel Roller	SP54	74	Detroit Diesel	4-5 3N	140	2500	16	80	83	83	H	100
Caterpillar	Gen Set	–	–	Caterpillar	8-cyl. W22 3208	210	2800	16	80	81	–	V	100
Caterpillar	Tractor	D8H	63	Caterpillar	46A 2065 R9D347	235	1200	16	80	90	90	X	50
Caterpillar	FEL	966C	73	Caterpillar	2P6300 3306	170	2200	10	50	89	89	V	60
Ingersoll-Rand	Compressor	Super Spiro Flo XL750	72	Diesel Alison Div.	6V71	228	2100	10	50	83	83	H	70
International-Harvester	Truck	Pay Holler	70	General Motors	12V71	456	2100	10	50	96	92	X	50
Caterpillar	Scraper	J619	63	Caterpillar	4-cyl. turbo D340	250	1900	8	40	89	–	X	55
WABCO	Scraper	D	67	GM DD	4-71	148	2100	8	40	87	–	H	50
General Tractors	Water Pump	8V71	70	General Motors	8V-71	318	2100	10	50	80	–	V	100
Caterpillar	Backhoe	245	75	Caterpillar	Straight 6	–	–	8	40	?	–	H	75
Caterpillar	Excavator Backhoe	235	74	Caterpillar	6-cyl. turbo 3306	–	–	–	–	77	77	V	70
Caterpillar	Backhoe	225	74	Caterpillar	3208	–	–	8	40	78	78	H	60
Michigan–Clark Equip. Co.	FEL	475B	72	Cummins	VTA1710C700	–	–	8	40	85	–	H	50
Dynapac	Steel Roller	CA25D	–	Caterpillar	3145	–	–	16	80	82	82	X	100
Caterpillar	Tractor Crawler	D8H	73	–	–	–	–	–	–	86	–	X	–
Terex	30-ton truck	3305	74	DD	8V-71T	–	–	8	40	92	–	X	50
A H & D	Crawler crane	7250	73	DO AD	6-87N	–	–	8	40	85.5	–	–	–
Caterpillar	Compactor	824B	69	Caterpillar	–	–	–	8	40	80	–	V	–
WABCO	Truck	120B	–	Caterpillar	D348	950	2100	20	140	–	–	X	50
Unit Rig	Truck	M100	–	Caterpillar	D348	950	2100	20	140	90	–	X	50
WABCO	Truck	170C	–	Detroit Diesel	DD16V149T1	1492?	1900	20	140	–	–	X	–
WABCO	Truck	120B	–	DD	DD12V149T	1000	1900	20	140	–	–	H	–
Dart	FEL	600	–	DD	16V-71	–	–	15	105	85	–	H	40
Ingersoll-Rand	Air Compressor	DL1200	70	DD	12V-71	–	1800	8-24	–	99	–	H	–
Ingersoll-Rand	Air Compressor	DXL1200	70	DD	12V-71	–	1800	8-24	–	98	–	H	–
Hough	FEL	400	72	Cummins	V1710C	635	2100	8	40	92-99	–	X	–
Hughes Tool	Drill Rig	LLHD100	75	DD	6-71	238	2100	8	40	90	–	V	–
Rex	Slip Form Paver	–	74	Caterpillar	3304T	125	2100	8	40	80	–	X	100

AD-A050 813 CONSTRUCTION ENGINEERING RESEARCH LAB (ARMY) CHAMPAI--ETC F/G 13/3
CONSTRUCTION-SITE NOISE CONTROL COST-BENEFIT ESTIMATION TECHNIC--ETC(U)
JAN 78 F M KESSLER, P D SCHOMER, R C CHANAUD

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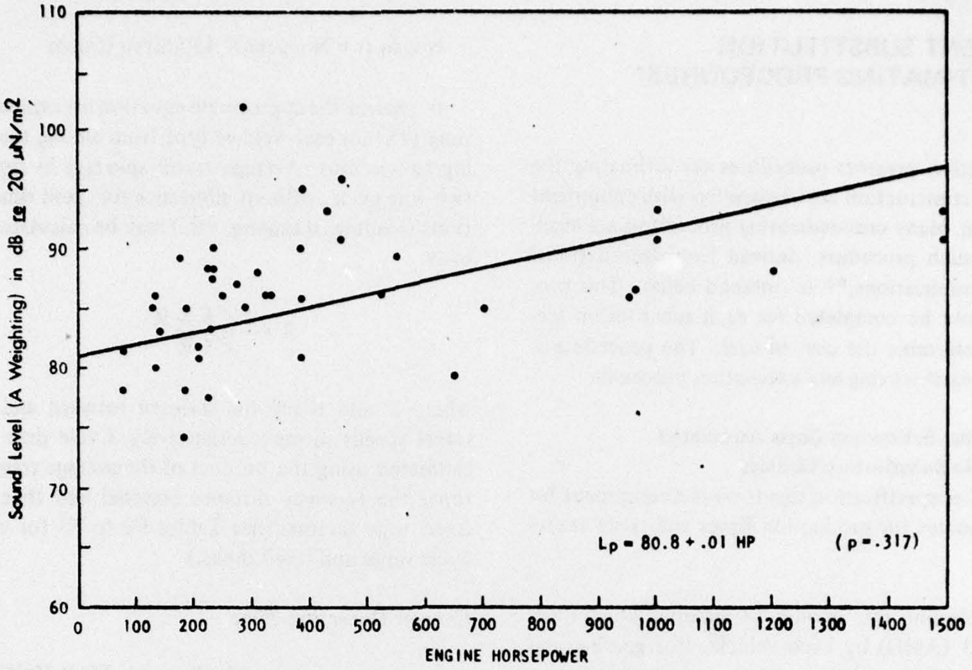

Figure E1. Equipment sound level (at 50 ft [15 m]) as a function of engine horsepower (Donaldson tests).

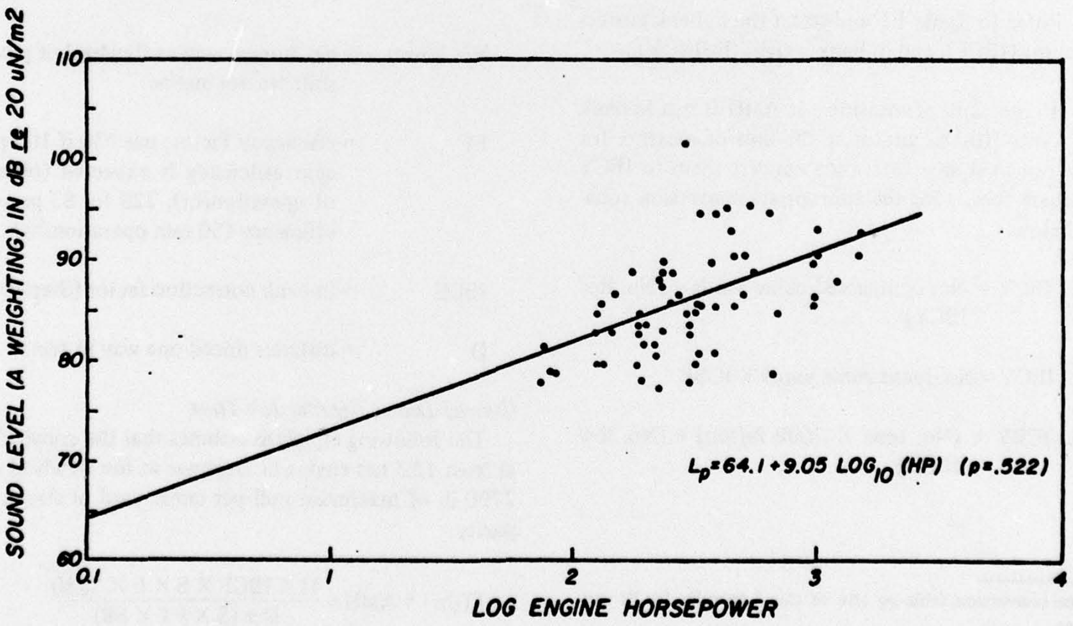

Figure E2. Equipment sound level (at 50 ft [15 m]) as a function of logarithm of engine horsepower (Donaldson tests).

APPENDIX F:

EQUIPMENT SUBSTITUTION COST-ESTIMATING PROCEDURES*

This section presents procedures for estimating the increase in construction cost associated with equipment substitution. Many cost-estimating procedures are available. One such procedure, derived from International Harvester publications,** is outlined below. This procedure would be completed for each substitution scenario to determine the cost of each. The procedure is specific to earthmoving and excavation processes.

Procedure for Estimating Costs Associated with Vehicle Substitution Choices

1. Gather specification sheets on the equipment for which estimates for production times and costs are required.

2. Determine the amount of material which must be handled (AMH) by each vehicle. For grading and plowing activities, estimate the area to be graded or plowed.

3. Determine the type of material to be moved or excavated.

4. Refer to Table F1 and select the in-bank correction factor (IBCF), and in-bank weight (lb/IBCY).

5. If the unit of measure for AMH is not in-bank cubic yards (IBCY) and/or if the unit of measure for area is not in square feet, then convert them to IBCY and square feet, using the appropriate conversion equations below:

$$\text{No. IBCY} = \text{No. compacted cubic yards} \div (\text{No. lbs/IBCY})$$

$$\text{No. IBCY} = \text{No. loose cubic yards} \times \text{ICBF}$$

$$\text{No. ICBY} = (\text{No. tons} \times 2000\ \text{lb/ton}) \div (\text{No. lbs/IBCY})$$

$$\text{No. sq ft} = \text{No. sq yd} \times 9\ \text{sq ft/sq yd}$$

$$\text{No. sq ft} = \text{No. acre} \times 43{,}560\ \text{sq ft/acre}$$

6. Select the appropriate equation for estimating job time (JT) for each vehicle type from among the following subsections. Average travel speed(s) in mph for a two-way cycle, without allowance for fixed time operations (loading, dumping, etc.) may be calculated as follows:

$$S = \frac{2 \times F \times R}{F + R}$$

where F and R are the selected forward and reverse travel speeds in mph, respectively. Cycle time may be estimated using the product of the average travel speed times the two-way distance traveled and then adding fixed time factors. (See Tables F2 to F5 for common cycle times and fixed times.)

Crawler Dozer Job Time

$$\text{JT(hr)} = \text{AMH} \div \frac{\text{Net Power} \times \text{EF} \times \text{IBCF}}{D + 50}$$

where AMH = total amount of job material to be handled in in-bank cubic yards (Step 5)

Net Power = net horsepower at flywheel of power shift tractor engine

EF = efficiency factor, use 330 if 100 percent efficiency is expected (60 min of operation/hr), 220 for 83 percent efficiency (50 min operation/hr)

IBCF = in-bank correction factor (Step 4)

D = distance dozed one way in feet.

Crawler-Drawn Scraper Job Time

The following equation assumes that the crawler has at least 12.5 net engine horsepower at the flywheel and 2700 lb of maximum pull per cubic yard of struck capacity.

$$\text{JT(hr)} = \text{AMH} \div \frac{H \times \text{IBCF} \times S \times E \times 5280}{D + (S \times FT \times 88)}$$

AMH = total amount of job material to be handled in in-bank cubic yards (Step 5)

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*See conversion table pg 104 of this Appendix for SI conversions.

***Basic Estimating*, Construction Equipment Division (International Harvester). *Earthmoving Principles: A Guide to Production and Cost Estimating* (International Harvester, 1975).

H = SAE heaped capacity in loose cubic yards

IBCF = in-bank correction factor (Step 4)

S = travel speed in mph; a suggested speed is 4.9 mph, which requires 12.5 net flywheel horsepower per pay yard of scraper capacity at approximately 200 lb/ton of rolling resistance. This speed may be replaced by the product of the maximum speed adjustment factor provided by Table F6

E = efficiency; fraction of each hour that machine is engaged in productive operation (example: 55 min of productive operation out of every hour would equal 0.92)

d = distance of two-way round trip haul in feet

FT = fixed cycle time related to loading, dumping, acceleration, turning; an estimate of 1.85 min per cycle is suggested

5280 = conversion factor = 5280 ft/mi

88 = conversion factor = 5280 ft/mi ÷ 60 min/hr.

Tractor Ripper Job Time

$$JT(hr) = \frac{AMH}{DP \times W \times S \times E \times 196}$$

AMH = total amount of job material to be handled in in-bank cubic yards (Step 5)

DP = depth of penetration per pass, in feet

W = effective width of ripper in feet

S = travel speed in mph, usually 1.2 to 1.5 mph

E = efficiency; fraction of each hour that machine is engaged in productive operation (example: 55 min of productive operation out of every clock hour would equal 0.92).

Motor Grader Job Time

$$JT(hr) = \frac{Area \times NP}{BL \times AA \times S \times E \times 3520}$$

Area = job to be graded in square feet (Step 5)

NP = number of passes required to achieve the desired grade

BL = blade length in ft

AA = blade angle adjustment factor (Table F7)

S = travel speed in mph

E = efficiency; fraction of each hour that vehicle is operated productively (example: 55 min of productive operation out of every hour would equal 0.92)

3520 = adjustment factor of 2/3 (because of overlap of Y_3 for each pass) times the conversion factor of 5280 ft/mi.

Pay Loader Job Time

$$JT(hr) = AMH \div \frac{H \times IBCF \times E \times 60}{C}$$

AMH = total amount of job material to be handled in in-bank cubic yards (Step 5)

H = heaped capacity in loose cubic yards

IBCF = in-bank correction factor (Step 4)

E = efficiency; fraction of hour that vehicle is operated productively (example: 55 min of productive operation out of every clock hour would equal 0.92)

C = cycle time in minutes

60 = conversion factor: 60 min/hr.

Self-Propelled Scraper Job Time

$$JT(hr) = AMH \div \frac{H \times IBCF \times S \times E \times 5280}{D + (S \times FT \times 88)}$$

AMH = total amount of job material to be handled in in-bank cubic yards (Step 5)

H = heaped capacity of scraper bowl in loose cubic yards

IBCF = in-bank correction factor (Step 4)

S = travel speed in mph; 22.7 mph is suggested; this speed requires 15 hp/cu yd of scraper capacity at 65 to 75 lb/ton of gross vehicle weight rolling resistance. S may be replaced by the product of the maximum speed time. The speed adjustment is provided in Table F6

E = efficiency, fraction of hour that vehicle is operated productively (example: 55 min of productive operation per clock hour would equal 0.92)

D = two-way, round trip haul distance in feet

FT = fixed time constant, in minutes, for loading, acceleration, turning and dumping; 2 min per cycle is suggested.

5280 = conversion factor = 5280 ft/mi

88 = conversion factor = 5280 ft/mi ÷ 60 min/hr.

Job Time of Tractor Drawn Harrows, Plows and Cultivators Used in Construction Work

$$JT(hr) = \frac{Area}{5280 \times S \times \text{[illegible]}}$$

Area = job area to be plowed in square feet (Step 5)

S = travel speed in mph

W = effective width of implement in feet

E = efficiency; fraction of each hour that vehicle is operated productively (example: 55 min of productive operation out of every clock hour would equal 0.92)

5280 = conversion factor = 5280 ft/mi.

Job Time for Sheepsfoot Compactors or for Tractor Drawn Sheepsfoot Rollers

Drawbar Pull necessary to pull a sheepsfoot roller(s) = total weight of roller(s) × .25

$$JT(hr) = AMH \div \frac{W \times D \times S \times E \times 16.3}{SHF \times NP}$$

AMH = total amount of job material to be compacted in in-bank cubic yards (Step 5)

W = effective width of roller in feet (for compactors, it equals 2 times the width of one wheel). If two rollers are pulled, one behind the other, W equals the width of just one of the rollers: what changes is that half the number of passes which must be made to achieve the desired compaction.

D = depth of compacted lift in inches

S = travel speed of vehicle in mph

E = efficiency; fraction of each hour that vehicle is operated productively (example: 55 min of operation out of every clock hour would equal 0.92)

SHF = shrinkage factor; relationship of compacted cubic yards divided by in-bank cubic yards. This factor should be provided by job specifications

NP = number of passes required to achieve the desired compaction; this depends on type and moisture content of soil and weight of roller

16.3 = conversion factor = 5280 ft/mi ÷ 12 in./ft ÷ 27 ft^3/cu yd.

Job Time for Wheel Tractor Backhoe Production

$$JT(hr) = \frac{AMH}{E \times H \times IBCF \times DDF \times SAF \times MLF \times 8.3}$$

AMH = total amount of material to be handled in in-bank cubic yards (Step 5)

E = efficiency; fraction of each hour that vehicle is operated productively; (example: 55 min of productive operation out of every clock hour would equal 55/60 or 0.92)

H = heaped capacity of bucket in cubic feet

IBCF = in-bank correction factor (Step 4)

DDF = digging depth factor, see Table 8

SAF = swing angle factor, see Table 9

MLF = material loadability factor, see Table 10

8.3 = conversion factor equal to 225 cycles/hr ÷ 27 cu ft/cu yd. 225 = the standard number of cycles per hour; deviations from this standard are adjusted for by the variables: DDF, SAF, and MLF.

Job Time for Truck-Type Excavator

$$JT(hr) = \frac{AMH}{H \times IBCF \times E \times DDF \times SAF \times MLF \times 155}$$

AMH = total amount of material to be handled in in-bank cubic yards (Step 5)

H = heaped capacity in cubic yards

IBCF = in-bank conversion factor (Step 4)

E = efficiency; fraction of each hour that vehicle is operated productively (example: 55 min of productive operation out of every clock hour would equal 55/60 or 0.92)

DDF = digging depth factor, see Table F11

SAF = swing angle factor, see Table F12

MLF = material loadibility factor, see Table F13

155 = standard number of cycles per hour; deviations from standard are accounted for by the DDF, SAF, and MLF variables.

Job Time for Off-Highway Haulers

$$JT(hr) = \frac{AMH \times CT}{H \times IBCF \times E}, \text{ where } CT = \frac{D}{MS \times SF \times 5280}$$

AMH = total amount of material to be handled in in-bank cubic yards (Step 5)

CT = total cycle time in hours and equals the sum of the time required for each road section as defined above

H = heaped capacity in loose cubic yards

IBCF = in-bank correction factor (Step 4)

E = efficiency; fraction of each hour that the vehicle is operated productively (example: 55 min of productive operation out of every clock hour would equal 0.92)

D = distance of each road section in feet

MS = maximum speed in mph

SF = speed factor, Table F6

5280 = conversion factor = 5280 ft/mi.

7. Determine the hourly costs associated with owning or renting and operating each vehicle (HC_V) including hourly operator's wages. Procedures for estimating these costs can be obtained from equipment manufacturers.

8. *Determine the hourly operator's costs* (HC_O).

9. Multiply the job time (JT) calculated for each vehicle by its hourly costs (HC_V) and sum the results to get the total job cost associated with each vehicle (JC_V).

10. Multiply the job time (JT) calculated for each vehicle (JT) times the hourly wages paid to each vehicle's operator (HC_O) to calculate the total job cost associated with the operator of each vehicle.

11. Add the JC_O and JC_V calculated for each vehicle to get the job cost of each vehicle (JC) and sum the results to get the total job cost (TJC).

Table F1
Material Type Correlation Factors*

Material Type	In-Bank Correction Factor (IBCF)	In-Bank Unit Weight (lb/IBCY)
Ashes (hard coal)	0.93	700-1000
Ashes (soft coal)	0.93	1080-1215
Bauxite	0.75	2700-4325
Clay, dry	0.85	2300
Clay, light	0.80	2800
Clay, wet	0.75	3000
Coal, anthracite	0.74	2450
Coal, bituminous	0.74	2000
Coal, steam (compacted)	0.72	1890
Copper ore	0.74	3800
Earth, dry	0.80	2700
Earth, moist	0.80	3000
Earth, wet	0.85	3370
Earth, with sand and gravel	0.90	3100
Gypsum	0.57	4300
Gravel, dry	0.89	3250
Gravel, wet	0.88	3600
Granite	0.56-0.67	4600
Iron ore, hematite	0.45	6500-8700
Limestone, blasted	0.57-0.60	4200
Loam	0.83	2700
Mud, dry	0.83	2160-2970
Mud, moderately packed	0.83	2970-3510
Rock and stone, crushed	0.74	3240-3920
Sand, dry	0.89	3050
Sand, wet	0.87	3500
Shale, soft rock	0.60	3000
Slate	0.60	4590-4860
Trap rock	0.61	5075

***The material presented in Tables F1 through F13 is taken from *Earthmoving Principles: A Guide to Production and Cost Estimating*, with permission of International Harvester.**

Table F2
Pusher Cycle Time (min)

	Condition		
	Favorable	Average	Unfavorable
Back-track loading	0.9	1.3	1.7
Chain loading	0.7	0.9	1.2
Shuttle loading	0.7	0.9	1.2

Table F3
Scraper Loading Time (min)

	Open Bowl			Elevating	
Condition	Single Engine	Dual Engine	Pay Mate	Single Engine	Dual Engine
Favorable	0.40	0.35	0.90	0.70	0.45
Average	0.60	0.50	1.20	1.00	0.60
Unfavorable	0.80	0.70	1.50	1.30	0.75

Table F4
Front-End Loader Cycle Time (min)

	Rubber-Tires		Crawler
Conditions	0-5 cu yd	5+ cu yd	All
Favorable	0.30	0.42	0.42
Average	0.33	0.50	0.50
Unfavorable	0.42	0.66	0.58

Table F5
Turn and Dump Time (min) for Haulers and Scrapers

	Haulers		Scrapers	
Conditions	Bottom Dump	End Dump	Open Bowl	Elevating
Favorable	0.3	0.7	0.3	0.4
Average	0.6	1.0	0.4	0.5
Unfavorable	1.5	1.5	0.6	0.7

Table F6
Speed Factors (SF) for Off-Highway Haulers and Scrapers

Length of 2-Way Round Trip in ft	Starting from or Coming to a Stop in Haul Section	Moving when Entering Haul Road Section
400-1000	0.33-0.51	0.56-0.80
1001-2000	0.43-0.67	0.65-0.83
2001-3000	0.53-0.75	0.78-0.90
3001-4000	0.59-0.80	0.84-0.93
4001-5000	0.62-0.84	0.88-0.96
5001-6000	0.65-0.85	0.90-0.97
6001-7000	0.68-0.87	0.92-1.00
7001-above	0.71-0.95	0.95-1.00

Table F7
Blade Angle Adjustment (AA) Factor

Blade Angle	AA Factor
90	1.00
80	.98
70	.94
60	.87
50	.77
40	.64
30	.50
20	.34
10	.17

Table F8
Digging Depth Factor (DDF) for Backhoes

Depth (in ft)	DDF
4	1.00
6	0.95
8	0.90
10	0.85
12	0.80
14	0.75

Table F9
Swing Angle Factor (SAF) for Backhoes

Angle of Swing in Degrees	SAF
40-60	1.00
60-70	0.95
over 70	0.90

Table F10
Material Loadability Factor (MLF) For Backhoes

Conditions	MLF
Favorable	1.00
Average	0.85-0.95
Unfavorable	0.50-0.80

Table F11
Digging Depth Factor (DDF) for Track Excavators

Depth in feet	DDF
5	1.00
10	.95
15	.87
20	.78

Table F12
Swing Angle Factor (SAF) for Track Excavators

Angle of Swing (degrees)	SAF
45	1.00
60	.95
75	.90
90	.86
120	.81
180	.71

Table F13
Material Loadability Factor (MLF) for Track Excavators

Conditions	Type of Material	MLF
Favorable	loam, sand, gravel	0.85-1.00
Average	general earth, clay	0.65-0.85
Unfavorable	rock, roots, gumbo	0.50-0.65

SI Conversion Table

1 in. = 25.4 mm
1 ft = .3048 m
1 yd = .9144 m
1 in.^{2} = 6.54 cm^2
1 ft^2 = .092 m^2
1 yd^2 = .836 m^2
1 yd^3 = .764 m^3

1 mi = 1.609 km
1 sq mi = 2.589 km^2

1 acre = .404 ha = 40.46 m^2

1 lb = .453 kg
1 ton = 907 kg = .907 tonne

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