Economic Factors Relative to Drilling Large-Diameter Holes

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ABSTRACT

Since 1950, rotary-drilled, large-diameter holes, "big holes," with depths to over 300 feet and diameters of over 30 inches have become numerous and widespread. Fifty such holes have been drilled for access shafts to LPG mined caverns. Over 70 holes have been drilled for various other commercial activities. Over 150 holes have been drilled by the AEC for atomic testing purposes. These holes have ranged up to 300-inch diameters with 1,600-foot depths, 120-inch diameters with 570-foot depths, and 72-inch diameters with 4,800-foot depths. The accompanying tables show pertinent historical, technical and economic data on over 250 holes.

Although historical and technical data on rotary-drilled "big holes" may be found numerous in the literature, published economic data is limited. Curves presented in this paper show the upward trend of the costs on many factors as holes get bigger and deeper. Some of these factors are rig and equipment size, formation hardness, circulating media, bits and cutters, and shaft lining. Some costs tend to increase as exponential functions of depth and hole diameter.

By following the procedures outlined in this paper, estimated time and costs for rotary-drilled, large-diameter holes may be calculated.

INTRODUCTION

The purpose of this paper is to present a compilation of the available data on large-diameter holes or "big holes," to show the experience obtained to date, to show that "big hole" drilling is feasible and available to the industry, and to present economic data in such a manner that "ball park" estimates for comparative purposes can be made by anyone who is familiar with rotary drilling and the type of hole desired.

The text is divided into two parts. The first part is a discussion of factors involved in "big hole" drilling. The second part assumes a set of conditions and leads the reader through the procedure of an example problem.

Historical and technical data on "big holes" is extensively covered in the literature. On the other hand, economic data is lacking in most of the publications and extremely sketchy where it is mentioned. Most of the economic data shown in this paper was obtained directly from project files and not from the published literature. It was felt that a paper emphasizing economics would help clarify the overall perspective of "big hole" drilling.

DISCUSSION

Although the drilling of "big holes" has been accomplished for over 20 years, it has only been within the last 10 years that a significant number of large-diameter holes has been drilled. For the purposes of this paper, the discussion is limited to rotary drilled vertical holes larger than 30 inches in diameter and deeper than 300 feet in depth. A search of the literature has produced the references and bibliography attached as part of this paper.

A review of the literature revealed numerous descriptions of the equipment involved and the methods used to accomplish the many unique jobs. A compilation of data concerning the holes drilled for commercial purposes is presented in Appendix I.

One company, Fenix & Scisson, Inc., of Tulsa, Oklahoma, has drilled fifty "big holes" for the unique application of access shafts to mined underground storage chambers. A listing of these holes is shown in Appendix II.

Since 1961, the majority of the large-diameter holes have been drilled for the Atomic Energy Commission for underground testing of atomic devices. A compilation of data, including costs, concerning the AEC holes is shown in Appendix III. Most of the data shown has not been previously published but was accumulated directly from the files with the authorization of the AEC.

For the drilling of any particular "big hole," a series of interrelated factors must be considered, before an economic appraisal can be made. These factors, as much as possible, are considered individually in this paper.

Relationship of costs vs hole size and depth. It would be quite helpful if a single formula were available to calculate the costs of holes given a set of conditions, hole size and depth. Unfortunately, such a formula relating costs versus hole size or depth is not available nor easily derived. Given a generalized set of conditions, however, certain costs could be related:

1. To the approximate square of the diameter of the hole, such as mud volumes, cutter usage, circulating rate, drill pipe torsion and circulating requirement, liner, float shoe, penetration rate, cement volume.
2. To the approximate direct ratio of the diameter of the hole, such as bit cost, rotary speed, weight on bit, conductor pipe, trip time, location.
3. To the approximate 1.5 exponent of the hole depth, such as penetration rate, trip time, liner wall thickness.
4. To the approximate direct ratio of the hole depth such as cement volume by height, liner length, mud volumes, logs, cutter usage.
5. Variables depending on neither the hole size nor the depth, such as engineering, set-up charges.

A formula may be postulated such as:

$$\text{Cost} = A\ (\text{Diameter})^{B} + C\ (\text{Diameter})^{D} + E\ (\text{Depth})^{F} + G\ (\text{Depth})^{H} + I$$

where all functions are variables. It is foreseen that B would vary from 1.8 to 2.2, D would vary from 0.8 to 1.2, F would vary from 1.3 to 1.7, and H would vary from 0.8 to 1.2. A, C, E, G and I would vary widely. Specific cases may be calculated and values assigned to the variables for short extrapolations of ranges of hole diameters and depths. If sufficient cost data were compiled, the above formula could be further developed. The author suggests that drilling contractors and shaft owners could do industry a favor by publishing their cost data, thus providing wider cost experience than that which is now available. Without such information, each "big hole" must be analyzed by considering all the factors to be involved. Such an analysis follows in this paper.

Hole size. If a steel liner (casting) is to be installed, the size of the hole must be sufficient to accept the casing. Since no drilled hole is absolutely straight, the ability of the hole to accept the casing depends on the straightness of the hole, as well as the size.

As holes get deeper and bigger, external diameters and stiffness of the liners increase rapidly. Since different types of liners have varying abilities to enter a drilled hole (due to the structural features and stiffness of the liner) then the real problem is, how large does the hole need to be in order to accept the desired casing? Analytical means are presently being developed to determine the required hole size. Until such analysis is completed and reliable experience obtained, selection of hole size is of necessity quite arbitrary. For preliminary estimating, the data presented in Fig. 1 may be used for determining hole size.

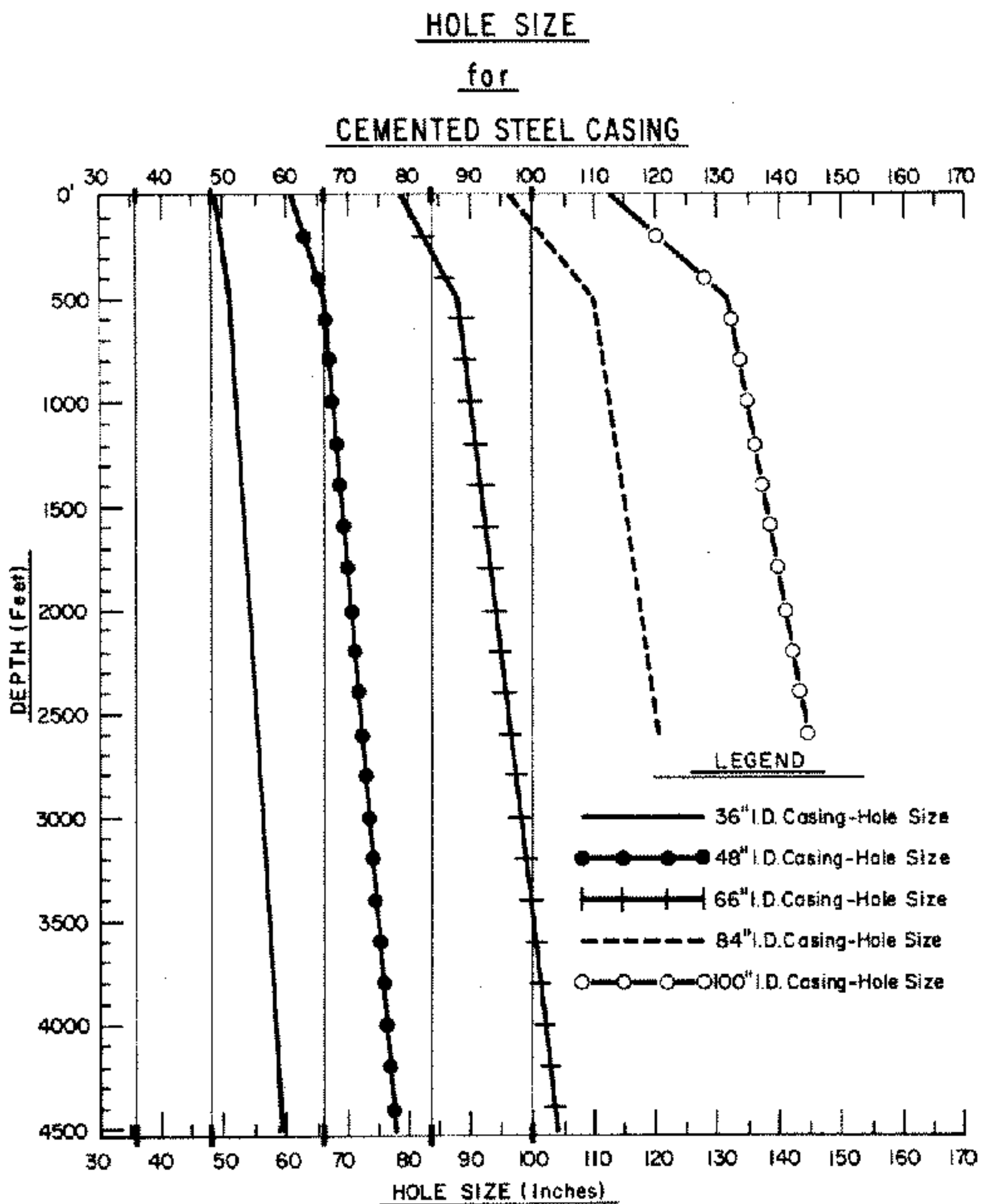


Figure 1

Bit. Until recently, "big hole" bits were quoted on special order; however, at least two bit manufacturers now have list prices. The average cost of single-pass bits by size is shown in Fig. 2. Stage-type bits and stacked hole-openers are also available but are now shown herein.

Cutter use. The replacement cutters used on "big hole" bits are a major cost item. This is particularly true when the formation is hard and abrasive or the bit is improperly cleaned by the circulating fluid. For estimating purposes, the cost of cutters may be calculated on a unit volume of material removed. Cutter-cost data in Table 1 is based on averages compiled from many holes under some of the better bit-cleaning conditions.

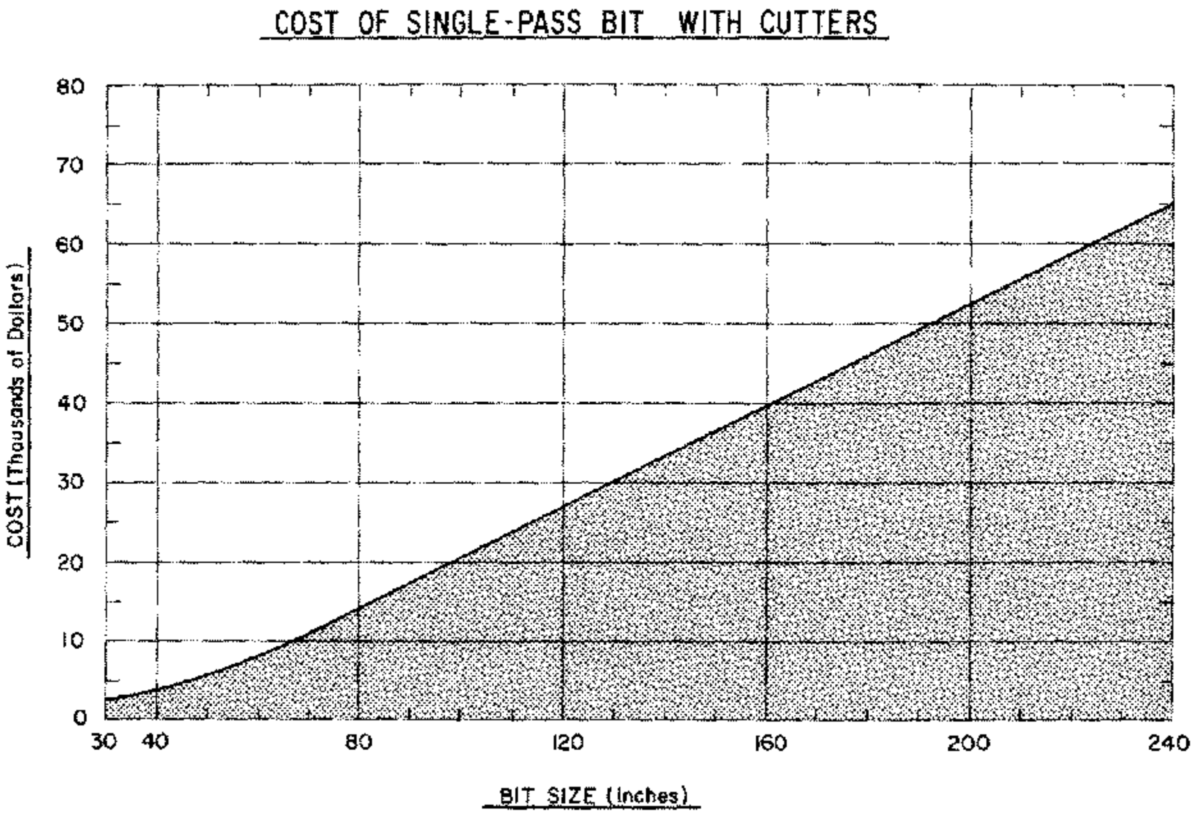


Figure 2

Weight on bit. As the hole size increases, the weight on the bit is generally increased to maintain a satisfactory drilling rate. Figure 3 shows the effect of increased bit weights on the drilling rate with oil-field size, tri-cone rock bits on medium to hard formations. "Big hole" bits, however, must be considered differently from tri-cone bits. The cutters and teeth on "big hole" bits are usually widely spaced and are designed for the bit weight available.

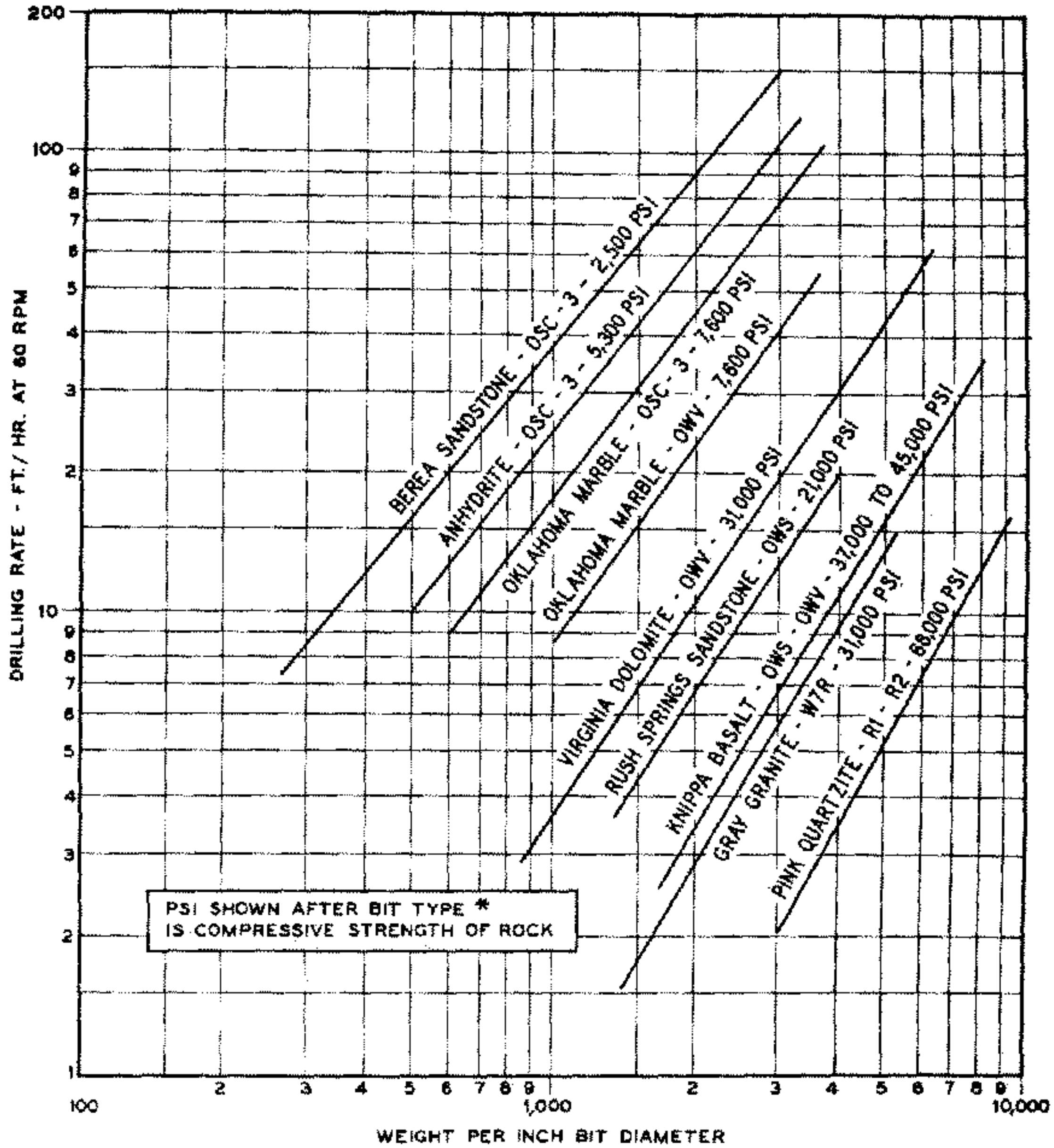
Heavy bit loadings may be impractical or uneconomical to obtain. Bottomhole cleaning, drill-pipe torque, or hole deviation may limit the bit load that can be applied. All the weight available cannot normally be applied to the bit; some weight must be suspended to plumb and keep the hole drilling vertically.

Table 1

Cutter Cost

Formation	$/cu. ft. Removed
Soft	0.50
Medium Soft	0.75
Medium Hard	1.00
Hard	1.50
Very Hard	2.00

Weight is normally applied to the bit through the use of dead weight (drill collars) just above the bit. For preliminary purposes, the data shown in Fig. 4 may be used for estimating drill collar requirements as a function of the type of formation being drilled and bit size.



*Hughes Tool Co. Classification.

Figure 3. Drilling Rate Versus Weight for New Rock Bits.

Various forms of drill collars have been used varying from steel tubular members to lead or ore-filled baskets. Various materials and the physical data for drill collars are shown in Fig. 5.

One popular style drill collar is constructed by placing cast-iron circular weights over a central tubular member. Typical physical data and costs for this type of collar are shown in Table 2.

Rotary speed. For a given size and type of bit, the drilling rate (assuming good bottom hole cleaning) increases as a function of the rotary speed. However, for "big holes," the high peripheral speeds of the outside cutters of the bit, and the torque involved, dictate that rotary speeds must be kept low. A rule-of-thumb for maximum rotary speed is:

$$\text{Rotary Speed (rpm)} = \frac{1440}{\text{Bit Diameter (inches)}}$$

Table 2

"Big Hole" Equipment Costs

Description	Weights, lbs.	Cost, $
Swivel, 650 ton, 12" ID	18, 000	19, 500
Swivel, 250 ton, 12" ID	7, 000	10, 700
Kelly, 12" ID, 14" OD, 42' Long	6, 400	4, 400
Stabilizer, 72"	21, 000	14, 000
Stabilizer, 52"	14, 000	11, 000
Reamer, 72"	21, 000	14, 000
Reamer, 52"	14, 000	11, 000
Drill Collar; 30" OD, 11" × 45' mandrel	140, 000	25, 000
Drill Collar; 40" OD, 16" × 45' mandrel	200, 000	37, 000
Drill Collar; 60" OD, 16" × 45' mandrel	300, 000	50, 000
Drill Collar; 72" OD, 20" × 45' mandrel	500, 000	86, 000
Hose, 12" × 50' × 65 psi	1, 600	1, 300
Sub 13-3/8" × 5'	1, 000	1, 100
Standpipe, 12" × 50'	3, 300	1, 000
Tongs, BJ Type DD, each	1, 400	4, 300
Pumps, 6750 GPM, Centrifugal, without drive		4, 200
Bit, 72", single-pass	14, 000	See Figure 2
Drill Pipe	See Table 4	

Most oil-field rigs are geared to several speed ranges, all of which are excessive for "big hole" rotating. Modification of the gear reduction system is usually necessary. The cost of this modification may range up to $20, 000 or more for big rigs.

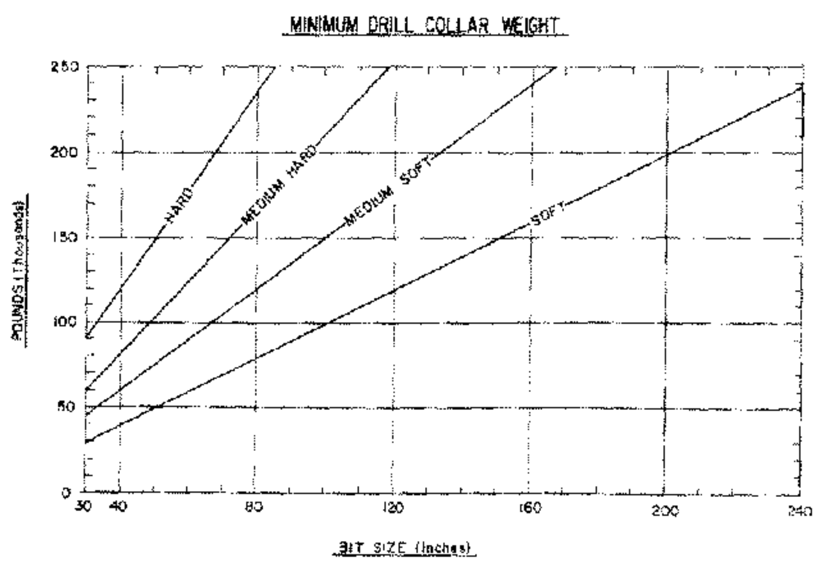


Figure 4

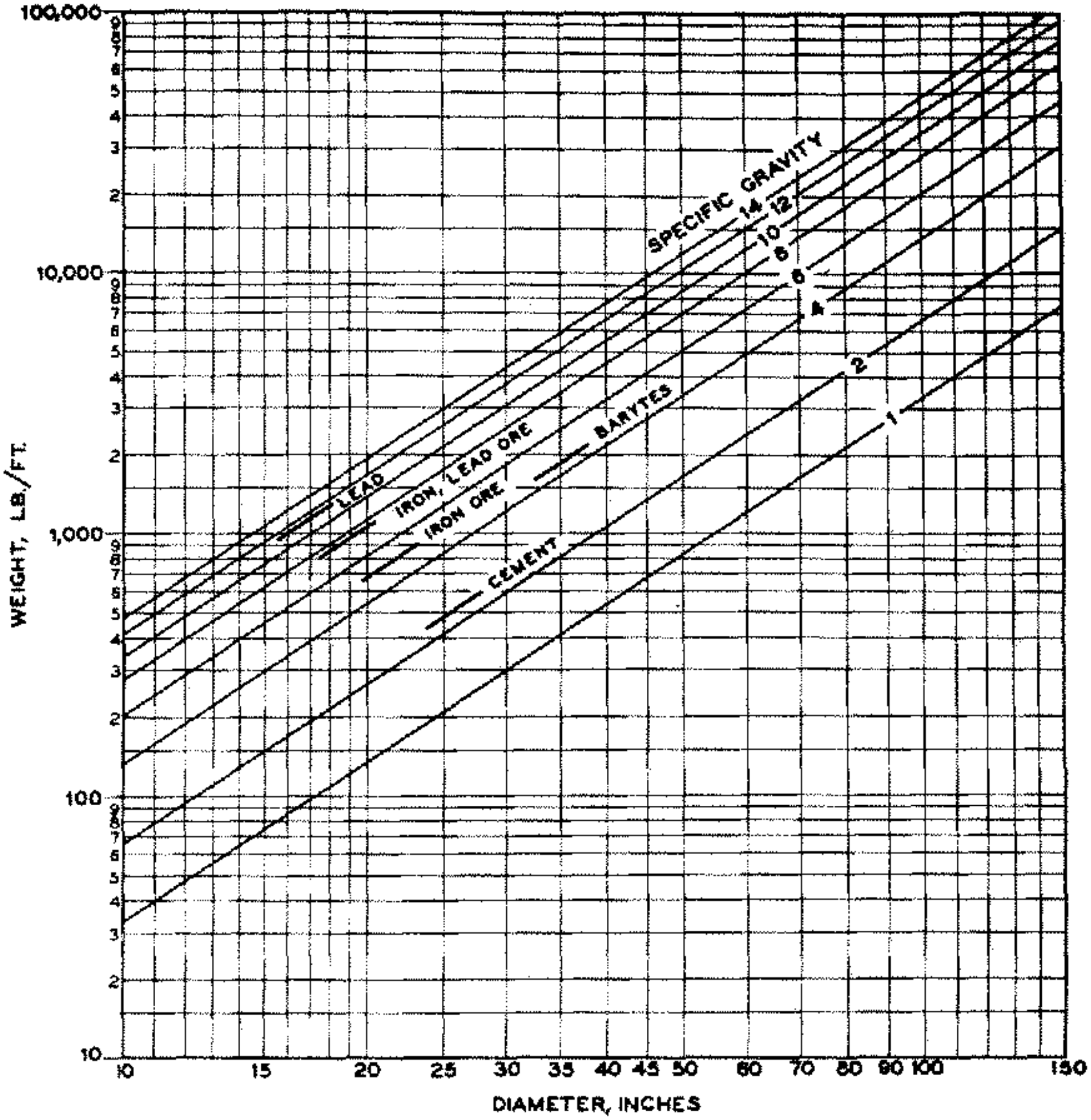


Figure 5. Diameter Versus Weight Per Foot of Height for Various Materials. (Morlan)

Torque. Laboratory data for small bits and empirical data for bits with diameters up to 72 inches have shown the torque can be predicted by the relationship:

$$T = 5252\,K\,D^{2.5}\,W^{1.5}$$

where: T = Torque, ft.-lb.
K = Formation characteristic
D = Bit diameter, inches
W = Weight on bit, lb./in. diameter in 1000 lbs.

This relationship can be reasonably extrapolated to at least 120 inches in diameter. Figure 6 allows a graphical solution of the equation. (Morlan, Mar. 1961, P. 14.)

Rotating horsepower. Rotating horsepower is a function of rotating torque and rotary speed and may be calculated by:

$$\text{Rotary Horsepower} = \frac{TN}{5252}$$

where: T = Rotary torque, ft.-lb.
N = Rotary speed, revolutions/minute

The plot of Fig. 6 includes this function.

Oil-field type rotary tables are not designed for the continual torque and horsepower requirements of "big hole" drilling. Therefore, most rotary tables must be specially rigged and maintained for the stringent drilling conditions. Unless the drilling contractor has readily available maintenance for his equipment, a spare rotary table should be on location.

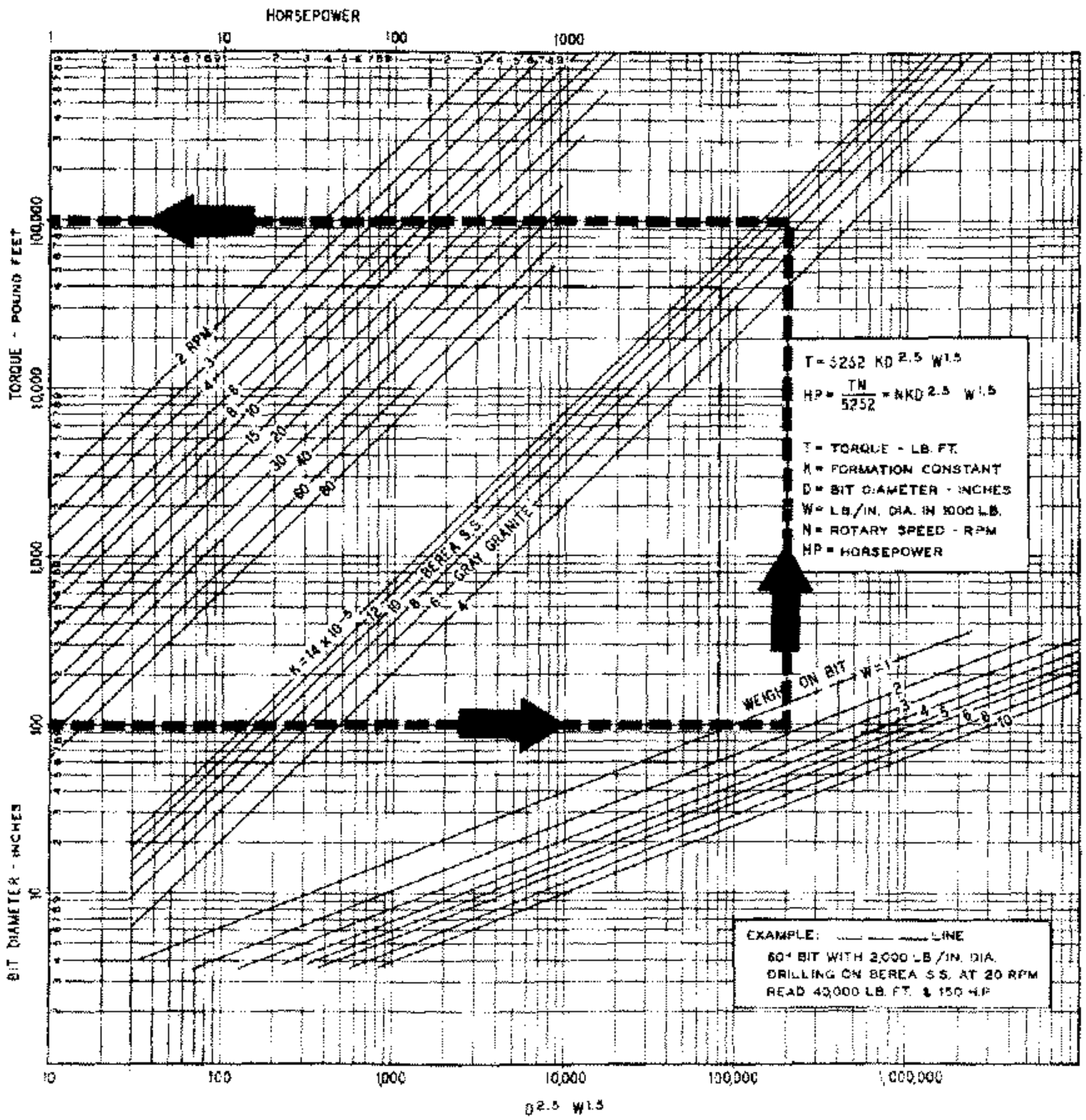


Figure 6. Torque Required Under Different Drilling Conditions. (Morlan)

Circulating system. The circulated fluid must function to effectively clean the bit and return the cuttings to the surface. When drilling with mud, a minimum circulating rate to use for effective bottom-hole cleaning is (Morlan, Mar. 1961, P. 4):

$$\text{Circ. Rate} = 50d$$

where: Circ. Rate = Gal./min.

d = Hole diameter, inches

Mud return annular velocities of 100 ft./min. are desirable but are generally impractical in direct circulation within "big holes." In practice, 25-40 ft./min. return annular velocities have yielded acceptable results, although "big holes" have been drilled with annular velocities less than 10 ft./min.

Decreasing annular velocities cause reduced circulation effectiveness and, generally, decreased penetration rates and increased cutter usage. The annular mud velocity achieved in any given drilling situation may be estimated from Fig. 7.

Mud volumes of over 1500 gpm at pressures less than 100 psi are usually supplied by centrifugal pumps. These pumps are not normally part of the oil-field rig equipment and should be considered as special "big hole" equipment. Centrifugal pumps capable of 6750 gpm at 35 psi back pressure can be purchased for $4200 without drive.

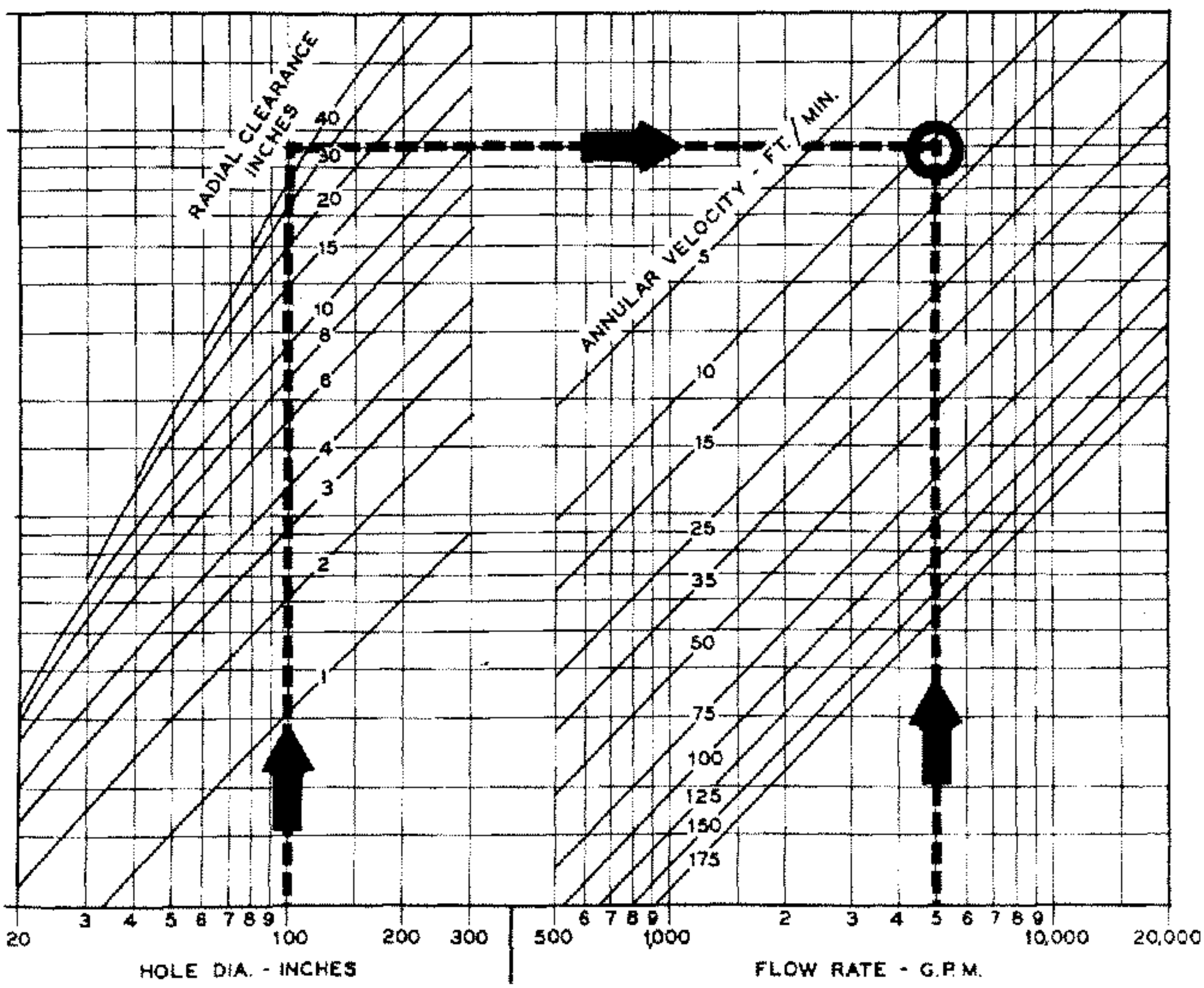


Figure 7. Annular Velocity Related to Flow Rate, Radial Clearance of Drill Stem and Hole Diameter. (Morlan)

Mud volumes to 1500 gpm at pressures over 500 psi are considered normal output from the two or three mud pumps used with the ordinary drilling rig.

Mud pump horsepower may be calculated by:

$$HP = \frac{PQ}{1714}$$

where: HP = horsepower
P = pressure in psi
Q = circulating rate, gpm

When air is used as the circulating fluid, water-free air return velocities of 3000 ft./min. are desirable. In most cases, air velocities for effective cutting removal are too low and must be aided by the injection of water and foaming agents.

Compressors with drive may be purchased from \$120-\$175 per compressor horsepower. Compressor rental may be calculated at $\frac{\text{Purchase Cost} \times 1.06}{12}$ per month. Compressor horsepower may be estimated at (24) (Compression Ratio) (Number of 10^6 cu. ft. of air per day).

In drilled holes which are over 48 inches in diameter, reverse circulation with returns inside the drill pipe, is becoming increasingly popular.

The requirements for other systems such as air-lift, air-foam, or eductor systems are beyond the scope of this paper. Table 3 is a rule-of-thumb recommendation for circulating systems. (Bowman, Oct. 1964, P. 5.)

Table 3*

Drilling Methods

Hole, Diameter Inches	Drilling Method	Circulating Media: For Wet Formation	Circulating Media: For Dry Formation
Up to 48	Single Pass, Conventional Circulation	Mud	Air
	or		
	Multipass, Conventional Circulation (with small drill pipe)	Mud	Air
48 to 96	Single Pass, Conventional Circulation	Mud	Mud
	or		
	Single Pass, Reverse Circulation	Mud	Air
96 to 144	Single Pass, Reverse Circulation	Mud	Air
Larger than 144	Multipass, Reverse Circulation	Mud	Air

*Based on Bowman Shaft Drillers, Inc. AAODC, Oct. 1964.

Circulating power. Positive displacement and centrifugal type mud pumps have an efficiency of about 70 percent. Air compressors usually operate at about 50 percent efficiency. Diesel fuel and butane costs are about \$0.008 per continuous horsepower-hour. Pump and engine maintenance will approximate fuel costs. Fuel and maintenance costs may be calculated by considering the rotating hours (hours in use), circulating horsepower and expected efficiencies.

Initial cost of diesel engines will vary from $50-$55 per continuous horsepower. To this capital outlay may be added $20-$30 per horsepower transmitted for mechanical power transmission equipment.

Formation drillability. Since formation compactness increases with overburden pressures, drilling difficulty, in general, increases with formation depth.

When using mud, the mud column on the formation being drilled holds the cuttings in place and the regrinding slows drilling. A minimum weight mud should be used, consistent with other requirements, in order to minimize this effect. In those cases where air may be used for drilling, the chip holddown is eliminated.

Abrasive formations tend to wear the cutters faster than non-abrasive formations thereby requiring more frequent cutter replacement. The time necessary to pull the bit and change the cutters decreases the overall productive drilling time and can be minimized by maintaining an optimum hydraulic system.

Normally, single-pass drilling is recommended. However, under certain conditions, it may be advisable to use a series of hole-opening passes for: (1) holes up to 48 inches, (2) holes over 144 inches or (3) very hard formations.

Bit cutters must be suited to the formation being drilled. Competent technical knowledge must be applied to obtain the proper bit usage. Penetration rates will vary with bit weights, rotary speeds, formation hardness and drillability, type and condition of bit cutters, and type and cleaning ability of the circulating media. All these factors are interrelated and make penetration rates extremely difficult to predict. However, for preliminary estimating purposes, the data presented in Fig. 8 may be used for predicting average penetration rates while rotating on bottom.

Drill pipe selection. The drill pipe serves the following three functions:

1. Torque transmission to the bit.
2. Suspension of the bit, the drill collar, and the drill pipe itself.
3. Conduction of the circulating media to the bit.

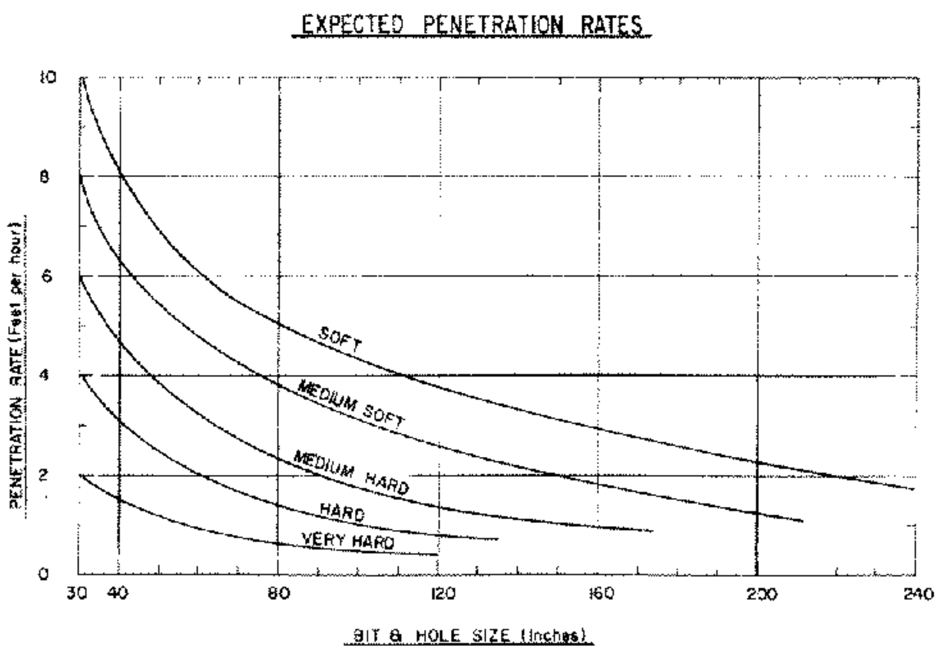


Figure 8

The drill pipe must be sufficient to withstand the torque encountered which, due to impact or shock loadings, could be twice the estimated bit rotation requirement. The tensile strength of the drill pipe should be at least twice the estimated suspended load. The inside diameter of the drill pipe must be compatible with the allowed pressure loss in the circulating system.

With the circulation rate established, the pressure loss through the drill pipe is calculated. A convenient method for estimating pressure loss due to friction may be obtained from Fig. 9. In case the mud pump, circulation rate, and drill pipe are incompatible, it is then necessary to re-evaluate the hydraulic system.

Curves are available for predicting dry air friction pressure losses through pipes, but liquid-air or solids-air friction pressure losses are not as well defined. The prediction of air friction pressure loss is more complicated and is beyond the scope of this paper.

For preliminary estimating purposes Fig. 10 may be used for drill pipe selection. Although 4 1/2-inch and 5 9/16-inch drill pipe is shown and is often used, its use for "big hole" drilling is not usually recommended.

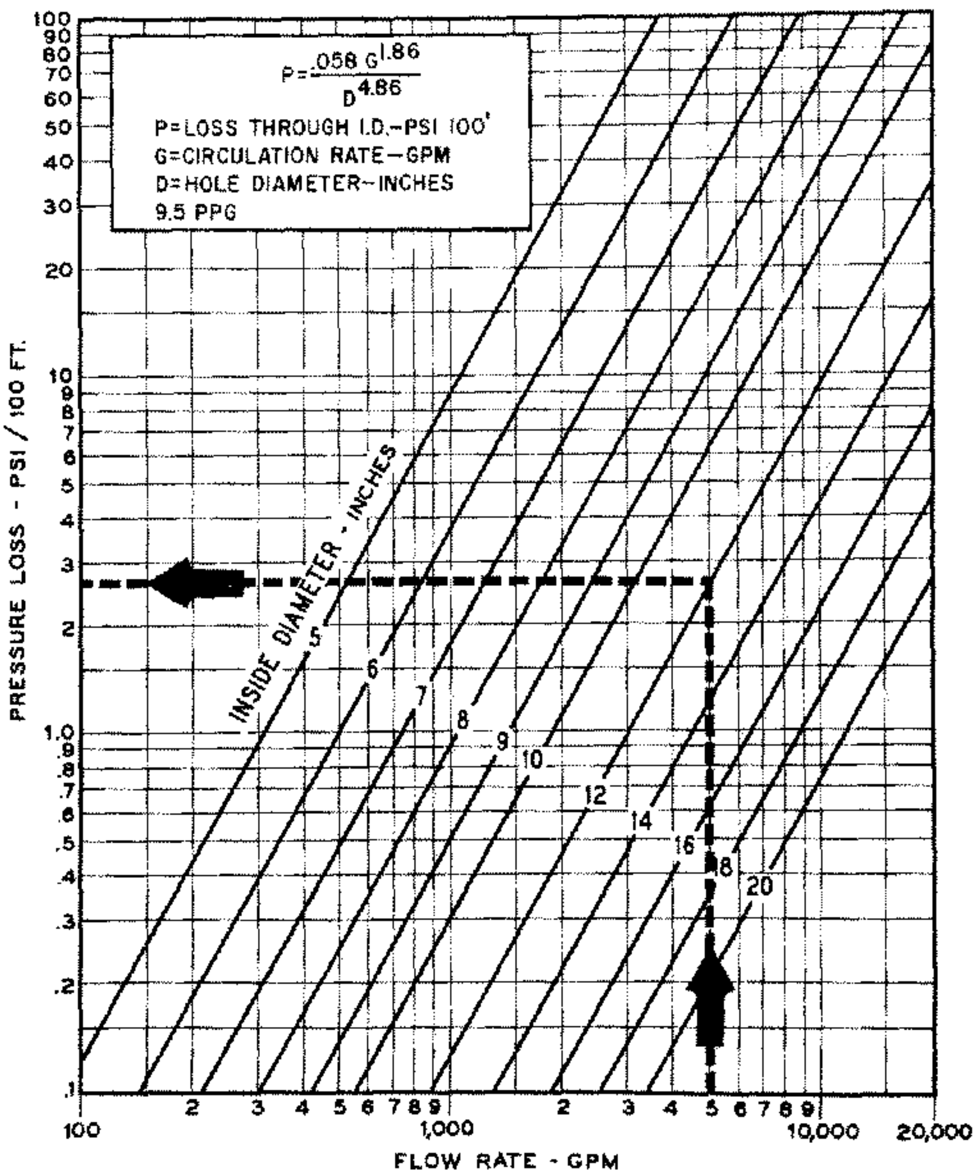


Figure 9. Flow Rate Versus Pressure Loss for Different Diameter Drill Stems. (Merlan)

Table 4 is a tabulation of the physical properties and general costs of the available drill pipe for "big hole" drilling.

Hoisting horsepower. Selection of the necessary rig hoisting capacity for "big hole" drilling depends primarily on the selection of the drill collar and drill pipe and the depth of the hole. Hoisting speeds up to 40 ft./min. should be expected with maximum expected loads. Once the maximum load is established, the hoist horsepower can be calculated by:

$$\text{Hoist Input Horsepower} = \frac{\text{Maximum Anticipated Load (lbs.)} \times \text{Hoist Speed (ft./min.)}}{\text{33,000 (ft.-lbs./min./H.P.)} \times \text{Efficiency}}$$

The efficiency should be decreased 2 to 2 1/2 percent per wireline strung between the blocks. For preliminary estimating purposes, an efficiency of 70 percent may be used.

Mud. If drilling mud is used, the hole is usually maintained full of mud. Hole volume increases as the square of the diameter; therefore, tremendous mud volumes must be supplied and maintained in drilling large-diameter holes. Figure 11 provides ready reference for calculating hole volumes.

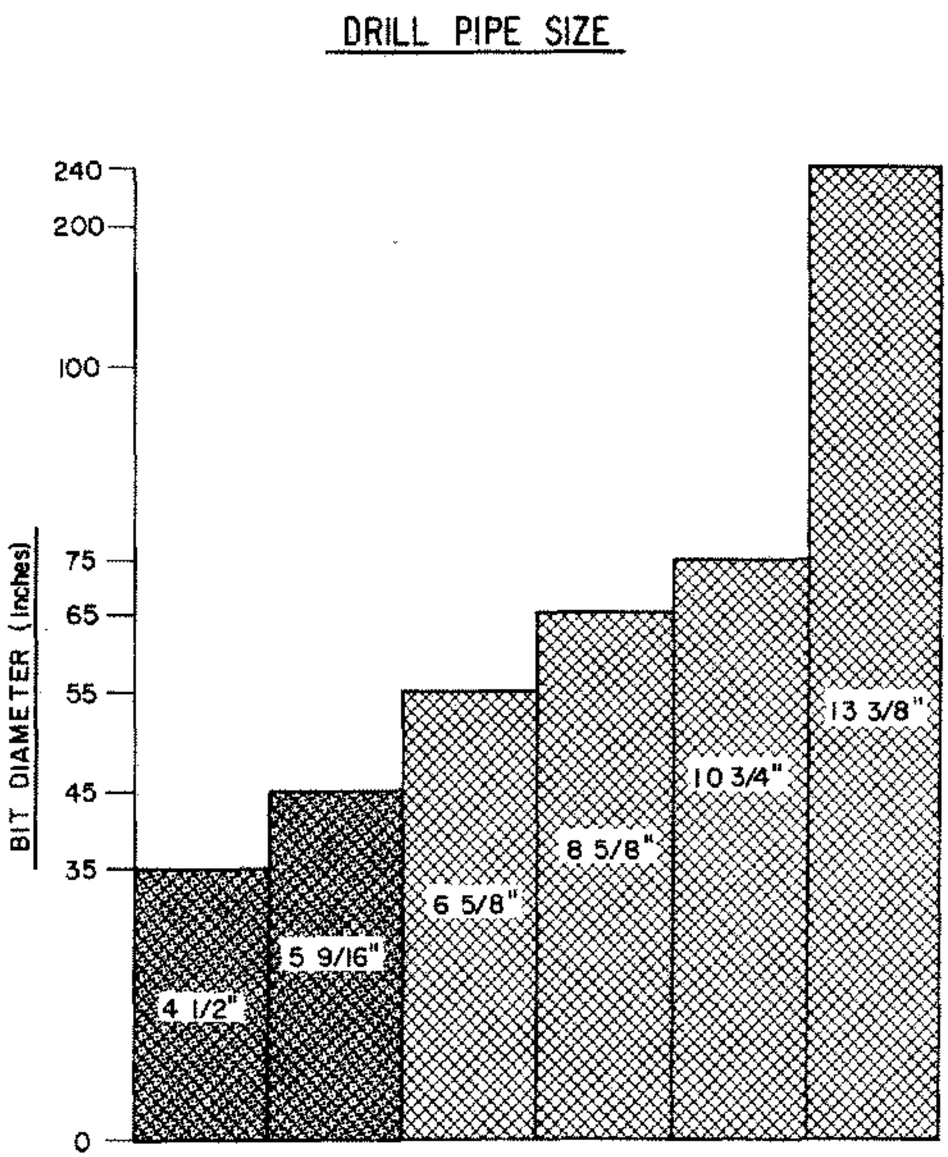


Figure 10

Table 4

Drill Pipe Data

Size Ins.	Grade	ID Ins.	Weight lbs./ft.	Pipe Tension 1000 lbs.	Pipe Torque 1000 ft.-lbs.	Tool Joint Tension 1000 lbs.	Tool Joint Torque 1000 ft.-lbs.	Cost $/100 ft.
4-1/2	E	3.8	18	330	31	1017	36	710
5-9/16	E	4.8	24	440	50	1320	58	890
6-5/8	E	6.0	27	490	70	1510	76	1030
7-5/8	N-80	6.6	49	890	150	2560	140	1870
8-5/8	N-80	7.6	59	1090	190	3190	180	1900
10-3/4	N-80	9.8	70	1290	320	4000	230	3360
13-3/8	N-80	12.4	89	1500	450	4250	540	4420
20	N-80	19	121	2580	1130	9870	1250	7150

Surface storage and adequate settling pits are also needed in the mud circulating system. Surface volumes depend largely on the cuttings and solids removal facilities available. If mechanical equipment is available for solids removal, then a minimum surface settling pit may be used. If there is a danger of rapid loss of mud to the hole, or if the solids removal procedure is inefficient, large volume mud pits may be required.

For long-term drilling, the gradual loss of mud to the hole and wastage with the solids removal will increase the volume of mud that must be mixed. For preliminary purposes, the total mud volume that must be mixed in drilling and completing a "big hole" may be estimated at 150 percent of the final drilled-hole volume for a short-term hole and up to 300 percent for a long-term hole. These volumes do not include unpredictable lost circulation quantities.

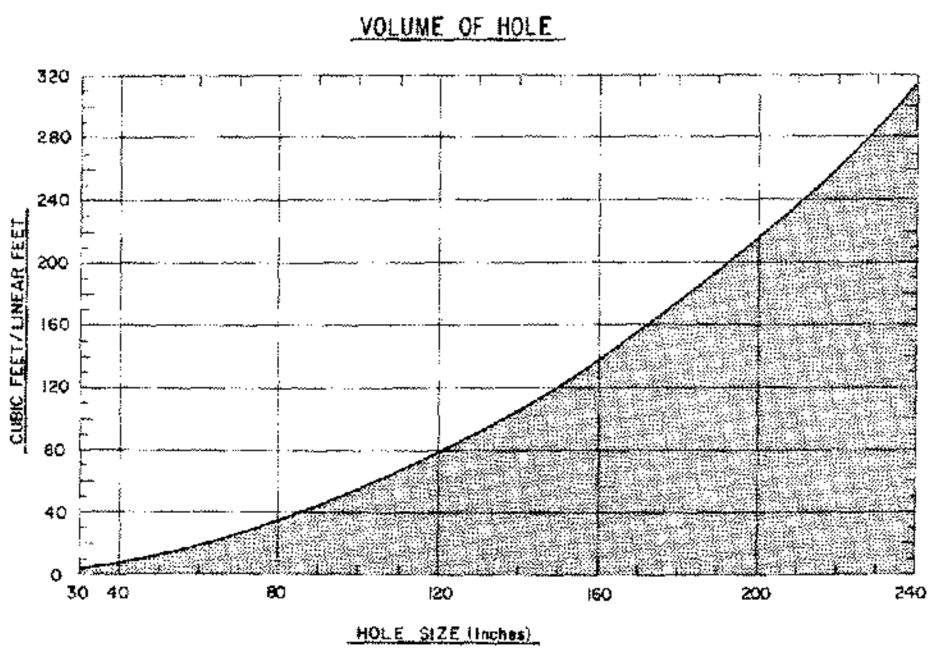


Figure 11

The cost of mixed mud varies widely depending on the type and treatment used. What is generally considered a minimum mud will cost $1/bbl. ($0.18/cu.ft.) and heavily-treated mud may range up to $6/bbl. ($1.07/cu.ft.).

The cost of maintaining a treated mud that inhibits the dispersion of drilled solids increases directly with the hole volume drilled. For estimating purposes, mud treatment costs for short-term drilling with a minimum mud will increase the costs by 50 percent and may range up to a 200 percent increase for a long-term hole where heavily-treated muds are required. Efficient solids removal facilities usually reduce mud maintenance costs.

Liner or casing. A steel liner is usually placed in drilled holes for hole, equipment and personnel protection. If incompetent ground or water must be sealed off as is usually the case, a thick-wall or reinforced liner to resist external pressure is required.

Liners must support their own weight in tension (unless buoyed) and resist collapsing pressures of the ground and subsurface waters. Various designs are available and each liner should be designed to fit the conditions of the hole. Liner design calculations present major problems and are beyond the scope of this paper.

Single wall liner which can be rolled from plate and welded into pipe will cost about 12¢/lb. Fabricated liner, using plate and welded reinforcing braces will cost 20¢ to 30¢ a pound, or more, depending on the steel and fabrication.

Typical liner data is included in Table 5. The data shown is for large volume purchases over the past several years by the Atomic Energy Commission and could run up to 20 percent greater for smaller-volume present-day purchases.

Table 5

Physical and Cost Data
Large-Diameter Steel Liner
Non-Reinforced

Description I.D., inches Wall, inches	Collapse psi	Cost $/ft.	Weight lb./ft.
23 × .5		14	
29 × .62		24	198
36 × .75	340*	27	294
42 × .625		37****	300
48 × .75	180*	36	390
48 × 1.00	370*	46	523
48 × 1.25	620*	63	657
48 × 1.75		87	929
52 × .625		39	
54 × .375		26****	
66 × .625	43**	42	445
72 × .75	55**	54	582
88 × .625		53	591
88 × .75	30***	70	711

* Considering 1/4-inch out of roundness and 30,000 psi steel.

** Considering 1/2-inch out of roundness and 30,000 psi steel.

*** Considering 1-inch out of roundness and 30,000 psi steel.

**** Commercial Purchases.

Welding. The steel liner is normally butt-welded section-by-section as it is run into the hole. For estimating purposes, a cost figure per butt-welded connection is shown in Fig. 12 and Fig. 13. Figure 12 represents the minimum costs while Fig. 13 represents the maximum costs. A reasonable estimate for "normal" operations such as that near a city, but requiring field welding may be 2 1/2 to 3 times the values shown in Fig. 12.

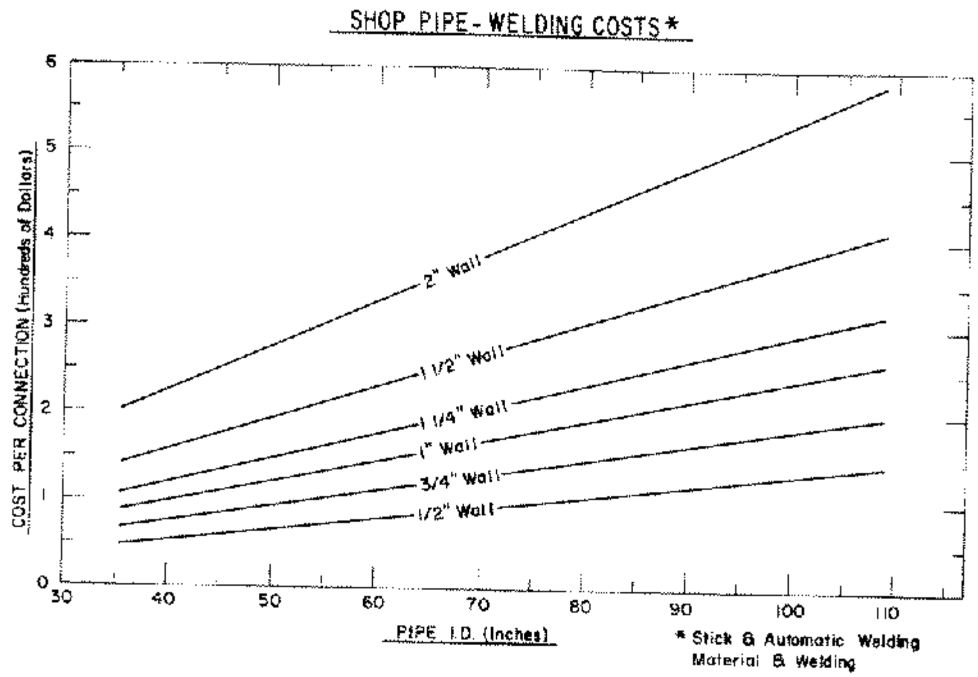


Figure 12

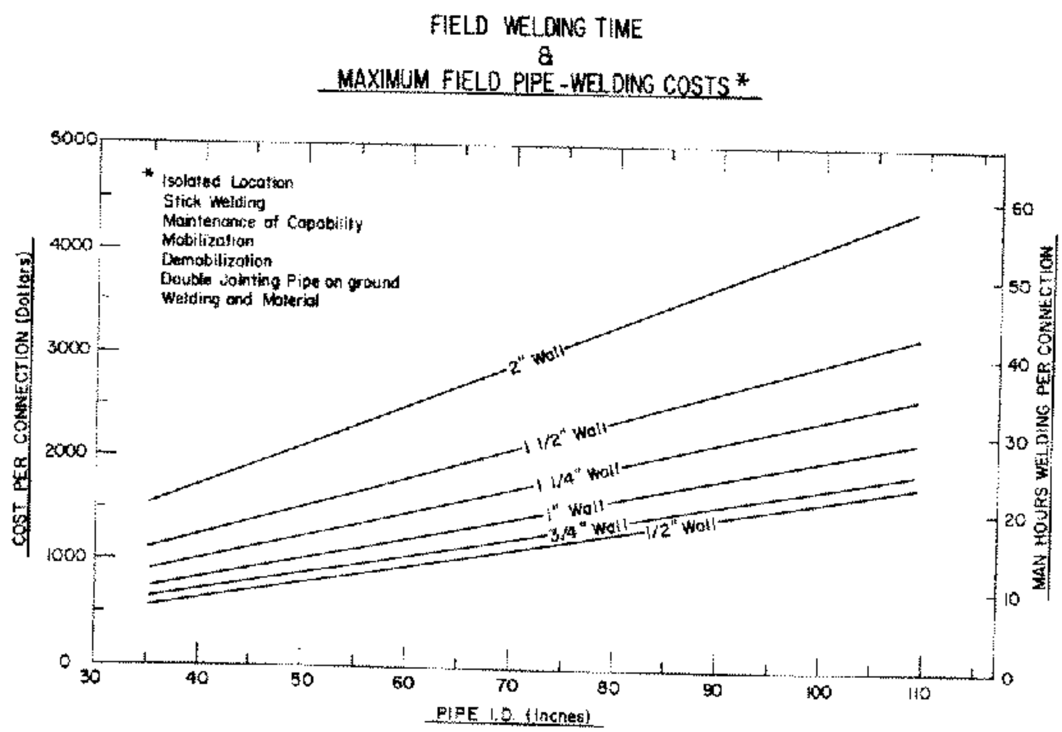


Figure 13

Float shoe. Steel liners are often run into the hole with drillable guides on the lower end of the liner. Many of these guides are provided with a cementing port and check valve and are termed float shoes. Figure 14 shows the costs for large diameter float shoes.

Cement. Steel liners are often sealed into the hole with a cement grout placed in the annulus between the liner and the hole. As can be expected, different types of cement present a cost range. The cost per cubic foot of cement in place generally ranges from $1.40 to $2.50. For estimating purposes, a $2.00 figure may be used for most holes where the cement is mixed and pumped by commercially available large volume cementing equipment.

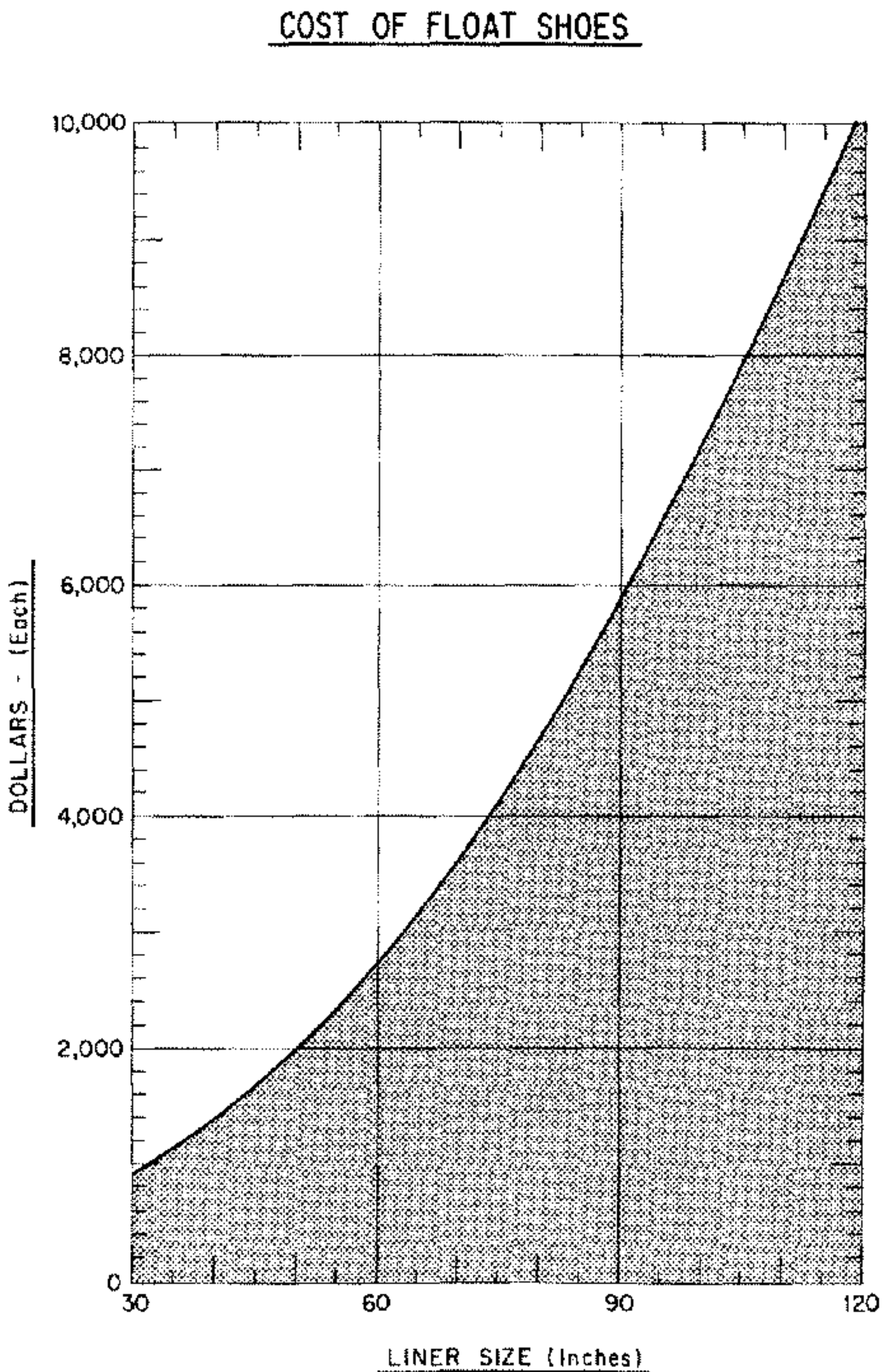


Figure 14

Mast and substructure. Once the size of the drill string, drill collars and bit is determined, the needed type and capacity of the drilling mast may be determined. If the mast is to be used to run the liner, design consideration should be based on the heaviest load required with a reasonable safety factor.

Special modifications to the substructure may be needed in order to handle the "big hole" equipment and the liner. Cost of such modifications are extremely variable and may range from $1,000 for minor modifications to $100,000 for major modifications.

Hoist. The rotating and hoisting capacity of the rig may be calculated from the requirements discussed above. Once the size of hoist (drawworks) and the size of the mast and substructure are determined, rig costs may be estimated. For estimating purposes, the basic rig and crew costs by rig horsepower are shown in Fig. 15. Costs shown do not include "big hole" accessory equipment, cutters, mud, contractor risk or profit. Reasonable contractor risk and profit are extremely variable and depend on the contract specifications and the size of job. For estimating purposes, 15 percent may be added to the cost shown in Fig. 15 for profit and low risk and 30 percent for profit and high risk.

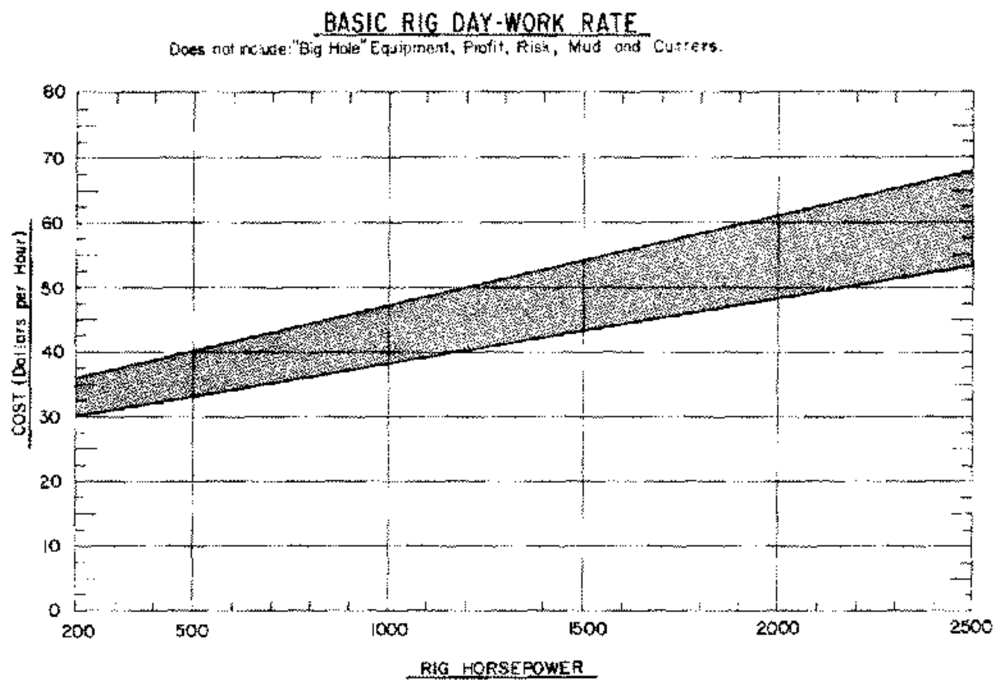


Figure 15

Rig up and rig down. Rig-up and rig-down time are extremely variable. The time depends on the rig mobility and the facilities available. For preliminary estimating, Fig. 16 may be used for rig-up and rig-down costs. Rig-up and rig-down time may be estimated from Fig. 17.

On bottom time. The ability to keep the bit on bottom rotating and drilling is of primary importance. If a rig is kept in good repair, is adequately constructed to handle "big hole" equipment, and is sufficiently powered, then on-bottom rotating time may approximate 70 percent of the total time from spud (start drilling) to total depth. This percentage will decrease as trip time (time to pull the bit out of hole) increases due to greater depths. When a rig is not kept in good repair, is not adequate for the job, or hole trouble is encountered, the on-bottom rotating time may decrease to 30 percent of spud to total depth time. For preliminary purposes, an estimate of 60 percent may be used.

Running liner. The amount of time required to run casing depends principally on welding time. Welding time is approximately 75 percent of the casing running time. Figure 13 may be

RIG-UP AND RIG-DOWN COSTS

Includes: Rig-up, Rig-down, Trucking, Rig, Time and Labor.

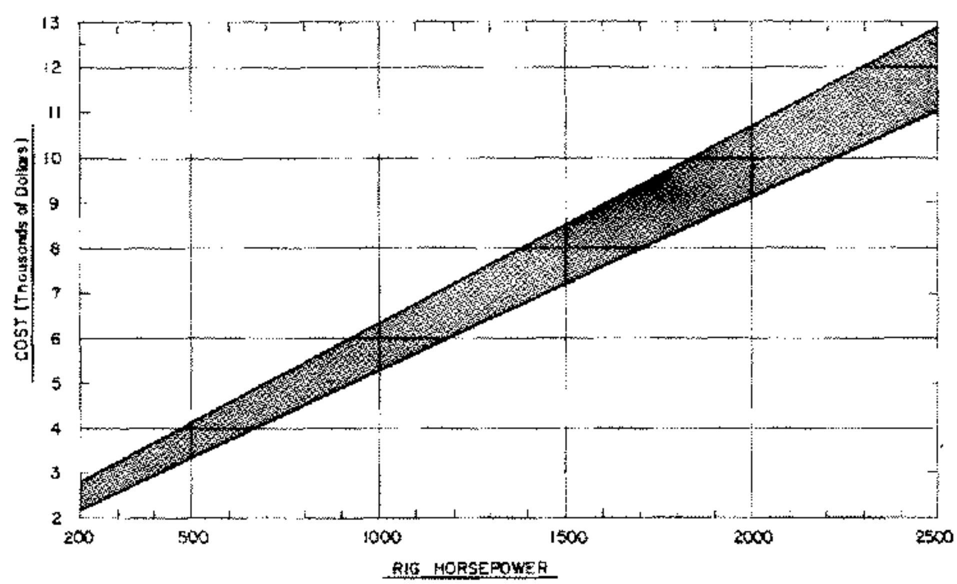


Figure 16

RIG-UP AND RIG-DOWN TIME

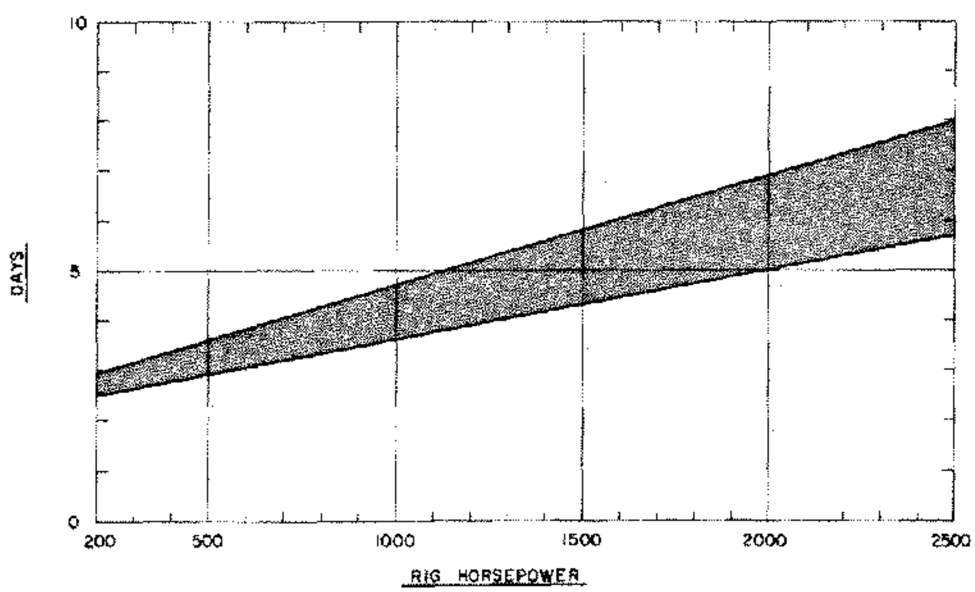


Figure 17

sed for preliminary estimates of this cost. In general, three men may weld on liners up to 36 nches, four men on liners from 36 to 66 inches, and five men on liners over 66 inches in diameter.

Cementing time. The time to cement a hole depends primarily on the number of cement tages to be placed. For preliminary estimating, one day per stage may be used.

Other time. Additional time may be spent logging, surveying, reaming, etc. Until the rilling program is established, arbitrary figures must be assigned.

Transportation. Rig transportation, especially for long distances, presents high costs. For estimating purposes, the basic rig transportation costs can be estimated from the rig weights shown in Fig. 18 and the rates shown in Table 6. Large diameter drill collar transportation, mud products, cement and other high-unit-weight materials may be estimated by the weight and rate figures of Table 6.

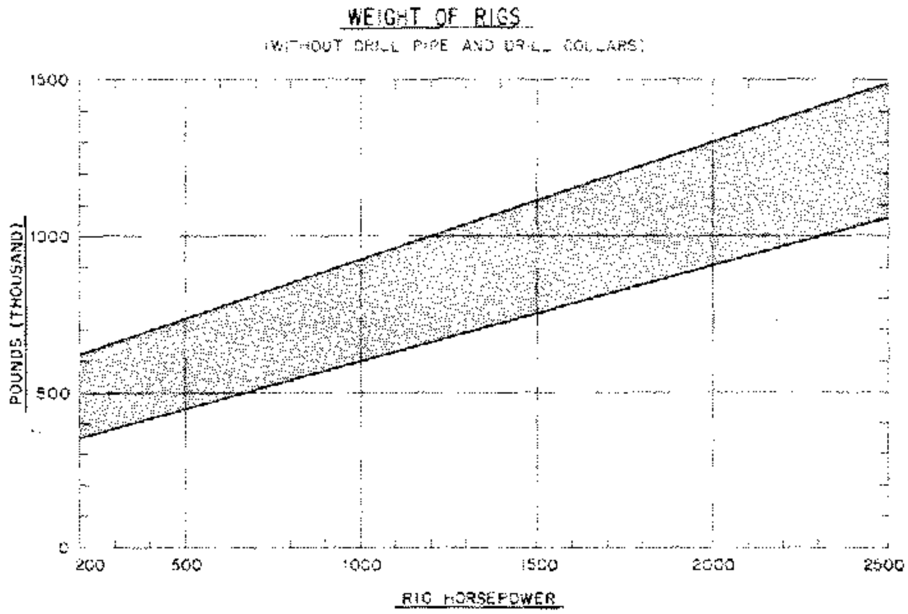


Figure 18

Auxiliary "big hole" equipment. No drilling contractor is equipped with a complete line of auxiliary "big hole" drilling equipment. Some drilling contractors have acquired limited equipment but most would need to purchase many special pieces of equipment necessary for diversified "big hole" drilling. Table 2 lists purchase costs of presently available "big hole" special equipment.

Contractors use variable means in writing-off or leasing capital equipment. For the special equipment of this type, a rate of 0.1 percent per operating day may be used for estimating purposes. For example, if $100,000 worth of special "big hole" equipment is required, the contractor would expect to be reimbursed $100 per day rental for this equipment.

Location preparation. Costs for preparing the location are extremely variable and may vary from less than $1,000 to over $100,000 depending on conditions encountered and facilities needed. Many "big holes" require a concrete foundation; foundations such as this have cost over $100,000. A discussion of foundation design is beyond the scope of this paper; however, for preliminary purposes, Fig. 19 may be used for estimating foundation costs.

Logging. The formation characteristics are usually determined by logging the core or pilot holes with electric, acoustic or radioactive tools. Charges are usually made based on the distance to the location, the time on the location, the depth of the hole, and the type of log required. A simplified typical charge schedule for these logs would be:

1. Base service charge of $225.
2. Depth charge, $0.07 per foot to deepest depth tool is run.
3. Logging charge, $0.07 per foot of hole logged.
4. Travel $0.50 per mile in excess of 150 miles round trip from the nearest station.
5. Stand-by time charge, $15 per hour over 10 hours prior to start of log.

Table 6

Transportation Costs

Miles	Cost, $/100 lbs. Pipe, Sack Goods	Machinery
10	.14	.16
30	.22	.25
50	.30	.31
100	.47	.47
150	.60	.60
200	.71	.71
300	.91	.91
400	1.12	1.12
500	1.32	1.32
600	1.53	1.53
700	1.72	1.73
800	1.87	1.97
900	2.04	2.19
1000	2.22	2.44
1500	2.94	3.62
2000	3.81	4.74

LOCATION PREPARATION

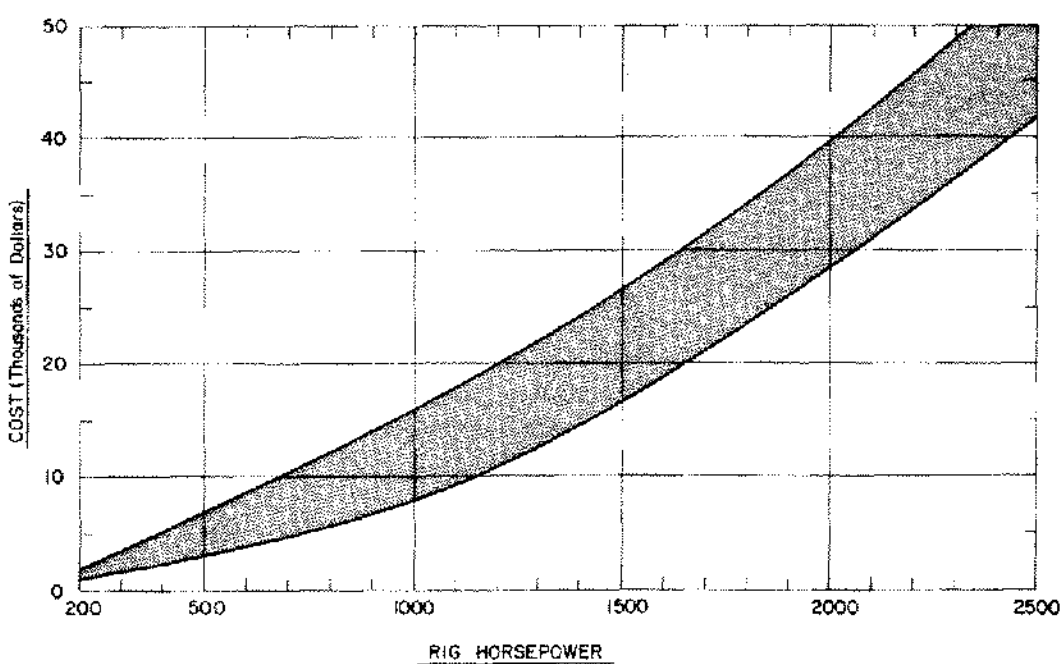


Figure 19

The size of the drilled hole is usually greater than the bit size. To determine the amount of cement to be placed, a caliper log may also be run. A simplified typical charge schedule would be:

1. Set up charge of $150.
2. Depth charge, $0.12 per foot, minimum of 200 feet.
3. Logging charge, $0.12 per foot, minimum of 150 feet.
4. Other, as shown on page 398 for logging.

Holes cannot be drilled absolutely straight. Therefore, directional surveys may be required to measure the displacement of the hole from the vertical and the direction of the displacement. Oil-field service charges may be applied to holes or pipe up to 20 inches.

Typical oil-field rates are:

1. Set up charge of $150.
2. Surveying charges, $0.10 per foot, minimum $300.
3. Depth charge, $0.04 per foot.
4. Stand-by after four hours, $10/hour.
5. Mileage after 150 miles, $0.35/mile.

Directional surveys in "big holes" are commonly contracted specifically for a hole. A typical charge would be:

1. Fixed charge, $1,000.
2. Special equipment, $100.
3. Other charges as shown previously.

Coring. Coring services may be used to obtain formation samples. For 2 1/8-inch cores above 500 feet, a core rig service could be:

1. Mobilize and demobilize: $500 to $1,000.
2. Drilling overburden: $6.50/foot.
3. Coring consolidated formation: $3.50 to $5.50/foot.
4. Stand-by, testing, etc.: $12 to $20/hour.

From 500 to 700 feet, the coring cost would increase to $6.50/foot. From 700 to 1,000 feet, the coring cost would range from $7.50 to $9.00/foot. Rigs to drill below 1,000 feet are common but not as widely available as are the core rigs. Oil-field drilling prices would prevail for work below 1,000 feet.

Cored holes should be geologically described. A geologist may be hired for $25-$50/hour. In some areas, the State geologist or a USGS geologist will describe the cores free of charge.

Cores may be tested in commercial laboratories for compressive strengths, porosity and permeability for about $10 a sample.

Handling equipment. Special equipment may be desirable in order to more effectively remove the cuttings from the settling pits. For the larger and deeper holes, a dragline bucket may be employed. A crane and bucket may be rented, without operator, for $1,200/month.

A crane may also be needed to move pipe when the liner is being run. A 10-, 20-, or 30-ton crane may be rented, without operator, for $400, $500, or $700/week, respectively.

Casing jacks may be required to run the casing. A rule-of-thumb for casing jack costs is $250 per ton of capacity.

COST CALCULATING PROCEDURES AND EXAMPLE

Estimating the cost of a drilled shaft is complicated, is not a scientific procedure, is subject to wide variations and must be tempered with a great deal of considered judgement. However, for preliminary estimating purposes, the procedure outlined below may be followed. Add the calculated costs to the compilation sheet at the end of this section.

Example Case (referred to throughout as the example): A 72-inch I.D. working shaft is desired to 3,400 feet. Geology is known from exploratory holes which have been previously drilled in the area. Regional structure is almost flat. No faults are known to exist in the intervals to be penetrated. Unconsolidated sands and gravels exist to 300 feet. Shale formations extend from 300 feet to 1,200 feet, unconsolidated sands from 1,200 feet to 1,500 feet, limestones from 1,500 feet to 3,000 feet, and evaporites from 3,000 feet to 3,400 feet. Water is abundant in the sands and gravels to 300 feet and in the sands from 1,200 feet to 1,500 feet. No fractured or vugular intervals are known which would cause loss of mud. Drilling records are available.

Geology. If a "big hole," costing from several thousand to several hundreds of thousands of dollars, is contemplated, then a good geological evaluation is warranted. If the geology is not known, a core hole should be drilled and core samples obtained. It will generally be found valuable to obtain: (1) a complete and detailed structural description including formation dip or faults, (2) a detail of drilling conditions, including mud, circulating rates, mud loss, penetration rates, bits used, bit weight, etc., and (3) a knowledge of hole conditions, such as sloughing formations or fractures, water table, water salinity, etc.

Example: A study of the geology of the above example indicates:

(1) The surface sands and gravels should be cased-off from the hole to prevent caving during the long period while drilling below 300 feet.
(2) No problem due to loss of mud should occur, thereby, indicating a good mud can be prepared and little mud treatment for loss-of-mud will be needed.
(3) The mud must keep the unconsolidated sands and water from entering the hole before the casing is set.
(4) The mud must be treated to prevent a fresh-water mud from dissolving the evaporites.
(5) The hole must be lined to total depth to provide a safe access shaft.
(6) The liner must be sealed in the hole to prevent water entry when the shaft is opened at the bottom.
(7) Hole deviation problems from dipping structures do not exist.

Core analysis. Perform core analysis to determine rock characteristics, evidence of fractures, vugs, soluble material, and compressive strength.

Example: Cores of the drilled formations in the example case are not available for analysis. Data must be interpreted from the drilling record of the exploratory holes and the expected similarity to other known formations.

Liner program. A review of the geological conditions may indicate that a protective steel liner is required for drilling. Such liners are usually desirable to: (1) cover loosely consolidated shallow formations, (2) cover zones subject to lost circulation, and (3) allow the circulating system to be changed. For each liner the minimum acceptable hole size must be determined.

If a liner design is available, liner costs can be estimated from Table 5 or calculated at a cost per pound figure as explained above.

Example: The unconsolidated sands to 300 feet must be covered. A protective liner to cover the loose sands in the 1,200 to 1,500 foot interval would be desirable but is ruled out because of the depth and size of the hole required to place the liner and also due to the cost of the protective liner itself. Therefore, a protective liner is to be set only from the surface to 300 feet.

The 72-inch I.D. working-shaft liner to 3,400 feet is selected with a dual wall and an 80-inch outside diameter. The liner must resist the hydrostatic pressures of water to 3,400 feet. A discussion of the design of liners is beyond the scope of this paper.

The 72-inch liner is a fabricated steel structure and will cost about 22¢ a pound. The liner weighs a total of about 2,000,000 pounds and should cost about $572,000. Considering a 1,000-mile delivery at the rates shown in Table 6, a transportation cost of $58,000 must be added to give a total liner cost of about $630,000.

The O.D. and physical characteristics of the working-shaft liner help determine the size of the hole to be drilled to 3,400 feet. The size of the hole selected for the working-shaft liner then determines the I.D. of the 300 feet of protective liner.

The protective liner is selected to be 102 inches I.D. and 105 inches O.D. The liner is designed to resist collapsing pressure of the formation water head should the hole be evacuated by loss of mud.

The 102-inch liner selected is rolled plate steel and will cost about 12¢ a pound. The liner weighs about 480,000 pounds and should cost about $57,600. Transportation, as above, will add $11,000 for a total liner cost of $68,600.

Hole size. From the mining requirement, the desired size and depth of the shaft is known. Refer to Fig. 1 to determine the hole size required.

Example: A 72-inch liner is six inches bigger than the 66-inch liner shown in Fig. 1. Interpretation shows a 98-inch hole is required for the 66-inch liner at 3,400 feet. A comparable 104-inch hole should be expected for the 72-inch liner. Since the hole is not expected to be crooked and the liner is of a smooth-wall design with the grout lines between the two walls, the hole is arbitrarily selected to be 100 inches.

A 102-inch liner is comparable to the 100-inch liner shown in Fig. 1. A 123-inch hole size is shown at 300 feet of depth. A 120-inch size is arbitrarily selected.

Circulating system. From the geology study, decide on the circulating media to be used. From the circulating media, and the pressure and volume requirements, determine the circulating system best suited for the situation.

Mud circulating volumes can be estimated from Fig. 11. Calculate mud volumes to be mixed and apply a cost and usage factor. Calculate the pumping system requirements from the flow rate and pressure drop.

Example: Mud will be used throughout the hole. A fresh-water mud will be used to near the top of the evaporites at which time the mud system will be converted to a salt-saturated type. Saturation of the system will depend on the composition of, and the amount of, evaporites to be penetrated. Several alternatives exist. One alternative would be to set pipe in the top of the evaporites and drill the evaporites with air. A further analysis of the design of the mud program is beyond the scope of this paper.

From Fig. 11, the volume of mud in the 100-inch hole is estimated to be 187,000 cubic feet or 33,500 barrels. Surface storage and losses from long-term drilling will double the amount to be mixed to 67,000 barrels. Considering a moderately treated mud with long-term drilling, mud cost will range to $4/barrel of mixed mud. Mud cost is then estimated to be $268,000.

A circulating rate of 50 times the hole diameter (inches), or 5,000 gpm, is desirable for bit cleaning. From Fig. 7, an annular velocity with 5,000 gpm and 13 3/8-inch drill pipe in a 100-inch hole is shown to be about 12 ft./min. Both the circulating rate of 5,000 gpm and the annular return rate are on the low side of acceptable values for hole cleaning.

From Fig. 9, the friction pressure loss of the 5,000 gpm rate of mud flowing through 13 3/8-inch drill pipe is 2.7 psi/100 ft. or 92 psi through 3,400 feet. Two pumps rated at 6,750 gpm at 83 feet of head, with one for stand-by, are then required. The cost of these pumps, $12,600, should be added to the list of special "big hole" equipment. The engine drive is to be taken from the present rig equipment and will not need to be furnished.

Horsepower to drive the 5,000 gpm capacity at 92 psi, considering 70 percent pump efficiency, is:

$$\text{Engine HP} = \frac{(92)}{(1714)}\,\frac{(5000)}{(.7)} = 380 \text{ HP}$$

Consider an average 300 HP output. Calculate fuel and maintenance cost at $0.016 per continuous horsepower-hour. Assume the hours rotating on bottom as working hours.

A discussion of an alternate system, such as reverse-flow with airlift, is beyond the scope of this paper.

Bit program. Send representative cores to one of the major bit manufacturers and request drillability studies. If given the size of hole, the conditions of the circulating fluid with the rotary speed and the bit weight range available, the manufacturer will recommend a type of bit cutter to produce a penetration rate with a given bit-weight and rotary speed.

Preliminary estimates of cutter costs may be made from Table 1 and Fig. 11. If drillability studies on the cores have been performed, the bit manufacturer may estimate cutter usage.

Example: In the absence of drillability studies, use estimating procedures shown in this report. Cutter cost estimates using Table 1 and Fig. 11 are:

0- 300 ft.	78 cu. ft./ft.	×	300 ft.	×	$0.50/cu. ft.	=	$ 11,700
300-1,200 ft.	54 cu. ft.	×	900 ft.	×	$1.00/cu. ft.	=	48,600
1,200-1,500 ft.	54 cu. ft.	×	300 ft.	×	$0.75/cu. ft.	=	12,000
1,500-3,400 ft.	54 cu. ft.	×	1,900 ft.	×	$1.25/cu. ft.	=	138,000
					TOTAL	=	$210,300

In all likelihood the 120-inch hole would be drilled with the 100-inch bit with an extension hole opener to 120 inches. The 120-inch bit cost from Fig. 2 is $26,000 and the cost is added to the list of special "big hole" equipment shown later in this report.

Drilling time. For preliminary estimates of penetration rates, use data from Fig. 8. If drillability studies are performed on core samples, use the drillability data. Consider a percentage on-bottom time to arrive at a spud-to-total depth estimated time as explained above.

Example: Cores are not available. Estimate penetration rates from Fig. 8. The top 300 feet of 120-inch hole can be expected to drill at 2 ft./hr. The 100-inch hole in limestone and the evaporites can be drilled at 1.5 ft./hr. The 100-inch hole in the unconsolidated sands can be drilled at 3 ft./hr.

Drilling time estimates are:

0- 300 feet	300 ft.	@ 2.0 ft./hr.	=	150 hrs.
300-1,200 feet	900 ft.	@ 1.5 ft./hr.	=	600 hrs.
1,200-1,500 feet	300 ft.	@ 1.5 ft./hr.	=	100 hrs.
1,500-3,400 feet	1,900 ft.	@ 1.5 ft./hr.	=	1,260 hrs.
		TOTAL	=	2,110 hrs.

On bottom times of 60 percent from start of drilling to total depth can be expected. This time does not include setting the surface pipe, logging, and surveying.

Drill pipe. Select a drill pipe compatible with the circulating media and system, rotating torque and tensile loads. For the preliminary estimate, use Fig. 10. For evaluation of the first estimate, compare the drill pipe selection with flow, torque and tensile requirements.

Torque requirements can be estimated from the expected bit loads and Fig. 6.

Friction pressure loss calculations can be made from Fig. 9. Tensile loading limits are shown in Table 4. List the drill pipe under special "big hole" tools shown later in this report.

Example: From Fig. 10, it is seen that 13 3/8-inch drill pipe is required for a 100-inch hole. The mud system also requires a 13 3/8-inch drill string for acceptable circulating rates.

From Fig. 4, it is seen that a minimum drill collar weight of 210,000 pounds is needed for the 100-inch bit in medium hard formations. Maximum bit weights of 140,000 pounds can be expected or 1,400 pounds per inch of bit diameter.

From Fig. 6, it is seen that torques up to 100,000 ft.-lbs. may be expected. From Table 4, it can be seen that the 13 3/8-inch drill pipe is compatible with this torque.

Weights of 210,000 pounds for drill collars, 272,000 pounds for 3,400 feet of 80 lb./ft. drill pipe and 20,000 pounds for a bit make a total of 502,000 pounds of tensile load. From Table 4, it can be seen that the 13 3/8-inch pipe is compatible with this tensile load.

The 13 3/8-inch drill pipe is then selected. From Table 4, 3,400 feet of 13 3/8-inch drill pipe is shown to cost $150,000. This cost figure is added to the list of special "big hole" equipment.

Drill collar. Select the weight desired from the recommended bit weights. Compare the weights available from the various sources of weighting material available, diameters and lengths involved as shown in Fig. 5 and Table 2.

Example: A drill collar, made of cast-iron ring weights having an O.D. of 60 inches, and weighing up to 300,000 pounds is selected. This drill collar can be purchased for $50,000. List the cost with the special "big hole" equipment.

Rig selection. With the drill collar, drill pipe and circulating system established, a rig type may now be selected. Hoisting capacity will usually determine the rig size. Consult Fig. 15 for rig costs; add risk and profit to this cost.

Example: The rig must hoist up to 300,000 pounds of drill collar and 292,000 pounds of drill pipe and bit. A rig to hoist this load at 40 ft./min. would require:

$$HP = \frac{592,000 \text{ lbs.} \times 40 \text{ ft./min.}}{33,000 \text{ ft.-lbs./min./HP} \times .7} = 1,000 \text{ HP}$$

From Fig. 15, a 1,000 HP rig is shown to cost $43./hr. on a day rate basis with no profit or risk. A day rate of $50./hr. for a low-risk operation would allow a reasonable profit.

Special "big hole" tools. List the special tools such as pumps, compressors, drill pipe, drill collar, bits, stabilizers, reamers, kelly, swivels, rotary hose, desanders, pits, etc., which may not be included as a normal component of an ordinary drilling rig. Calculate rental rate at 0.1 percent per day.

Example:

	Cost, $	Weight, lbs.
3,400 ft. of 13 3/8-inch Drill Pipe	150,000	272,000
1-120-inch Bit	26,000	20,000
1-60-inch Drill Collar	50,000	300,000
1-100-inch Stabilizer	20,000	25,000
1-100-inch Reamer	20,000	25,000
1-14-inch Kelly	4,400	6,000
1-12-inch Swivel	10,700	7,000
1-12-inch Rotary Hose	1,300	2,000
3 Centrifugal Pumps	12,600	30,000
2 Tongs	8,600	3,000
Elevators	5,000	1,000
Desanders and Mud Equipment	5,000	5,000
TOTALS	$313,600	696,000 lbs.

The rental of this equipment at 0.1 percent per day is:

$$\$310,000 \times 0.001 = \$310 \text{ Rental Cost/Day}$$

Cement. Refer to Figure 11 to obtain the annular volume. Calculate at dollars per cubic foot of volume.

Example:

(1) Working-shaft liner. Assume the annular spaces are to be filled to the surface. From Fig. 11, the 3,400 feet of annular volume is shown to be 82,000 cubic feet. The annular space is filled with cement at $2/cu.ft. for a cementing cost of $164,000.

A special chemical sealant for positive exclusion of water flowing in the annulus may be installed for $50,000. A discussion of the design and description of a special sealant is beyond the scope of this paper.

Assume 10 stages and 10 days time to place the cement.

(2) Protective liner. Assume the annular space is to be filled to the surface. From Fig. 11, the annular volume is shown to be 16 cu. ft./ft. At a cost of $1.80/cu. ft., the 300 feet of annulus can be filled for $8,600.

Assume 3 stages and 3 days time to place the cement.

Casing Jacks. Determine if the rig can run the casing either in total suspension or by flota-ion. If the liner cannot be lowered with the rig, casing jacks may be required. Use the $250/ton urchase cost and prorate the cost.

Example: Due to the weights of the liner, a casing jack is advisable. The jack must suspend up to 1,300 tons and, with a safety factor of two, will cost $325,000. For this study, assume a prorated cost of $70,000.

Location. Determine the requirements of the location, mud pits, foundation, conductor ipe, etc. Unless better estimating is possible, use Fig. 19 for costs.

Example: Assume a value of $12,000 from Fig. 19 for a 1,000 HP rig.

Mobilization and demobilization. Use Fig. 18 and Table 6 for rig transportation, and ig. 16 for rig-up and rig-down costs. Rig modifications may be necessary and should be in-luded here.

Example: Transportation estimates for the 1,000 HP rig made from Fig. 18 and considering a 250-mile move are indicated at $0.81/100 lbs. × 700,000 lbs. = $5,700.

Transportation costs for the special "big hole" equipment may be estimated from the weights shown previously with an estimated average distance to be moved. Consider 700,000 lbs. to be moved 1,000 miles for a cost of $2.22/100 lbs. × 700,000 lbs. = $15,500.

Rig-up and rig-down costs from Fig. 16 are indicated at $6,000. Rig modification needs are unknown; until the specific rig is known, assume $20,000 for the preliminary estimate.

Welding. If a liner design is available, welding costs can be obtained from Figs. 12 and 13 nd by applying appropriate factors.

Example: The 102-inch protective liner has a 3/4-inch wall thickness and can be shop welded for $220 per connection. Field welding can be accomplished for 3 × $220 or $660 per connection. The 120-inch liner will be run in 40-foot lengths or eight joints for a cost of $5,300.

The 72-inch liner has a 1/2-inch wall thickness with dual walls. Three connections must be welded to join two sections of pipe. Shop welding costs of $100 × 3 or $300 must be increased by a factor of three for field welding or $900 per joint. The 72-inch liner will be run in 80-foot lengths or 42 joints for a cost of $37,800.

The rig time to run the 102-inch liner will be eight joints × 28 man-hours with five men welding and welding time of 60 percent of rig time for 75 hours. The rig time to run the 72-inch liner will be 42 joints × three connections per joint × 15 hours per connection with five men welding and welding time of 60 percent of rig time for 630 hours.

Logging and surveying. Determine logging and surveying requirement and calculate the osts from data presented above or assign arbitrary values.

Example: For preliminary purposes, estimate an arbitrary $12,000 for logging and surveying.

Other. Determine accessory needs such as desanders and draglines.

Example: Consider a dragline, operated by one of the crew members, to remove the cuttings. Rent for $1,200/month.

Consider desanding units to treat 5,000 gpm. Add $5,000 to cost of special "big hole" equipment.

EXAMPLE

COMPILATION OF COSTS

72-INCH SHAFT TO 3,400 FEET

I. Location		$ 12,000
Pits, Foundation, Conductor pipe		
II. Rig Mobilization and Demobilization		$ 47,200
Transportation, rig	$ 5,700	
Transportation, "big hole" tools	$ 15,500	
Rig up and rig down	$ 6,000	
Modifications	$ 20,000	
III. Interval 0 - 300'		
A. Rig Work, 431 hrs. at $50/hr.		$ 21,600
1. Drilling, 150 hrs. × 1/0.6 - 250 hrs.		
2. Non-drilling		
a. Reaming, 24 hrs.		
b. Surveys, logs, 10 hrs.		
c. Rig up and run liner, 75 hrs.		
d. Cement and wait on cement, 72 hrs.		
B. "Big Hole" Equipment		$ 4,300
332/24 days at $310/day		
C. Cutters		$ 11,700
D. Circulating System		
mud; mix and treat (included with following items).		
E. Pipe, 102 inches		$ 68,600
Purchase,	$ 57,600	
Transportation,	$ 11,000	
F. Cement		$ 8,600
G. Pump fuel and maintenance		$ 100
174 hrs. × 300 HP × $0.016/HP-hr.		

H. Services				$ 7,900
1. Welding	$ 5,300			
2. Surveys and Logs	$ 2,000			
3. Dragline, 0.5 month at $1,200/mo.	$ 600			
IV. Interval, 300 - 3,400'				
A. Rig Work, 4,370 hrs. at $50/hr.				$ 218,500
1. Drilling, 1,960 hrs. × 1/0.6 = 3,260 hrs.				
2. Non-drilling				
a. Reaming, 96 hrs.				
b. Surveys, logs, 48 hrs.				
c. Rig up to run liner, 48 hrs.				
d. Run liner, 630 hrs.				
e. Cement and wait on cement, 240 hrs.				
f. Evacuate liner, 48 hrs.				
B. "Big Hole" Equipment Rental				
3,356/24 active days at $310/day				$ 43,400
C. Cutters				$ 198,600
D. Circulating System				$ 268,000
mud; mix and treat				
E. Pipe, 72 inches				$ 630,000
Purchase	$572,000			
Transportation	$ 58,000			
F. Cement				$ 164,000
G. Special Sealing				$ 50,000
H. Pump, fuel and maintenance				$ 9,900
2,056 hrs. × 300 HP × $0.016/HP-hr.				
I. Services				$ 122,800
1. Welding	$ 37,800			
2. Surveys and Logs	$ 10,000			
3. Dragline, 4.5 months at $1,200	$ 5,000			
4. Jack Rental	$ 70,000			
			Total	$1,887,200
			Use	$1,900,000

APPENDIX I

COMMERCIALLY DRILLED BIG HOLES

A search of the literature and contact with various organizations and personnel concerned with "big hole" drilling has produced the list of, and data concerning holes drilled by rotary means (calyx included) with diameters greater than 30 inches to depths greater than 300 feet. Access shafts drilled for LPG storage caverns are listed separately in Appendix II.

TABLE I-1

COMMERCIALLY DRILLED BIG HOLES

April, 1965

Location	No. of Holes	Year	Owner	Hole Size Inches	Hole Depth Feet	Cased Size Inches	Cased Depth Feet	Type Drill, Circulation	Reference	Time, Cost, Remarks	Geology
Germany-Holland	30	From 1927		to 108	to 427			Mud	1, 9, 84		
Grass Valley, Cal.	1	1936	Brunswick Mine	60	1, 125			Calyx	56		
Ely, Minn.	1	1938	Zenith Mine	66	1, 208			Calyx	56	7 months	
Geogebic Iron Range, Wisc.	1	1942-1944	Cary Mine	66	2, 487			Calyx	56	605 days	
Arkansas	8	1943-1958	Reynolds Mining	48-84				Mud			
Illinois		1948		78	400			Mud, 6 passes	81		
Holland	1	1949-1952	Dutch State		700	177		Mud	83	930 days	
Russia	Several	1950-1955						Reverse mud, 2 passes	50		
Holland	1	1954-1959	Dutch State	301	1, 680	216		Reverse mud, 4 passes	1, 3, 50	1, 263 days drlg. 31 lining	Sediments, Marl, Limestone
Holland	1	1954-1959	Dutch State	301	1, 660	216		Reverse mud, 4 passes	50	1, 130 days drlg., 44 lining, 13 sealing	Sediments, Marl, Limestone
Germany	2	1954-1959						Reverse mud	50	Nearly identical to Dutch State Beatrix Shafts	
Morgantown, W. Va.	14	1954-1959	Trotter Coal	76	400-550	No		Zeni machine	2, 3, 95	55 drlg. days to drill 452' in 1956	Limestone, Sandstone
Beckley, W. Va.	2	1957-1959	Mead Coal	76 1/2	536	No		Zeni machine	2, 3, 62	Drilled 4-5'/Hr.	Hard Rock
Bauxite, Ark.	3	1956-1958	Reynolds Mining	82	510-525	82 72	80 TD	Mud, 2 passes	53, 54	3 holes in 23 months	Sediments, Sand, Coal, Clay
Grants, N. Mexico	2	1958	Phillips Pet.	46	930 1, 432	36		Mud, 4 passes	86	50 days spud to complete on 930' hole, 64 days spud to complete on 1, 432' hole	Sand, Shale, Sandstone
Russia		1958		288		258			50		
Russia	40	1959-1962		to 82	to 1, 800			Mud	5, 50	Reaction Turbo-drlg. 6 fph with 79" bit	

TABLE I-1 (Continued)

Location	No. of Holes	Year	Owner	Hole Size Inches	Hole Depth Feet	Cased Size Inches	Cased Depth Feet	Type Drill, Circulation	Reference	Time, Cost, Remarks	Geology
Jefferson Co., Tenn.	1	1959	Amer. Zink Young Mine	66	650	No		Calyx	36		Hard Rock
Gallup, N. Mexico	1	1960	Phillips	52	486	40+		Mud, multiple pass	37	Uranium Mine Vent	
Amarillo, Texas	8	1960	City	36	to 800	20		Mud, 2 passes	40	Water Wells	Clay, Gravel, Sandstone
West Virginia	2	1959	N. American Coal	76 1/2	Avg. 590	72		Zeni machine	14, 37	Mine Vent	
West Virginia	4	1960		72	Avg. 500				14	Mine Vent	
Viburnum, Mo.	3	1960	St. Joseph Lead	52	Avg. 700	46	TD	Mud, 3 passes	14	Drilled 1 hole per month	Chert, Limestone, Dolomite
Grants, N. Mexico	1	1960	Kermac Nuclear	90	710	72	710	Mud, 2 passes	42, 89	45 days start to complete. Cutter Cost $20,125.	Shale, Sandstone
Shirley Basin, Wyo.	1	1960		42	350			Mud, 2 passes	37	Uranium Mine Vent	Soft
Grants, N. Mex.	4	1960	Kermac Nuclear	44	586 to 822	36	TD	Mud, 2 passes	78	Avg. 12-16 days total; $32,000 to $39,400 Drill, Hang Csg.; Four shafts in ten weeks.	Shale, Sand, Sandstone
Grants, N. Mex.	1	1960	Rare Metals	40	1,038			Mud, 5 passes	81	$125,000 to drill. 54 days on hole.	
Bauxite, Ark.	2	1960	Reynolds Mining	48	1,300 1,400	42		Mud		Mine Shaft	
Ontario, Canada	1	1961	Western Gypsum	60 44	205 400	48	200	Mud, single pass	7	23 days drlg., total 46 days. Cutter cost $9,470.	170' Soft, 130' Limestone
Canada		1961		60	600				37	Gypsum Mine Vent	
Grants, N. Mex.	7	1961-1962	Kermac Nuclear	48	Min. 540 Avg. 692 Max. 848	42	TD	Mud, single pass	37	9-15 days each. $5,000 Avg. Cutter cost. $1,500 Avg. mud cost.	Sandstone, Shale
New Mexico	2	1961	Lance Corp.	44	400 645	36		Mud, 2 passes	37	10 days, 21 days	Sandstone, Shale
New Mexico	1	1961	Phillips Petr.	64	837	52	TD	Mud, multiple pass	14, 37	Uranium Mine Vent	
Gas Hills, Wyoming	1	1963	Union Carbide	48	360	36	TD	Mud, 1 pass		Drilled 360' in 62 rotating hrs. 4 days spud to TD	Sand, Shale,

TABLE I-1 (Continued)

Location	No. of Holes	Year	Owner	Hole Size Inches	Hole Depth Feet	Cased Size Inches	Cased Depth Feet	Type Drill, Circulation	Reference	Time, Cost, Remarks	Geology
Gas Hills, Wyoming	1	1963	Union Carbide	60	398	48	TD	Mud, 1 pass		9.6 days spud to release. Mud cost $3,100. Contractor cost $21,300. 1 set cutters.	Sand, Shale, Boulders
Gas Hills, Wyoming	1	1964	Union Carbide	60	451	48	TD	Mud, 1 pass	31	10.2 days spud to release 2 sets cutters. Mud Cost $10,000 Cont. cost $19,300.	Shale, Sand, Boulders
Cote Blanche Isl., La.	1	1963	Carey Salt	130 90	570 1,400	92	570	Reverse Mud, 1 pass	14	20 days to drill 130" to 570'	Sediments to top of salt
Russia		Now		252					3		
Carlsbad, N. Mex.	1	1963	Kermac Potash	124 102	935 1,650	104	935	Reverse Mud, 2 passes	3, 59, 60	Spud to release 5 1/2 months. Cutter cost $87,000.	Sandstone, Anhydrite Dolomite, Clay, Evaporites
Jefferson Isle, La.	1	1963-1964	Diamond Crystal	130 90	242 881	92	225	Reverse mud, 1 pass	14	Cutter Cost $20,240; 130" hole 1.8 fph, 90" hole 2.6 fph	Soft to 170' Salt below 170'
Arkansas	1	1964	Reynolds Mining Co.	96	375	84	376	Mud			
Arkansas	1	1964	Reynolds Mining Co.	86	525	72	502	Mud			
Bonanza, Utah	12	1964-1965	American Gilsonite	62	600-1,100	Gunnited		Reverse water	11	To 900' in 2-3 weeks	Gilsonite Veins in Sandstone
Ellington, Mo.	1	1964-1965	Ozark Lead	84	1,250	72	990	Mud, 3 passes		Cutter Cost $57,000, Mud Cost $23,000. Spud to release 12 months	150' Unconsolidated 850' Dolomite 400' Shale
Lynn Lake, Manitoba	1	1965	Sherritt-Gorden	48	3,000	No		Air, Second pass cuttings down pilot		Gabbro 1'/hr. Amphibolite 1.8'/hr.	Diorite, Gabbro,
New Market, Tenn.	1	1965	New Market Zinc	72	1,400			Mud, 3 passes			Limestone, Dolomite
Arkansas	1	1965	Reynolds Mining Co.	60	350	48	350	Mud			

APPENDIX II

One company, Fenix and Scisson, Inc. has contracted drilling of access shafts to mined LPG storage caverns. To the best of our knowledge, no other organization has employed drilled access shafts for LPG mined storage.

Table I below lists the drilled shafts.

Many of the holes listed were drilled with small water-well-drilling type rigs. All holes have been lined with 42-inch I. D. steel casing. For the holes less than 500 feet deep, 5/8-inch wall pipe costing about $37/ft. was run and cemented to surface.

TABLE II-1

52" – 55" Drilled, 42" I. D. Cased
LPG Storage Caverns

Fenix & Scisson, Inc.

June 1965

Year	No.	Depth, Feet*	Contractor Costs, $**	Location	Cavern Owner
1956	1	300		Demopolis, Alabama	Sinclair Oil & Gas Co. Tuloma Gas Products Co.
1957	2	340		Linden, New Jersey	Esso Standard Oil Co.
1958	3	340		Linden, New Jersey	Esso Standard Oil Co.
1958	1	340		Marcus Hook, Pennsylvania	Sun Oil Company
1959	4	340		Middletown, Ohio	Texas Eastern Trans. Co.
1959	2	380		Siloam, Kentucky	Columbia Hydrocarbon Corp.
1960	1	340		Middletown, Ohio	Texas Eastern Trans. Co.
1960	1	425		Marcus Hook, Pennsylvania	Sun Oil Company
1960	2	475		Wood River, Illinois	Shell Oil Company
1960	1	320		Omaha, Nebraska	Metropolitan Utilities Dist.
1961	1	360		Marcus Hook, Pennsylvania	Sun Oil Company
1961	2	330		Middletown, Ohio	Texas Eastern Trans. Co.
1961	1	480		Oakland City, Indiana	Texas Eastern Trans. Co.
1961	1	475		Wood River, Illinois	Shell Oil Company
1961	1	340		Ponca City, Oklahoma	Continental Oil Company
1961	1	420		Covington, Kentucky	Union Light, Heat & Power Co.
1961	1	330		Wood River, Illinois	Tuloma Gas Products Co.
1962	1	330		Middletown, Ohio	Texas Eastern Trans. Co.
1962	1	375		Wood River, Illinois	General Facilities, Inc.
1962	1	440		Baltimore, Maryland	Baltimore Gas & Elec. Co.
1962	1	540		Erskine, Minnesota	Signal Oil & Gas Company
1962	1	440		Burke, Virginia	Washington Gas Light
1963	1	380		Greensburg, Pennsylvania	Texas Eastern Trans. Co.
1963	1	420	41,000	Calvert City, Kentucky	Warren Petroleum Corp.
1963	2	345	23,000/ea.	Middletown, Ohio	Texas Eastern Trans. Co.
1963	1	500	31,000	Omaha, Nebraska	Metropolitan Utilities Dist.
1963	1	400	29,000	Cincinnati, Ohio	Cincinnati Gas & Elec. Co.
1963	2	340	27,000/ea.	Greenwood, Nebraska	Mid-America Pipeline Co.
1963	2	485	57,000/ea.	Iowa City, Iowa	Mid-America Pipeline Co.
1963	3	375	23,000/ea.	Tuscola, Illinois	U. S. Industrial Chemicals
1964	1	320	32,000	Miller, Missouri	General Facilities Co.
1964	1	425	32,000	Drumright, Oklahoma	Service Pipeline Company
1964	2	500	43,000/ea.	Normandy, France	Shell Berre
1965	1	350	57,000	Milner, Georgia	Dixie Pipeline Company

*Average or Approximate.

** Costs to drill hole. In most cases, Contractor supplied:
Rig, personnel, bits, reamers, cutters,
fishing tools, drift surveys, mud pits,
mud, and set any surface pipe needed.
Costs do not include location, roadway, pipe, cement.

APPENDIX III

"BIG HOLES" DRILLED FOR THE ATOMIC ENERGY COMMISSION

In the last five years, the majority of the total number of "big holes" and the total footage of "big holes" drilled in North America have been drilled by the Atomic Energy Commission. Most of this work has been concentrated at the Nevada Test Site located 80 miles northwest of Las Vegas. The areas drilled at the test site can be roughly divided into two categories, the "flats" and the "mesas" areas.

Flats. The area with the majority of the drilling is located in the relatively flat valleys between the mountain ranges. In general, the "flats" drilling penetrates dry alluvium to about 800 feet and tuffs below that depth. Up until 1963, holes were drilled with mud, then a change was made to drilling with air and foam. If much hole is made below 1,000 feet, an intermediate casing string is set through the alluvium section to prevent hole sloughing. Published articles (Crews, Presley) have discussed the drilling procedures and problems involved.

Costs are extremely variable because of:

1. the difference in drilling the alluviums some of which are loose and cause sloughing into the hole,
2. the intermittent setting of intermediate pipe through the alluvium,
3. the shut-down periods while awaiting the test events,
4. the special requirements and experiments for the continually changing program,
5. the practice of moving several type rigs on and off the hole to perform various functions,
6. the bookkeeping procedures with the inherent problem of cost gathering that a long-term open-job number has in a large organization.

Recent typical drilling cost data for the "flats" is shown in Figs. III-1 and III-2. Data for the 36-inch cased holes is relatively consistent because of the shallower depths and because the data represents the last of more than 60 holes drilled from 1961 through 1964. Most of the 48-inch cased holes have been drilled since 1962 and the data shown in Fig. III-2 represents the first two years of a major 48-inch program.

A compilation of most of the holes drilled on the "flats" at NTS is shown in Table III-1.

TABLE III-1

"BIG HOLES" DRILLED ON "FLATS"
NEVADA TEST SITE
ATOMIC ENERGY COMMISSION

March, 1965

Year	Number of Holes	Drilled Hole Size, Inches	Drilled Hole Depth, Feet Max.	Drilled Hole Depth, Feet Min.	Drilled Hole Depth, Feet Avg.	Cased Hole I.D. Inches	Cased Hole Depth Feet
1959	5	44			500	36	TD
1960							
1961	8	42	2,515	205	1,140	29	TD
	9	42-48	1,168	205	473	36	TD
1962	23	42	1,375	500	870	29	TD
	37	42-48	1,630	442	810	36	TD
	1	56			1,395	42	TD
	2	60	1,705	750		48	TD
1963	25	42-48	985	204	585	36	TD
	1	64			904	42	TD
	30	64	2,689	204	1,000	48	TD
1964	3	42-48	755	405	590	36	TD
	33	64	2,150	445	1,120	48	TD

Mesa. The "big hole" drilling on the "mesas" at the Nevada Test Site started in 1962 with he drilling of two "big holes." These holes, cased with 48-inch pipe to about 2,000 feet, were !rilled using experimental methods and have been described in the literature (Johnson, Farson).

A compilation of most of the "big holes" drilled on the "mesa" areas at the Nevada Test Site s included in Table III-2.

Recent drilling activity has been increased considerably by efforts on Pahute Mesa. Here, ıoles six feet in diameter have penetrated the tuffs and rhyolites to a maximum depth of 4,800 eet. With fractured formations and a water table at a depth of 2,000 feet, extreme drilling con-litions must be met. Reverse circulated air and dual concentric drill strings with specially made :quipment are used to drill the holes. Several recent articles (Parker, Bowman, Hall, Hobbs, 3urke) have discussed the drilling procedures and problems involved.

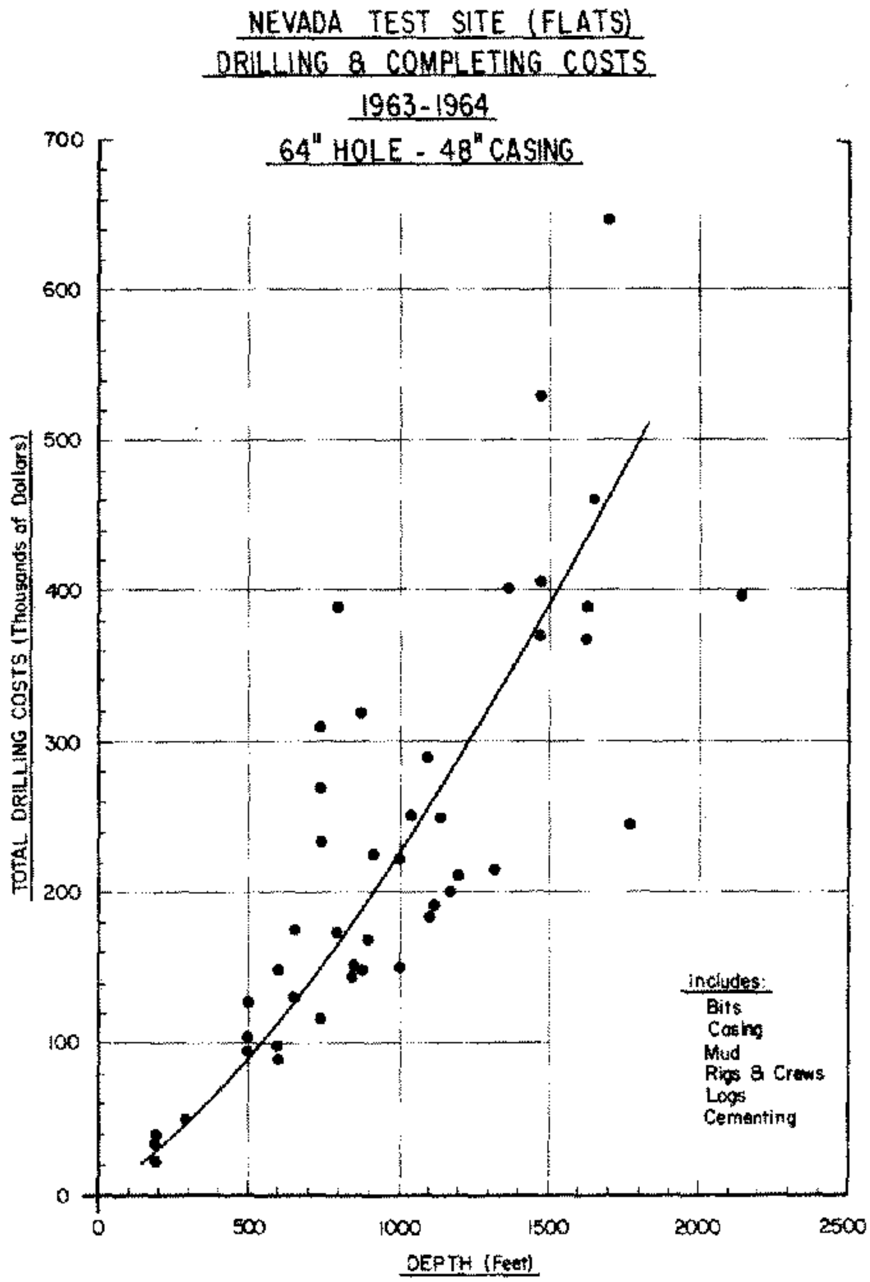


Figure III-1

The costs shown for the Pahute Mesa holes were paid through the drilling contractors and vary depending upon the items covered and the work performed. Four holes used the drilling rig to run and cement the casing.

The seven holes drilled on Pahute Mesa from late 1963 to early 1965 were the first of a series of holes and involved much experimentation. Expected times and costs of the second group of the series should be considerably less.

Other. Several other holes have been drilled for the AEC. Most of these holes are also listed in Table III-2. Costs are extremely varied due to varied contract and drilling conditions. For proper cost perspective, each case would need to be analyzed separately, which is beyond the scope of this paper.

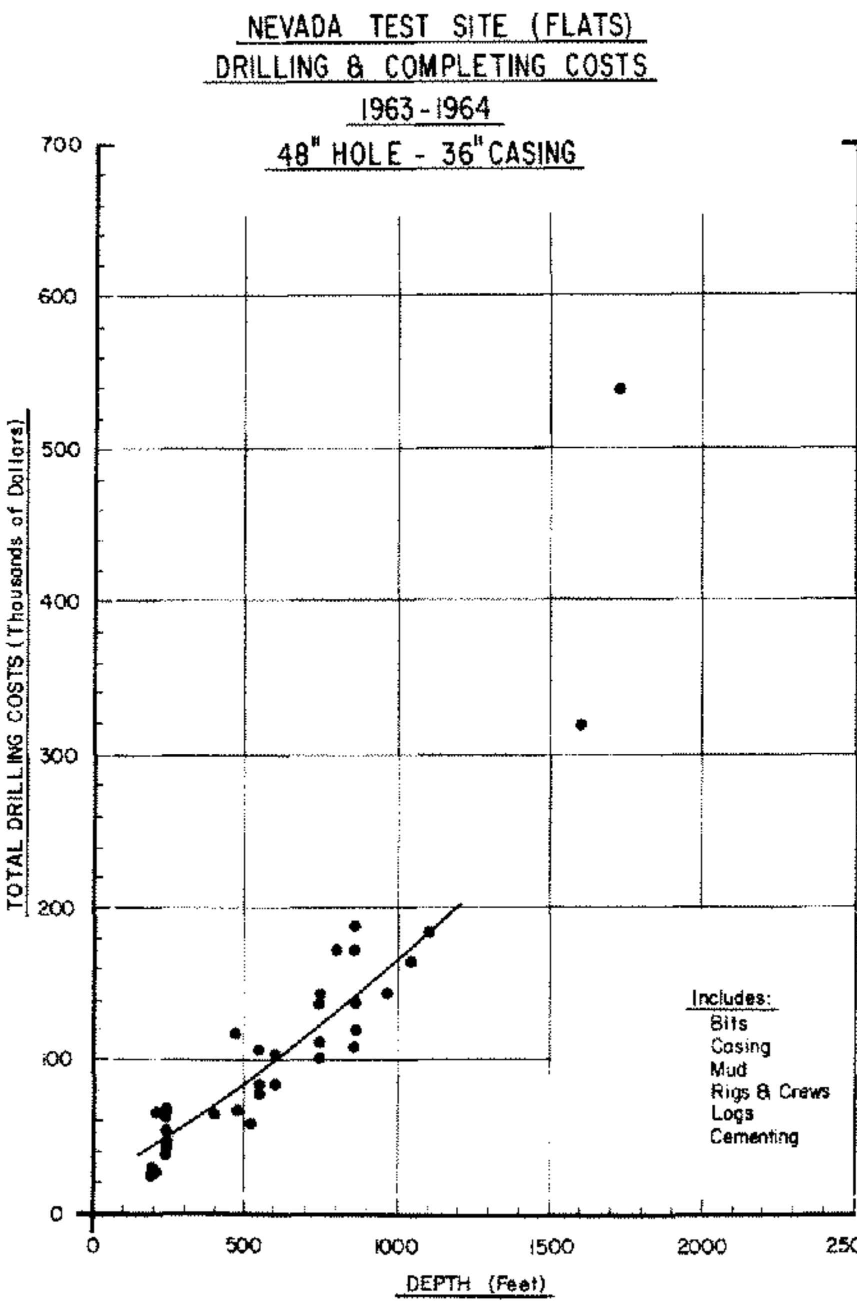


Figure III-2

TABLE III-2

"BIG HOLES" DRILLED FOR THE ATOMIC ENERGY COMMISSION
(Other than those shown in Table III-1)

April, 1965

Location	Year	Hole Size Inches	Hole Depth Feet	Cased Size Inches	Cased Depth Feet	Method Drill, Circulation	Reference	Time, Cost, Remarks	Geology
3 Holes NTS, Flats	1957-58	42	to 500	36	250	Mud	86		Alluvium
NTS, Area 15	1959-60	44	965	36		12 1/4" with air, 44" with mud.	4, 37, 88	12 1/4" hole, 18 days to drill, 47 days to ream to 44". Total 65 days drilling	Granite
Winfield, Louisiana	1960	44 39	437 800	40 38	437 800	Mud	37, 81		Sand, Shale
NTS, Ranier Mesa	1962	64	2, 144	48	1, 942	Single Pass. Mud to 907', Reverse air 907' to TD	50, 58	95 active drilling days	Tuffs
NTS, Ranier Mesa	1962	60	2, 504	48	2, 152	5 passes, Air	14	5 months	Tuffs, lower 450' Granite
Tatum Dome, Miss.	1963	88	900	70	900	2 passes, Mud	43	2 days to drill 15" pilot. 19 days to drill 88" hole	Sand, Shale to 950', Caprock, limestone, dolomite to 1, 500' salt to TD
Tatum Dome, Miss.	1963	57 41 29	950 1, 600 2, 200	42 30	950 1, 500	Mud, 2 passes	43	12 days to drill 57" hole, 30 days to drill 41"	Sand, Shale to 950', Caprock limestone, dolomite to 1, 500', salt to TD
NTS, Flats	1963	84	645	72	646	Air		Drilling 6. 2 days, Case and Cmt. 10 days	Alluvium
NTS, Ranier Mesa	1963	36	1, 774			Air		2 months	Tuffs
NTS, Pahute Mesa	1963	52 48	1, 005 2, 540	36	2, 511	Single Pass, Reverse Air		Contractor Cost $1, 010, 000, 72 days spud to 2, 170'	Tuffs
NTS, Flats	1964	160 108	306 709	144 72	304 705	Single Pass, Reverse Circ. Airlift		Rig up and down 5. 8, Shut down 47. 5, Survey etc. 6. 9, Fish 10. 5, Casing and Cement 12. 3, Repairs 9. 7, Drilling 65. 3, Total 158 days	Alluvium

TABLE III-2 (Continued)

Location	Year	Hole Size Inches	Hole Depth Feet	Cased Size Inches	Cased Depth Feet	Method Drill, Circulation	Reference	Time, Cost, Remarks	Geology
NTS, Flats	1964	96	429	72	402	Air and Foam		Rig up and down 2.3, log etc., 0.3, Case and Cmt. 2.8, Other 2.3, Working 5.0, Total 15 days	Alluvium
Tatum Dome, Miss.	1964	48	950	29	950	2 passes, Mud		Surface casing for deeper hole, 14 days spud to 950'	Sand, Shale
NTS, Pahute Mesa	1964	72	3,375	48	3,350	Reverse Air		120 days spud to 2,170', 32 days 2,950'-3,375', Cutter Cost $177,400, Cont. Cost $1,860,000*	Tuffs, Rhyolites
NTS, Pahute Mesa	1964	96 72	665 4,200	74 48	605 **	Reverse Air		48 days spud to 665' includes 9 days Wait on Eqpt., 50 days 665' to 2,170', 41 days 2,300' to 4,000'. Cutter Cost $115,000. Cont. Cost $1,400,000*	Tuffs, Rhyolites
NTS, Pahute Mesa	1964	72	4,202	48	**	Reverse Air		60 days spud to 2,500', 83 days 2,700' to 4,200', Cutter Cost $119,000. Cont. Cost $1,200,000*	Tuffs, Rhyolites
NTS, Pahute Mesa	1965	72	3,177	48	2,344	Reverse Air		135 days spud to 2,170' includes 31 days reaming and fishing. 39 days 2,500' to 2,950' Cont. Cost $1,800,000*	Tuffs, Rhyolite
NTS, Pahute Mesa	1965	72	4,800	48	**	Reverse Air		50 days spud to 2,000', 27 days 2,300' to 3,100', 75 days 3,200' to 4,300'. Cutter Cost $128,000. Cont. Cost $1,800,000.*	Tuffs, Rhyolites
NTS, Pahute Mesa	1965	72	2,884	48	2,763	Reverse Air		75 days spud to 2,090'	Tuffs, Rhyolites
NTS, Pahute Mesa	1965	48	615	36	605	Aerated Mud		22 days spud to 615'	Tuffs

*Cost includes: Contractor rig and crew, cutters, air, water.
Cost does not include: Casing, cement, big hole equipment tools such as bits, drill collar stabilizers, reamers, drill pipe, kelly, swivel, AEC, engineering or inspection charges, location or access.

**Casing not run to date.

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