IR 83-2760

NUREG/CR-3545

Comparison of Energy Measurements in the Standard Penetration Test Using the Cathead and Rope Method

Phases I and II
Final Report

Prepared by W. D. Kovacs, L. A. Salomone, F. Y. Yokel

National Bureau of Standards

Prepared for
U.S. Nuclear Regulatory Commission

NOTICE

Availability of Reference Materials Cited in NRC Publications

Most documents cited in NRC publications will be available from one of the following sources:

1. The NRC Public Document Room, 1717 H Street, N.W.
   Washington, DC 20555
2. The NRC/GPO Sales Program, U.S. Nuclear Regulatory Commission,
   Washington, DC 20555
3. The National Technical Information Service, Springfield, VA 22161

Although the listing that follows represents the majority of documents cited in NRC publications, it is not intended to be exhaustive.

Referenced documents available for inspection and copying for a fee from the NRC Public Document Room include NRC correspondence and internal NRC memoranda; NRC Office of Inspection and Enforcement bulletins, circulars, information notices, inspection and investigation notices; Licensee Event Reports; vendor reports and correspondence; Commission papers; and applicant and licensee documents and correspondence.

The following documents in the NUREG series are available for purchase from the NRC/GPO Sales Program: formal NRC staff and contractor reports, NRC-sponsored conference proceedings, and NRC booklets and brochures. Also available are Regulatory Guides, NRC regulations in the *Code of Federal Regulations*, and *Nuclear Regulatory Commission Issuances*.

Documents available from the National Technical Information Service include NUREG series reports and technical reports prepared by other federal agencies and reports prepared by the Atomic Energy Commission, forerunner agency to the Nuclear Regulatory Commission.

Documents available from public and special technical libraries include all open literature items, such as books, journal and periodical articles, and transactions. *Federal Register* notices, federal and state legislation, and congressional reports can usually be obtained from these libraries.

Documents such as theses, dissertations, foreign reports and translations, and non-NRC conference proceedings are available for purchase from the organization sponsoring the publication cited.

Single copies of NRC draft reports are available free upon written request to the Division of Technical Information and Document Control, U.S. Nuclear Regulatory Commission, Washington, DC 20555.

Copies of industry codes and standards used in a substantive manner in the NRC regulatory process are maintained at the NRC Library, 7920 Norfolk Avenue, Bethesda, Maryland, and are available there for reference use by the public. Codes and standards are usually copyrighted and may be purchased from the originating organization or, if they are American National Standards, from the American National Standards Institute, 1430 Broadway, New York, NY 10018.

GPO Printed copy price: $4.50

NRC Form 122
(7-83)

U.S. NUCLEAR REGULATORY COMMISSION

DOCUMENT REQUEST/CONTROL

DATE OF REQUEST: 4/26

HOLD FOR PICKUP	
MAIL-RUN/STOP SYSTEM	
MAIL	X

REQUESTER'S NAME	TELEPHONE NO.	MAIL STOP *(If NRC Hq.)*

ORGANIZATION *(Division/Branch)*

MAILING INFORMATION *(If other than NRC Hq.)*

NAME	JOHN TAYLOR
ORGANIZATION	NATIONAL BUREAU OF STANDARDS
STREET ADDRESS	DIVISION 349, Room A536 ADMIN
CITY	WASHINGTON, DC 20234
STATE	
ZIP CODE	

FOR DISTRIB. SVS. USE ONLY

REQUEST RECEIVED BY

TELEPHONE	X
MAIL	
WALK-IN	
DOCUMENT PICKED UP	

MATERIAL REQUESTED

INVENTORY BOX NO.	LOC.	SE-QUENCE	DOCKET AND/OR PUBLICATION NUMBER	NUMBER OF COPIES
			NUREG/CR-3545	1

E: 1

NATIONAL BUREAU OF STANDARDS
JOHN TAYLOR
RM A530
DIVISION 344 ADMIN
WASH DC 20234

ORDER NO. : [illegible]-00001
ORDER TYPE: [illegible]

DOCUMENT NO.	QTY @	COST	TOTAL COST	COMMENTS
NUREGCR3545	1	.00		

TOTAL DOCUMENTS ORDERED : 1
TOTAL DOCUMENTS ENCLOSED: 1

NUREG/CR-3545
RA

Comparison of Energy Measurements in the Standard Penetration Test Using the Cathead and Rope Method

Phases I and II
Final Report

Manuscript Completed: July 1983
Date Published: November 1983

Prepared by
W. D. Kovacs, L. A. Salomone, F. Y. Yokel

Geotechnical Engineering Group
National Bureau of Standards
Washington, DC 20234

Prepared for
Division of Health, Siting and Waste Management
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555
NRC FIN B7457

ABSTRACT

Studies conducted on the Standard Penetration Test (SPT) and its present use in engineering practice show that a wide variation in the use of different pieces of SPT equipment, procedures and personnel results in a range of energy measured in the drill rods from 30 to 85 percent of the standard SPT energy. The potential energy and kinetic energy of the hammer were measured prior to impact, and the energy passing through the drill rods was calculated from a force-time measurement in the rods. It was found that safety (type) hammers tend to allow more kinetic energy to pass through the hammer-anvil system than donut (type) hammers. The energy passing through the drill rods was calculated by using a digital processing oscilloscope and an SPT Calibrator. Lessons learned in evaluating the energy measurement by these two methods are discussed. The combined effect of the drill rig used, the operator and his procedures, and the SPT equipment should be considered when energy is to be evaluated. The variation of average energy ratio within various drill rig models was found to be about as large as that among drill rig models. It was therefore impossible to make a statistically significant estimate of the reference energy which is representative of the average energy delivered in the U.S. practice.

EXECUTIVE SUMMARY

The National Bureau of Standards performed 1087 energy measurements on various drill rigs performing Standard Penetration Tests (SPT) on seven sites. The data from these tests were combined with other available data and the following conclusions were drawn:

1. The variability of the energy passing through the drill rod as delivered by present U.S. equipment and procedures is too great to be eliminated by a modification of procedures alone. Equipment, as well as procedures, would have to be modified to achieve satisfactory results.

2. The adjustment of SPT N-value data to a common reference energy appears to yield promising results; however, the energy would have to be measured in the drill rod rather than the point of hammer impact. The method presently used to measure the energy in the drill rod produces reasonable and checkable results, but has not yet been verified by an independent theory or measurement system.

3. While it is desirable that the reference energy approximate a current or past national average energy, the data sample available is not large enough to permit a statistically significant estimate of the national average energy.

4. The energy passing through the drill rod is not the only source of variability in the SPT results. The use of liners in the SPT sampler is also an important source of variability. The effect of the liner and the liner clearance provided in U.S. samplers must be considered when evaluating SPT results from other countries.

The following recommendations are made on the basis of these conclusions:

1. SPT equipment and procedures be established which minimize the variability of the blow count. This would require a tripping mechanism, a standard hammer/anvil/drill rod system, a standard spoon with or without liner, and standard drilling procedures.

2. Until the SPT equipment is standardized:

(a) The energy passing through the drill rod should be monitored and the test results referenced to a standard energy, either the national average or an internationally accepted energy level.

(b) The use of liners in the sampler should be eliminated.

(c) The test procedures be modified to minimize the test variability.

3. The following interim test procedures should be specified for determining liquefaction potential:

(a) Safety (type) hammer with AW drill rod stem with a stroke of at least 35 in (889 mm).

(b) Two turns of new rope around the cathead.

(c) Use of an 8 in (203 mm) clean, shiny cathead.

(d) AW (parallel wall) drill rod.

(e) Rotary drilling with mud.

(f) Upward deflecting wash drilling bit.

(g) Blow count rate of 30 to 40 blows/minute.

(h) An SPT sampler with no liners [I.D. of 1.5 in (38.1 mm)].

(i) The mud fluid level in the bore hole should at all times be at the top of the bore hole.

(j) A 2 in (50 mm) colored band shall be permanently marked on the hammer guide pipe (from 28 to 30 in above the anvil) to help the operator produce an average 30 in fall height.

(k) ER_i should be constantly monitored and recorded.

[Procedures c, e, f, and h are based on findings by Schmertmann (1977).]

4. The following additional research be conducted:

(a) Check the present load cell integration method of determining ER_i by an independent energy theory and associated measuring system.

(b) ER_i measurements for typical Japanese SPT practices to better interpret available liquefaction data.

(c) Study of the effect of drill rod configurations on the energy transmission.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF TABLES

LIST OF TABLES (continued)

NOTATION

A	= cross-sectional area of the drill rods, cm^2
c	= theoretical compressive or p wave velocity of sound in the steel drill rod, m/s
c_m	= measured compressive or p wave velocity of sound in the steel drill rod, m/s
D	= donut hammer
DPO	= Digital Processing Oscilloscope
E	= Young's modulus of the drill rods, N/m^2
E_i	= energy passing through the drill rods at the point of measurement, as determined by equation 3.2; J
E_v	= energy for velocity, i.e., kinetic energy just before impact, J
E^*	= theoretical free fall energy <u>assuming</u> a 30 in (762 mm) fall, equals 4200 in-lbs (475 J)
ER_i	= energy ratio for F(t) based on a 30 in (762 mm) fall, E_i/E^*
$ER_{i\ Calib}$	= energy ratio for F(t) from SPT Calibrator
$ER_{i\ DPO}$	= energy ratio for F(t) from integration using the DPO
ER_{im}	= measured energy ratio for F(t)
ER_{ic}	= the selected energy ratio for F(t)
ER_v^*	= energy ratio for velocity, E_v/E^*
ETR	= energy transfer ratio = $ER_i/ER_v = E_i/E_v$
F_i	= incident compressive force, F(t) measured in the drill rods
$F(t)$	= measured force-time history in the load cell during impact
g	= acceleration of gravity
H	= measured hammer fall height
K_1	= correction factor to account for the location of the load cell below the anvil, eq. 3.3
K_2	= correction factor based on drill stem length, eq. 3.4

K_c = correction factor to take into account that the measured compressive wave velocity is less than the theoretical wave velocity, eq. 3.5

ℓ = distance from the point of impact to the bottom of the sampler

ℓ' = $(\ell - \Delta\ell)$

M_h = mass of the hammer

N = blow count, N-value, or penetrations resistance, blows per foot

N_c = corrected blow count for a specified energy

N_m = measured blow count

S = safety hammer

t = time

t_m = measured integration time

W = hammer weight

$\Delta\ell$ = distance from the point of impact to the load cell

ρ = mass density of the drill rods

σ_i = incident stress measured in the drill rods

PREFACE

This is the final report of studies performed under phases I and II of interagency agreement RES-80-121 between the U.S. Nuclear Regulatory Commission and the National Bureau of Standards. Some of the data presented were generated in studies sponsored by the U.S. Bureau of Reclamation and the California Department of Water Resources.

1. INTRODUCTION

1.1 PURPOSE

One of the most significant recent developments in the evaluation of cyclic liquefaction potential[1/] of sands has been the identification of the large number of factors which significantly affect the cyclic characteristics of any given sand. It has been shown that all of these factors correlate with the penetration resistance. Most factors which increase the resistance of a sand to liquefaction also tend to increase the penetration resistance in the Standard Penetration Test (SPT) as defined by ASTM D 1586 (Schmertmann, 1978; Seed, 1979). For this reason, reasonably good correlation has been observed between cyclic characteristics and penetration resistance (Seed, 1979). Kovacs (1979), Kovacs et al., (1977) and Schmertmann (1978) have demonstrated the wide variability in the conditions utilized in this supposedly standardized test procedure. For a given site, standard penetration resistance values can vary by a factor of 3 or more at a given depth and relative density. Schmertmann (1978) presents a qualitative comparison of penetration resistance with liquefaction factor of safety and suggests a useful degree of correlation between SPT N-value and the factor of safety against liquefaction. However, a necessary prerequisite for using the Standard Penetration Test as a measure of the cyclic liquefaction potential of sands is an increase of its reliability by better standardization. However, Serota and Lowther (1973) and Marcuson and Bieganousky (1977) have pointed out from the consistency of their results that the SPT is reproducible if test variables are controlled.

This study provides information which can be used to improve the reliability and reproducibility of the Standard Penetration Test.

1.2 SCOPE

The plan of research consisted of two phases: Phase I, preliminary studies on energy calibration, and Phase II, establishment of a national average energy. These phases involved:

Phase I:

- Information gathering on present SPT use and practice.
- Selection of methods and equipment to calibrate drill rig systems.

Phase II:

- Use of the calibration methods selected in Phase I to calibrate representative drill rigs now being used in engineering practice, and to assemble a data base that can be used to assemble a "national average energy" (the average of the energies transmitted through the drill rod in U.S. SPT practice).

[1/] As described by Seed et al., (1983).

1.3 BACKGROUND

Variables affecting the reproducibility of the Standard Penetration Test include personnel, equipment, and procedures. While some of the equipment and procedures that affect the test are standardized, many are not.

The variables affecting the SPT, which are summarized by Kovacs et al., (1981), directly or indirectly affect the energy that is transferred through the drill rods to the sampler. Schmertmann and Palacios (1979) concluded that the energy reaching the sampler is inversely proportional to the blow count, N. Thus, if the variability of energy passing through the drill rod can be reduced, the N-value will be more reproducible and consistent.

Figure 1.1 illustrates the locations where energy was measured during this study. In figure 1.1, a 140 lb (63.5 kg) hammer falls from an assumed height of 30 in (76 cm) (Point A) and has a potential energy of mgH, or 4200 in-lbf (475 J). In an ideal free-fall system, all of the potential energy would be converted into kinetic energy at Point B when the hammer impacts the anvil. However, because the hammer release mechanism does not produce true free fall, the kinetic energy prior to impact (Point B) is less than the potential energy. Further energy loss occurs through the anvil (Point B'). The available kinetic energy, E_v, produces compressive stress wave energy, E_i, in the drill rod as measured at Point C by a load cell. Because of energy transmission losses through the anvil and drill rod, the energy in the drill rod, E_i, is less than the available kinetic energy, E_v. The efficiency of the anvil to transmit the available kinetic energy has been defined by Kovacs et al., (1981), as the energy transfer ratio, ETR.

The methods used to evaluate the energy available in the SPT test include:

a) measurement of actual hammer fall height (Potential Energy)
b) kinetic energy just before impact, E_v
c) energy passing through the drill rods as measured by a load cell located at a minimum of ten drill rod diameters below the anvil, E_i.

Kovacs et al., (1977), Kovacs (1979), Kovacs et al., (1981) and Goble and Ruchti (1981) have measured a) and b) above. On the other hand, Schmertmann and Smith (1977), Schmertmann and Palacios (1979) and Kovacs et al., (1981) have measured the energy passing through the drill rods. The results of these studies have documented the wide variation in the measured energies [30 to 85 percent of the free-fall energy (Schmertmann and Palacios, 1979)] for the SPT using different drill rigs. Because of this variation, the corresponding range in N values could vary by a factor of three in the same soil at the same location. One important key to improving the effectiveness of the SPT is a reduction in the variability of the energy passing through the drill rod, E_i. This can be accomplished by either calibration of the test or standardization of the equipment used. Calibration of the test may be accomplished in three steps:

1) The selection of a measurement method which will allow reliable and economic evaluation of the energy being delivered by drill rig equipment now used in U.S. engineering practice.

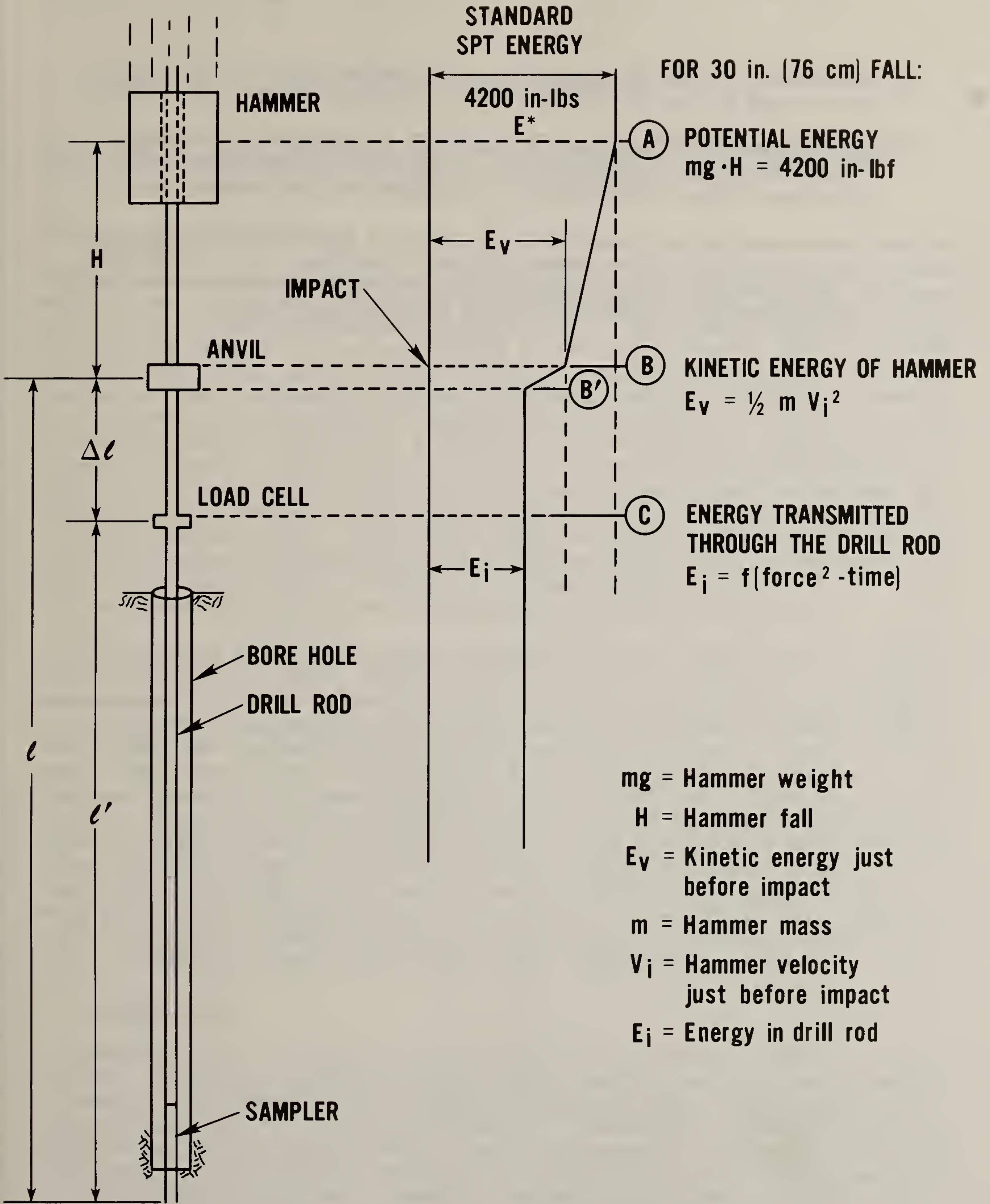


Figure 1.1 Illustration of the various energies measured during this study

2) Measurement of the energy delivered by various types of drill rigs encountered in typical U.S. engineering practice.

3) Establishment of a Reference Energy such as the National Average Energy suggested by Kovacs et al., (1981) with which penetration resistance values (blow counts or N values) can be correlated.

This study addresses the calibration of the SPT (the three items above) and is presented in accordance with the tasks outlined in section 1.2. Standardization of the test procedures and equipment would require a modification of SPT standards to minimize the variables that now exist in the SPT.

2. EXISTING SPT EQUIPMENT AND FIELD TEST PROCEDURES

This section describes the wide variability in equipment and test procedures encountered in engineering practice in the United States and abroad which contributes to the drill rod energy, E_i, variation.

2.1 AVAILABLE DRILL RIGS

Various manufacturers fabricate a wide variety of drill rigs for soil exploration. These drill rigs have different features which influence the penetration resistance obtained during the test. The standard penetration test is performed primarily by means of using a rope and cathead to raise and lower the 140 lb (63.5 kg) hammer. Other "lifting" devices are also commercially available. They include, but are not limited to, automatic free fall hammers and automatic and semiautomatic hydraulic hoisting devices. A partial listing of available drill rigs used to perform the SPT is presented in table 2.1. Figure 2.1 assists in defining the terms α, β, and cathead rotation direction referred to in the table. The number of turns of rope around the cathead is defined (Kovacs, 1980) as the angle in degrees of contact the rope makes around a cathead divided by 360. The contact angle will vary with the drill rig used and the direction of cathead rotation (see figure 2.1). For a "nominal 2 turns," the actual number of turns will be approximately 1 3/4 or 2 1/4 turns, for counterclockwise (CCW) and clockwise (CW) rotation, respectively.

Two studies were made of the number and model of drill rigs presently being used to perform the SPT in the U.S. In one study, the various State Highway Departments were asked to list the drill rigs they used to perform the SPT. In the second study, members of the Association of Soil and Foundation Engineers (ASFE) were asked through ASTM (Kovacs, 1982) to list the manufacturer, model, and number of drill rigs they used to perform the SPT. In some instances, some of the consulting firms reported that they do not own drill rigs and contract out their drill services. Thus, it is possible that some of the drill rigs listed may have been mentioned more than once if more than one consulting firm within a city uses the same drilling contractor. Table 2.2 summarizes the results of the two studies on drill rig population. It is recognized that the numbers in Col. 2 of table 2.2 are substantially below what the individual manufacturer has actually built and represent only a partial listing of the actual drill rigs used in engineering practice.

2.2 HAMMER TYPES

A variety of types of 140 lb (63.5 kg) hammers are currently used to perform the SPT. The present ASTM standard (D 1586) does not specify a particular type of hammer. They include: a) pin-guided hammer; b) donut shaped hammer; c) safety hammer; and d) Japanese donut hammer. Figure 2.2a, taken from Fletcher (1965) shows the pin guided hammer. Note the presence of the hard wood cushion block which strikes against the top of the exposed drill rod. The presence of the cushion block tends to moderate the peak force. The 44 in (112 cm) long pin inserted in the drill rod guides the hammer during its fall.

Table 2.1 Characteristics of Some Drill Rigs Used to Perform the SPT

Company (1)	Model (2)	ΔT Turns (3)	Cathead Diameter (inches) (4)	C.H. Speed (RPM) (5)	C.H. Speed (FPM) (6)	Cathead Rotation[1] Direction (7)	α Rope[2] Angle (degrees) (8)	No. of Crown Sheaves (9)	Diameter of Sheave (inches) (10)	Wgt. of Crown Sheave (pounds) (11)	Dist. from Crown Sheave to C.H. 14.5 to 19.5 (12)	Rope[7] Diameter (inches) (13)
Acker	N-5C	-.25	6	123	193	CCW	2	1	12	18	14	1
	N-5W	+.25	6	123	193	CW	2	1	12	18	14	1
	N-10	+.25	6	110	173	CW	4	1	12	18	16	1
	N-18	+.25	8	68	142	CW	4	1	12	18	25	1
	ADII	-.25	8	160	335	CCW	7	2	8	8	24	1
	MKII	-.25	6	141	221	CCW	4	1	12	18	22	1
	MP	+.25	6	136	214	CW	3	2	10	10	23	1
	Mot Cat	+.25	4.5	172	203	CW	-3	1	4.75	2	14	0.75
	Soil Mech	-.33	6	145	228	CCW	-30	2	4.75	2	10	0.75
Central Mine Equipment	45B	+.18	8	454[3]	950[3]	CW[4]	30	2	8	6	14.5 to 19.5	1
	45C	+.18	8	382	800	CW	30	2	8	6	13.5	1
	55	+.18	8	454	950	CW	30	2	8	6	20.5 to 24.4	1
	75	+.25	8	454	950	B[6]	0-20	2	8	6	20.5 to 27.5	1
	450	+.25	8	454	950	B	0-20	2	8	6	19.5	1
	550	+.25	8	454	950	B	0-20	2	8	6	19.5	1
	750	-.2	8	544	1139	CCW	0-20	2	8	6	20.5 to 24.5	1
	750 YL	+.25	8	463	970	B	0-20	2	8	6	26	1
Failing	1250	-.2	6.5	100	170	CCW	15	1	10	12	25	1.25
	CF-15	-.2	6.5	100	170	CCW	15	1	10	12	25	1.25
	1500	-.22	6.5	100	170	CCW	10	1	9.3	11	39.1	1.25
	250	-.2	6.5	100	170	CCW	15	2	5.5	5	20	1.25
	FA-100	-.2	6.5	100	170	CCW	15	1	10	12	20	1.25
Mobile Drilling	B-30S	+.25	6	249-781	391-1227	CW	0	2	7	4.5	NA	1
	B-33	+.25	8	129-815	270-1707	CW	0	2	7	4.5	NA	1
	B-47	+.25	6	280	440	CW	0	2	7	4.5	14	1
	B-40L12	+.25	8	195	408	CW	0	2	7	4.5	11	1
	B-40L17	+.25	8	195	408	CW	0	2	7	4.5	16	1
	B-41L22	+.25	8	195	408	CW	0	2	7	4.5	21	1
	B-50	+.25	8	72-190	151-398	CW	0	2	7	4.5	18 or 23	1
	B-53	+.25	8	65-192	136-402	CW	0	2	7	4.5	18 or 23	1
	B-56	+.25	8	228	478	CW	0	2	7	4.5	23.2	1
	B-61	+.25	8	85-540	178-1317	CW	0	1	7	13.4	26	1
	B-80	+.25	8	65-192	136-402	CW	0	2	7	4.5	20	1
Soil Test	DR 2005A	-.25	6.5	0-288	0-490	B	-	2	6	1.5	14.5	1
Sprague & Henwood	142	-.25	8	48-305[5]	101-639	CCW	0	2	10	25	20	1
	40C	-.25	6.5	124-774	211-1317	CCW	0	1	16	35-40	10	1
	37	-.25	6.5	98-273	167-465	CCW	0	1	10	25	10	1

(1) See figure 2.1 for definition.
(2) See figure 2.1 for definition. Nominal angle α given for horizontal drill rig position.
(3) Maximum vaues given for CME rigs.
(4) Both directions possible.
(5) High range speed depends on gear used.
(6) Both directions.
(7) Manila rope recommended.

Table 2.2 Summary of Drill Rig Models Used in Engineering Practice with Numbers >1

MFGR & Model	Total (3+4)	ASFE[a] Survey	Hiway Survey
(1)	(2)	(3)	(4)
Acker			
AD II	16	14	2
Hillbilly	20	3	17
LD11	2	2	
MC	23	7	16
MK II	14	5	9
MP	2	2	
N10	4		4
SM	2		2
TH	4	4	
Misc.	9	6	3
American Rig			
550 M	4	4	
Misc.		1	
CME			
45B	57	40	17
45C	40	25	15
55	120	85	35
65			
75	27	19	8
85			
450	3	3	
550	12	12	
750	6	6	
750XL	17	12	5
Misc.	3	1	2
Concore			
A-5 Senior	7	7	
Misc.	1	1	
Failing			
36	16	16	
250	8	5	3
750	11	11	
1250			
1500	53	33	20
2000	2	2	
CDF2	3		3
CF15			
FA10D			
MD-1			
Misc.	5	3	2

MFGR & Model	Total (3+4)	ASFE Survey	Hiway Survey
(1)	(2)	(3)	(4)
Joy			
B12	23	23	
22	5	5	
125			
RAM RODII			
Misc.	5	1	4
Meyhew			
200	5	5	
500	3	3	
600			
1000	2	2	
Misc.	3	1	2
Mobile Drill			
B30	11	7	4
B305	7	4	3
B31	4		4
B33	10	3	7
B34	7	4	3
B40	2	2	
B40L	43	20	23
B50	27	16	11
B52	11	4	7
B53	30	20	10
B56	27	8	19
B61	87	61	26
B80	4	2	2
Minute Man			
Misc.	3	2	1
Penn Drill			
Test Borer	5	5	
SIMCO			
2400	4	4	
4000TR	10	8	2
Sprague & Henwood			
36	4	4	
37			
40C	97	38	59
142	2	2	
Monkey	4	4	
Misc.	1	1	

The following model drill rigs were also mentioned in the surveys as having only one rig.

BOYLES BBS25	Frankz	Longyear 1; 24; 34; Junior
Bucyrus Erie	Houston HIVAC	Sullivan
Caldwell 150	Hydradrill	Wint. W Portadrill
CP 15	Knight & Stone	
Damco 500	Little River	

[a] Kovacs (1982).

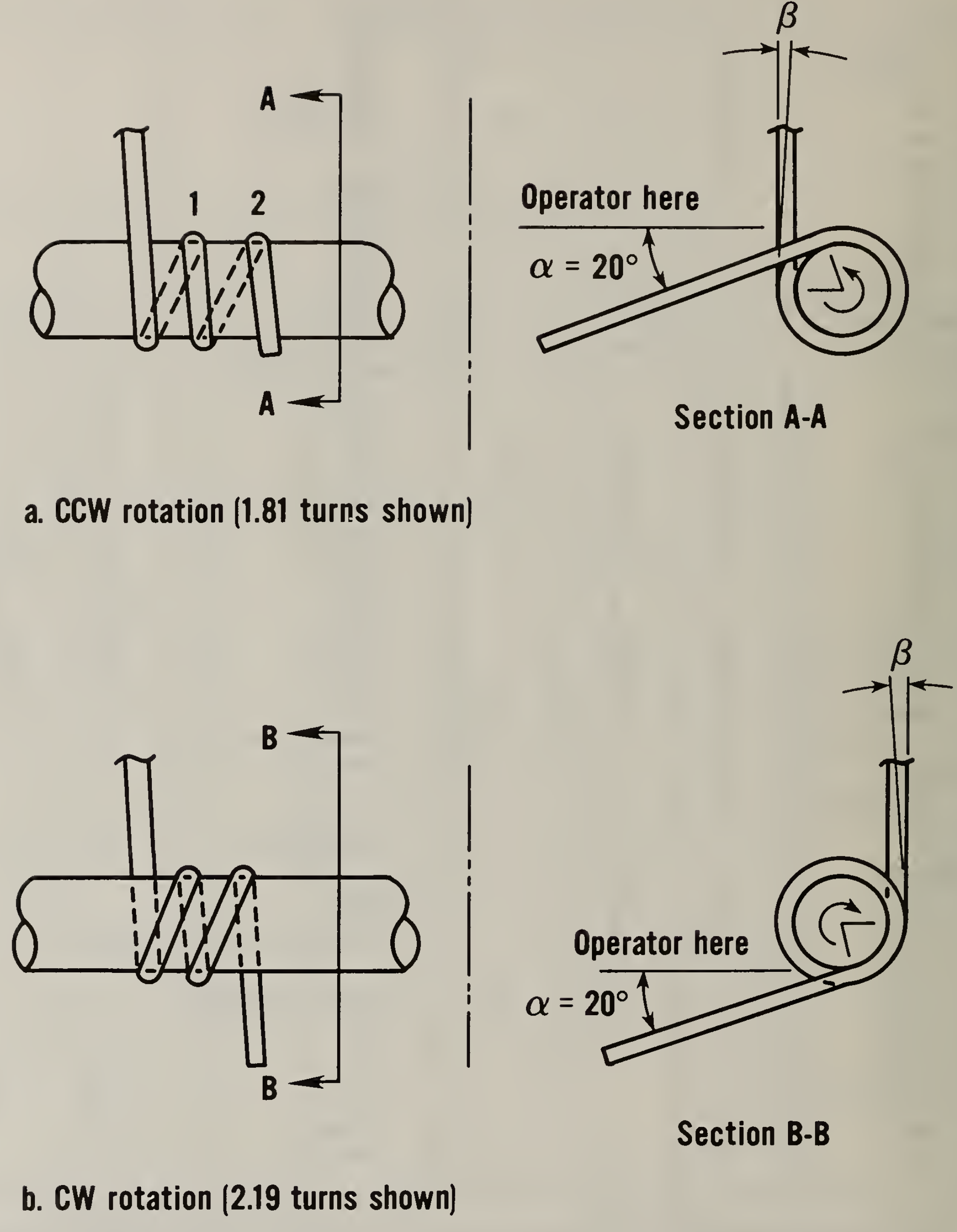


Figure 2.1 Definitions of the number of turns and the angle α and β for (a) CCW rotation and (b) CW rotation of the cathead

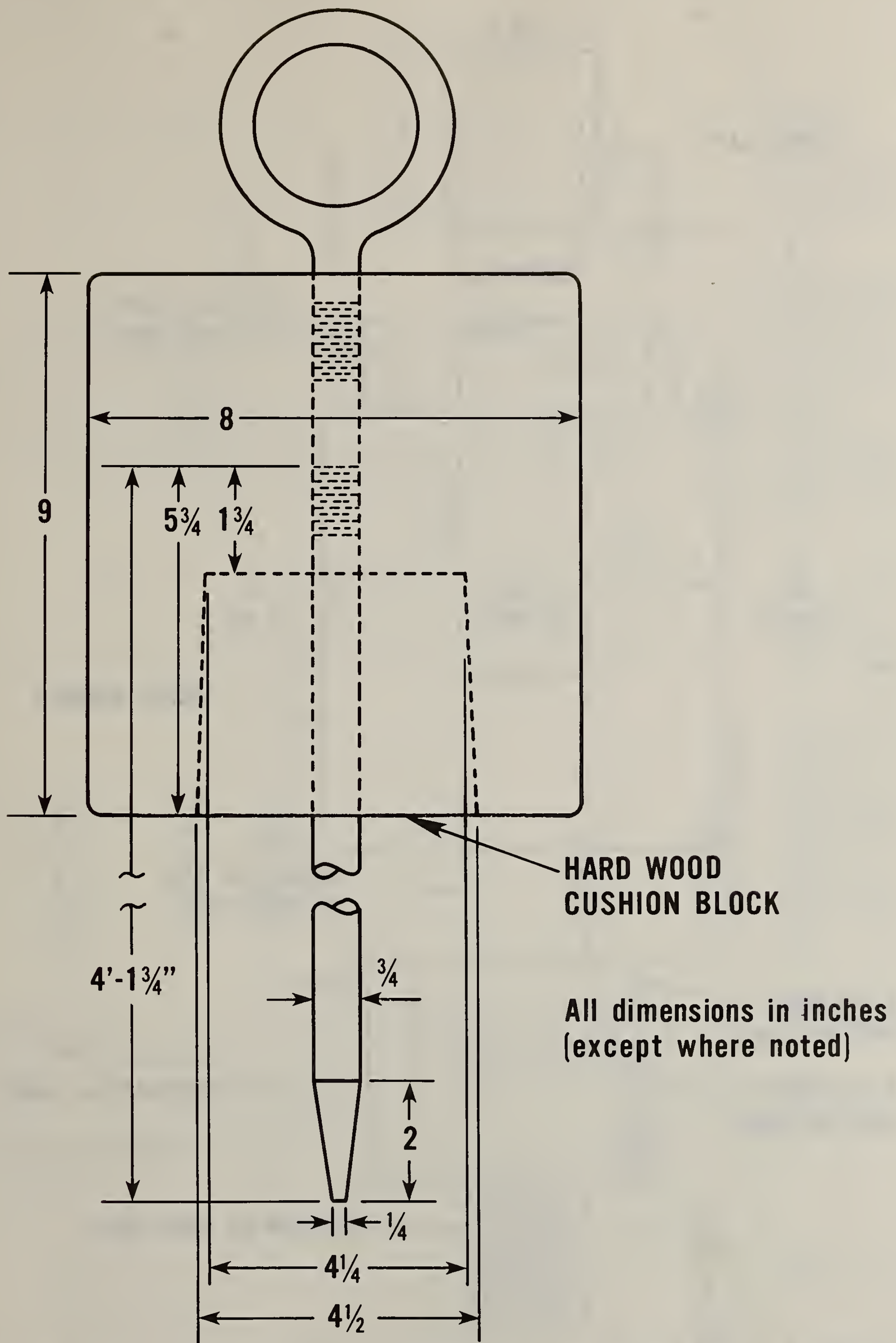


Figure 2.2 SPT 140 lb (63.5 kg) hammers - (a) pin-guided hammer

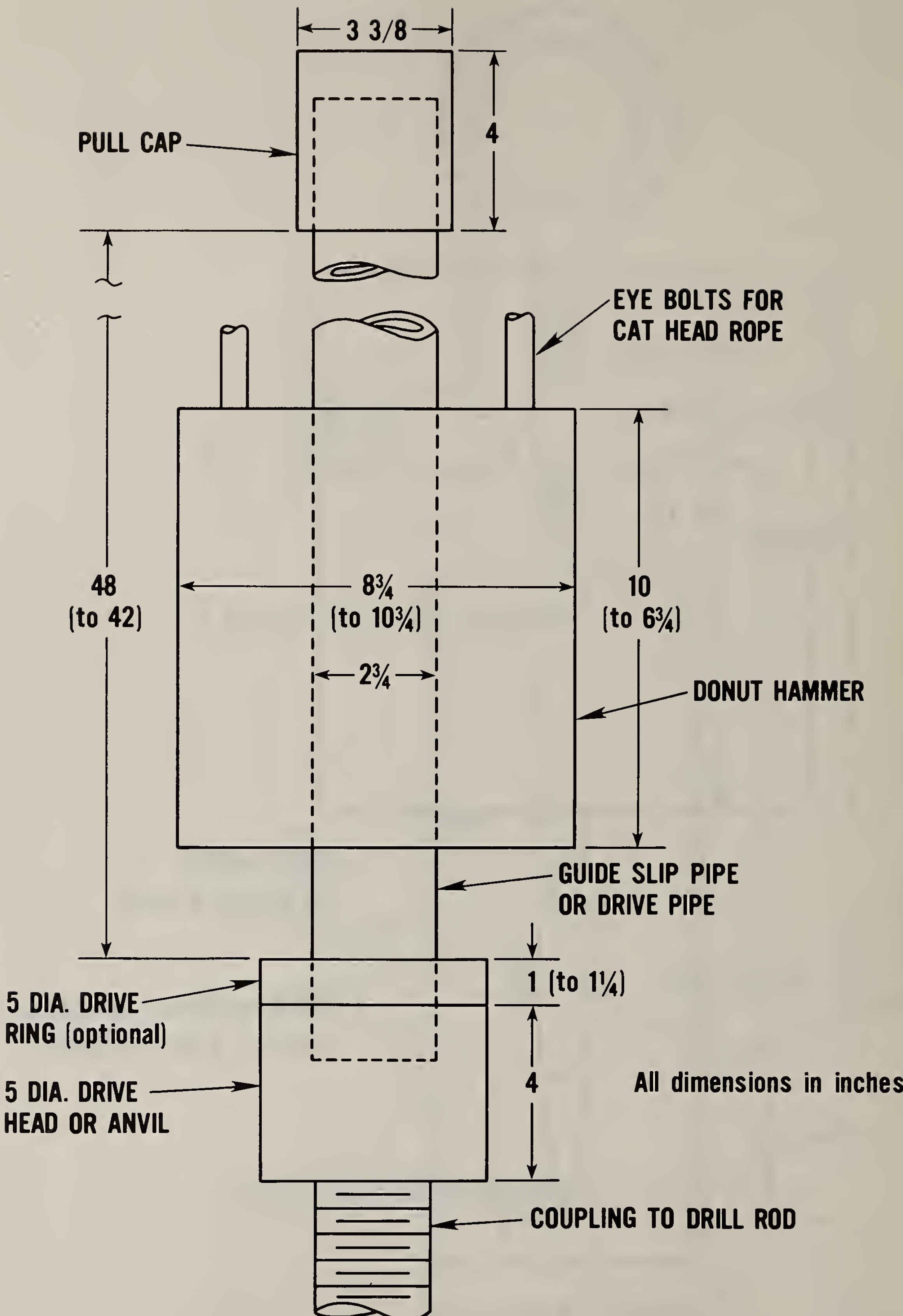


Figure 2.2 SPT 140 lb (63.5 kg) hammers - (b) donut hammer with typical dimensions shown

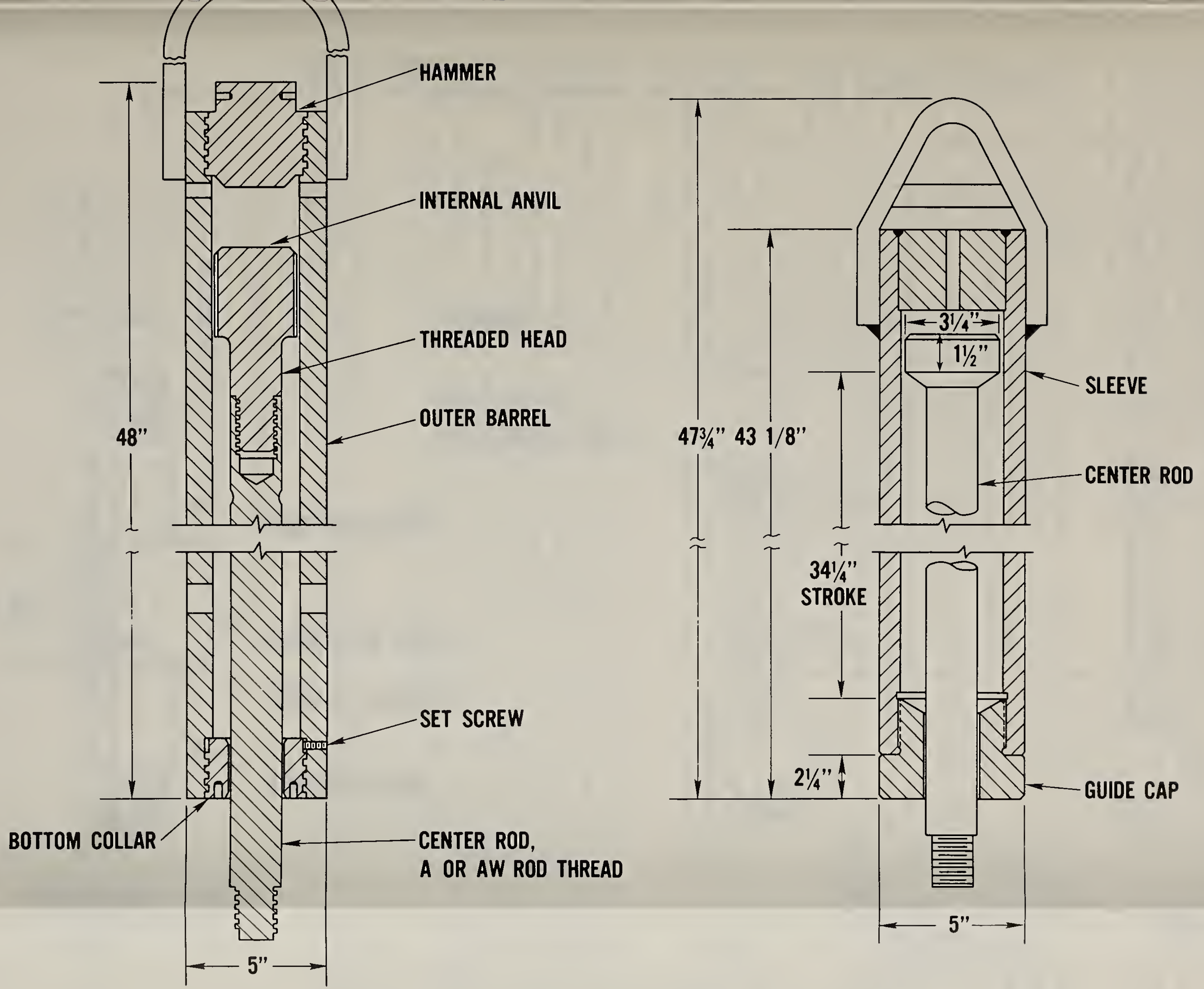


Figure 2.2 SPT 140 lb (63.5 kg) hammers - (c) safety hammer with typical designs

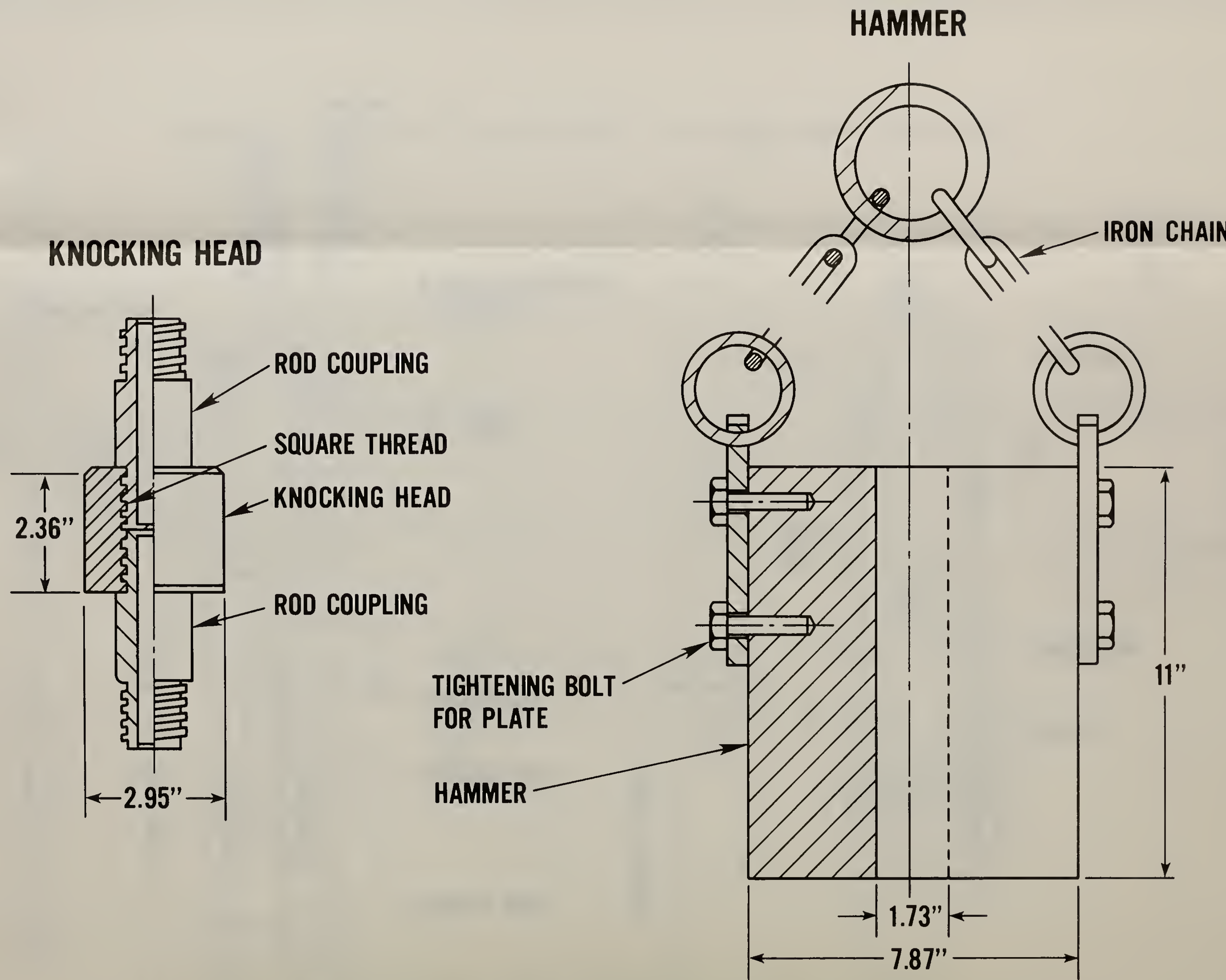


Figure 2.2 SPT 140 lb (63.5 kg) hammers - (d) donut-type hammer and anvil used in Japan

The donut (shaped) hammer is shown in figure 2.2b and is manufactured as a right circular cylinder as well as an oval cylinder. Generally, the inside diameter of the hammer is larger than the outside diameter of the slip pipe by approximately one quarter-inch. The "drive ring" is an optional piece of equipment that is used with a donut hammer by some operators to protect the face of the hammer and the anvil during driving.

Figure 2.2c shows typical safety hammers which were developed in the mid 1950's by the California Division of Highways. The bottom collar of the safety hammer tends to maintain the alignment between the hammer and anvil during the fall. One safety hammer manufacturer provides a stroke of 29.75 in (75.6 cm). Consequently, the average fall height using this hammer will be below the 30 in (76 cm) standard. Safety hammers are manufactured with variable size drill rods. The AW rod size is the most popular. In addition, the hammer rods used may be either hollow or solid rods. The rod connection to the anvil or impact block may be either welded or threaded with a lock pin. The implication of the variable rod cross sectional area on energy transfer and measurement is discussed in section 3.2.

For comparison purposes, figure 2.2d shows the standard hammer, knocking head (anvil), and rod size that are used in Japan (Japanese Industrial Standard, JIS A1219-1961 (Reaffirmed: 1976). Generally the Japanese hammer is smaller in diameter and taller than U.S. hammmers; the anvil is considerably smaller than the U.S. anvil.

Some district offices of the U.S. Army Corps of Engineers and the Waterways Experiment Station use a hydraulically operated chain driven trip hammer. Marcuson and Bieganonsky (1977a, b) have used a hammer of this type in their studies. The hammer itself is approximately 5 1/2 in (140 mm) in diameter and 15 3/4 in (400 mm) long, and consists of a steel casing that is filled with lead. "The hammer is mechanically lifted to a 30 in (760 mm) drop height by two lugs positioned on a continuous chain. The chain is driven by a hydraulic motor connected to the hydraulic system of the drill rig. The rate of driving (is) approx. 15 blows/min..." (Marcuson and Bieganonsky, 1977a).

The following numbers summarize the distribution of hammer types obtained from ASFE study (Kovacs, 1982) where 180 questionnaires were sent out and 116 replies were received.

71	- Safety hammer (56 percent of total)
41	- Donut hammer (33 percent of total)
14	- Pin-guided hammer (11 percent of total)
126	Total (some respondents use more than one hammer type. Seven respondents did not know what type of hammer was used and 6 did not give a reply.)

Table 2.3 Summary of Typical SPT Drill Rod Information from Manufacturers Catalogs

Drill Rod Size	Upset Wall	Parallel Wall	X-Sectional Area in^2	OD in	ID Parallel in	ID Upset in	Weight Per Foot of Rod[a]			
							1' lbs	2' lbs	5' lbs	10' lbs
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
E		x	0.834	1 5/16	13/16		3	6	14.5	29
A		x	0.847	1 5/8	1 1/8		4.5	8.5	20	38
B	x		1.301	1 29/32		1 13/32	6[c]	10.5[c]	25	47
N	x		1.289	2 3/8		2	10[c]	13.5[c]	27	49
EW		x	0.795	1 3/8	15/16		3.5	6.5	15	31
AW	x	x	1.178	1 3/4	1 1/4	(1 7/16[b])	5	8	21 18[b]	42 33[b]
BW	x		1.141	2 1/8	1 3/8[c]	1 3/4	9[c]	11[c]	24	43
NW	x		1.212 (2.270)[c]	2 5/8	2[c]	2 5/16	11[c]	15[c]	31	55

[a] Without coupling
[b] Upset wall available
[c] Usually furnished with parallel wall for 1 and 2 ft lengths.

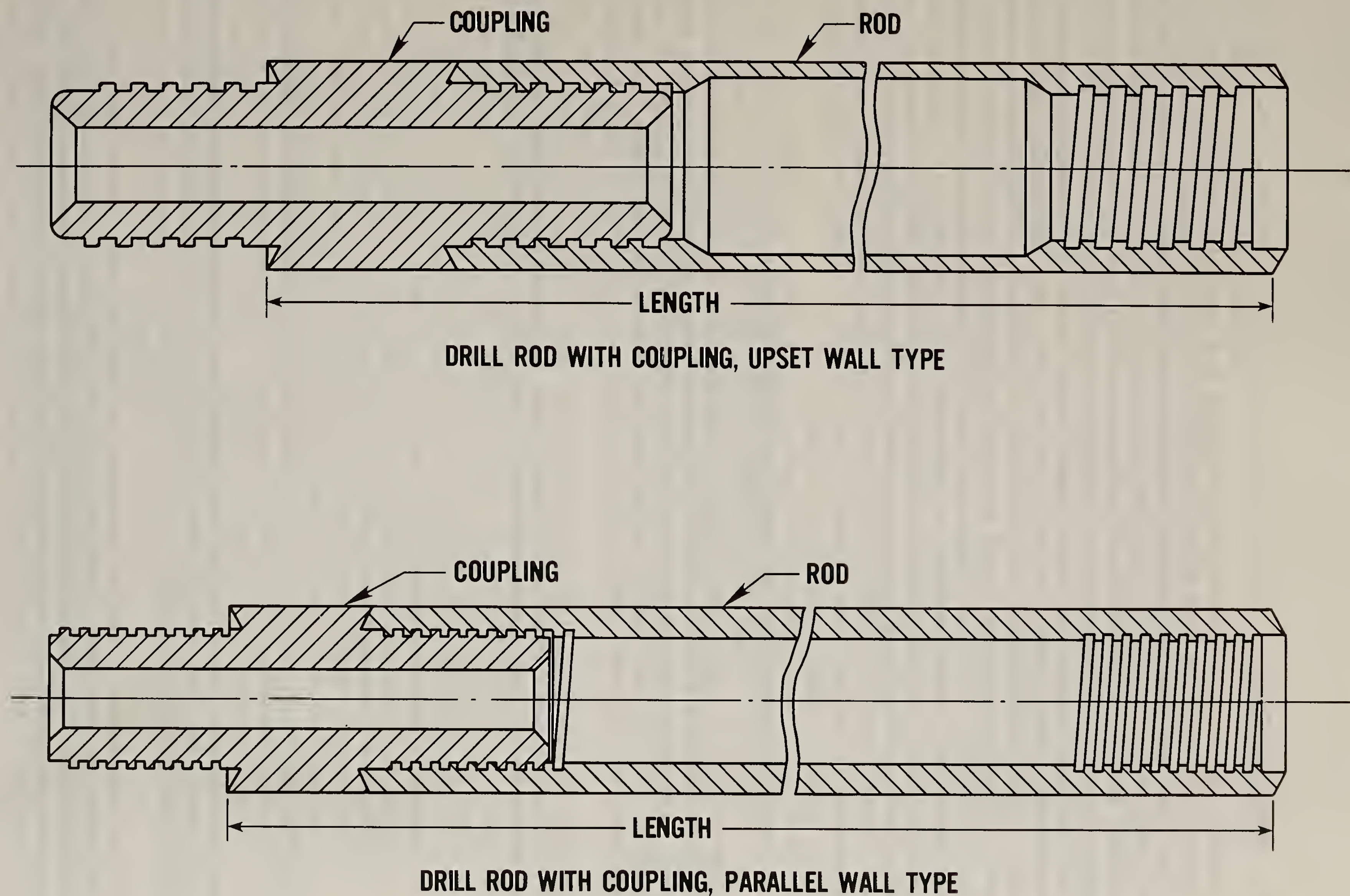


Figure 2.3 Illustration of drill rod wall types - (a) parallel wall (b) upset wall

2.3 DRILL ROD TYPES

A variety of drill rod sizes are available and permitted by ASTM D 1586 to perform the SPT. The rods are available in 1, 2, 3, 5, and 10 ft (0.30, 0.61, 0.91, 1.52, and 3.05 m) lengths including coupling. Drill rods are available in upset wall and parallel wall thicknesses. The parallel wall rods have a constant cross-sectional area throughout their length (except for the coupling); while the upset wall rods have a reduced wall thickness in the interior of the rod, just past the threads (see figure 2.3). Table 2.3 summarizes typical dimensions of drill rods available for the SPT. For the single letter size rods, either parallel wall or upset wall is available. For the double letter size (W symbol for heavier wall thickness), both wall types are available. For the AW size, both wall types are available for different lengths. Usually only the 1 and 2 foot sections of BW and NW size are parallel wall sizes, while the 5 and 10 foot sections come in upset wall. The importance of cross-sectional area in energy measurement will be discussed in section 3.2. Since 1961, the problem of drill rod size variation has been solved in Japan by standardizing the equipment (Yoshimi and Tokimatsu, 1983) where the "cone-pulley method" (cathead and rope) is used.

2.4 FIELD SPT PROCEDURES AND OPERATOR CHARACTERISTICS

Variation in procedures and operator characteristics were observed during this study. Differences in the number of turns of rope around the cathead, the speed in which the blows are made and the inability of the operator to achieve the 30 in (76 cm) fall height were observed. In addition, there is a lack of conformity in the use of SPT sampler liners during the test, as described below.

From the ASFE survey, 83 of 116 stated that they stipulate the number of turns of rope around the cathead that the driller or operator may use. When asked how many turns of rope were ordinarily used, ninety respondents replied as follows:

Using 1 turn only:	2
Using 1 & 2 turns only:	7
Using 2 turns only:	68
Using 2 & 3 turns only:	5
Using 3 turns only:	8.

From this breakdown it appears that two turns of rope around the cathead is the most popular practice.

When the engineer was asked if the driller was allowed to switch the number of turns during the day, 19 said yes; 84 said no; 4 did not know one way or another; and 9 did not reply.

The rate and manner in which operators perform the test varies substantially. Some operators will use a continuous motion achieving a rate of 50 $\pm$ 10 blows per minute, the "rhythmic" procedure, while others will use a "hold-drop" procedure at an approximate rate, from 15 to 25 blows per minute. In the hold drop procedure, the operator slowly raises the hammmer (by rope) until the

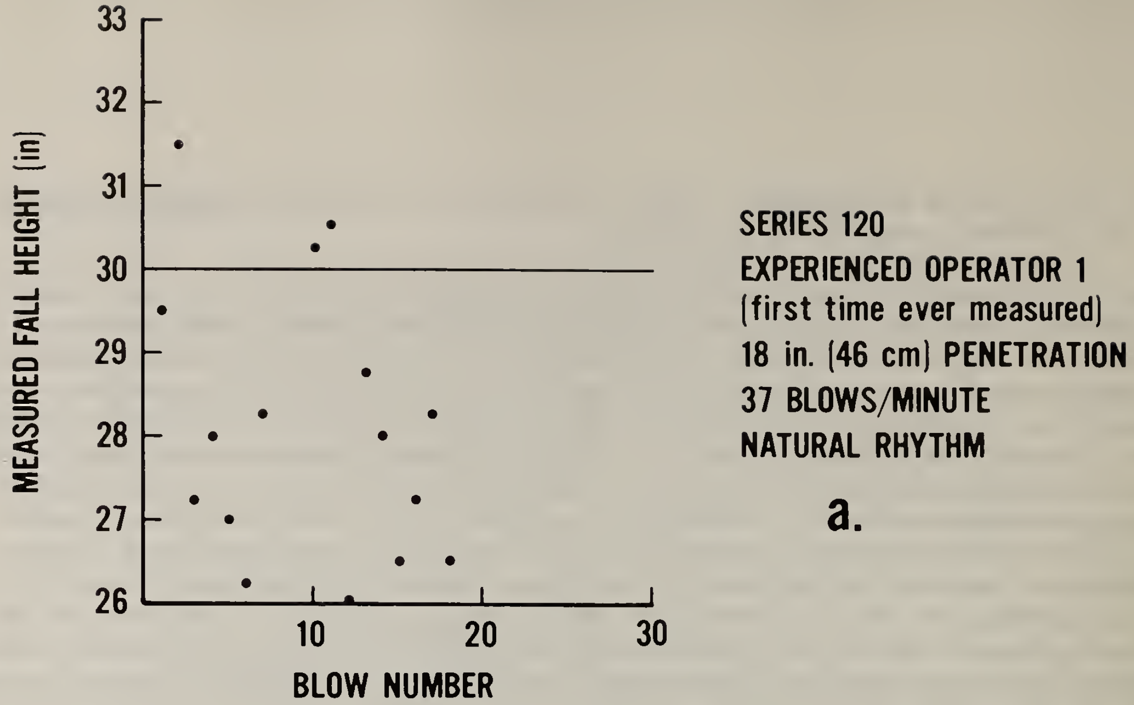
30 in (76 cm) mark is visible. Then, the operator quickly releases the rope into the cathead, completing the blow.

Figure 2.4 illustrates how the fall height varied with each blow for three experienced operators. Operator 1 performs the test using a continuous motion (figure 2.4a, b) while operator 2 attempts the 30 in (76 cm) fall using the hold-drop method (figure 2.4c). Note how the fall height with each blow varied for operator 1. Operator 2, who was experienced but used the hold-drop method, appears to have held the rope at the same locations during sampler penetration and changing his position at the four times when the fall height was below the gradual increasing trend (for example, at blows 4, 12, 14, and 17). Figure 2.4d, shows a third experienced operator who used a cathead and rope. There is considerable variability in the fall height produced by operators 1 and 3. There also seems to be a tendency for the average produced in any one run by the same operator to differ from the standard 30 in (76 cm) fall height. These examples plus those published elsewhere (Kovacs, et al., 1981) illustrate the wide variation in fall height that occurs with experienced drillers when performing the SPT.

Figure 2.4 also shows some tendency for a warm up effort during the performance of the SPT, with fall height and therefore energy tending to increase with additional blows. Figure 2.4c shows this trend most strongly. The blows needed for 0 to 6 in (0 to 150 mm) penetration allow the operator to establish his rhythm and are not counted to establish the N value or "blowcount". However, all the average energy ratios (later discussed) reported herein are comprised from all the blows and not the last 12 in (300 mm) of the prescribed 18 in (450 mm) drive. Perhaps this aspect must be addressed in future reporting of energy ratios (ER_i).

A very important detail regarding the practice of performing the SPT involves the use of liners inside the SPT sampler. Present construction of the SPT sampler, according to ASTM D 1586, requires that the inside diameter of the cutting shoe be 1 3/8 in (35 mm) and the inside diameter of the barrel be 1 1/2 in (38 mm). Schmertmann (1979) points out that most drillers do not use liners with the 1 3/8 in (35 mm) inside diameter SPT sampler shoe. This extra space reserved for a liner allows for reduced frictional resistance during sampling and may account for a 30 percent reduction in N value for insensitive clays and a 10 percent reduction for sands (Schmertmann, 1978). According to the ASFE survey, 60 respondents stated that they use the 16 gauge liner while 43 do not; seven respondents did not know and there were five "no responses." However, W.L. Acker estimates that 5 percent or less obtain the liners at the time of purchasing SPT split barrel samplers. Further, he estimates that 5 percent or less purchase of the ASTM (D 1586) SPT sampler shoe (personal communication, 1983). Attention to this detail is very important, and it is recommended that a decision be made which practice to use, and subsequently one or the other practice be used consistently.

SPT standards in Japan (Japanese Standards Association, 1976) and the United Kingdom (British Standards Institution, 1975) do not allow a space for liners; the inside diameter of the barrel remains identical to the cutting shoe at 1 3/8 in (35 mm).



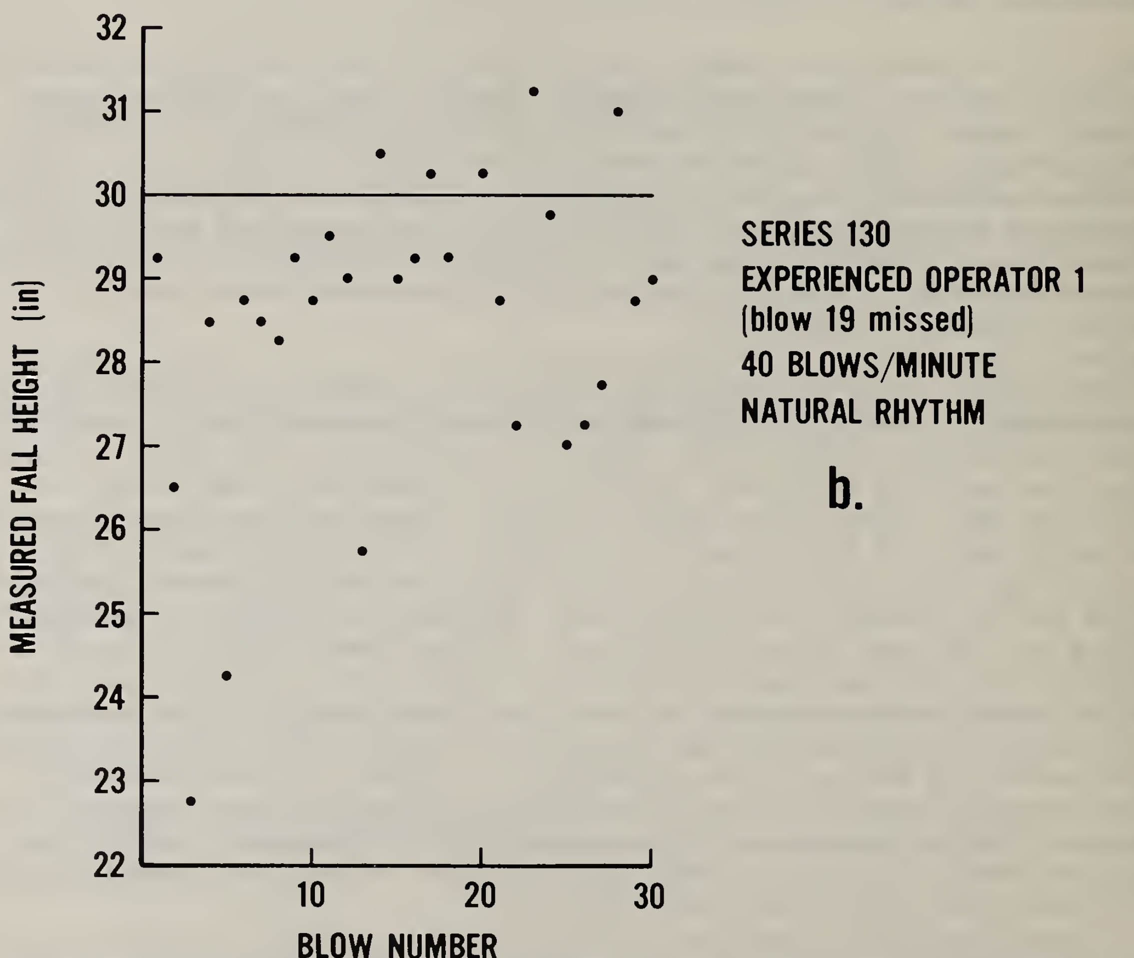
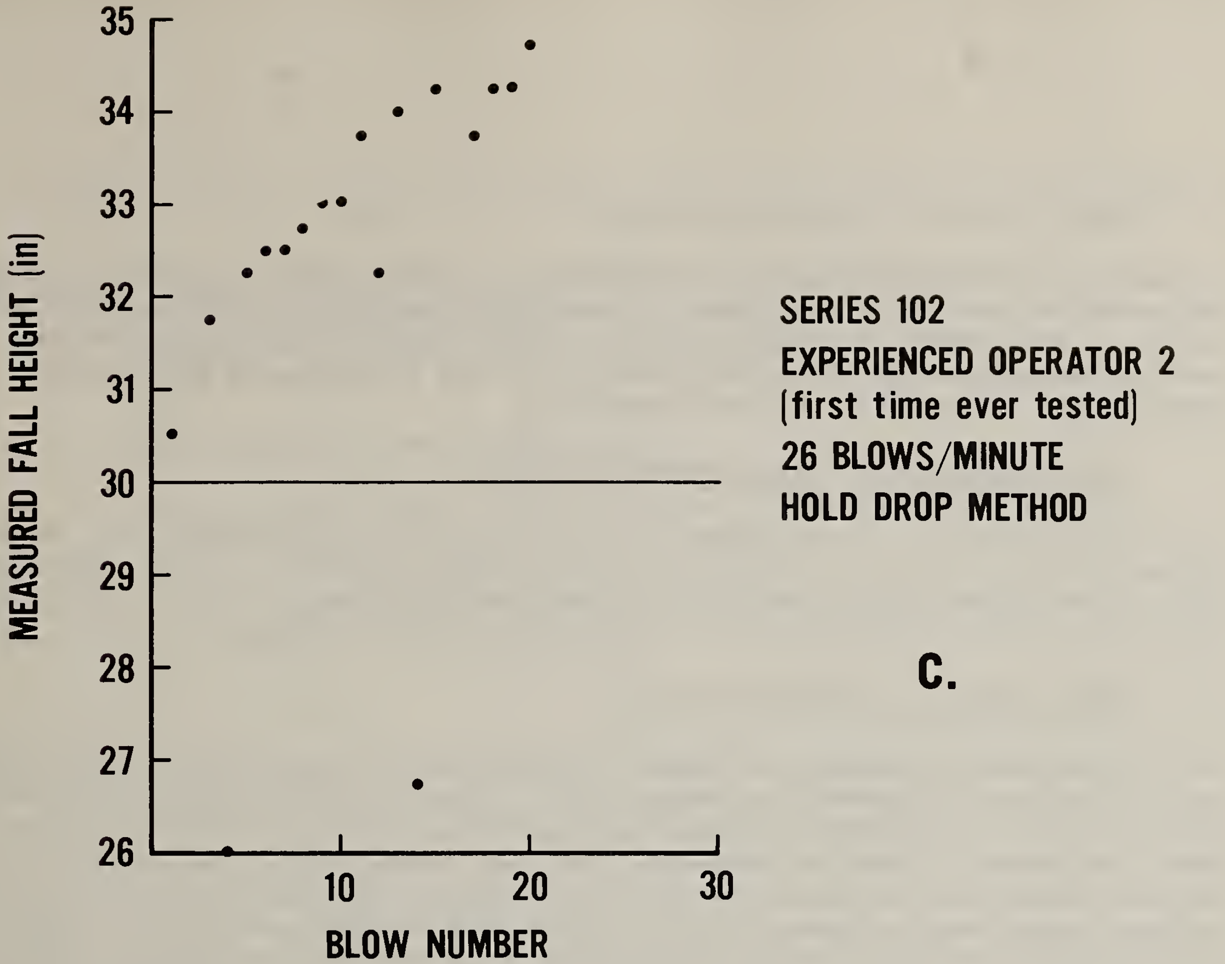


Figure 2.4a Typical results of fall-height vs. blow number from experienced drill rig operators performing the SPT - (a), (b), and (d) usual rhythmic method; (c), hold-drop method



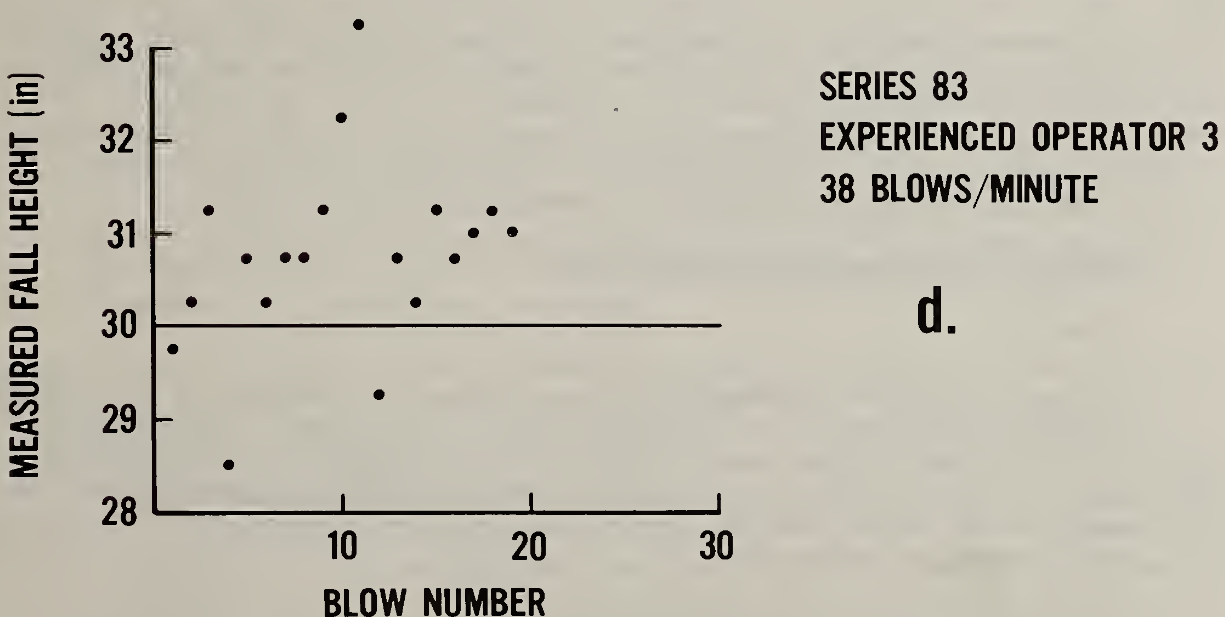


Figure 2.4b Typical results of fall-height vs. blow number from experienced drill rig operators performing the SPT - (a), (b), and (d) usual rhythmic method; (c), hold-drop method

3. CURRENT METHODS OF ENERGY MEASUREMENT

Presently (1983), NBS measures the SPT energy at three points in the SPT system: The potential energy of the hammer is measured via the fall height; the kinetic energy of the hammer is measured via the hammer impact velocity; the energy passing through the drill rod is measured via the force in the drill rods. These energy measurements are now described.

3.1 POTENTIAL ENERGY OF HAMMER BEFORE RELEASE

The potential energy of the hammer is calculated from the measured fall height. The measurement of the fall height is accomplished together with the measurement of the hammer impact velocity as described by Kovacs et al., (1981). The accuracy of this measurement is to the nearest 1/8 in (3 mm).

3.2 KINETIC ENERGY JUST BEFORE IMPACT

The kinetic energy just before impact is determined by measuring the fall-time relationship of the hammer during its fall. From this relationship, the fall height and the instantaneous velocity just before impact are obtained, from which the kinetic energy is computed. Detailed procedures to accomplish the velocity measurement for the three types of hammers mentioned in section 2.2 has been described by Kovacs et al., (1981), and by Goble and Ruchti (1981) for safety hammers. We denote this energy as E_v and the corresponding energy ratio for velocity, ER_v, which is defined as the ratio of E_v divided by mg of the hammer times the measured fall height. A second measure of the energy ratio for velocity is ER_v^*, which is defined as E_v divided by 4200 inch-pounds. This latter energy ratio is referenced to the prescribed energy of the 140 lb (63.5 kg) hammer falling 30 in (760 mm). The accuracy of the hammer impact velocity measurement is as good as the accuracy of the time and the distance measurements involved and there is no ambiguity in the interpretation of its results. The next section describes the measurement of the energy passing through the drill rods. The percentage of the energy just before impact that is measured in the rods is further discussed in section 3.4.2.

3.3 ENERGY PASSING THROUGH THE DRILL ROD

3.3.1 Theory

A useful summary of the one-dimensional wave theory as applied to drill rods is provided by Schmertmann and Palacios (1979) with further details given Palacios (1977) and is discussed further by Hall (1982). For convenience to the reader, a short summary is provided below. The energy transmitted from the hammer to the drill rods in the form of the first compressive stress wave is given in terms of stress as

$$E_i = \frac{A}{\sqrt{E\rho}} \int_o^t \sigma_i^2 \, dt \qquad (3.1)$$

and in terms of force as

$$E_i = \frac{c}{AE} \int_o^t F_i^2 \, dt = \frac{1}{A\sqrt{E\rho}} \int_o^t F_i^2 \, dt \tag{3.2}$$

where E_i = energy passing through the drill rod at the point of measurement
A = drill rod cross-sectional area
c = compressive wave velocity in the steel drill rod
E = Young's modulus of the steel drill rod, above and below the load cell
ρ = mass density of the steel drill rod
F_i = incident compressive force, F(t) measured in the drill rods
t = the time from impact until the return of the reflected tensile stress wave to the hammer/anvil interface.

Once the force-time relationship is known, the energy in the stress wave in the drill rod may be computed using equation 3.2.

3.3.2 Application of Theory

The force-time relationship is measured by a load cell placed at least ten drill rod diameters below the anvil to be a sufficient distance from a discontinuity. The theory assumes that the stress in the drill rod above and below the load cell is F/A, where F is the measured force in the load cell and A is the cross-sectional area of the drill rod. However, because of combinations of couplings, reducers, and upset wall and/or parallel wall drill rods, the theory is seldom completely satisfied in practice. Also, the load cell introduces a discontinuity in the drill stem cross-sectional area. Several corrections to equation 3.2 are required to account for departures from theory. They are:

a) K_1, a correction to account for the load cell not being at the point of impact,

b) K_2, a correction to account for drill rod length, and

c) K_c, a correction which accounts for deviations from assumed rod characteristics. One deviation which was observed is that the actual compressive stress wave velocity in the steel drill rod tends to be less than the theoretical velocity.

Since the point of impact is some distance, $\Delta\ell$, from the load cell, a correction factor K_1 must be included (revised, from Hall, 1982).

$$K_1 = \frac{1 - \exp\left[-4A\rho\ell/M_h\right]}{1 - \exp\left[-4A\rho\,(\ell-\Delta\ell)/M_h\right]} \tag{3.3}$$

where K_1 = a correction to account for the load cell not being at the point of impact
ℓ = distance from the point of hammer impact to the bottom of the sampler
$\Delta\ell$ = distance from the point of impact to the location where F_i is measured

M_h = mass of the hammer
exp = base of the natural logarithm raised to some power.

The second correction, K_2, involves the total length of the rod and its effect on the duration of the first compressive wave pulse (Hall, 1982). If the total length of the rod is "short", then the compressive wave returns prematurely to limit the energy being "pumped in" by the hammer. The second correction is necessary to compare drill rods at the same (infinite) length.

$$K_2 = \frac{1}{1 - \exp\left[-4A\rho\ \ell/M_h\right]} \tag{3.4}$$

where K_2 = a correction to account for drill rod length

The last correction factor, K_c, was suggested by Schmertmann (Private Communication 1982) and involves a small correction to account for the fact that the time required for a tensile stress wave to return from the end of the sampler to the point of force measurement is longer than the theoretical time required. Even though this phenomenon has not been fully explained at this time, it is tentatively attributed to a deviation from the assumed elastic rod properties and perhaps rod coupling effects and the calculated energy is modified accordingly.

Thus:

$$K_c = \frac{c_m}{(E/\rho)^{1/2}} \tag{3.5}$$

where K_c = a correction to account for the actual compressive wave velocity in the steel rods and couplings.
c_m = compressive wave velocity as calculated from the measured time of return of a reflected wave.

When these corrections are applied, equation 3.2 becomes:

$$E_i = \frac{K_1 K_2 K_c}{A\sqrt{E\rho}} \int_o^t [F(t)]^2\, dt \tag{3.6}$$

and $E = 29.7 \times 10^6$ psi, (0.20 TPa)
$\rho = 7.24 \times 10^{-4}$ lb-sec^2/in^4 (7.85 Mg/m^3)

While the accuracy of the measurements of the potential energy and kinetic energy is only limited by the accuracy of the distance and time measurements involved, the measurement of E_i depends on theoretical assumptions and idealizations and at this time it has not been validated by an independent energy measurement. However, the measurement is at a point which is below the anvil and closer to the sampler and thus accounts for energy losses which occur after the hammer impact, and therefore conveys important and necessary information on hammer and anvil characteristics. The data on E_i obtained in this study appear reasonable when compared to the E_v data, and it is also reasonable to assume that for the same drill rod size and configuration a valid comparison of different hammer and anvil configurations can be made. The data in this report will be re-evaluated by NBS if and when independent calibration data for the measurement of E_i become available.

There are several methods by which equation 3.6 may be readily evaluated. These methods are described below.

3.3.2.1 Digital Processing Oscilloscope

The digital processing oscilloscope (DPO) is a real time oscilloscope that converts the analog force-time history into digital form at an adjustable, desired rate. The entire time history may be displayed for viewing. The output from the load cell is recorded in analog form in the field on tape at 60 in/s (1.54 m/s) and later played back at 1 7/8 in/s (48 mm/s) providing a time expansion of 32.00. The tape is played back into the DPO and a digital force-time history is obtained. The DPO is programmable and performs the integration of equation 3.6 automatically once the integration limits are set manually. The details of this procedure have been discussed elsewhere (Kovacs et al., 1981).

3.3.2.2 Other Equipment

Hall (1982) documents the use of an electronic analog instrument that can be utilized in the field to obtain the energy passing through the drill rod, E_i, in real time after each blow of the SPT hammer. Figure 3.1 presents a block diagram of the key elements of this device described as the SPT Energy Calibrator or just Calibrator.[2/] A photograph of the device is shown in figure 3.2 with three cables attached. The left most cable connects the Calibrator to the load cell mounted in the drill stem. The remaining two cables, labeled "trigger" and "force" in figure 3.2, connect the Calibrator to a field oscilloscope or a tape recorder. The trigger cable output allows the integration time of the Calibrator (performing equation 3.2) to be monitored. On the other hand, the force cable output allows the force-time history to be monitored. A cable from the force jack to the tape recorder allows a permanent analog record to be made that can later be reproduced on the DPO.

The Calibrator used in this study was modified in several ways to maximize its use.

a. The internal circuitry has been altered to allow two different load cells to be used interchangeably with the flip of a switch instead of going through an elaborate internal instrument calibration;

2/ "Certain commerical equipment, instruments, or materials are identified in this report to specify adequately the experimental procedure. Such identification does not imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose."

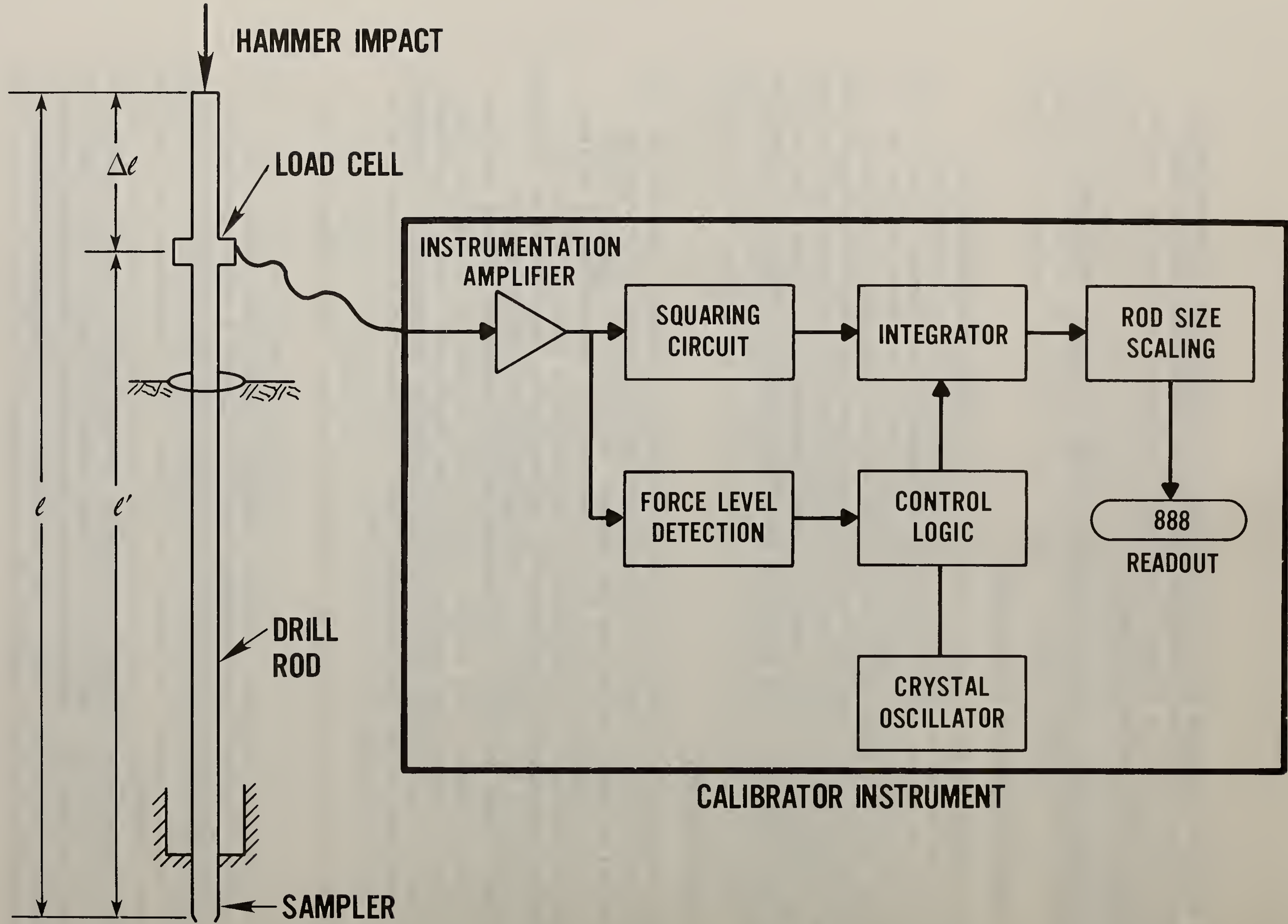


Figure 3.1 Schematic showing the key elements of an SPT energy calibration instrument (modified after Hall, 1982)

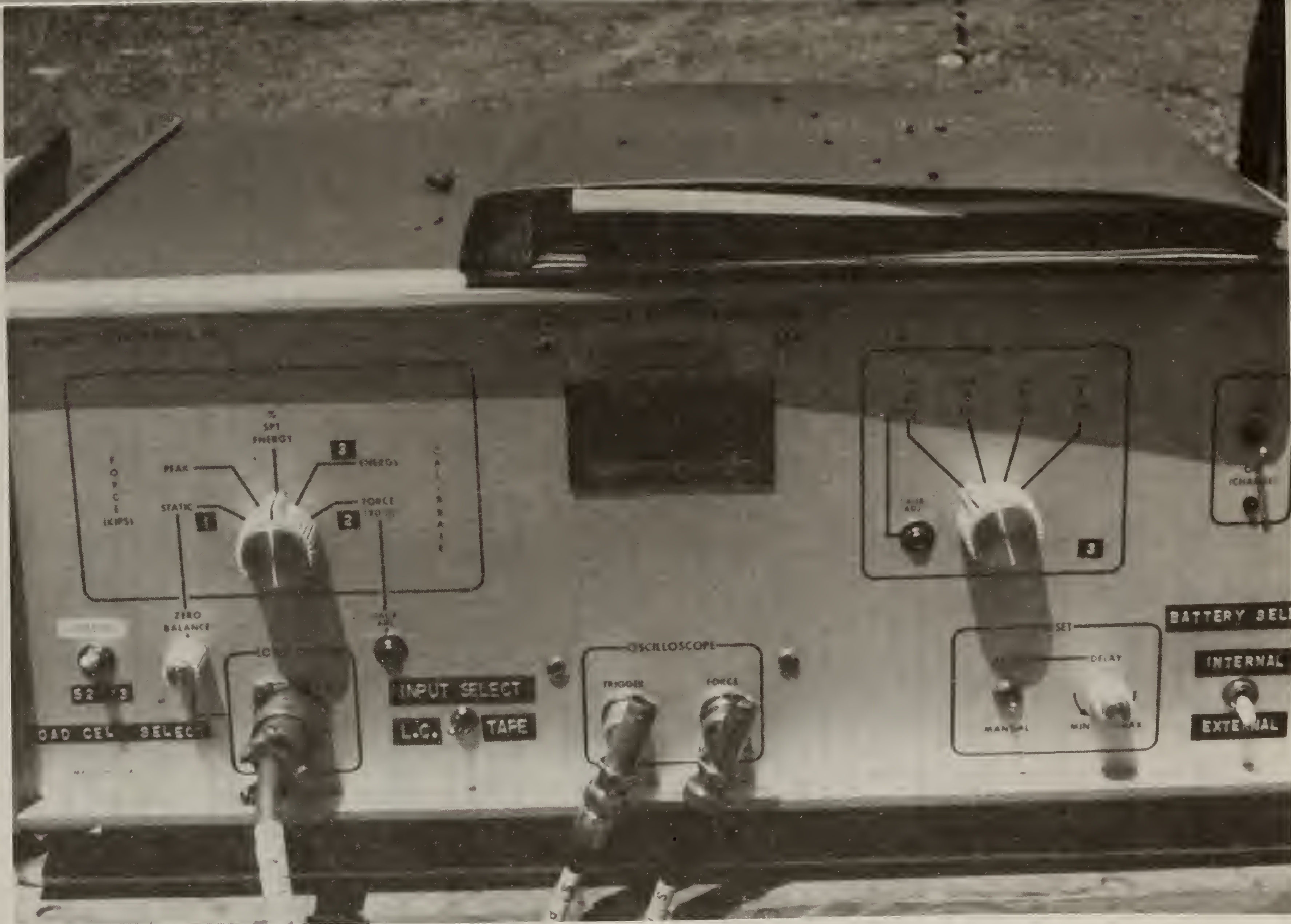


Figure 3.2 Photograph of SPT energy calibrator

b. A new circuit was added to allow a new, higher capacity piezoelectric load cell to be used for field use.

c. A new circuit was added to allow the use of a tape recorded F(t) signal as input to the Calibrator to check actual field readings.

d. Provision to use an external (12 volt) battery as a backup power source.

To use this instrument, a three-step field calibration is necessary prior to each field test: 1) the first step involves setting zero load on the load cell when the 140 lb (63.5 kg) hammer rests on the anvil prior to testing; 2) the second step introduces an electronic signal equivalent to a 20,000 lb (8.9×10^4N) load into the Calibrator for use in step 3; and 3) the third step involves adjusting a pot until the required calibration number shown in table 3.1 for the rod size used appears on the Calibrator display. The display on the face of the instrument shows the output from the Calibrator's integration of equation 3.2, using a 20,000 lb (8.9×10^4N) square wave as the force history and an integration time of t = 8.192 ms, divided by the standard SPT energy of 4200 in-lbs (475 J), E*. For example, for AW (parallel wall) rod, the Calibrator display number is 452 using equation 3.7. When the pot is adjusted so that this number appears on the display, one can be assured that the electronic device is working properly.

$$452_{AW} = \frac{100 \left[\frac{c}{AE} \int_0^t \quad [F(t)]^2 dt \right]}{4200 \text{ in-lbs}} \tag{3.7}$$

It should be pointed out that the Calibrator is programmed for using a theoretical value of c = 16878 ft/s (5144 m/s). There is a need to correct equation 3.3 for the experimental value of c, according to equation 3.5, including corrections K_1 and K_2.

3.4 RESULTS OF ENERGY MEASUREMENT STUDIES

3.4.1 General

The tables and figures in this section provide information on the energy delivered by the various drill rig systems as measured by the kinetic energy at impact and the energy passing through the drill rod. Following introductory comments about typical energy output from the hammer kinetic energy and the force time approaches, a detailed discussion of the data is provided.

Typical results of the kinetic energy just before impact have been presented by Kovacs et al. (1981). This report primarily presents data on E_i, the energy passing through the drill rods. The kinetic energy at impact is discussed as required to document the differences between the kinetic energy just before impact and the energy in the drill rod.

Table 3.1 Tabulation of Calibrator Display Numbers for Drill Rod Areas

Calibrator Display No.	Rod Size	Area (in^2)
(1)	(2)	(3)
493	A	1.079
452	AW	1.177
413	N	1.288
[466]	[BW]	[1.141]
235	NW[a]	2.264
[439]	[NW[b]]	[1.212]

[a] Parallel wall rod
[b] Upset wall rod

Numbers in brackets do not appear on Calibrator selection switch area.

Typical measurements of the force-time history for safety and donut hammers are shown in figures 3.3a and 3.3b taken from four different test series. In these four cases, NW upset wall drill rod of the same length was used. In each of these four blows, the energy ratio for velocity, ER_v^*, was different and varied from 0.63 to 0.80. The energy ratios for E_i were evaluated by the DPO and the Calibrator and were generally within two or three percentage points of each other. An important feature of the force-time history shown in figure 3.3 is the location where the force curve crosses zero force and becomes negative. The time, t_m, at which the crossover occurs is the time when the returning tensile wave cancels the downward compressive wave. This time may be computed theoretically by dividing two times the drill rod length, ℓ' (from the load cell to the bottom of the sampler) by the theoretical compressive wave velocity, c, of the steel drill rod. Note that the measured compressive wave velocity varied from 14,400 ft/s (4389 m/s) to near the theoretical value of 16,878 ft/s (5144 m/s). From these examples and the figures that will be presented subsequently, it should be apparent that each individual blow is different in small ways from any other, just as the fall height varies substantially from one blow to another (see figure 2.4).

For some of the test series performed, deviations from the typical force-time relationships shown in figures 3.3a and 3.3b were observed. The deviations observed can be classified into two groups.

a) Group 1 - Those force-time histories that contain electronic glitches as shown in figures 3.4a and 3.4b.

b) Group 2 - Those force-time histories that contain a significant returning compressive wave (figure 3.5) without the usual initial tensile wave return (figure 3.3a, b).

Electronic shorts in the load cell wires were the cause of the deviations observed in Group 1. Typically, the load cells take substantial punishment with peak forces averaging 20 to 25 kips (89 to 111 kN) for each blow. Because the load cell serves as input to the DPO and the Calibrator, both instruments can experience the same problem.

The presence of glitches can cause the Calibrator to prematurely cut off the integration time prior to the actual crossover point from compressive to tensile stress, resulting in a reduced value of energy ratio, $ER_i = E_i/E^*$ (see figures 3.4a and 3.4b).

For this study, where glitches occurred, the DPO was used to bypass the glitches and approximately compute the energy in the drill rods for the correct time interval.

The deviations in Group 2 can be explained by referring to Timoshenko (1934). When a prismatic bar is struck, in the case of a free end (drill) rod, a compressive wave is reflected as a similar tension wave. In the case of a fixed end (drill) rod, a compressive wave is reflected as a similar compressive wave (Timoshenko, 1934). Under certain SPT driving conditions which have not been well defined thus far, except as "hard driving," compressive wave returns have been observed randomly within a series of blows.

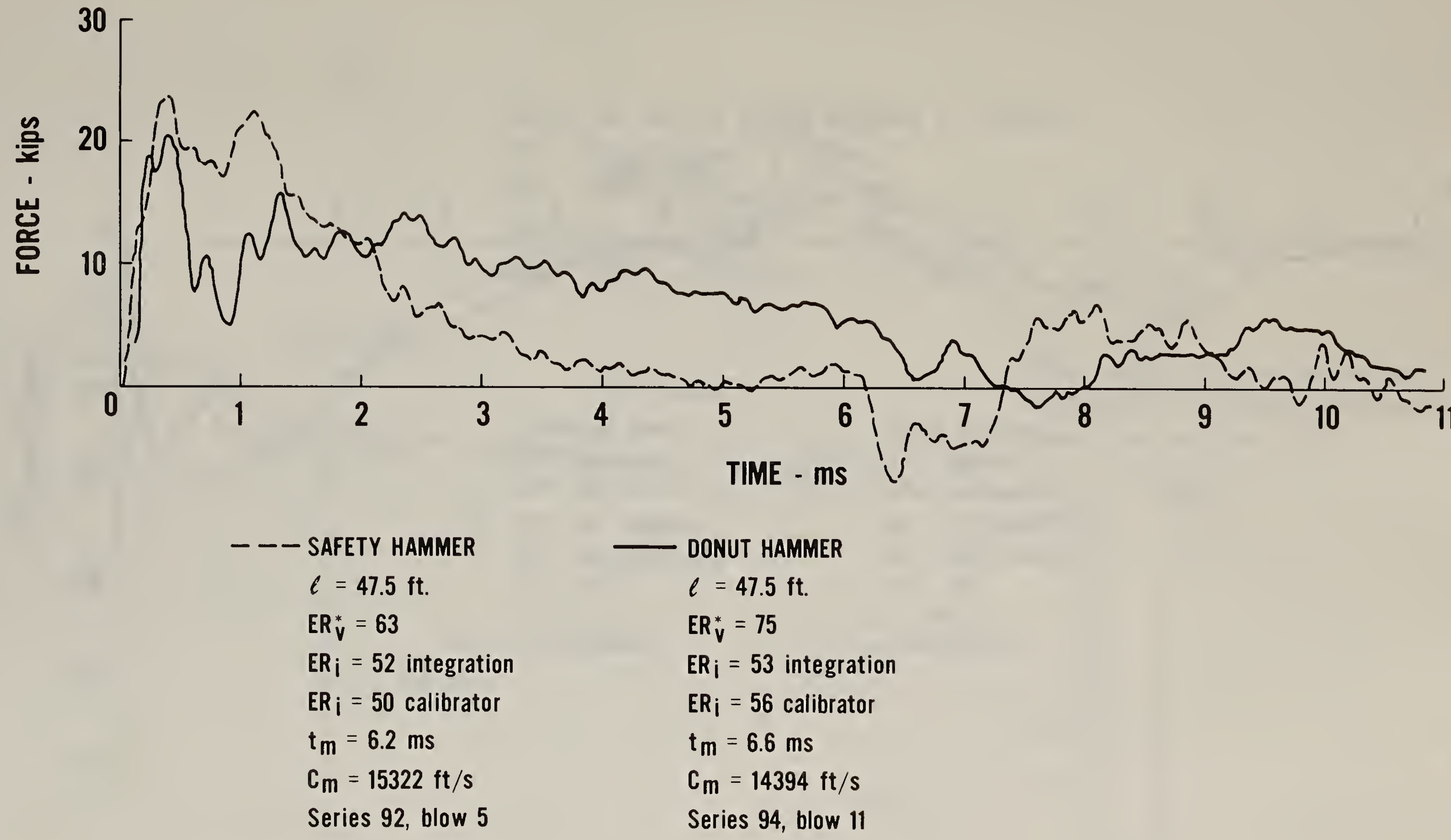


Figure 3.3a Examples of typical force-time histories of safety hammers and donut hammers

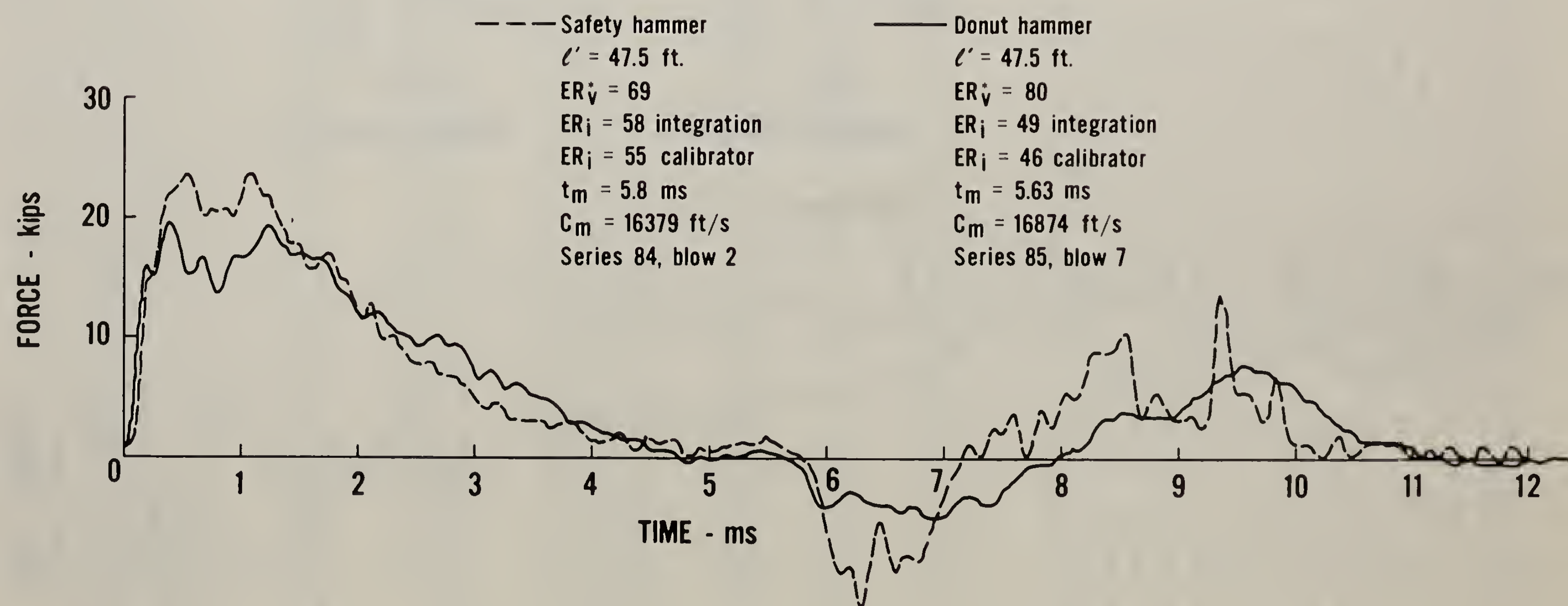


Figure 3.3b Examples of typical force-time histories of safety hammers and donut hammers

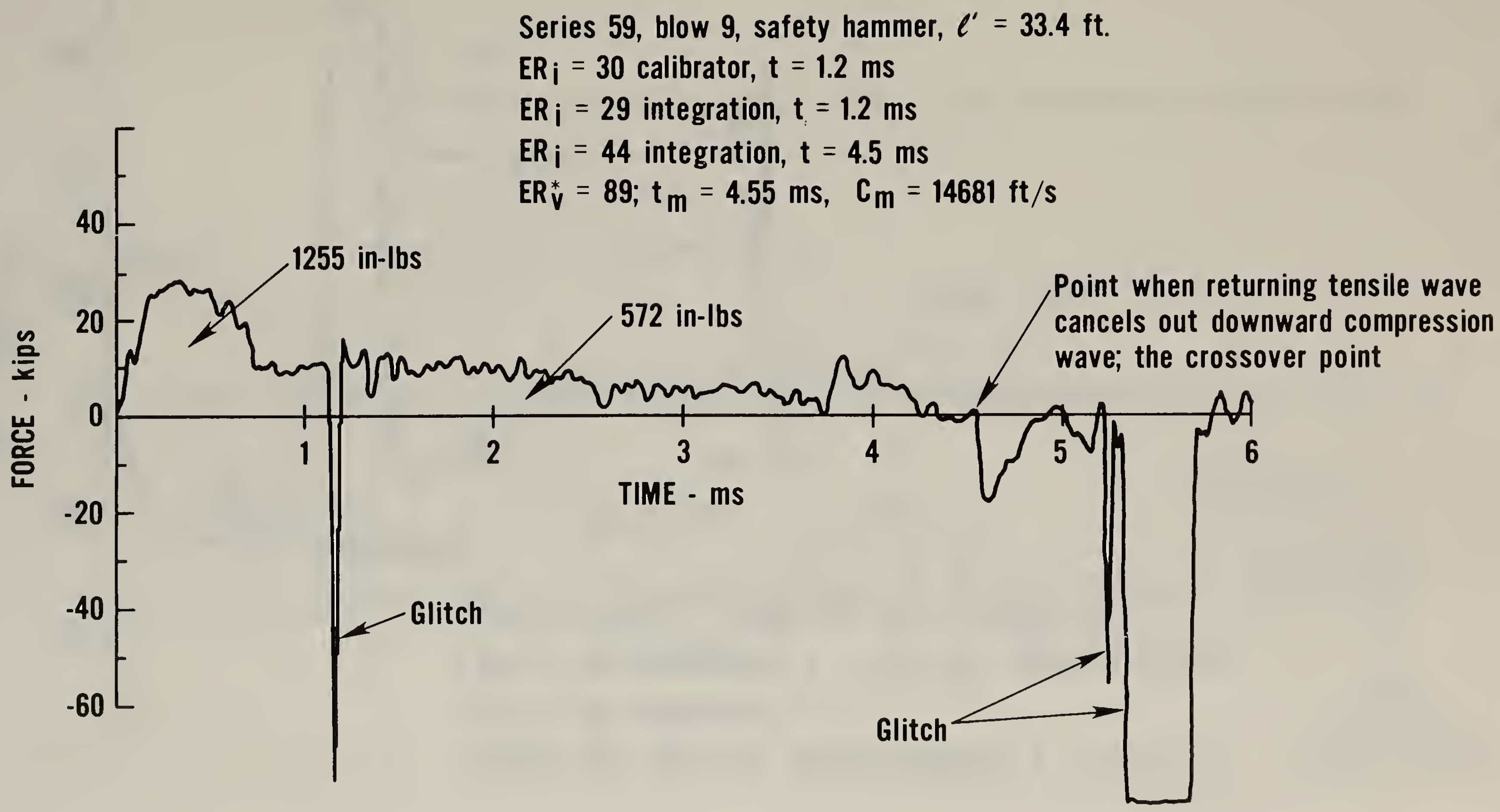


Figure 3.4a Two examples of electronic shorting of load cells during impact

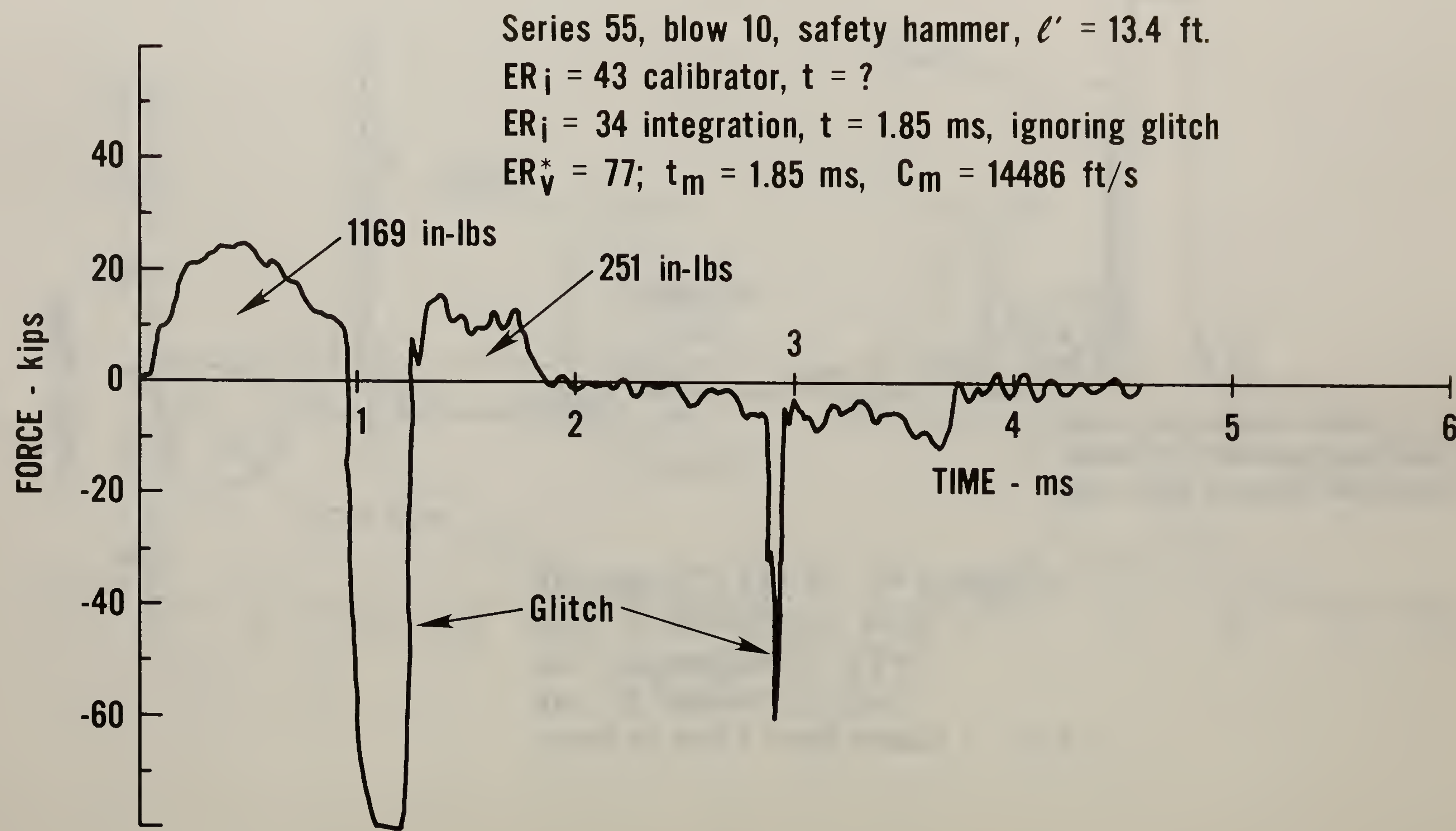


Figure 3.4b Two examples of electronic shorting of load cells during impact

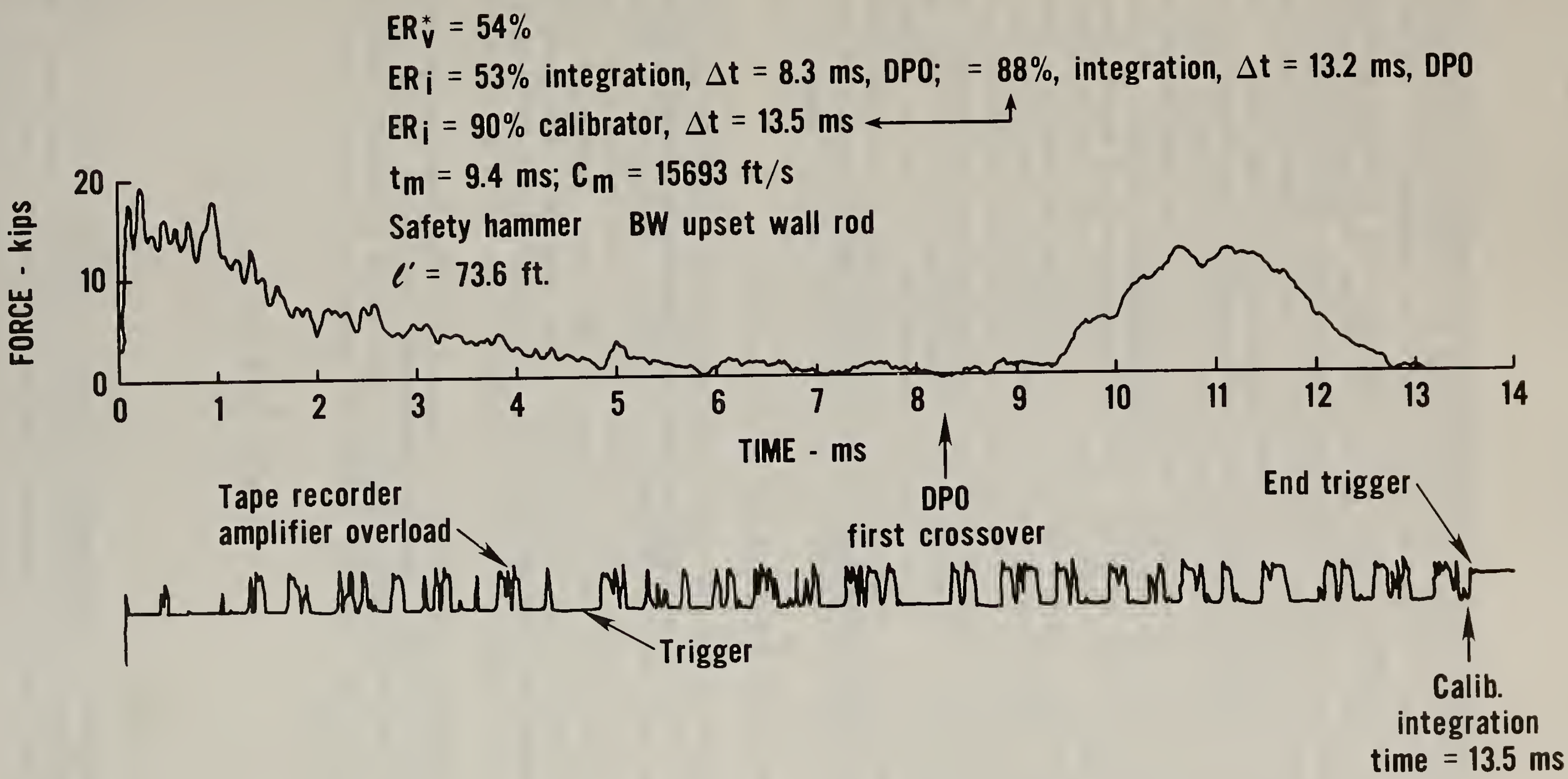


Figure 3.5 Illustration of compressive wave return force-time history and trigger (duration) time

Figure 3.5 illustrates a blow where such a compressive wave returned from the SPT sampler which caused the Calibrator to integrate the force-time curve well above the computed value of 2 ℓ'/c (8.92 ms assuming C = 16,500 ft/s).[3/] Similar compressive wave returns have been observed in pile driving (Gravare and Hermansson, 1980). A value of ER_i = 0.90 was determined from the Calibrator with an integration time (based on the trigger measurement) of 13.5 ms. When the integration is performed on the DPO with an integration time of 13.2 ms, ER_i = 0.88, showing close agreement to the Calibrator value. Naturally, the DPO operator would recognize what was occurring and choose an integration time of 9.4 ms, close to the computed value of $2\ell'/c$. However, the first crossover point of the force-time curve occurs at 8.3 ms for this blow and the resulting ER_i = .53, or almost one-half of the Calibrator reading. The writers have observed many instances where the Calibrator reading would sometimes double randomly, during a series of blows. A solution to this problem is to monitor the integration (trigger duration) time of the Calibrator. Blows that have integration times that are inconsistent with the computed value of 2 ℓ'/c should be discarded. This measurement may be made either by a commercially available digital timer that attaches directly to the trigger jack of the Calibrator or by means of attaching a storage oscilloscope to the oscilloscope jack of the Calibrator. Under these circumstances, it may be necessary for two individuals to take data depending on experience: one who reads the Calibrator data (using a hand held tape recorder); the second observing the blow on the scope or reading (and verbally recording) the digital timer.

3.4.2 Results of Energy Measurements

Field test data from six drill rigs and eleven operators are presented, and field test results and implications are discussed. Table 3.2 summarizes the test Series and test conditions. A series is defined as a collection of SPT hammer blows performed under a given set of conditions; e.g., rig, hammer, operator, depth, rod, etc. In many of the cases studied, the fall height, H, and kinetic energy just before impact, E_v, have been obtained along with the energy transmitted through the drill rods, E_i, calculated using the DPO. For Series 79 through 130, SPT Calibrator data are also presented.

When the measured energies are compared with the standard potential energy [4200 in-lbf (475J)], a useful parameter, the energy ratio, is defined for the purpose of discussing test results. The ratio of kinetic energy just before impact, E_v, to the standard potential energy is defined as the energy ratio for velocity, ER_v^*.

$$ER_v^* = \frac{E_v}{E^*} \times 100, \text{ percent} \tag{3.8}$$

[3/] The Calibrator is programmed to cease integration when the force becomes zero upon the return of the reflected tensile stress wave. When a compressive stress wave is returned, the Calibrator will not cease integration at 2 ℓ'/c and thus overestimate the energy passing through the rods.

Table 3.2 Tabulation of Test Series Performed and Test Conditions

Site	Series	Drill Rig	Hammers[a]	Personnel	Test Procedures	Other
(1)	(2)	(2)	(3)	(5)	(6)	(7)
A	48-61	CME 45	D, S	1 experienced operator	2 turns (of rope around cathead)	Depth varied, AW rod
B	79-101	Mobile B-61	S, D	4 experienced and 3 inexperienced operators	1, 2, & 3 turns; free fall and hold drop tests	Constant depth, NW rod
C	102-109	Mobile B-61	S, D	3 experienced operators	1, 2 & 3 turns; free fall tests	Constant depth, BW rod
D	110-112	Longyear AC-150	S	2 experienced operators	2 turns	constant depth, BW rod
E	113-119	CME 75	S	3 experienced operators	1, 2, & 3 turns; free fall tests	Constant depth, BW rod
F	120-130	Failing 1500	S	3 experienced operators	1, 2, & 3 turns; free fall tests	constant depth, BW rod

D denotes donut (type) hammer and S denotes safety (type) hammer.

The ratio of the kinetic energy transmitted through the drill rod, E_i, divided by the standard potential energy is defined as the energy ratio for F(t), ER_i.

$$ER_i = \frac{E_i}{E^*} \times 100, \text{ percent} \tag{3.9}$$

In subsequent paragraphs, the energy ratios defined above will be used to:

a) Establish the efficiency of the hammer delivery system, ER_v^*.

b) Compare the results between the energy passing through the drill rod, ER_i as measured by the DPO and the SPT Calibrator.

c) Study the relative efficiency of the various hammer-anvil systems in transmitting the kinetic energy just before impact to the drill rod.

d) Study the effects of personnel (operators), equipment (drill rig, hammer, drill rod) and procedures (fall height, rate of blow count, depth) on the energy transmitted through the drill rod, ER_i.

A summary of results and test variables for Series 48 through 130 is presented in table 3.3. Individual field data of ER_i, percent from the SPT Calibrator are presented in appendix tables A-1 through A-7 while tabulation of individual fall heights for some series are given in appendix tables B-1 through B-4.

The average energy ratio for velocity, ER_v^*, from columns 13 in this table for all the drillers using two turns of rope around the cathead is approximately 73 percent, with a standard deviation of 10.2 percent and a range from 50 to 90 percent.

The energy ratio ER_i was determined using the DPO and the SPT Calibrator. Individual data points for selected blows for Series 48 through 130 (excluding free-fall test data) are presented in table 3.4 where energy ratios from the Calibrator and those computed using the DPO are listed. To facilitate the comparison between the two methods, figure 3.6 has been drawn. Data points that had integration times greater than 2 ℓ'/c were not used and are identified by the superscript "d" on table 3.4.[3/] The equation of the line on figure 3.6 based on a linear regression analysis is:

$$ER_{i\ Calib} = 1.076\ ER_{i\ DPO} - 3.37 \tag{3.10}$$

where $ER_{i\ Calib} = ER_i$ from the SPT Calibrator,

$ER_{i\ DPO} = ER_i$ computed using the DPO,

and has a correlation coefficient of 0.976. The least square's fit line is very close to the one-to-one equality line in the range of interest (0.4 to 0.7).

The Energy Transfer Ratio, ETR, has been defined (Kovacs et al., 1981) as:

Table 3.3 Tabulation of Results and Testing Variables Using Two Turns of Rope Around the Cathead

Type Rig	Series	Hammer Type	Operator	No. of Data Points	Avg. Fall Height	Fall Hgt Stnd Dev.	Calibrator Avg ER_i	Calibrator ER_i Stnd Dev.	Calibrator ER_i CV	No. of Data Points	DPO Avg ER_i	DPO Avg ER_v^*	$\Delta\ell$	ℓ	Test Rate
					(in)	(in)	(%)	(%)	(%)		(%)	(%)	(Ft)	(Ft)	(b/min)
(1)	(2)	(3)	(4)	(5)	(6	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
CME 45	48	D	A	5	33.1	0.6	–	–	–	5	30	90	2.9	21.3	–
	49	D	A	5	32.5	0.5	–	–	–	5	38	90	2.9	26.3	–
	50	D	A	–	–	–	–	–	–	5	36	–	2.9	31.3	–
	51	D	A	–	–	–	–	–	–	4	34	90	2.9	36.3	–
	52	D	A	1	31.8	–	–	–	–	5	33	88	2.9	41.3	–
	54	S	A	5	29.0	1.2	–	–	–	5	33	67	5.2	13.6	–
	55	S	A	5	31.8	0.8	–	–	–	5	38	77	5.2	18.6	–
	56	S	A	5	34.0	0.8	–	–	–	5	42	82	5.2	23.6	–
	57	S	A	5	33.9	0.5	40	0	0	5	41	86	5.2	28.6	–
	58	S	A	5	33.5	1.2	–	–	–	5	42	83	5.2	33.6	–
	59	S	A	5	34.3	0.6	–	–	–	5	43	83	5.2	38.6	–
	60	S	A	5	34.3	1.4	–	–	–	5	42	88	5.2	43.6	–
	61	S	A	5	34.8	0.9	–	–	–	5	40	88	5.2	48.6	–
Mobile B-61	79	S	B	30	–	–	47.2	3.4	7.2	4	43	–	7.3	45.8	41
	80	S	B	22	–	–	51.8	2.3	4.3	4	52	–	7.3	47.8	47
	81	S	C	21	a	a	54.5	6.7	12.2	a	a	a	7.3	50.8	54
	82	D	C	15	31.4	1.0	43.1	6.1	14.2	5	39	73	1.3	44.8	34
	83	S	C	19	30.8	1.0	55.6	5.8	10.5	3	56	70	7.3	50.8	38
	84	S	D	22	29.8	1.0	53.6	4.9	9.0	3	58	71	7.3	52.8	30
	85	D	D	21	30.1	0.5	41.4	5.2	12.6	4	47	71	1.3	46.8	32
	86	D	D	22	a	a	59.8	9.6	16.1	a	a	a	1.3	46.8	35
	87	D	D	20	a	a	47.4	6.1	12.9	a	a	a	3.5	49.0	33
	88	S	D	20	a	a	62.8	4.5	7.2	a	a	a	7.3	52.8	39
	89	S	D	20	a	a	52.8	6.1	11.5	a	a	a	7.3	52.8	36
	90	S	E	25	a	a	58.1	6.5	11.1	a	a	a	7.3	52.8	39
	91	S	E	25	a	a	68.0	6.1	9.6	a	a	a	7.3	52.8	43
	92	S	E	20	30.3	0.9	46.9	7.7	16.4	3	53	67	7.3	54.8	39
	93	D	E	47	a	a	57.5	8.4	14.6	a	a	a	3.3	50.8	41
	94	D	E	21	30.3	0.8	55.1	6.3	11.4	3	53	71	3.3	50.8	43
Mobile B-61	95	S	C	52	–	–	45.8	2.3	5.0	4	48	–	7.3	47.3	40
	96	S	C	20	a	a	45.1	1.9	4.3	a	a	a	7.3	47.3	41
	97	S	E	20	a	a	46.7	1.9	4.0	a	a	a	7.3	47.3	39
	98	S	E	20	29.2	0.5	44.7	2.0	4.5	3	49	59	7.3	47.3	41
	99	S2	C	20	a	a	47.4	2.3	4.8	a	a	a	5.7	45.7	40
	100.1	S2	E	20	a	a	49.1	1.7	3.4	a	a	a	5.7	45.7	41
	100.2	S2	C	11[b]	a	a	55.5	1.1	2.0	a	a	a	5.7	45.7	11
	100.3	S2	C	14[c]	a	a	32.8	2.5	7.6	a	a	a	5.7	45.7	22
	100.4	S2	C	14	a	a	49.7	1.8	3.7	a	a	a	5.7	45.7	29
	100.5	S2	F	15	a	a	50.9	1.0	2.0	a	a	a	5.7	45.7	–
	100.6	S2	G	1	a	a	45	–	–	a	a	a	5.7	45.7	–
	100.7	S2	G	1[b]	a	a	48	–	–	a	a	a	5.7	45.7	–
	100.8	S2	G	1[c]	a	a	31	–	–	a	a	a	5.7	45.7	–
	100.9	S2	G	1	a	a	43	–	–	a	a	a	5.7	45.7	–
	100.10	S2	H	10	a	a	50.1	1.8	3.6	a	a	a	5.7	45.7	–

Table 3.3 Tabulation of Results and Testing Variables Using Two Turns of Rope Around the Cathead (Continued)

Type Rig	Series	Hammer Type	Operator	No. of Data Points	Avg. Fall Height	Fall Hgt Stnd Dev.	Calibrator Avg ER_i	Calibrator ER_i Stnd Dev.	Calibrator ER_i CV	No. of Data Points	DPO Avg ER_i	DPO Avg ER_v^*	$\Delta\ell$	ℓ	Test Rate
					(in)	(in)	(%)	(%)	(%)		(%)	(%)	(Ft)	(Ft)	(b/min)
(1)	(2)	(3)	(4)	(5)	(6	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
Mobile B-61	102	S	I	17	32.3	2.4	60	6.0	10.0	15	59	68	6.0	44.6	26
	103	S	J	21	30.3	0.4	49	4.0	8.2	4	47	57	6.0	44.6	19
	104	S	K	22	30.8	0.3	54	5.1	9.5	4	51	65	6.0	44.6	17
	105	S	I	18[d]	31.9	2.2	60	5.4	8.9	4	57	70	6.0	46.6	17
	106A	S	I	9[c]	33.6	0.7	43	5.5	12.8	4[c]	43	46	6.0	46.6	17
	106B	S	I	10[b]	33.8	0.9	72	7.2	10.0	4[b]	67	76	6.0	46.6	17
	108	D	I	20	28.4	0.3	63	6.1	9.7	4	58	73	1.7	42.3	14
	109	D	I	19	28.1	0.4	65	12.0	18.3	4	62	75	1.7	45.3	15
Longyear HC 150	110	S	K	25	--	--	69	3.9	5.6	a	a	a	5.0	78.6	15
	111	S	K	20	29.8	0.4	72	2.4	3.3	4	70	71	5.0	78.6	20
	112	S	J	20	29.6	0.1	85	15.3	18.0	4	48	50	5.0	78.6	13
CME 75	113	S	J	24	29.6	0.1	67	7.5	11.3	4	66	69	5.9	89.5	13
	114A	S	J	5[c]	30.0	0.7	56	12.4	22.2	5[c]	55	57	5.9	89.5	11
	114B	S	J	6[b]	29.8	0.7	79	2.1	2.7	4[b]	78	79	5.9	89.5	11
	115	S	K	19	30.0	0.4	74	5.4	7.3	4	69	75	5.9	89.5	20
	117	S	I	23	29.9	0.1	79	6.2	7.8	5	72	70	5.9	91.5	12
	119	S	J	17[e]	29.7	0.3	76	4.1	5.4	4	73	76	5.9	91.5	14
Failing 1500	120	S	L	14	28.4	2.0	58	6.7	11.7	5	53	57	4.0	46.5	37
	121	S	L	20	29.6	1.0	68	3.4	5.1	4	58	68	4.0	46.5	36
	122	S	M	20	30.0	1.0	74	2.6	3.5	4	68	70	4.0	46.5	29
	123	S	N	10	30.3	1.0	74	3.4	4.6	5	69	70	4.0	46.5	30
	127A	S	L	10[b]	29.7	1.2	75	5.5	7.3	4[b]	66	73	4.0	46.5	21
	127B	S	L	10	29.9	1.3	64	3.4	5.4	4	53	61	4.0	46.5	40
	127C	S	L	10[c]	29.2	2.3	55	3.7	6.7	4[c]	44	44	4.0	46.5	21
	128A	S	L	10[b]	30.0	0.5	81	2.6	3.2	4[b]	66	76	4.0	48.5	15
	128B	S	L	10	28.3	1.9	74	4.7	6.3	4	62	63	4.0	48.5	42
	128C	S	L	7[c]	29.8	1.2	57	4.0	7.1	4[c]	42	47	4.0	48.5	40
	130	S	L	30	28.5	1.9	81	6.3	7.8	6	58	64	4.0	48.5	40

NOTES:
a. Tape recorder not used. Only data on ER_i from Calibrator obtained.
b. 1 1/4 turns of rope around the cathead.
c. 3 1/4 turns of rope around the cathead.
d. A 2 ft section of BW parallel wall rod was added below the load cell, above 35.2 ft of BW upset wall drill rod for Series 105, and added above 40.0 ft of drill rod for Series 128.
e. A 2 ft section of BW parallel wall rod was inserted at 40 ft in the 80 ft upset wall drill rod.

1 ft = 305 mm.

Table 3.4 Summary of Energy Data from Individual Blows

Series	Blow No.	Hammer Type	ER_i Calib.	ER_i DPO	ER‡	ETR (5/6)	Series	Blow No.	Hammer Type	ER_i Calib.	ER_i DPO	ER‡	ETR (5/6)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(1)	(2)	(3)	(4)	(5)	(6)	(7)
48	9	D		23	81	28	56	8	S		43	89	48
	10			28	85	33		13			42	77	55
	11			34	93	37		15			43	87	49
	12			34	93	37		16			40	83	48
	13			32	100	32		18			42	72	58
49	15	D		38	86	44	57	1	S	40	42	82	51
	16			37	89	42		2		40	40	84	48
	17			36	95	38		3		40	43	86	50
	18			35	89	39		7		40	42	88	48
	19			43	92	47		9		--	39	88	44
50	1	D		35	--	--	58	6	S		38	80	48
	2			36	--	--		8			42	80	53
	3			37	--	--		9			44	85	52
	4			34	--	--		10			42	85	49
	5			36	--	--		11			44	86	51
51	8	D		34	93	37	59	8	S		42	84	50
	9			34	88	39		9			44	88	50
	13			29	93	31		10			42	86	49
	17			38	87	44		11			45	83	54
								12			40	72	56
52	11	D		32	85	38	60	3	S		40	80	50
	12			32	93	34		16			42	91	46
	14			34	91	37		17			42	84	50
	15			32	87	37		18			44	91	48
	16			33	84	39		19			43	93	46
54	20	S		30	65	46	61	8	S		33	84	39
	21			35	63	56		9			39	84	45
	23			31	65	48		10			42	93	45
	24			33	70	47		11			43	89	48
	26			35	74	47		12			41	89	46
55	6	S		37	80	46	79	9	S	45	42	--	--
	7			39	79	49		13		48	45	--	--
	8			38	77	49		22		35	34	--	--
	9			36	70	51		30		48	50	--	--
	10			38	77	49							

Notes: After the data was collected for Series 48 through 61, it was found that the F(t) curves contained glitches, similar to figure 3.4 thus, the Calibrator ER_i data should not be used. The F(t) cures were adjusted using the DPO to remove the glitch and replace it with a smooth line approximation. Series 57 did not contain any glitches. Only column 7 should be used in this table for Series 48 through 61. Data in column 5 contain corrections K_1 and K_2.

Table 3.4 Continued

Series	Blow No.	Hammer Type	ER_i Calib.	ER_i DPO	ER_v^*	ETR (5/6)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
80	3	S	51	53	--	--
	8		46	46	--	--
	14		50	51	--	--
	22		54	57	--	--
82	1	D	42	42	83	51
	2		42	43	62	69
	3		44	44	77	57
	11		38	36	75	48
	12		28	29	67	43
83	6	S	55	58	68	85
	7		55	57	71	80
	13		54	55	69	80
84	2	S	55	58	69	84
	3		57	59	72	82
	4		56	58	72	81
85	6	D	47	50	71	70
	7		46	49	80	61
	8		46	49	83	59
	14		37	39	73	53
92	5	S	50	52	63	83
	8		49	52	65	80
	15		51	54	68	79
94	8	D	58	56	67	83
	11		56	53	75	71
	15		57	49	70	70
95	2	S	47	47	--	--
	3		48	48	--	--
	9		45	47	--	--
	25		45	51	--	--
98	2	S	48	51	62	82
	6		46	50	59	85
	8		44	46	57	81
102	1	S	61	58	74	78
	3		63	62	71	87
	4		64	61	64	95
	5		58	56	63	89
	6		62	62	65	95
	7		60	61	71	86
	10		54	58	69	84
	11		58	60	65	92
	13		57	61	69	88
	14		51	55	70	79
	15		75?	72	69	104
	17		56	56	71	79
	18		63	64	67	96
	19		53	57	65	104
	20		71?	68	73	93
103	4	S	46	47	59	80
	12		49	48	53	91
	17		49	51	57	89
	20		47	47	59	80
104	4	S	54	53	64	83
	9		53	55	65	85
	13		53	54	64	84
	15		53	53	65	82
105	5	S	61	62	69	90
	8		56	58	69	84
	13		62	61	72	85
	15		58	57	70	81
106	2[b]	S	43	46	47	98
	3[b]		41	44	47	94
	4[b]		42	42	49	86
	10[b]		45	40	41	98
	12[a]	S	69	68	78	87
	13[a]		77	70	74	95
	16[a]		70	66	72	92
	18[a]		67	62	79	78

Table 3.4 Continued

Series	Blow No.	Hammer Type	ER_i Calib.	ER_i DPO	ER_v^*	ETR (5/6)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
107	1[c]	S	87	88	91	99
	2[c]		92	93	97	96
	4[c]		92	93	91	102
	5[c]		92	90	98	92
108	13	D	63	60	79	76
	15		61	64	71	90
	18		60	56	70	80
	19		62	57	72	79
109	3	D	71	65	71	92
	8		61	60	71	85
	14		66	66	71	93
	15		67	63	90	70
111	7	S	78	73	71	103
	9		78	71	72	99
	10		77	70	71	99
	14		76	69	71	97
112	15	S	82[e]	47	50	94
	16		90[e]	53	54	98
	18		85[e]	52	50	104
	19		80[e]	41	47	87
113	6	S	67	69	69	100
	10		65	65	66	98
	11		70	69	72	96
	12		70	68	70	97
114	6[a]	S	78	73	73	100
	7[a]		78	78	85	92
	9[a]		81	75	78	96
	11[a]		78	71	81	88
115	2	S	74	72	73	99
	7		76	75	79	95
	9		73	73	76	96
	11		75	72	73	99

Series	Blow No.	Hammer Type	ER_i Calib.	ER_i DPO	ER_v^*	ETR (5/6)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
116	1[c]	S	93	92	91	101
	2[c]		94	90	93	97
	3[c]		95	98	98	100
	5[c]		106	97	97	100
	6[c]		104[e]	65	62	105
117	2	S	66	66	65	102
	3		70	69	64	106
	5		70	67	65	103
	7		83	80	78	103
	8		84	80	72	111
	9		83	84	73	115
	10		81	79	74	107
118	2[c,f]	D	69	79	90	88
119	1	S	75	73	78	94
	3		73	73	72	101
	5		79	77	85	91
	9		77	73	71	102
120	3	S	58	55	58	95
	5		56	52	56	93
	10		57	53	57	93
	14		62	59	56	105
	18		58	56	56	100
121	4	S	68	64	67	96
	10		67	64	65	100
	11		67	55	66	83
	15		67	60	67	90
122	4	S	75	70	73	96
	7		75	71	72	96
	14		73	69	64	99
	15		74	71	71	100
123	1	S	70	65	70	93
	4		75	73	74	99
	6		75	69	70	99
	7		72	69	63	110
	8		72	69	72	96

Table 3.4 Continued

Series	Blow No.	Hammer Type	ER_i Calib.	ER_i DPO	ER_v^*	ETR (5/6)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
124	1[c]	S	97	92	95	97
	2[c]		97	93	97	96
	3[c]		96	93	98	95
125	1[c]	D	96	81	97?	84?
	2[c]		76	71	97	73
	3[c]		96	95	91	104
126	1[c]	Trip	97	93	93	100
127	13	S	63	62	53	117
	17		62	60	62	97
	19		66	61	65	94
	20		65	61	64	95
	4[a]		74	71	71	89
	7[a]		77	73	73	95
	8[a]		75	74	74	91
	9[a]		74	73	73	88
	21[b]		59	47	47	83
	23[b]		52	41	41	76
	25[b]		56	43	43	86
	26[b,d]		53	43	43	105?
128	11[d]	S	73	69	69	100
	13[d]		79	66	62	106
	16[d]		72	63	57	111
	19[d]		71	64	65	98
	1[a]		80	68	74	92
	4[a]		82	65	78	83
	7[a]		82	66	77	86
	10[a]		81	66	76	87
	24[b]		58	35	43	81
	25[b]		57	37	42	88
	29[b,d]		62	44	50	88
	30[b,d]		63	44	53	94
129	1[c]	S	97	93	93	100
	2[c]		100	98	91	108
	3[c,d]		106	97	93	104
130	1[d]	S	81	64	63	102
	4[d]		84	62	63	98
	8[d]		82	63	66	95
	15[d]		81	63	63	100
	21[d]		78	59	62	95
	29[d]		80	63	63	100

Notes: All tests are two (nominal) turns of rope around the cathead unless stated otherwise.

a. One turn of rope around the cathead
b. Three turns of rope around the cathead
c. Free fall test, where hammer is string suspended 30 in (760 mm) above anvil, then cut
d. Integration time of Calibrator greater than computed value of $2\ \ell'/c$
e. Spurious shape of F(t) curve
f. Fall height = 28.0 (71 cm)

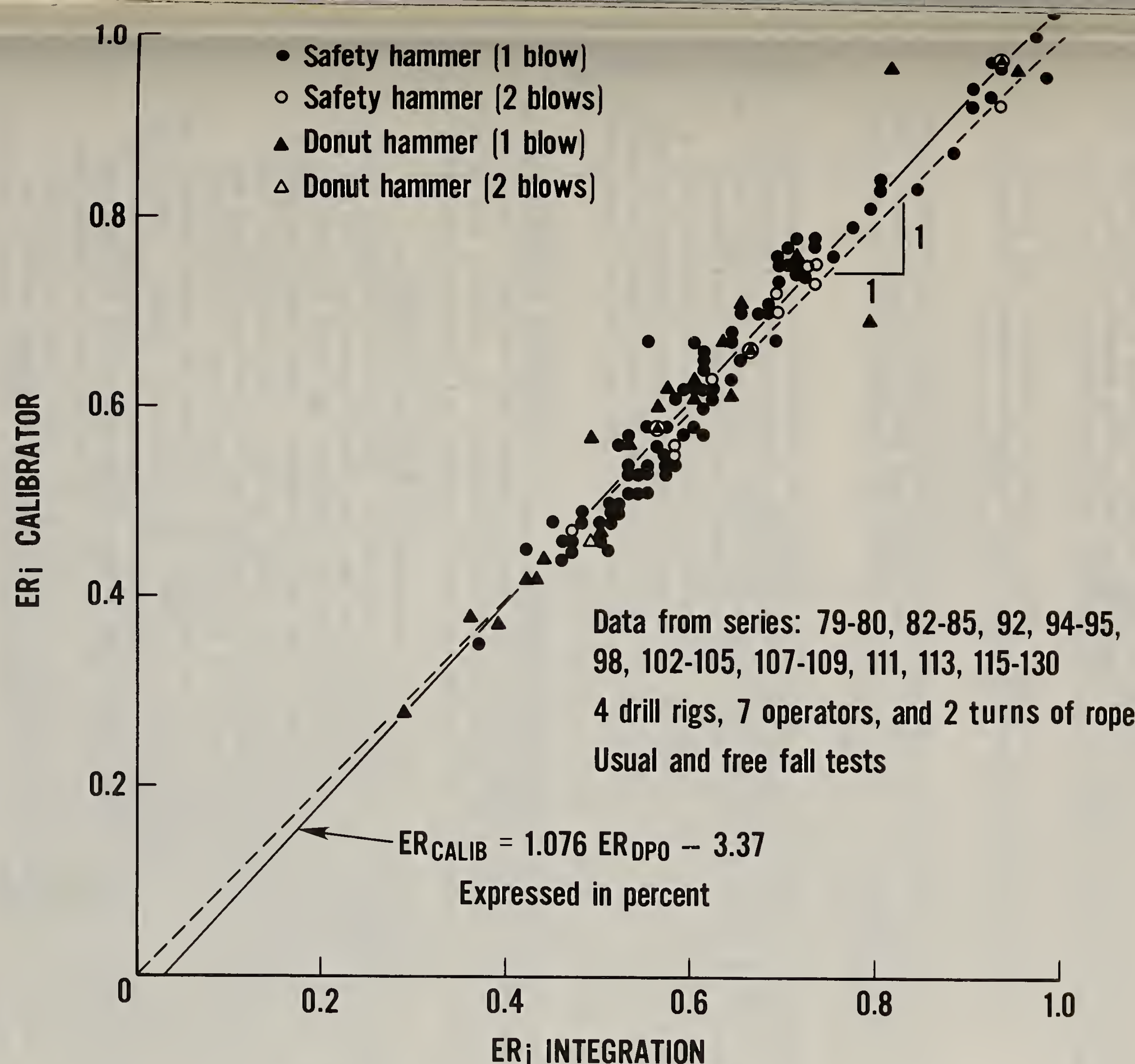


Figure 3.6 Comparison of energy ratios using the SPT Calibrator and the Digital Processing Oscilloscope (DPO)

$$ETR = \frac{E_i}{E_v} = \frac{ER_i}{ER_v^*} \tag{3.11}$$

Data from table 3.4, col. 7, together with other data taken from Kovacs et al., (1980) are shown in figure 3.7 for both donut and safety hammers. The accuracy of the data presented is affected by two parameters:

1. Instances where a compressive stress wave is returned, and thus E_i for the calculator is overestimated. The instances account for most of the data where ETR > 1, which is physically impossible.

2. Effect of the drill rod geometry and possibly other parameters on the results of the calculated E_i which are not yet fully understood. The validity of the caluclated E_i was not yet corroborated by an independent energy measurement.

Nevertheless the data provide an indication of the importance of considering the effect of the hammer-anvil assembly on energy transmission. Figure 3.7 gives a clear indication that ETR is more variable for donut hammers than it is for safety hammers, and that there are apparently significant differences between different safety hammers. This latter observation is derived from a comparison of the three histograms for three different safety hammers at the bottom of the figure. To what extent the difference between those histograms is also attributable to the drill rod geometry (AW, NW, and BW rods were used) has not been determined at the present time.

The drill rig, SPT equipment and procedures, and the drill rig operator have a combined effect on the magnitude of the energy ratios ER_v^* and ER_i. The data from table 3.3 can be used to separate these variables and evaluate the effects of personnel, equipment, and procedures on the energy delivered in the test.

In Series 48 through 52, operator A consistently delivered an ER_v^* of approximately 90 percent (column 13), leading to reasonably consistent results of ER_i of 30, 38, 36, 34, and 33 percent for the donut hammer (col. 12). In these tests, the average fall height (where measured) was 32.5 in (826 mm), which is higher than the standard. The same operator, when using the safety hammer (usually used) produced smaller values of ER_v^*. The reason for this performance can be further examined by calculating the ratio of E_v/mgH and thereby filtering out the effects of fall height fluctuation. This ratio varies from 0.815 to 0.830, with an average of 0.825 for the donut hammer; and from 0.69 to 0.76, with an average of 0.74, for the safety hammer. Thus, the safety hammer in this instance lost significantly more of the energy before impact than the donut hammer. The resulting average values of ER_i for the safety hammer were 33, 38, 42, 41, 42, 43, 42, and 40 percent at depths measured from 5 to 40 ft (1.5 to 12 m). It should be noted that the average value of ER_i for Series 54 (col. 12) is low relative to other tests. In this case, the operator used the safety hammer after a day of testing with the donut hammer.

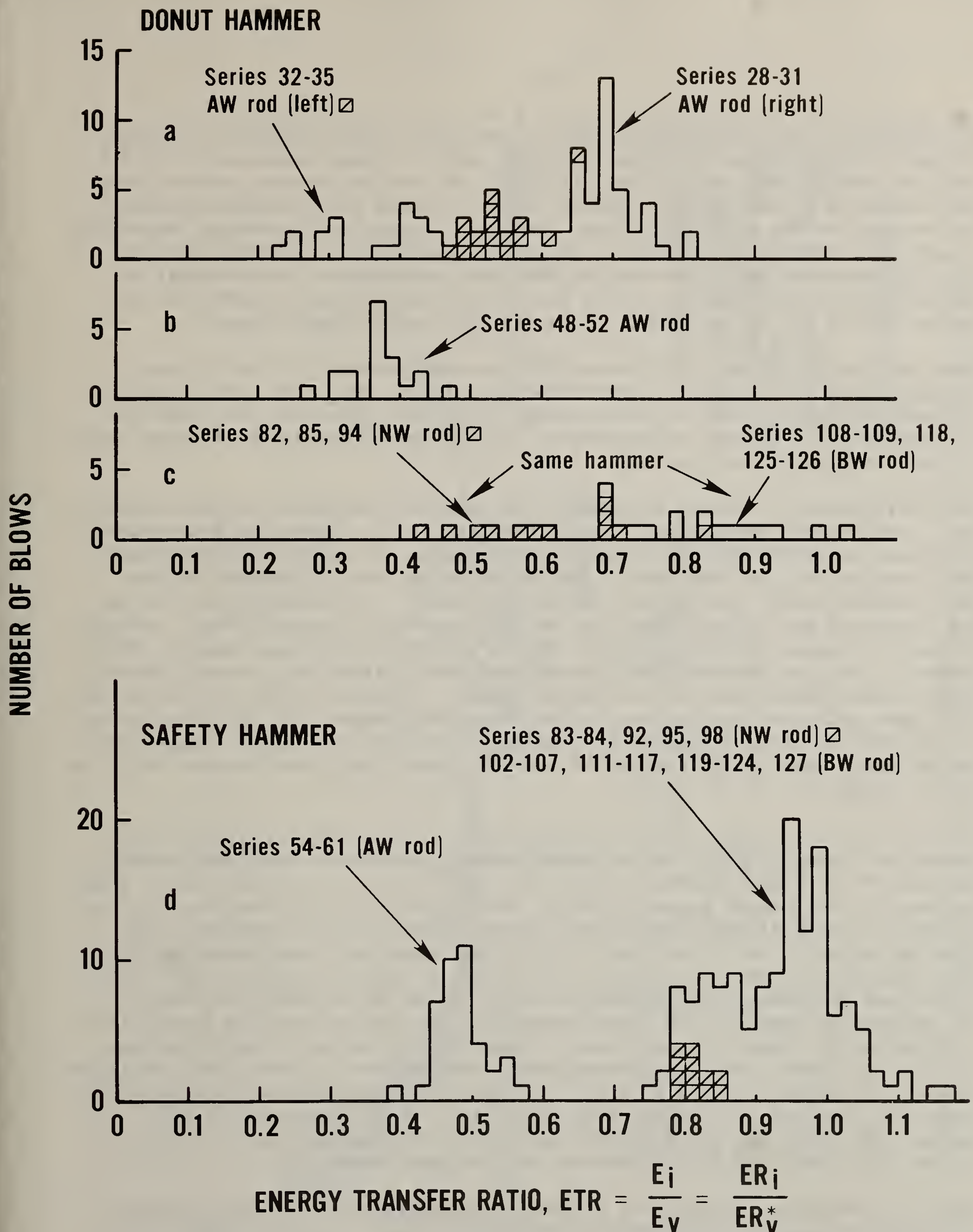


Figure 3.7 Histograms of energy transfer ratio, ETR, for donut and safety hammers

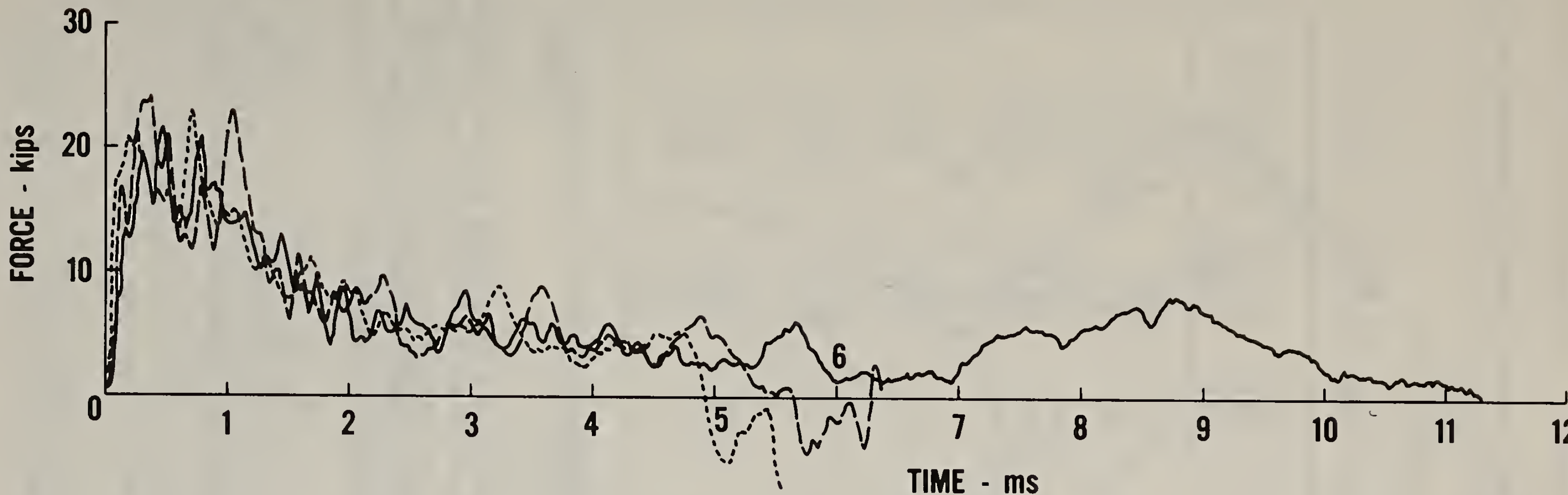
An example of three operators using the same drill rig but getting different values of ER_i is given in Series 102, 103, and 104 where operators I, J, & K obtained average ER_i values (col. 8) of 60, 49, and 54 percent, respectively. When operator I came back to redo the series (Series 105), he again obtained 60 percent for ER_i (col. 8). Other examples of operators obtaining consistent results can be seen in table 3.3. It is interesting to note that only part of the difference in ER_i's produced by the three operators is attributable to differences in fall height. There are also differences in the ETR, and to a lesser extent in the percentage of energy lost before hammer impact.

When the results of ER_i are listed for the usual operator of his rig and equipment, we again observe a variation of results: ER_i = 40, 47, 46, 60, 69, 67, and 58 percent (col. 8) from Series 57, 79, 95, 102, 110, 113, and 120, respectively. A further discussion of average ER_i values for drill rigs tested to date is given in section 4.2.

The differences in ER_i due to hammer type have been described before (Kovacs et al., 1981; Martin and Douglas, 1981; Robertson et al., 1982; and Schmertmann and Palacios, 1979) and are observed, for example, in Series 52 and 60 where the depth and ER_v^* are the same. The values of ER_i are 33 percent for the donut hammer and 42 percent for the safety hammer. In Series 82 and 83, ER_i for the donut and safety hammer are 43 and 56 percent, respectively. Usually the safety hammer provides a larger ER_i in the drill rods than does the donut hammer. Youd and Bennett (1983) found that the N values are generally more with a donut hammer than with a safety hammer. They attributed the difference to a more efficient energy transfer of the safety hammer. In six check tests at one site in holes drilled with a hollow stem auger, the donut hammer gave N values which were on the average 45 percent higher than those obtained with the safety hammer.

It was found that a wide variety of drill rod size is used in engineering practice. Brown (1977) found no significant difference in his field studies between SPT N values obtained with A rods and N rods up to 110 ft (34 m) depth in loose to very dense granular soils. From equation 3.2 we see that E_i, the energy in the drill rods, is inversely proportional to the cross-sectional area of the drill rod. The typical drill rod sizes and their cross-sectional area have been given in table 3.1. It is not uncommon to install short sections (one to three feet) of parallel wall rod on top of upset wall rod to attach the SPT hammer. One might expect adverse effects from the abrupt discontinuities of cross-sectional area. Figure 3.8 illustrates the force-time history for three blows of a safety hammer under three different rod configurations. The insertion of a 2 ft (0.7 m) section of parallel wall rod below the load cell resulted in a higher peak force but no real difference in ER_i. In Series 128B, blow 16, a compressive wave return is noted (similar in shape to figure 3.5) resulting in an incorrect ER_i Calibrator reading.

Table 3.5 shows the differences between ER_v^* delivered by different operators using safety hammers with different drill rigs. Again, it can be seen that the differences are considerable. When the ER_v^* values are adjusted to the actual fall height, column 5, it can be seen that the differences are not substantially diminished. Thus, other parameters contribute to the energy



	Series	Blow No.	ER_i Calib.	ER_i Integr.	ER_v	Calibrator Integr. t (ms)	Observed Integr. t (ms)	ℓ' (ft)	Drill Stem Configuration
- - - - - - -	102	6	62	61	65	4.62	4.92	38.6	LC + 35 ft. upset wall + sampler
— — —	105	5	61	61	69	4.93	5.5	40.3	LC + 2 ft. parallel wall + 35 ft. upset wall + sampler
———	128 B	16	72	51	57	11.3	11.3	44.5	LC + 2 ft. parallel + 40 ft. upset wall + sampler

All two turns, safety hammer

Figure 3.8 Comparison of force-time wave forms when a 2-ft (61 cm) section of BW parallel wall drill rod is inserted just below load cell loss during the hammer fall. To what extent these parameters are operator dependent has not been established.

Table 3.5

Summary of Average Energy Ratios for Velocity

Series	Operator	ER_v^* (%)	H, in (in)	$ER_v^* \times 30/H$[a] (%)
(1)	(2)	(3)	(4)	(5)
83	C	70	30.8	68.2
84	D	71	29.8	71.5
102	I	68	32.3	63.2
103	J	57	30.3	56.4
104	K	65	30.8	63.3
111	K	71	29.8	71.5
112	J	50	29.6	50.7
115	K	75	30.0	75.0
117	I	70	29.9	70.2
119	J	76	29.7	76.8
121	L	68	29.6	68.9
122	M	70	30.0	70.0
123	N	70	30.3	69.3

[a] Energy ratio for velocity adjusted for actual fall height.

The rate at which the SPT is performed may vary by a factor of three or more. Some operators are very deliberate with rates between 11 and 26 blows per minute (Series 102 to 119), while others use higher rates (40 to 50 blows per minute). Operator C reduced his rate from 54 to 38 blows per minute when energy measurements were taken (see Series 81 and 83, col. 16). We observed no relationship between ER_i and blow count rate.

Figure 3.9 illustrates the variation of average energy ratio, ER_i, versus drill rod length from field tests at four different sites. The energy ratio is adjusted for drill rod length effects and, therefore, should remain constant with depth unless the SPT procedure is altered by the operator for some reason or another. As expected, the safety hammers are seen to have higher energy ratios than the donut hammers. Observe the wide range of energy ratios measured, from about 25 to 75 percent.

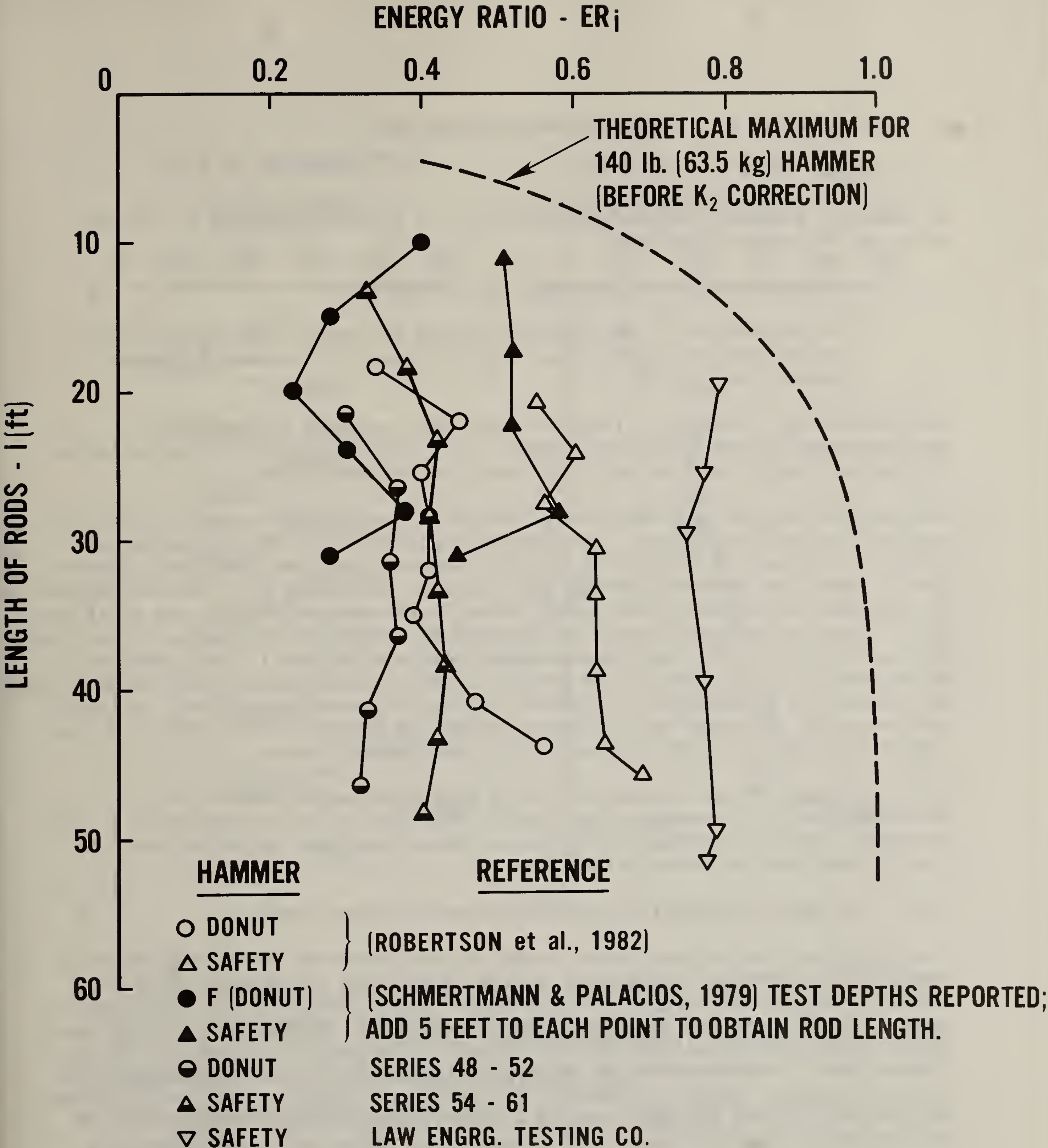


Figure 3.9 Variation of average energy ratio, ER_i, vs. drill rod length for two types of SPT hammers. All data include K_2 correction.

4. ESTABLISHMENT OF A REFERENCE ENERGY LEVEL (REL)

4.1 GENERAL

It has been previously noted (see section 1.3) that the accuracy of the SPT could be improved in two ways:

1. Standardization of equipment and procedures.

2. Determination of the energy delivered by typical U.S. equipment and procedures and referencing of all SPT data to a common reference energy level.

The information previously discussed deals with energies delivered by miscellaneous equipment and procedures. This section deals with the establishment of an energy level to which SPT data can be referenced.

The question arises what this energy should be, and at which point in the SPT system it should be defined. In ASTM Standard Method D 1586, the potential energy is defined as 4200 in-lbf (475J). However, the data presented indicate that a specified potential energy does not lead to uniform test results because of the wide variations in the energy actually transmitted through the drill rod (E_i). Greater uniformity could be achieved by specifying the energy transmitted through the drill rod. One problem which has to be solved if this approach is to be used is the calibration of the measurement methods used to determine E_i by an independent measurement. To date this has not been accomplished. A second problem to be addressed in the future concerning the use of our present design correlations with the SPT N value is the past average energy.

The following sections present available data that can be used in the determination of an average value for E_i, which is typical of present U.S. SPT practice. The data may have to be re-evaluated when data on the accuracy of the E_i measurements becomes available.

4.1.1 The Need to Establish a National Average Energy (NAE)

The concept of the NAE was first brought to the attention of the profession by Kovacs et al. (1981). The average energy ratio, ER_i, for a given drill rig model is the average energy ratio determined from a statistically significant number of drill rigs of that particular model. When all the data are averaged, based on the number and availability of drill rigs used throughout the United States, then a weighted NAE for the drill rigs used in U.S. practice under normal operating conditions (drill rig, hammer, and operator) can be determined. Once known, the NAE can then be used as a reference energy for SPT practice. The next three figures show SPT blow count data versus depth performed by three separate drill rigs (at three different sites) all using two types of hammers in the same or adjacent borings. The average energy ratio, ER_i, was obtained for each SPT. Figure 4.1 from Robertson et al., 1982, shows a blow count profile for both the safety hammer (triangle data points) and donut hammer (circle points). The average energy ratio, ER_i, is located adjacent to the data point, in parentheses. The donut hammer, transferring less energy

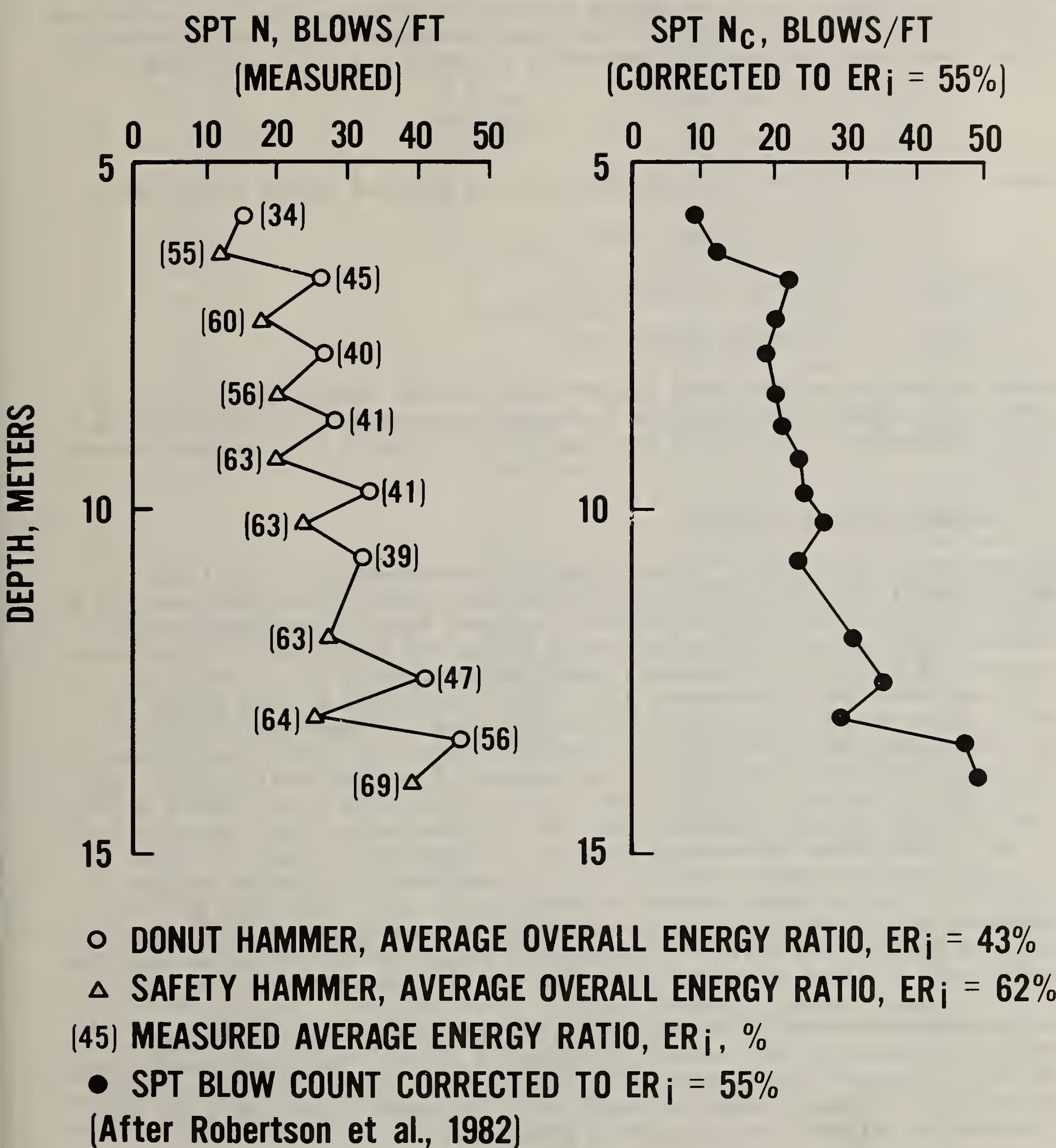


Figure 4.1 Comparison of SPT N values using alternative donut and safety hammer with energy corrected N_c values to ER_i equal to 55 percent (after Robertson et al., 1982)

into the drill rods, has the higher blow count. Robertson et al. chose to correct each data point to an energy ratio of 55 percent. Their correction was carried out assuming an inverse variation of N value with E_i, as suggested by Schmertmann and Palacios, 1979, according to equation 4.1, and dividing E_i E^*.

$$N_c = N_m \frac{(ER_i)_m}{(ER_i)_c} \quad (4.1)$$

where N_c = the corrected blow count for the selected Energy Ratio, $(ER_i)_c$

N_m = the measured blow count

$(ER_i)_m$ = the measured energy ratio

$(ER_i)_c$ = the selected energy ratio.

When the blow counts from both hammers are corrected using equation 4.1, the resulting N value profile is more consistent with depth. Figures 4.2 and 4.3 show other examples where when blow counts are corrected to 55 percent average energy.

4.2 PRESENT DATA ON THE NAE

As was stated previously: Because there are approximately 37 drill rig models used in the United States, a significant amount of data will have to be accumulated and a statistical analysis performed before an NAE can be established. Using a common reference energy as the rod energy should allow reproducible and consistent blow counts among different drill rigs. Since the publication of data by Kovacs et al., (1981), the number of data points for drill rigs has increased from 33 to 56. The data are summarized in table 4.1. The data presented in table 4.1 are based on either the integration of the F(t) curve by a DPO or from the direct readout of the SPT Calibrator, or both. Where both values are available, the Calibrator was used unless review of F(t) time history indicated "hard driving" and the integration times were in excess of $2\ell'/c$. The notes appended to table 4.1 document how the data in table 4.1 were used to present the values of ER_i graphically for safety hammers in figure 4.4a and for donut hammers in figure 4.4b. Note that there are two different scales for the energy ratio ER_i for figures 4.4a and 4.4b. The top scale is based on the results of equation 3.2 with corrections K_1 and K_2. The lower scale is based on equation 3.6 that includes corrections K_1, K_2 and K_c.

The arithmetic average of the ER_i data shown on figure 4.4 which is not a weighted average, is 56.2 percent, uncorrected for the actual compressive wave velocity. Applying the K_c correction (16000/16878), a value of 53.3 percent is obtained. However, since not every drill rig model is used with the same frequency, a weighted average must be determined.

If it is assumed that the data presented in table 2.2, "A Summary of Drill Rig Models Used in Engineering Practice with numbers >1," is representative of the frequency of present-day use, then the weighted average of the energy ratio data shown in figure 4.4 may be computed by:

Table 4.1 Tabulation of Average ER_i

[Computed Assuming Compressive Wave Velocity in Rods = 16848 ft/s (5144 m/s)]

ER_i (%)	Hammer Type	Drill Rig Model	No. of Turns	Rod Type	Remarks	Reference
(1)	(2)	(3)	(4)	(5)	(6)	(7)
71	S	CME 45	3	AW		Schmertmann and Smith (1977)[a]
74	S	CME 45	3	AW		Schmertmann and Smith (1977)[a]
53	S	CME 45B	4	AW		Schmertmann and Smith (1977)[a]
59	S	Failing 1500	3-4	NW		Schmertmann and Smith (1977)[a]
47	S	Mayhew 1000	3	AW		Schmertmann and Smith (1977)[a]
57	S	Failing 1500	3	NW		Schmertmann and Smith (1977)[a]
55	S	CME 45	3	AW		Schmertmann and Smith (1977)[a]
56	S	CME 45	3	AW		Schmertmann and Smith (1977)[a]
54	S	CME 65	3	AW		Schmertmann and Smith (1977)[a]
71	S	CME 55	4	AW		Schmertmann and Smith (1977)[a]
57	S	Failing 1500	N/A	NW	Wire-Drum	Schmertmann and Smith (1977)[a]
56	S	Acker M-2	2			Brown, R.E. (1980) Private Communication
53	S	Acker M-2	2			Brown, R.E. (1980) Private Communication
55	S	Mobile B-34	N/A		Safe-T-Driver	Brown, R.E. (1980) Private Communication
76	D	CME 55	3			Brown, R.E. (1980) Private Communication
44	S	CME 55	2			Brown, R.E. (1980) Private Communication
64	S	Mobile B-33 ATV	2			Brown, R.E. (1980) Private Communication
50	S	Mobile B-80	N/A		Safe-T-Drive	Schmertmann, J.H. (1980) Private Communication
41	S	Mobile B-80	2			Schmertmann, J.H. (1980) Private Communication
60	S	CME 45	2		Mud Bug	Schmertmann, J.H. (1980) Private Communication
51	D	CME 45	1		Swamp Buggy	Steinberg, S.B. (1980) Private Communication
36*	D	CME 45	2		Swamp Buggy	Steinberg, S.B. (1980) Private Communication
45	D	CME 45	2			Steinberg, S.B. (1980) Private Communication
71	D	CME 55	2		Oper. D	Steinberg, S.B. (1980) Private Communication
60*	D	CME 55	2		Oper. F	Steinberg, S.B. (1980) Private Communication
42	D	Joy B-12	2		Oper. A	Steinberg, S.B. (1980) Private Communication
55*	D	Joy B-12	1		Oper. G	Steinberg, S.B. (1980) Private Communication
46	S	Mobile B-34	N/A		Safe-T-Driver, J	Steinberg, S.B. (1980) Private Communication
32	D	Mobile B-61	3		Oper. A	Steinberg, S.B. (1980) Private Communication
40*	D	Mobile B-61	2		Oper. B	Steinberg, S.B. (1980) Private Communication
37*	D	Mobile B-61	2		Oper. C	Steinberg, S.B. (1980) Private Communication
68	S	CME 55	2.2	N	Old Rope	Kovacs, et al., 1981, Series 1[b]
69	S	CME 55	2.2	N	Old Rope	Kovacs, et al., 1981, Series 3
71	S	CME 55	2.2	N	Old Rope	Kovacs, et al., 1981, Series 6
75	S	CME 55	2.2	N	Old Rope	Kovacs, et al., 1981, Series 8
81	S	CME 55	2.2	N	New Rope	Kovacs, et al., 1981, Series 9[c]
77	S	CME 55	2.2	N	New Rope	Kovacs, et al., 1981, Series 11
73	S	CME 55	2.2	N	New Rope	Kovacs, et al., 1981, Series 17
62	S	CME 750	2.75	AW		Kovacs, et al., 1981, Series 19[d]
63	S	CME 750	2.75	AW		Kovacs, et al., 1981, Series 20
65	S	CME 750	2.75	AW		Kovacs, et al., 1981, Series 22
70	S	CME 750	2.75	AW		Kovacs, et al., 1981, Series 25
57	D	CME 55	2.2	AW		Kovacs, et al., 1981, Series 28[e]

Notes: The combination of the usual operator, his drill rig with cathead and rope, and the hammer are considered as a separate data point. When a second operator uses a rig that is not his own, that data point is denoted by an asterisk, *, and is not plotted on figure 4.4.

a. The values shown in column (1) have been revised to reflect a theoretical compressive wave velocity of 16,848 ft/sec. (5144 m/s). The original data were computed using C=16000 ft/s (4877 m/s). The text discusses how all the data in table 4.1 are used in figure 4.4.

b. The weighted average of Series, 1, 3, 6, and 8 taken as 72%

c. The weighted average of Series 9, 11, and 17 taken as 77%

d. The weighted averge of Series 19, 20, 22, and 25 taken as 63%

e. The weighted average of Series 28 and 31 taken as 57%

f. The weighted average for Series 32 and 33 taken as 35%

g. The weighted average for operator A taken a 66%

h. These data reduced using K_c correction from actual wave velocity measurements. The corresponding corrected values are 60, 70 and 64 percent, respectively.

Table 4.1 Continued

ER_i (%)	Hammer Type	Drill Rig Model	No. of Turns	Rod Type	Remarks	Reference
(1)	(2)	(3)	(4)	(5)	(6)	(7)
55	D	CME 55	2.2	AW		Kovacs, et al., 1981, Series 31
31	D	CME 45	2.2	AW		Kovacs, et al., 1981, Series 32[f]
46	D	CME 45	2.2	AW		Kovacs, et al., 1981, Series 33
78	S	CME 55	2	AW		Brown, R.E. (1981) Private Communication
40	S	Failing 1500	2	AW		Schmertmann, J.H. (1982) Private Communication
51	S	Failing 1500	2	AW		Schmertmann, J.H. (1982) Private Communication
63	S	Failing 1500	2	AW		Schmertmann, J.H. (1982) Private Communication
68	S	CME 45	1	AW	N~25	Schmertmann, J.H. (1982) Private Communication
31	D	Longyear 34	3	-	N~14, Lg. Anvil	Schmertmann, J.H. (1982) Private Communicatio
57	D	Failing 1500	2	N	V. Small Anvil	Schmertmann, J.H. (1982) Private Communication
59	S	Failing 250	2.75	N	Oper. A, N=15	Schmertmann, J.H. (1982) Private Communication[g]
69	S	Failing 250	2.75	N	Oper. A, N=62	Schmertmann, J.H. (1982) Private Communication[g]
59*	S	Failing 250	2.75	N	Oper. B, N=23	Schmertmann, J.H. (1982) Private Communication
71*	S	Failing 250	2.75	N	Oper. C, N=22	Schmertmann, J.H. (1982) Private Communication
55	S	Mobile B-50	2	AW	N=10	Schmertmann, J.H. (1982) Private Communication
62	S	Failing 1500	2.75	N	Oper. A, N=41	Schmertmann, J.H. (1982) Private Communication
59*	S	Failing 1500	2.75	N	Oper. B, N=17	Schmertmann, J.H. (1982) Private Communication
64*	S	Failing 1500	2.75	N	Oper. C, N=28	Schmertmann, J.H. (1982) Private Communication
50*	S	Failing 1500	2.75	N	Oper. D, N=19	Schmertmann, J.H. (1982) Private Communication
62	S	Failing 1500	2.75	N	Oper. C, N=6	Schmertmann, J.H. (1982) Private Communication
63	S	Failing 1500	2.75	N	Oper. C, N=14	Schmertmann, J.H. (1982) Private Communication
49*	S	Failing 1500	2.75	N	Oper. D, N>100	Schmertmann, J.H. (1982) Private Communication
60*	S	Failing 1500	2.75	N	Oper. A, N=15	Schmertmann, J.H. (1982) Private Communication
64	S	CME 55	1.75	AW	Oper. A, N=12	Schmertmann, J.H. (1982) Private Communication[h]
75*	S	CME 55	1.75	AW	Oper. B	Schmertmann, J.H. (1982) Private Communication
68	S	CME 45C	1.75	AW	Oper. A. (Ser. H)	Schmertmann, J.H. (1982) Private Comunication
43	D	Longyear 34	2			Campanella, R.G. and Robertson, R.K. (1982), Private Communication
62	S	Longyear 34	2			Campanella, R.G. and Robertson, R.K. (1982), Private Communication
39	D	Longyear 38	2			Campanella, R.G. and Robertson, R.K. (1982), Private Communication
47	S	Mobile B61	2	NW	Oper. A	Table 3.3, Series 79
48	S	Mobile B61	2	NW	Oper. B	Table 3.3, Series 95
60	S	Mobile B61	2	BW	Oper. A	Table 3.3, Series 102
49*	S	Mobile B61	2	BW	Oper. B	Table 3.3, Series 103
54*	S	Mobile B61	2	BW	Oper. C	Table 3.3, Series 104
70	S	Longyear HC150	2	BW	Oper. C	Table 3.3, Series 111
72	S	CME 75	2	BW	Oper. B	Table 3.3, Series 113 and 119
60	S	Failing 1500	2	BW	Oper. D	Table 3.3, Series 128B and 130
33	D	CME 45	2	AW		Table 3.4, Series 52
40	S	CME 45	2	AW		Table 3.4, Series 61

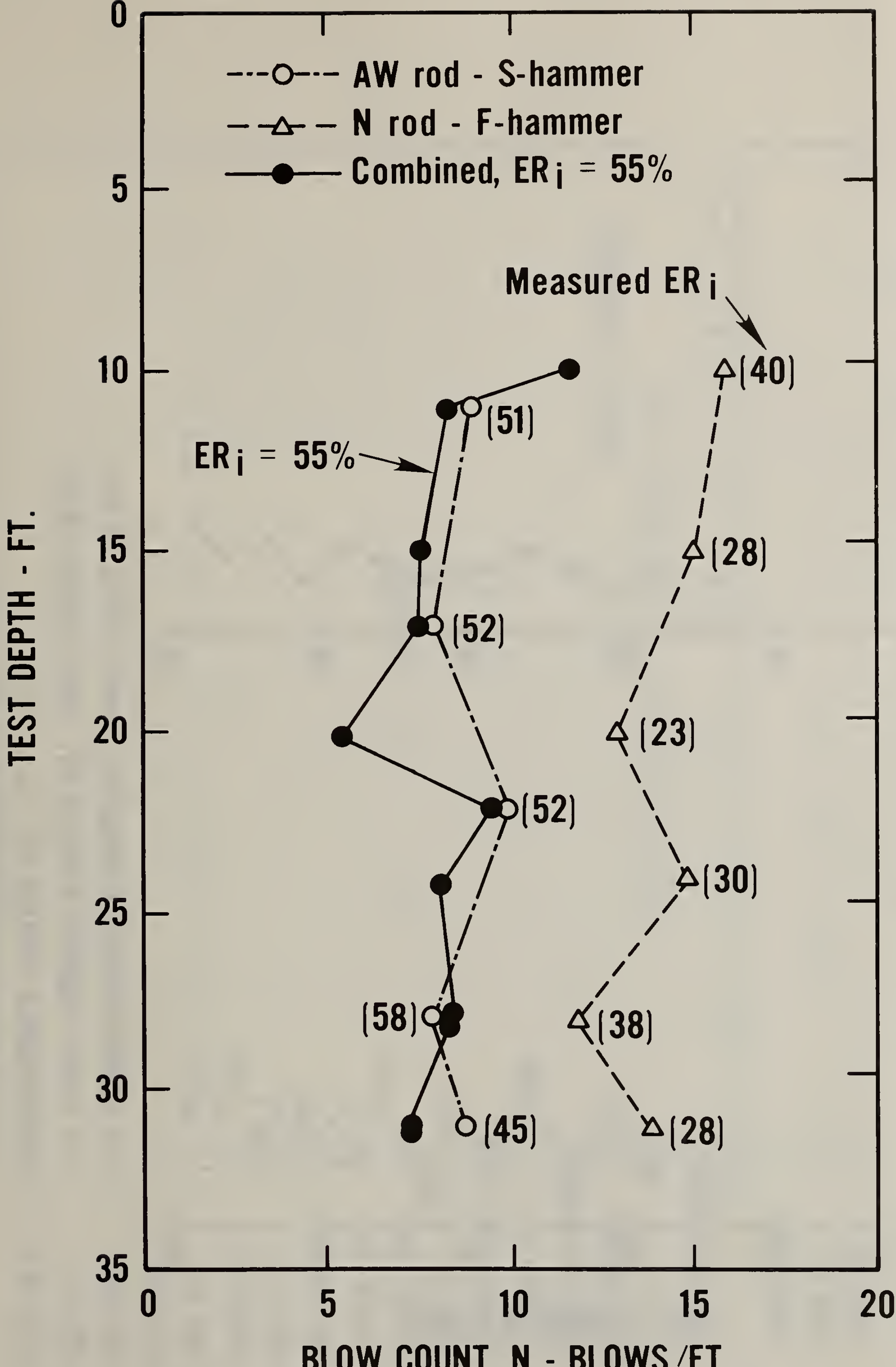


Figure 4.2 Comparison of SPT N values using safety hammer and F (donut) hammer with energy corrected N_c values to ER_i equal to 55 percent (modified from Schmertmann and Palacios, 1979)

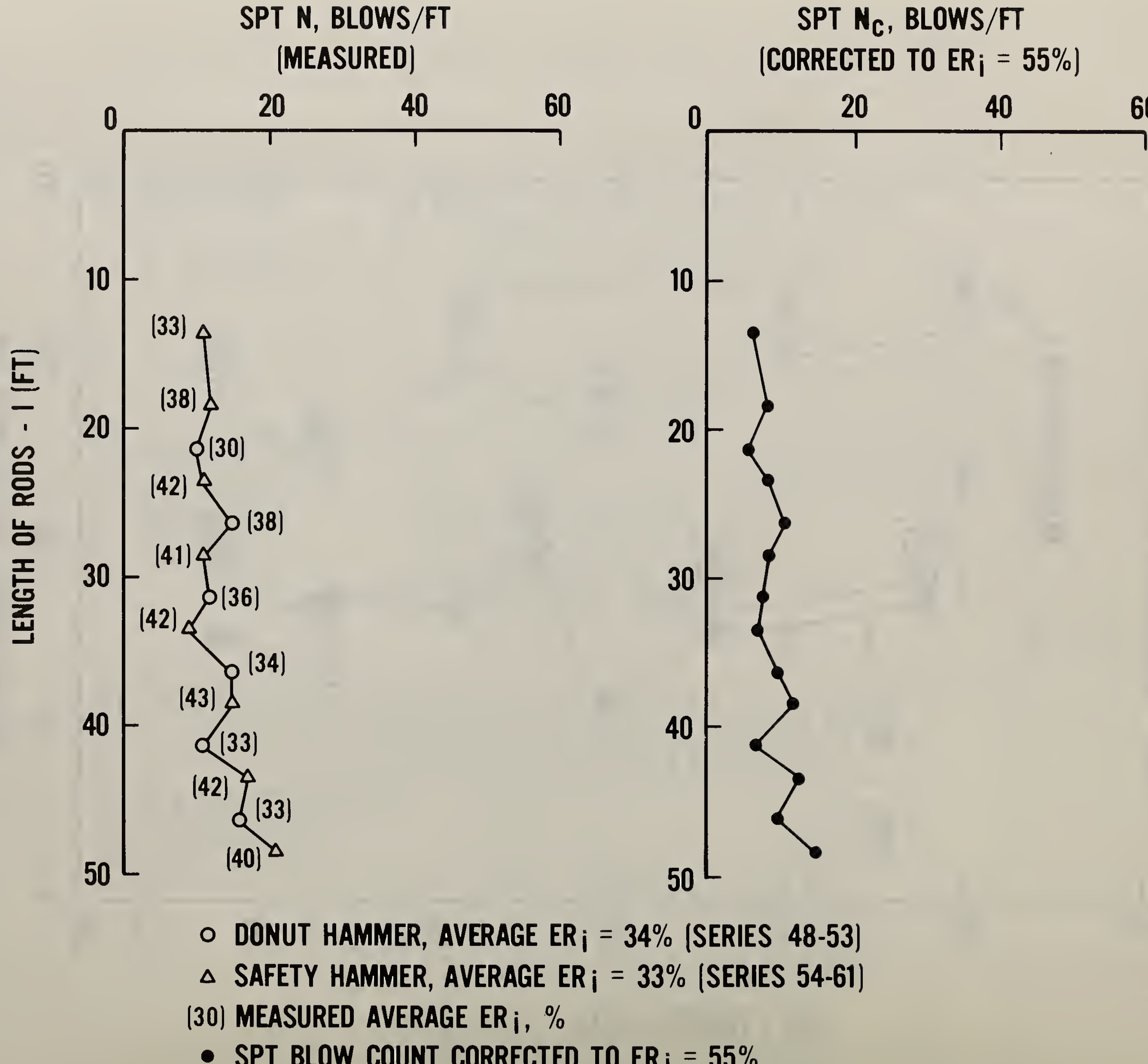


Figure 4.3 Comparison of SPT N values using safety hammer and donut hammer with energy corrected N_c values to ER_i equal to 55 percent

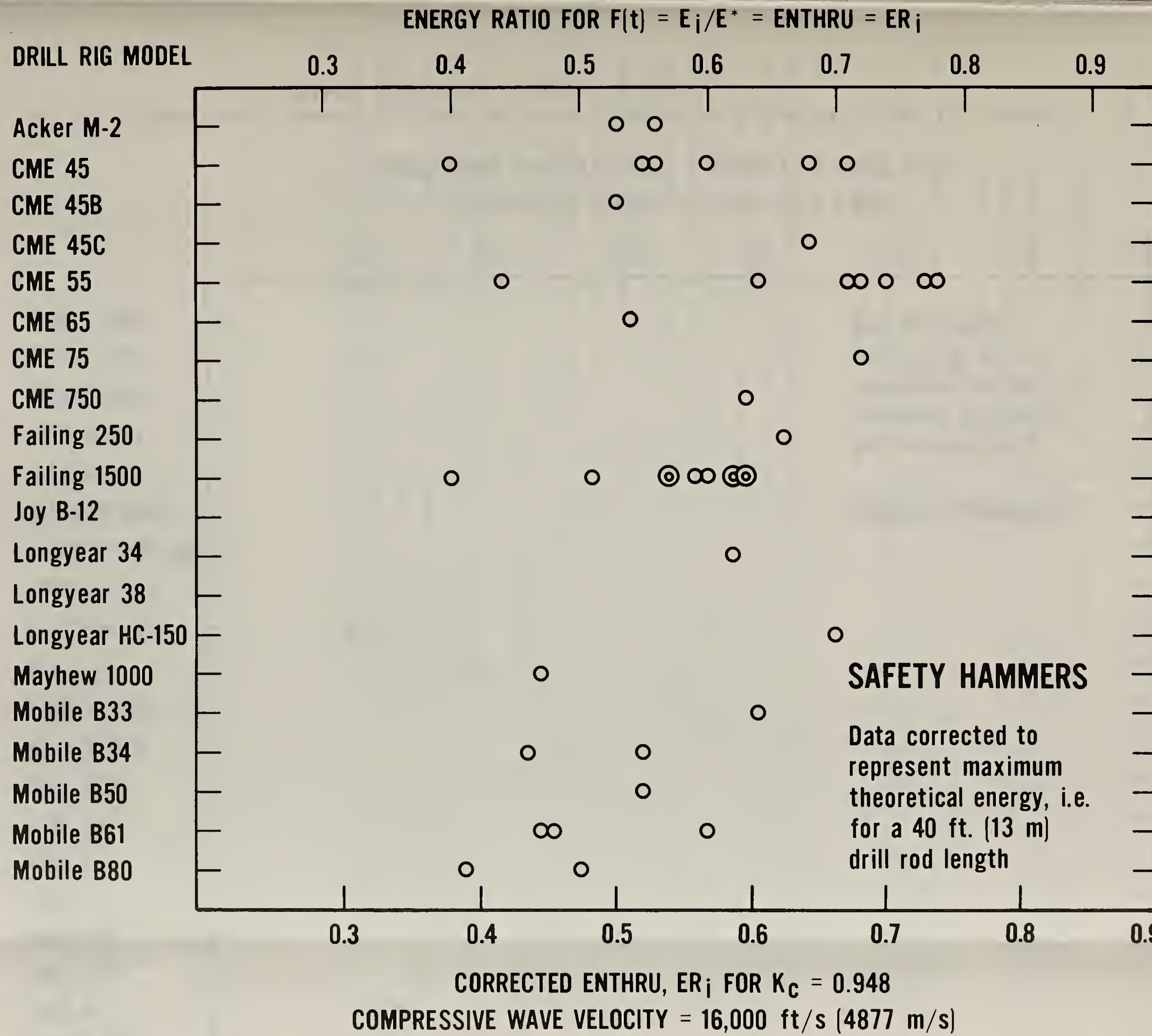


Figure 4.4a Summary of data to date of energy ratio for F(t), ER_i (a) safety hammers (b) donut hammers

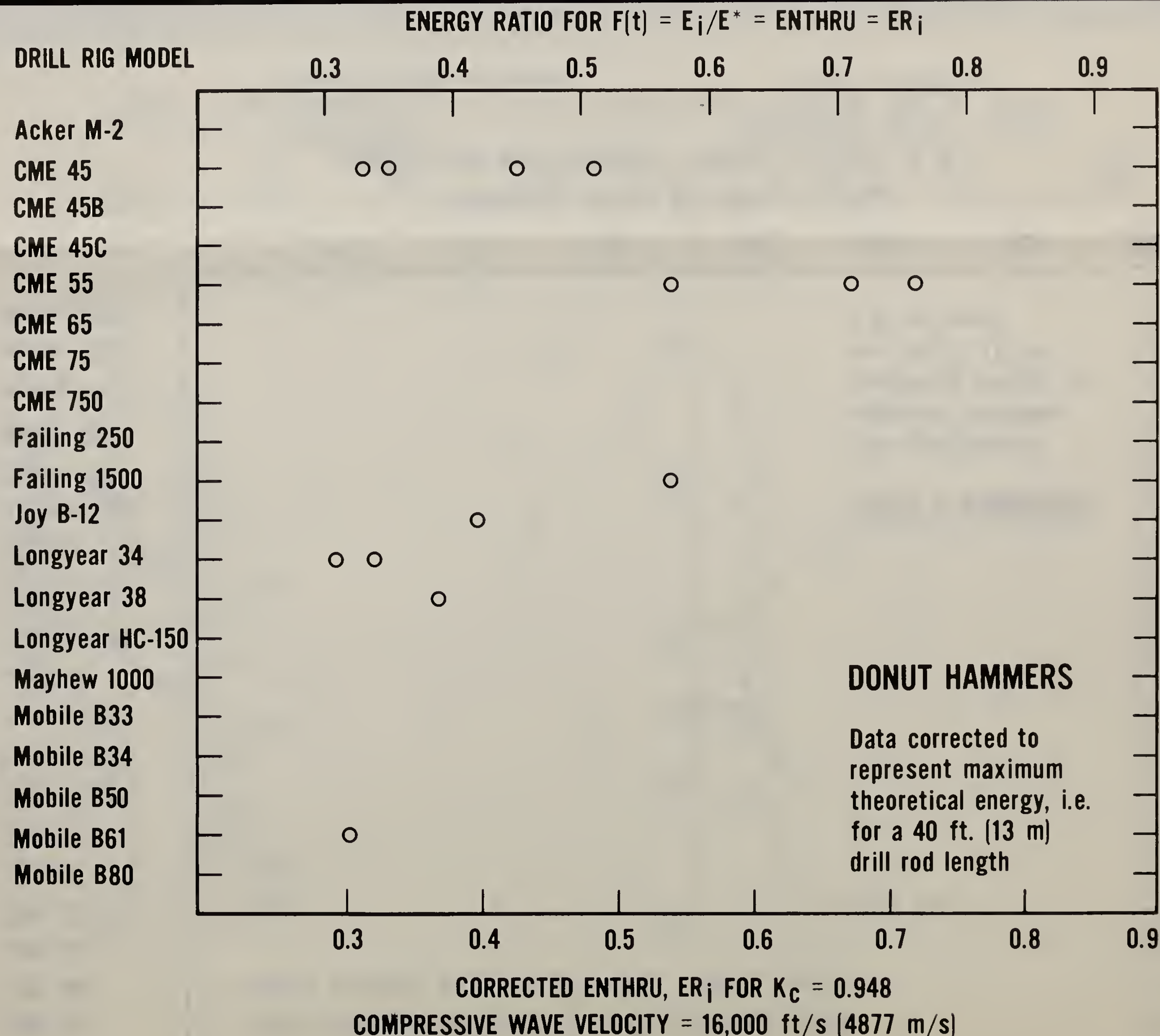


Figure 4.4b Summary of data to date of energy ratio for F(t), ER_i (a) safety hammers (b) donut hammers

$$ER_i \text{ (Avg for Fig 4.1)} = \Sigma \frac{(A \cdot B)}{\Sigma B} \times 100 \qquad (4.2)$$

where

A = average value of ER_i for a given drill rig model, data from table 4.1

B = frequency of use as determined by the number of drill rigs of a given model, column 2 of table 2.2, divided by the sum of all the drill rig models in column 2, table 2.2 (952 ea).

Such a computation for table 4.1 leads to a value of 58.8 percent. When this value (58.8 percent) is corrected for a compressive wave velocity of 16,000 ft/s (4877 m/s) (16,000/16,878) the corresponding average would drop to 55.7 percent, rounded off to 56 percent.

The wide scatter in the data shown in figure 4.4a and b raises the question whether the observed differences between the measured energy ratios among the various drill rig models are statistically significant (not caused by scatter of data for individual rigs) or whether the differences can be explained by the natural variation in the data. To test this hypothesis, a one-way analysis of variance (ANOVA) was performed for each of the two sets of data (safety and donut hammers). The results of the ANOVA indicate that a comparison of the differences within a drill rig model are about as large as the differences in energy ratios between drill rig models themselves. The comparisons are not large enough to obtain statistical significance (at the 5 percent level) based on the available data. Based on this result, there is no strong reason to use any specific weighting procedure to compute an average energy ratio for figures 4.4a and 4.4b. At this time (1983), a simple unweighted average will suffice.

The observed trend of energy variability underscores the need to standardize the SPT equipment and procedures and/or measure energy on some prescribed basis so that blow counts may be compared among various drill rigs on a common basis. A method for energy measurement based on the theory discused in section 3.3.1 is now (1983) under discussion with ASTM D 18. The intent is to permit blow count adjustments and comparisons using equation 4.1.

5. FINDINGS, CONCLUSIONS, AND RECOMMENDATIONS

5.1 FINDINGS

Based on this investigation, it was thought that:

1. The hammer potential energy, kinetic energy just before impact, the energy passing through the drill rods, and the energy transfer ratio, ETR, vary from blow to blow during the SPT.

2. A wide variety of drill rigs are used to perform the SPT in engineering practice.

3. Three types of SPT hammers are primarily currently used in engineering practice. In the order of decreasing popular use they are the safety hammer, donut, and the pin-guided hammer.

4. Based on the studies described in this report, the use of the safety hammer is almost twice as much as the donut hammer in current SPT practice. The arithmetic average energy ratio, ER_i, for the safety hammer is 59 percent, while that for the donut hammer is 47 percent based on results in figure 4.4a, 4.4b.

5. Some district offices of the U.S. Army Corps of Engineers and the Waterways Experiment Station have used a hydraulically operated, chain driven trip-hammer whose dimensions are approximately 5 1/2 in (140 mm) in diameter and 15 3/4 in (400 mm) long and consists of a lead filled steel casing. No published energy ratio data is available on these hammers.

6. At least five sizes of drill rod are used to perform the SPT. They are A, AW, BW, N, and NW rod sizes. Depending on size, some drill rods are available both in upset wall and parallel wall. When required, short sections of parallel wall rod may be used with longer sections of upset wall rod with relatively no change in energy ratio, ER_i, reading.

7. Two procedures for raising and lowering the SPT hammer are used in practice. They are the hold-drop procedure with a rate of 15 to 25 blows/minute and the regular (or continuous) rhythmic procedure with a rate of 30 to 60 blows/minute.

8. Most drill rig operators use 2 turns of rope around the cathead.

9. Based on results from experienced drill rig operators performing the SPT, a wide, random variation of fall heights can be expected with each blow, as well as the corresponding energy ratio for velocity, ER_v. A 3 in (76 mm) difference in fall height in sequential blows is not uncommon. The average fall height of the average of seventy-five test series was found to be 30.98 in (787 mm) with a standard deviation of 1.48 in (38 mm) and a coefficient of variation of 4.8 percent.

10. The SPT sampler as manufactured in the U.S. today has an enlarged inside diameter past the cutting edge or shoe to allow for the inclusion of liners, bringing the I.D. equal to that of the cutting shoe. However, liners are seldom used in engineering practice in the U.S. The use of liners inside the SPT sampler varies internationally. Liners are not used in the U.S.; but the inside diameter of the split barrel is 1.5 in (38 mm) while the standard samplers used in Japan and the United Kingdom are 1 3/8 in (35 mm), the same diameter of the cutting shoe.

11. When the energy is measured in the drill rods by a load cell, it is necessary to correct the computed energy for: the load cell not being at the point of impact; the drill rod length not being infinite; and for the actual compressive stress wave velocity being less than the theoretical value.

12. The cross-sectional area setting on the SPT Calibrator may be used only for NW parallel wall rod. If NW upset wall rod is used, a correction factor of 1.873 (2.27 in^2/1.212 in^2) must be applied (multiplied) to the ER_i reading.

13. Electronic glitches and compressive wave returns are two situations that caused abnormally high readings of ER_i by the SPT calibrator. This phenomena goes undetected unless the wave form is monitored and/or the actual integration time (of equation 3.6) is compared with the computed value of 2 ℓ'/c.

14. It is imperative to measure the integration time of the Calibrator in the field in order to insure that the load cell is working properly, as well as to interpret the data properly. In the event an excessively high reading occurs due to a compressive wave return instead of the usual tensile wave return, the integration time can be compared with the computed return time based on the rod length and a return compressive wave identified and the data rejected.

15. The energy transfer ratio of the donut hammer and the safety hammer are different. It appears that the donut hammer transfers the available kinetic energy just before impact in a much more random way than the safety hammer.

16. Nearly identical values for the energy ratio ER_i were obtained from the SPT Calibrator and the Digital Processing Oscilloscope (DPO). However, the SPT Calibrator by itself does not permit viewing of the force-time wave form. An oscilloscope must be attached.

17. The insertion of a 2 ft (0.7 m) section of BW parallel wall below the load cell and above a 35 ft (10.7 m) and a 40 ft (12.2 m) section of BW upset wall drill rod resulted in higher peak forces but no appreciable differences in ER_i.

18. When SPT N values are corrected for a common energy, more consistent N values are obtained when comparing test results for safety and donut hammers at the same site (see figures 4.1, 4.2, and 4.3).

19. Since the introduction of the concept of the national average energy (NAE) in 1981, information on the average energy ratio, ER_i of drill rigs has increased from 33 to 56 drill rigs. The present (1983) observed variation in energy derived by a given drill rig model is almost as great as the variation of ER_i among drill rig models.

5.2 CONCLUSIONS

Based on the data and findings in this report, the following conclusions are drawn:

1. The hammer to rod transfer of energy (ETR) is important, variable, and unpredictable. Therefore, the energy in the drill rods, ER_i cannot be predicted from hammer kinetic energy but needs to be measured directly in the rods.

2. The variability of the energy passing through the drill rod as delivered by present U.S. equipment and procedures is too great to be eliminated by a modification of procedures alone. Equipment as well as procedures would have to be modified to achieve satisfactory results.

3. More than one drill rig-SPT system (which includes the operator in the rope-cathead method) at a site can produce N-value variability due to ER_i variability among the drill rigs. N-value varies approximately inversely with ER_i. Correcting blow counts with known average energy ratios to a specified common energy ratio provides a more consistent profile of N values with depth.

4. While it is desirable that the reference energy level approximate the national average energy, the data sample presently available is too variable to permit a statistically significant estimate of the national average energy.

5. The methods presently used to measure the energy in the drill rod appear to give reasonable and consistent results but have not yet been verified by an independent theory and measurements.

6. The energy passing through the drill rod is not the only source of variability in the SPT results. The use of liners in the SPT sampler is also an important source of variability. The effect of the I.D. clearance when omitting the liner in U.S. samplers must be considered when evaluating SPT results from other countries.

7. The potential energy and kinetic energy of the hammer just before impact are the most reliable (checkable) energy measurements. The use of equation 3.6 to compute the energy passing through the drill rods by either the DPO or the Calibrator is considered satisfactory but not as reliable as the other two energies mentioned.

8. The drill rig, the SPT equipment (hammer, cathead and rope), and the operator should be considered as a unit when SPT energy is being evaluated.

9. The use of blow count data across international borders should be used with caution as the energy passing through the drill rods is not known in other countries and because of the equivalent use of liners in other countries.

10. In order to assure the actual occurrence of a tension wave cutoff as assumed in the use of equation 3.6 (integration of the force squared-time curve), it is necessary to confirm that the integration time compares favorably with the computed cutoff time of $2\ \ell'/c$.

11. Based on limited tests, the inclusion of or intermixing of parallel wall drill rods with upset wall drill rods does not appear to affect ER_i values.

5.3 RECOMMENDATIONS

Based on the conclusions from this report, the following recommendations are made:

1. SPT equipment and procedures be established which minimize the variability of the blow count. This would require a tripping mechanism, a standard hammer/anvil/drill rod system, a standard sampler with or without liner, and standard drilling procedures.

2. Until the SPT equipment is standardized:

    (a) The energy passing through the drill rod should be monitored and test results referenced to a standard energy, either the national average energy or an internationally accepted energy level.

    (b) The use of liners in the sampler should be eliminated, but the 1.5 in. barrel I.D. retained.

    (c) The test procedures be modified to minimize the test variability.

3. If we were to recommend SPT testing conditions to use in evaluating the liquefaction potential of an <u>important</u> structure on a site, we would recommend the following conditions:

    (a) Safety (type) hammer with AW drill rod stem with an available stroke of at least 35 in (889 mm).

    (b) Two turns of new rope around the cathead.

(c) Use of an 8 in. (203 mm) clean, shiny cathead.

(d) AW (parallel wall) drill rod.

(e) Rotary drilling with mud.

(f) Upward deflecting wash drilling bit.

(g) Blow count rate of 30 to 40 blows/minute.

(h) An SPT sampler with no liners [I.D. of 1.5 in (38.1 mm)].

(i) The fluid level in the bore hole should be at all times higher than the groundwater level. This can be accomplished by requiring that the surface of the drilling mud be at the top of the bore hole at all times.

(j) A 2 in (50 mm) colored band shall be permanently marked on the hammer guide pipe [from 28 to 30 in (711-762 mm) above the anvil] to help the operator produce an average 30 in fall height.

(k) ER_i and integration time should be monitored and recorded as needed during penetration from 6 to 18 in (300 to 450 mm).

[Procedures c, e, f, and h are based on findings by Schmertmann (1977).]

4. It is suggested that the blow count rate used in performing the Standard Penetration Test remain consistent for a given site and job. This is especially true in the case of performing the SPT in saturated silts where negative pore pressures may develop. In loose silts, the opposite may result where positive pore water pressures are induced. It is recommended that a rate of 30 to 40 blows per minute be specified, which is not that difficult for operators to obtain. Until further testing is performed in the field, this could provide a compromise and eliminate another variable in the SPT. However, with the advent of automatic SPT hammers operating at 50 to 60 blows per minute, field studies should be performed to determine the effect of testing rate on the N value with the above mentioned soil conditions.

5. To be consistent with present engineering practice, it is recommended that liners not be used in the SPT sampler during the performance of the SPT. This approach is presently being suggested in the revision of ASTM Standard D 1586. Because of the wide variation in energy ratio for velocity, it is recommended that only the ER_i measurement be made which does, in fact, control the blow count unless it is desired that energy transfer ratio information be obtained.

6. When ER_i data is reported, it is suggested that it contain the three corrections (one for load cell location with respect to the point of impact, K_1, length of drill stem, K_2, and effect of the measured compressive wave velocity in the rods, K_c).

7. Thus, if the energy ratio is to be measured for the purpose of establishing an equivalent blow count to some specified ER_i, then it is recommended that the energy ratio be determined during the performance of the SPT rather than on an infrequent basis. ER_i measurements, along with a check on the integration time, should be made to give the engineer confidence that the system (drill rig, operator, and hammer) average ER_i falls within a band of $\pm$ 5 percent. The number of measurements of ER_i may require a once per hour or once per day or once per month check of ER_i, depending on experience and changes in the system.

8. Sufficient data to recommend a reference energy level (REL) appears to be available in the report. The earliest ER_i measurements led others to suggest that the current average ER_i values in practice were around 50 to 55 percent. Our data base also gives overall weighted and unweighted averages of about 55 percent. We therefore tentatively recommend using a reference ER_i of 55 percent for N-value adjustments based on ER_i measurements.

9. The following additional research be conducted:

   (a) Check the present load cell integration method of determining ER_i by an independent energy theory and associated measuring system.

   (b) ER_i measurements for typical Japanese SPT practices to better interpret available liquefaction data.

   (c) Acquisition of a larger database to determine the national average energy.

   (d) Study of the effect of drill rod and anvil configurations on the energy transmission.

   (e) Study the effect of borehole diameter and drilling method on N value.

   (f) Study the types of SPT hammers used historically so as to evaluate the "past national average energy." Such a study would allow a comparison of past energy levels with present and future automatic hammer energy levels when using SPT design correlations established in the past.

6. ACKNOWLEDGMENTS

This study was primarily sponsored by the Division of Health, Siting, and Waste Management, Earth Science Branch of the Office of Nuclear Regulatory Research of the U.S. Nuclear Regulatory Commission (NRC) and partially by the Division of Research of the United States Bureau of Reclamation, the Department of Water Resources, State of California, and by the Structures Division, Center for Building Technology, National Engineering Laboratory of the National Bureau of Standards.

Keith R. Eberhardt of the Statistical Engineering Division, The Center for Applied Mathematics of NBS provided the Analysis of Variance (ANOVA) of the data presented in figure 4.1. R.E. Brown of Law Engineering Testing Company provided some energy ratio data with depth that were used in figure 3.9.

Critical review and helpful suggestions concerning this report have been provided by R.E. Brown and J.H. Schmertmann. Their contribution is greatly appreciated.

7. REFERENCES

British Standards Institution (1975), "Methods of Test for Soils for Civil Engineering Purposes," BS 1377, Test 19, Determination of the Penetration Resistance Using the Split-Barrel Sampler, pp. 103-104.

Brown, R.E. (1977) "Drill Rod Influence on Standard Penetration Test," Journal of the Geotechnical Engineering Division, ASCE, Vol. 103, No. GT11, pp. 1332-1336.

Casagrande, A. (1976), "Liquefaction and Cyclic Deformation of Sands: A Critical Review," Presented at the Fifth Panamerican Conference on Soil Mechanics and Foundation Engineering, Buenos Aires, Argentina, November, 1975; Reprinted as Harvard Soil Mechanics Series No. 88, January 1976, 27 pp. and figures.

Casagrande, A. and Casagrande, L. (1968), "Report, to American Electric Power Service Corporation on Foundation Investigations for the Donald E. Cook Nuclear Power Plant," Appendix G of Amendment 5, Cambridge, Mass.

Castro, G. (1975), "Liquefaction and Cyclic Mobility of Saturated Sands," Journal of the Geotechnical Engineering Division, ASCE, Vol. 101, No. GT6, pp. 551-569.

Fletcher, G.F.A. (1965), "Standard Penetration Test: Its Uses and Abuses," Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 91, No. SM4, pp. 67-75.

Goble, G.G. and Ruchit, P. (1981), Measurements of Impacts Velocity on Penetration Testing Systems," Dept. of Civil, Environmental and Architectural Engineering, University of Colorado, October, 171 pp.

Gravare, G-J. and Hermansson (1980), Practical Experiences of Stress Wave Measurement," International Seminar on the Application of Stess Wave Theory on Piles, A.A. Balkema, Rotterdam, pp. 99-120.

Hall, J.R. (1982), "Drill Rod Energy as a Basis for Correlation of SPT Data," Proceedings of the Second European Symposium on Penetration Testing, Amsterdam, A.A. Balkema, Rotterdam, Vol. 1, pp. 57-60.

Japanese Standards Association (1976), "Method of Penetration Test of Soils," Japanese Industrial Standard (JIS) 1219-1961 (Reaffirmed: 1976), Edition 6, Tokyo, Japan, 3 pp.

Kovacs, W.D. (1979), "Velocity Measurement of a Free-Fall Hammer," Journal of the Geotechnical Engineering Division, ASCE, Vol. 105, No. GT1, pp. 1-10.

Kovacs, W.D. (1980), "What Constitutes A Turn," Geotechnical Testing Journal, ASTM, Vol. 3, No. 3, pp. 127-130.

Kovacs, W.D. (1982), "Results and Interpretation of SPT Practice Study," Geotechnical Testing Journal, ASTM, Vol. 4, No. 3, pp. 126-129.

Kovacs, W.D., Evans, J.C., and Griffith, A.H. (1977), "Towards a More Standardized SPT," Proceedings, Ninth international Conference on Soil Mechanics and Foundation Engineering, Tokyo, Japan, Vol. II, Paper 4-18, pp. 269-276.

Kovacs, W.D., Salomone, L.A., and Yokel, F.Y. (1981), "Energy Measurement in the Standard Penetration Test," Building Science Series 135, U.S. Government Printing Office, Washington, D.C., 99 pp.

Marcuson, W.F., III, and Bieganousky, W.A. (1977a), "Laboratoary Standard Penetration Tests on Fine Sands," Journal of the Geotechnical Engineering Division, ASCE, Vol. 103, No. GT6, June, pp. 565-588.

Marcuson, W.F., III, and Bieganousky, W.A. (1977b), "SPT and Relative Density in Course Sands," Journal of the Geotechnical Engineering Division, ASCE, Vol. 103, No. GT11, pp. 1295-1309.

Palacios, A. (1977), "The Theory and Measurement of Energy Transfer During SPT Test Sampling," Thesis Presented to the University of Florida at Gainesville, Florida, in 1977, in partial fulfillment of the requirements for the degree of Doctor of Philosophy, 391 p.

Robertson, P.K., Campanella, R.G. and Wightman, A. (1982), "STP-CPT Correlations," Soil Mechanics Series No. 62, University of British Columbia, Dept. of Civil Engineering, October, 19 p.

Schmertmann, J.H. (1978), "Use the SPT to Measure Dynamic Properties? - Yes, But...!," Dynamic Geotechnical Testing, ASTM STP 654, American Society for Testing and Materials, pp. 341-355.

Schmertmann, J.H. (1979), "Statics of SPT," Journal of the Geotechnical Engineering Division, ASCE, Vol. 105, No. GT5, pp. 655-670.

Schmertmann, J.H. and Palacios, A. (1979), "Energy Dynamic of SPT," Journal of the Geotechnical Engineering Division, ASCE, Vol. 105, No. GT8, pp. 909-926.

Schmertmann, J.H. and Smith, T.V. (1977), "A Summary of SPT Energy Calibration Services Performed for the Florida DoT Under Service Contact 99700-7150-010," Final Research Report 245*D73, College of Engineering, University of Florida, Gainesville, Florida, 21 pp, Appendices.

Seed, H.B. (1979), "Soil Liquefaction and Cyclic Mobility Evaluation for Level Ground During Earthquakes," Journal of the Geotechnical Engineering Division, ASCE, Vol. 105, No. GT2, pp. 201-255.

Seed, H.B., Idriss, I.M., and Arango, I (1983)", Evaluation of Liquefaction Potential Using Field Performance Data," Journal of Geotechnical Engineering," ASCE, Vol. 109, No. 3, pp. 458-482.

Serota, S. and Lowther, G. (1973), Dicussion of "Accuracy of Relative Density Measurements by Travenas, F. and La Rochelle, P. (1972), GEOTECHNIQUE, Vol. XXIII, No. 2, pp. 301-303.

Timoshenko, S. (1934), Theory of Elasticity, 1st Ed., McGraw-Hill Book Co., New York, 416 pp.

Yoshimi, Y. and Tokimatsu, K. (1983) "SPT Practice Survey and Comparative Tests," to be published in Soils and Foundations, Japanese Society of Soil Mechanics and Foundation Engineers.

Youd, T.L. and Bennett, M.J. (1983), "Liquefaction Sites, Imperial Valley, California," Journal of Geotechnical Engineering, ASCE, Vol. 109, No. 3, pp. 440-457.

ENERGY RATIO FOR $F(t) = E_i/E^* = ENTHRU = ER_i$

Table A-1 Tabulation of Field Data ER_i, Percent from SPT Calibrator Series 79 through 90

Blow No.	Test Series											
	79	80	81	82	83	84	85	86[a]	87[a]	88[a]	89[a]	90[a]
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
1	50	--	56	42	55	56	--	54	77	75	58	73
2	51	--	53	42	--	55	--	69	51	65	53	65
3	50	51	50	44	64	57	--	142	48	65	59	56
4	49	52	46	47	54	56	--	91	45	57	49	62
5	50	55	48	44	--	60	37	65	41	62	59	53
6	50	54	55	48	55	63	47	54	75	81	49	64
7	49	50	55	47	55	58	46	42	44	60	64	68
8	47	46	58	35	--	58	46	101	45	69	55	53
9	45	50	63	46	55	55	49	81	55	63	55	116
10	48	50	51	54	58	50	41	96	91	65	65	55
11	48	52	45	38	--	53	44	59	76	69	91	47
12	51	50	62	28	75	49	34	52	47	61	48	52
13	48	49	49	44	54	46	46	57	42	57	76	60
14	45	50	68	41	--	51	37	61	41	67	48	69
15	49	52	55	47	52	49	35	60	87	80	46	51
16	50	52	64		52	47	47	74	45	57	49	55
17	43	51	52		54	46	33	106	47	57	44	53
18	51	53	64		52	54	42	45	105	98	49	53
19	45	54	49		53	--	39	90	49	68	49	78
20	45	52	55			60	39	74	64	72	52	68
21	49	--	46			50		61				56
22	35	54				53		70				84
23	47	55										58
24	43	55										107
25	46	52										64
26	47											
27	42											
28	47											
29	49											
30	48											
Average ER_i	47.2	51.8	54.5	43.1	55.6	53.6	41.4	72.9	58.7	67.4	55.9	64.3
Standard Deviation	3.4	2.3	6.7	6.1	5.8	4.9	5.2	23.7	19.4	10.1	11.3	16.7
Coef. of Variation	7.2	4.3	12.2	14.2	10.5	9.0	12.6	32.4	33.0	15.1	20.3	25.8
Operator	B	B	C	C	D	D	D	D	D	D	D	E
Hammer	S	S	S	D	S	S	D	D	D	S	S	S

a. Erroneous readings observed. Interpretation given in table A.4.
The symbol -- indicates data were not obtained.

ENERGY RATIO FOR $F(t) = E_i/E^* = ENTHRU = ER_i$

Table A-2 Tabulation of Field Data ER_i, Percent from SPT Calibrator Series 91 through 100.1

Blow No.	Test Series											
	91	92	93[a]	93[a]	94	95	95	96	97	98	99	100.1
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
1	63	51	55	94	57	44	45	41	49	48	40	50
2	60	51	115	102	67	47	47	41	49	48	46	49
3	56	50	87	92	50	48	49	43	44	45	47	51
4	58	54	59	99	45	45	50	47	47	47	49	48
5	59	50	122	75	52	45	42	43	45	45	49	52
6	62	30	57	82	58	47	50	46	44	46	49	51
7	59	33	53	59	59	49	45	46	44	44	47	51
8	68	49	55	56	58	41	45	45	47	44	48	49
9	61	49	53	114	61	45	49	43	47	43	46	50
10	64	49	38	89	51	43	49	45	47	43	49	48
11	67	50	40	52	56	44	47	45	47	43	47	47
12	63	50	140	66	52	45	44	45	48	46	50	48
13	66	55	82	71	52	42	44	47	45	43	50	45
14	67	39	106	56	65	46	45	46	48	46	49	47
15	65	51	109	82	57	45	44	46	46	46	49	50
16	76	46	62	73	62	48	45	48	48	42	48	49
17	63	51	90	86	49	48	45	45	46	42	47	49
18	56	29	65		45	45	44	46	45	42	47	49
19	54	49	69		48	46	44	47	47	42	46	49
20	70	51	121		51	46	49	46	51	43	45	50
21	78		62		62	45	42					
22	54		103			45	43					
23	57		82			49						
24	64		55			45						
25	64		66			45						
26			114			43						
27			90			47						
28			104			48						
29			81			45						
30			98			49						
Average ER_i	63.0	46.9		80.5	55.1		45.8	45.1	46.7	44.7	47.4	49.1
Standard Deviation	6.1	7.7		24.1	6.3		2.3	1.9	1.9	2.0	2.3	1.7
Coef. of Variation	9.6	16.4		29.9	11.4		5.0	4.3	4.0	4.5	4.8	3.4
Operator	E	E		E	E		C	C	E	E	C	E
Hammer	S	S		D	D		S	S	S	S	S	S

Table A-3 Tabulation of Field Data ER_i, Percent from SPT Calibrator Series 100.2 through 100.10

	Test Series								
Blow No.	100.2	100.3	100.4	100.5	100.6	100.7	100.8	100.9	100.10
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
1	57	40	52	52	45	48	31	43	52
2	56	33	51	52					51
3	56	32	49	50					51
4	55	33	52	52					50
5	55	33	50	50					52
6	53	32	49	51					52
7	57	33	51	50					47
8	56	31	52	52					48
9	55	30	48	51					49
10	55	--	51	49					49
11	56	33	47	50					
12		31	--	50					
13		30	48	51					
14		35	49	52					
15			47	52					
Average ER_i	55.5	32.8	49.7	50.9	45	48	31	43	50.1
Standard Deviation	1.1	2.5	1.8	1.0	--	--	--	--	1.8
Coef. of Variation	2.0	7.6	3.7	2.0	--	--	--	--	3.6
Operator	C	C	C	F	G	G	G	G	H
Hammer	S	S	S	S	S	S	S	S	S
Turns	1.25	3.25				1.25	3.25		

ENERGY RATIO FOR $F(t) = E_i/E^* = ENTHRU = ER_i$

Table A-4 Tabulation of Reinterpretated Field Values of ER_i, Percent from SPT Calibrator

Blow No.	Test Series						
	86	87	88	89	90	93	93
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1	54	*	*	58	*	55	*
2	69	51	65	53	65	*	*
3	*	48	65	59	56	*	*
4	*	45	57	49	62	59	*
5	65	41	62	59	53	*	*
6	54	*	*	49	64	57	*
7	42	44	60	64	68	53	*
8	*	45	69	55	53	55	*
9	*	55	63	55	*	53	*
10	*	*	65	65	55	38	*
11	59	*	69	*	47	40	*
12	52	47	61	48	52	*	59
13	57	42	57	--	60	*	56
14	61	41	67	48	69	*	*
15	60	*	--	46	51	*	*
16	74	45	57	49	55	62	52
17	*	47	57	44	53	*	66
18	45	*	*	49	53	65	71
19	*	49	68	49	--	69	56
20	74	64	*	52	68	*	*
21	61				56	62	*
22	70				--	*	*
23					58	*	
24					*	55	
25					64	66	
Average ER_i	59.8	47.4	62.8	52.8	58.1		57.5
Standard Deviation	9.6	6.1	4.5	6.1	6.5		8.4
Coef. of Variation	16.1	12.9	7.2	11.5	11.1		14.6
Operator	D	D	D	D	E		E
Hammer	D	D	S	S	S		D

Notes:

The symbol --- indicates data was not obtained.

The symbol * indicates data not used as compressive wave reflection suspected by abnormally high field reading.

Table A-5 Tabulation of Field Data ER_i, Percent from SPT Calibrator Series 102-109

Blow No.	Test Series[a]							
	102	103	104	105[b]	106A[c]	106B[c]	108	109
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1	61	46	55	--	--	75	61	56
2	59	45	57	60	43	69	64	53
3	63	55	61	--	41	77	60	71
4	64	46	54	69	42	81	66	51
5	58	46	52	61	35	85	70	72
6	62	54	45	63	36	70	45	47
7	60	56	52	54	49	65	68	55
8	--	50	50	56	48	68	55	61
9	--	56	53	67	51	67	64	56
10	54	44	62	68	45	63	56	56
11	58	45	61	59			66	79
12	--	49	55	64			59	56
13	57	53	53	62			63	71
14	51	43	59	57			68	66
15	75	46	53	58			61	67
16	60	49	55	54			68	83
17	56	49	59	53			68	83
18	63	48	45	54			60	--
19	53	48	50	58			62	77
20	71	47	57	62			70	84
21		46	48					
22			46					
Average ER_i	60.3	48.6	53.7	60.4	43.3	72.0	62.7	65.5
Standard Deviation	6.0	4.0	5.1	5.4	5.5	7.2	6.1	12.0
Coef. of Variation	10.0	8.2	9.5	8.9	12.8	10.0	9.7	18.3
Operator	I	J	K	I	I	I	I	I
Hammer	S	S	S	S	S	S	D	D

a. All tests conducted on a Mobile B61 Rig using 2 nominal turns using BW upset wall unless noted otherwise.

b. A 2 foot section of BW parallel wall rod was inserted above the 40 foot section of BW upset drill rod.

c. Series 106A-used 1 nominal turn of rope while 3 nominal turns of rope around the cathead used in Series 106B.

Table A-6 Tabulation of Field Data ER_i, Percent from SPT Calibrator Series 110-119

Blow No.	Test Series[a]								
	110	111	112	113	114A[b]	114B[b]	115	117	119[c]
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
1	79	--	66	80	43	84	86	68	80
2	78	--	68	61	49	84	79	71	74
3	77	78	69	65	67	87	69	75	78
4	80	83	70	64	67	87	--	87	86
5	76	81	72	57	74	81	--	75	85
6	83	79	69	72		84	80	88	77
7	74	78	105	67			81	89	76
8	76	76	100	77			71	90	76
9	69	78	101	66			78	89	82
10	71	77	113	70			77	87	86
11	72	82	102	75			80	86	86
12	75	74	107	75			68	85	85
13	74	75	101	77			83	86	83
14	70	76	103	54			80	86	85
15	84	75	88	61			79	88	85
16	75	76	97	78			78	85	77
17	73	75	115	76			77	84	--
18	77	76	91	80			82	78	87
19	68	74	86	74			90	91	
20	69	75	100	78			89	90	
21	72	76		81			79	92	
22	--	75		80				90	
23	72			78				81	
24	71			80					
25	71								
26	73								
Average ER_i	74.4	77.0	91.2	71.9	60.0	84.5	79.3	84.4	81.7
Standard Deviation	4.2	2.6	16.4	8.1	13.3	2.3	5.8	6.6	4.4
Coef. of Variation	5.6	3.4	18.0	11.3	22.2	2.7	7.3	7.8	5.4
Operator	K	K	J	J	J	J	K	I	J
Hammer	S	S	S	S	S	S	S	S	S

a. Tests from 110 to 112 performed using a Long year HC 150 rig, 2 turns, using BW upset wall rod; tests from 113 to 119 performed using a CME 75 rig, 2 turns using BW upset wall rod unless noted otherwise. The cross-sectional area reported in the Sprague & Henwood catalog shows the BW upset rods to be 0.966 in^2. The SPT Calibrator will not accommodate such a small area directly and a value of "500" was used to set the device in step 3 of the calibration procedure. Subsequently, an error was found in the S&H catalog by NBS and the correct cross-sectional area of the BW upset wall rods is 1.141 square inches. Thus to correct the field data for the correct area, multiply each value by 446/500 or 0.932. The average values reported in table 3.3 have been corrected. This table contains actual field data only.

b. Series 114A used 1 turn of rope while series 114B used 3 turns on rope around the cathead.

c. A 2 foot section of BW parallel wall rod was inserted above the 40 foot section of BW upset rods.

Table A-7 Tabulation of Field Data ER_i, Percent from SPT Calibrator Series 120-130

Blow No.	Test Series[a]										
	120	121	122	123	127A[b]	127B[b]	127C[b]	128A[c]	128B[c]	128C[c]	130[d]
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
1	67	65	79	75	94	73	63	86			87
2	--	70	80	86	84	65	62	89			80
3	62	70	82	84	75	68	56	88			81
4	--	73	80	80	79	62	59	88			90
5	60	77	79	75	84	65	60	90			79
6	58	69	78	80	73	72	57	89			78
7	64	78	80	77	83	67	61	88			79
8	52	71	74	77	81	72	63	80			88
9	--	78	80	78	80	71	64	86			80
10	61	72	83	79	77	70	51	87			86
11	82	72	80						78		95
12	60	75	78						79		97
13	54	73	78						85		101
14	66	69	78						74		83
15	59	72	79						74		87
16	--	68	79						77		94
17	57	75	77						79		92
18	62	79	82						81		89
19	--	73	81						76		82
20		70	75						90		94
21										--	84
22										--	89
23										--	93
24										58	103
25										57	77
26										64	85
27										55	84
28										67	92
29										62	86
30										63	84
Average ER_i	61.7	72.5	79.4	79.1	81.0	68.5	59.6	87.1	79.3	60.9	87.3
Standard Deviation	7.2	3.7	2.8	3.6	5.9	3.7	4.0	2.8	5.0	4.3	6.8
Coef. of Variation	11.7	5.1	3.5	4.6	7.3	5.4	6.7	3.2	6.3	7.1	7.8
Operator	L	L	M	N	L	L	L	L	L	L	L
Hammer	S	S	S	S	S	S	S	S	S	S	S

a. All tests conducted using a Failing 1500 drilling rig using 2 nominal turns of rope around the cathead and BW Sprague & Henwood upset wall rod unless stated otherwise. The cross-sectional area reported in the Sprague & Henwood catalog shows the BW upset rods to be 0.966 in^2. The SPT Calibrator will not accommodate such a small area directly and a value of "500" was used to set the device in step 3 of the Calibration procedure. Subsequently, an error was found in the S&H catalog by NBS and the correct cross-sectional area of the BW upset wall rods is 1.141 square inches. Thus to correct the field data for the correct area, multiply each value by 466/500 or 0.932. The average values reported in table 3.3 have been corrected. This table contains actual field data only.

b. Series 127 A, B, & C, used 1, 2, and 3 nominal turns of rope, respectively.

c. Series 128 A, B, & C, used 1, 2, and 3, nominal turns of rope, respectively. A 2 foot section of BW parallel wall was placed just below the load cell on top of 40 feet of BW upset wall.

d. A 2 foot section is included above the 40' rod, just below the load cell.

Table B-1 Tabulation of Individual Fall Heights During Testing, Series 82-98

Blow No.	Test Series						
	82	83	84	85	92	94	98
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1	31.0	29.75	--	--	30.13		33.13
2	31.25	30.25	30.00	--	30.50	30.37	29.75
3	32.75	31.25	30.50	30.5	28.50	30.37	29.50
4	32.25	28.5	29.63	30.5	30.25	30.50	30.13
5	33.0	30.75	30.13	30.25	28.75	30.62	29.13
6	31.88	30.25	30.50	31.0	30.00	28.37	29.37
7	--	30.75	29.75	29.75	30.50	30.75	28.87
8	--	30.75	30.00	31.13	28.75	29.63	28.75
9	--	31.25	29.75	30.50	30.37	30.37	29.63
10	--	32.25	29.75	30.50	29.5	29.00	28.63
11	30.38	33.25	31.00	29.50	30.53	30.5	28.75
12	30.00	29.25	29.50	30.13	28.50	31.37	27.5
13	30.75	30.75	28.13	29.75	31.50	30.00	
14	30.87	30.25	29.25	30.00	29.25	30.37	
15	30.75	31.25	29.25	30.37	30.00	30.00	
16		30.75	31.00	29.50	30.5	29.75	
17		31.0	30.75	30.25	29.5	30.63	
18		31.25	30.75	29.50	32	30.0	
19		31.00	26.75	29.25	30.00	31.50	
20			30.87	29.50	30.00	29.63	
21			28.75			29.63	
22			30.50				
23							
24							
25							
Average Fall Height, in	31.4	30.8	29.8	30.1	30.0	30.3	29.2
Standard Deviation, in	1.0	1.0	1.0	0.5	0.9	0.8	0.5
Coef. of Variation, %	3.2	3.2	3.4	1.7	3.0	2.6	1.7
Operator	C	C	D	D	E	E	E
Hammer	D	S	S	D	S	D	S

Table B-2 Tabulation of Individual Fall Heights During Testing, Series 102-112

Blow No.	Test Series									
	102	103	104	105	106A	106B	108	109	111	112
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
1	30.50	30.00	30.50	31.00	33.75	33.25	28.00	28.50	29.75	29.50
2	---	30.50	30.75	31.00	34.25	34.25	29.00	28.25	29.75	29.75
3	31.75	30.50	30.50	32.00	33.75	34.50	28.50	28.00	30.00	29.50
4	26.00	30.25	30.50	32.00	33.75	34.25	28.50	28.50	29.75	29.75
5	32.25	29.00	30.25	32.00	33.75	33.75	29.50	28.25	29.00	29.75
6	32.50	30.00	30.50	27.75	33.50	34.25	28.00	28.25	29.50	29.50
7	32.50	30.50	30.50	26.00	34.00	31.50	28.25	---	30.00	29.50
8	32.75	30.75	31.25	31.75	32.00	---	28.25	28.00	29.50	29.75
9	33.00	30.50	30.75	30.00	33.00	34.25	28.50	28.00	29.75	29.50
10	33.00	29.75	30.75	32.50	34.50	34.25	28.50	28.25	29.75	29.75
11	33.75	30.25	31.00	---			28.50	28.00	30.00	29.50
12	32.25	30.50	30.75	32.25			28.25	28.25	29.25	29.50
13	34.00	30.75	30.75	33.25			28.25	28.25	30.25	29.50
14	26.75	30.25	30.50	33.25			28.50	28.50	29.75	29.75
15	34.25	30.50	31.00	33.25			28.50	28.25	29.75	29.75
16	---	30.50	30.75	33.50			28.25	---	30.25	29.75
17	33.74	30.25	30.75	33.25			28.25	---	30.25	24.50
18	34.25	---	31.00	33.25			28.50	27.25	29.50	29.75
19	34.25	30.00	31.00	34.00			28.25	---	30.00	29.50
20	34.75	30.50	31.25	34.50			28.50	27.25	30.00	29.50
21		30.50	30.75						29.25	
22			31.00						30.50	
23										
24										
25										
26										
27										
28										
29										
30										
Average Fall Height, in	32.3	30.3	30.8	31.9	33.8	33.6	28.4	28.1	29.8	29.6
Standard Deviation, in	2.4	0.4	0.3	2.2	0.9	0.7	0.3	0.4	0.4	0.1
Coef. of Variation, %	7.5	1.3	0.9	6.8	2.8	2.1	1.2	1.3	1.2	0.4
Operator	I	J	K	I	I	I	I	I	K	J
Hammer	S	S	S	S	S	S	D	D	S	S
Turns	2	2	2	2	3	1	2	2	2	2

Note: Operator I used a "hold-drop" lifting procedure to perform the SPT. His safety hammer usually hit the underside of the anvil, surpassing the 30 in (76 cm) mark each time.

Table B-3 Tabulation of Individual Fall Heights During Testing, Series 113-123

Blow No.	Test Series									
	113	114A	114B	115	117	119	120	121	122	123
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
1	29.75	29.75	30.00	30.00	---	30.25	29.50	30.00	29.50	29.75
2	29.50	29.75	30.00	29.25	29.75	29.75	31.50	28.50	29.00	31.00
3	29.50	29.75	30.00	29.50	29.75	29.75	27.25	28.75	30.00	31.75
4	30.00	29.75	29.50	30.00	---	29.50	28.00	29.50	30.25	31.00
5	29.50	31.25	29.75	30.00	30.00	29.25	27.00	30.75	30.75	29.75
6	29.50		29.50	30.50	---	29.75	26.25	29.25	30.75	30.50
7	29.75			29.75	30.00	29.75	28.25	31.50	30.25	29.25
8	29.25			31.00	30.00	29.75	---	29.25	29.75	30.00
9	29.75			30.00	30.00	29.75	---	31.25	31.00	28.25
10	29.50			30.50	30.00	30.00	30.25	29.25	31.00	31.25
11	29.50			30.25	---	29.50	33.50	28.75	29.75	
12	29.50			29.75			30.50	30.25	30.25	
13	29.75			30.00			26.00	28.50	30.75	
14	29.50			30.25			28.75	28.75	30.00	
15	29.50						28.00	29.75	30.50	
16	---						26.50	30.25	27.00	
17	29.75						27.25	30.25	29.50	
18	29.75						28.25	31.50	31.25	
19	27.50						26.50	30.50	30.50	
20	29.75							28.50	29.00	
21	30.00									
22										
23										
24										
25										
26										
27										
28										
29										
30										
Average Fall Height, in	29.6	30.0	29.8	30.0	29.9	29.7	28.4	29.6	30.0	30.3
Standard Deviation, in	0.2	0.7	0.3	0.4	0.1	0.3	2.0	1.0	1.0	1.0
Coef. of Variation, %	0.2	2.2	0.8	1.5	0.4	0.9	7.2	3.3	3.2	3.5
Operator	J	J	J	K	I	J	L	L	M	N
Hammer	S	S	S	S	S	S	S	S	S	S
Turns	2	3	1	2	2	2	2	2	2	2

Table B-4 Tabulation of Individual Fall Heights During Testing, Series 127-130

Blow No.	Test Series									
	127A	127B	127C	128A	128B	128C	130			
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
1	30.75	30.00	29.75	29.50	29.75	---	29.25			
2	31.00	32.25	24.75	30.00	27.75	---	26.50			
3	29.25	28.50	30.25	29.50	29.25	---	22.75			
4	29.75	30.25	26.75	30.50	30.00	29.75	28.50			
5	30.50	29.75	28.50	31.00	25.25	29.75	24.25			
6	27.25	31.50	29.25	30.50	28.25	32.25	28.75			
7	30.00	29.50	32.00	29.75	25.00	29.25	28.50			
8	30.50	27.75	31.25	29.75	27.50	29.75	28.25			
9	29.25	30.25	30.50	29.75	30.00	28.75	29.25			
10	28.50	29.25	---	30.00	30.25	29.00	28.75			
11							29.50			
12							29.00			
13							25.75			
14							30.50			
15							29.00			
16							29.25			
17							30.25			
18							29.25			
19							---			
20							30.25			
21							28.75			
22							27.25			
23							31.25			
24							29.75			
25							27.00			
26							27.25			
27							27.75			
28							31.00			
29							28.75			
30							29.0			
Average Fall Height, in	29.7	29.9	29.2	30.0	28.3	29.8	28.5			
Standard Deviation, in	1.2	1.3	2.3	0.5	1.9	1.2	1.9			
Coef. of Variation, %	3.9	4.4	7.8	1.6	6.8	3.9	6.6			
Operator	L	L	L	L	L	L	L			
Hammer	S	S	S	S	S	S	S			
Turns	1	2	3	1	2	3	2			

NRC FORM 335 (11-81)

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

1. REPORT NUMBER *(Assigned by DDC)*
NUREG/CR-3545

4. TITLE AND SUBTITLE *(Add Volume No., if appropriate)*
Comparison of Energy Measurements in the Standard Penetration Test Using the Cathead and Rope Method

2. *(Leave blank)*

3. RECIPIENT'S ACCESSION NO.

7. AUTHOR(S)
William D. Kovacs, Lawrence A. Salomone and Felix Y. Yokel

5. DATE REPORT COMPLETED
MONTH July | YEAR 1983

9. PERFORMING ORGANIZATION NAME AND MAILING ADDRESS *(Include Zip Code)*
National Bureau of Standards
Department of Commerce
Washington, D. C. 20234

DATE REPORT ISSUED
MONTH November | YEAR 1983

6. *(Leave blank)*

8. *(Leave blank)*

12. SPONSORING ORGANIZATION NAME AND MAILING ADDRESS *(Include Zip Code)*
Division of Health, Siting and Waste Management
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555

10. PROJECT/TASK/WORK UNIT NO.

11. FIN NO.
B7457

13. TYPE OF REPORT
Final Report

PERIOD COVERED *(Inclusive dates)*

15. SUPPLEMENTARY NOTES

14. *(Leave blank)*

16. ABSTRACT *(200 words or less)*

Studies conducted on the Standard Penetration Test (SPT) and its present use in engineering practice show that a wide variation in the use of different pieces of SPT equipment, procedures and personnel results in a range of energy measured in the drill rods from 30 to 85 percent of the standard SPT energy. The potential energy and kinetic energy of the hammer were measured prior to impact, and the energy passing through the drill rods was calculated from a force-time measurement in the rods. It was found that safety (type) hammers tend to allow more kinetic energy to pass through the hammer-anvil system than donut (type) hammers. The energy passing through the drill rods was calculated by using a digital processing oscilloscope and an SPT Calibrator. Lessons learned in evaluating the energy measurements by these two methods are discussed. The combined effect of the drill rig used, the operator and his procedures, and the SPT equipment should be considered when energy is to be evaluated. The variation of average energy ratio within various drill rig models was found to be about as large as that among drill rig models. It was therefore impossible to make a statistically significant estimate of the reference energy which is representative of the average energy delivered in U.S. practice.

17. KEY WORDS AND DOCUMENT ANALYSIS
calibration; donut hammer; drill rods; energy; energy ratio; engineering practice; equipment; field tests; hammers; in-situ testing; safety hammer; soil tests; SPT; test procedures.

17a. DESCRIPTORS

17b. IDENTIFIERS/OPEN-ENDED TERMS

18. AVAILABILITY STATEMENT
Unlimited

19. SECURITY CLASS *(This report)*
Unclassified

21. NO. OF PAGES

20. SECURITY CLASS *(This page)*
Unclassified

22. PRICE
S

NRC FORM 335 (11-81)

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE, $300

FOURTH CLASS MAIL
POSTAGE & FEES PAID
USNRC
WASH D C
PERMIT No G 67