

Jan. 27, 1970

J. L. KELLY, JR
DRAG TYPE CORE DRILL FOR PAVEMENT OR ROCK
HAVING DISPARATE INCLUSIONS

3,491,844

Filed March 20, 1967

7 Sheets-Sheet 1

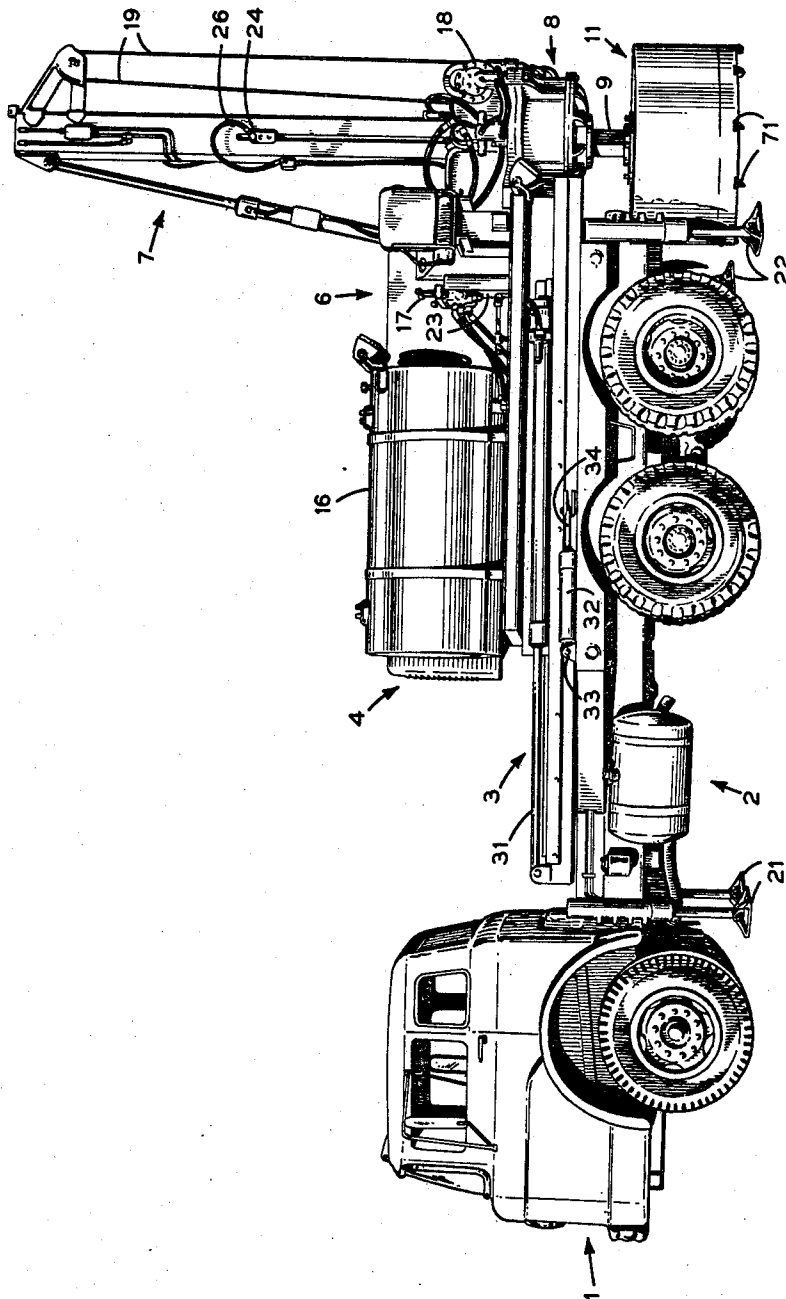


FIGURE 1

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7 Sheets-Sheet 2

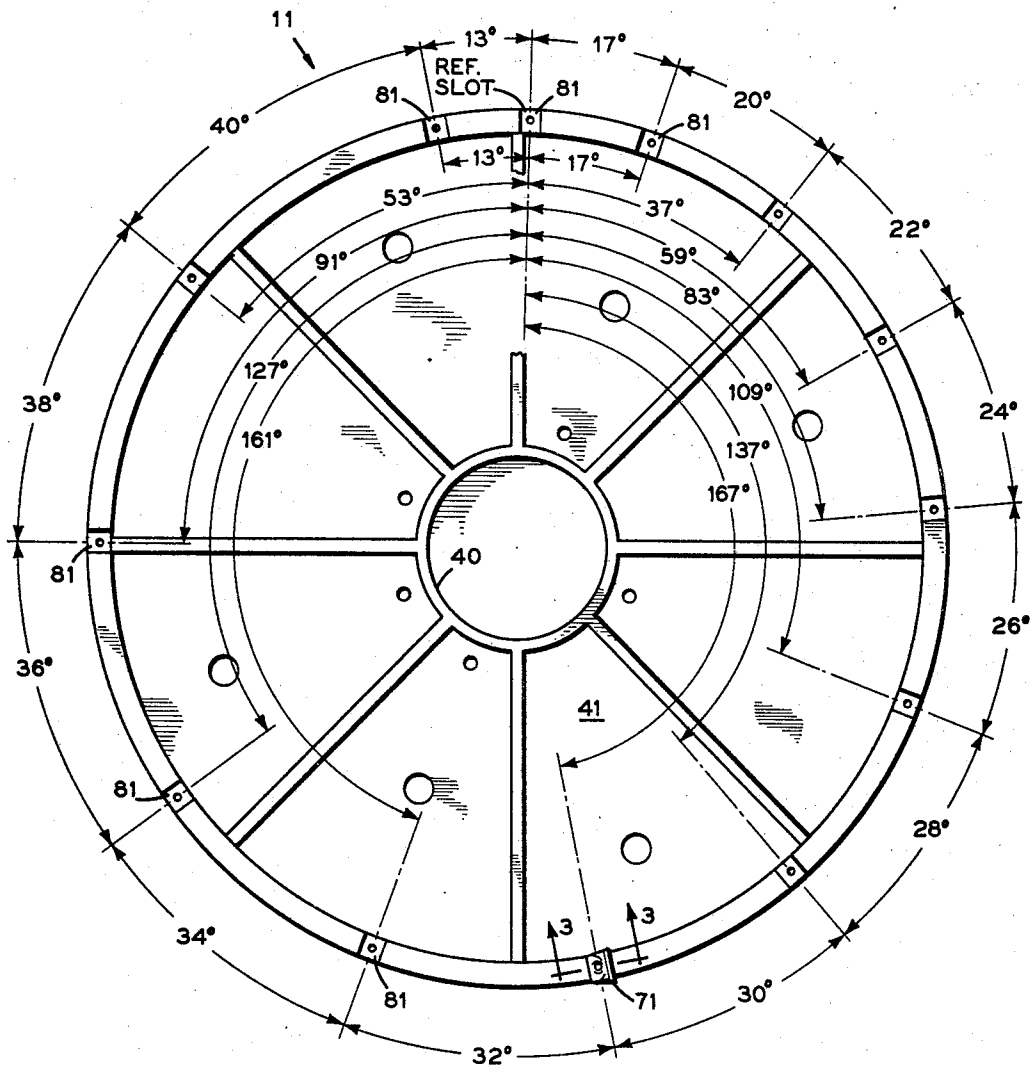


FIGURE 2

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7 Sheets-Sheet 3

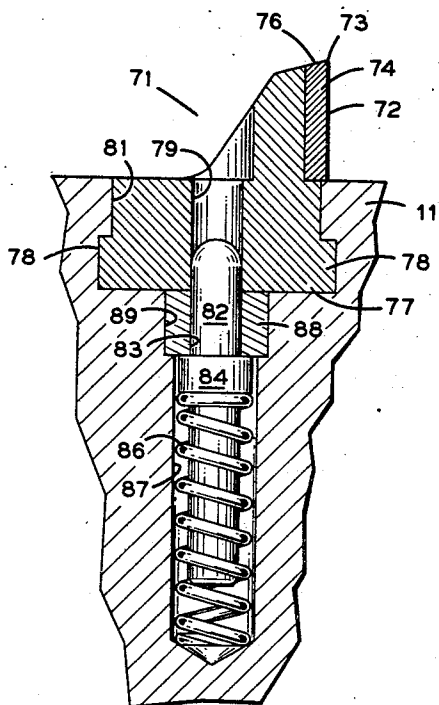


FIGURE 3

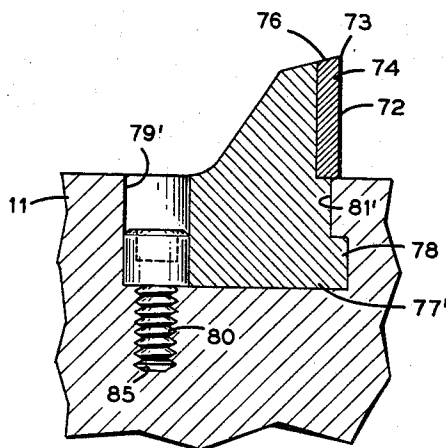


FIGURE 5

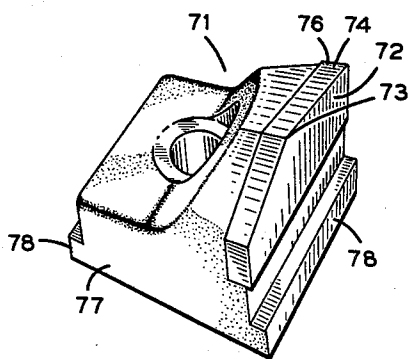


FIGURE 4

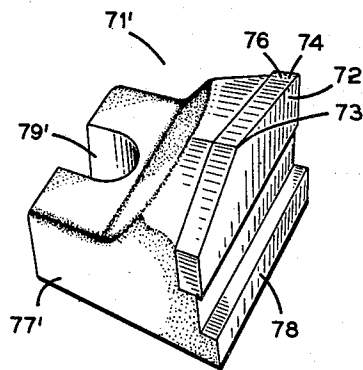


FIGURE 6

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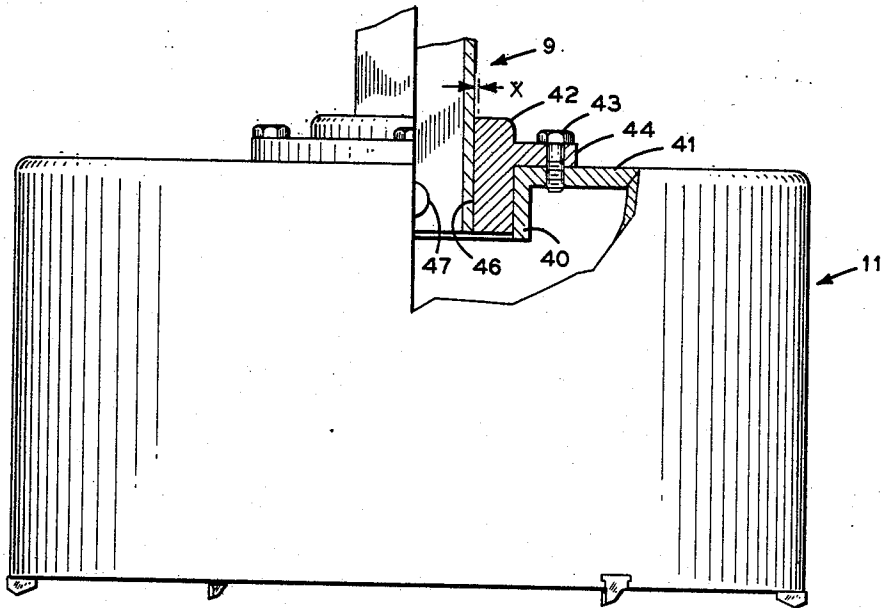


FIGURE 11

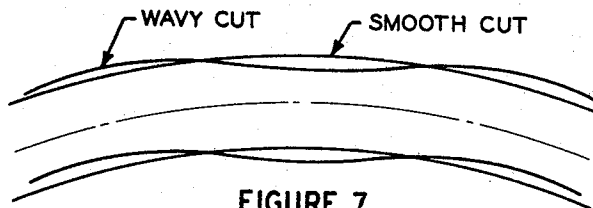


FIGURE 7



FIGURE 8

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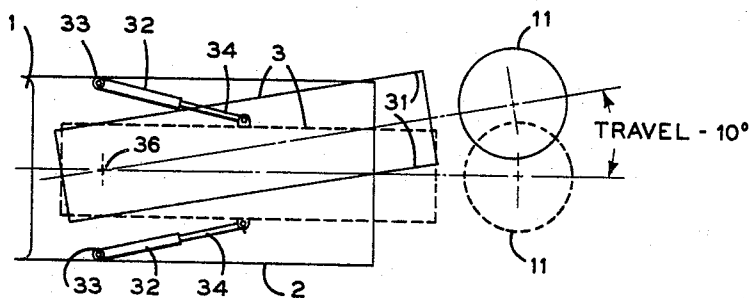


FIGURE 10

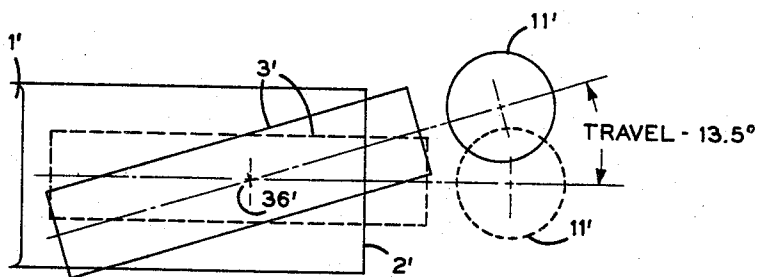


FIGURE 9
PRIOR ART
CONVENTIONAL

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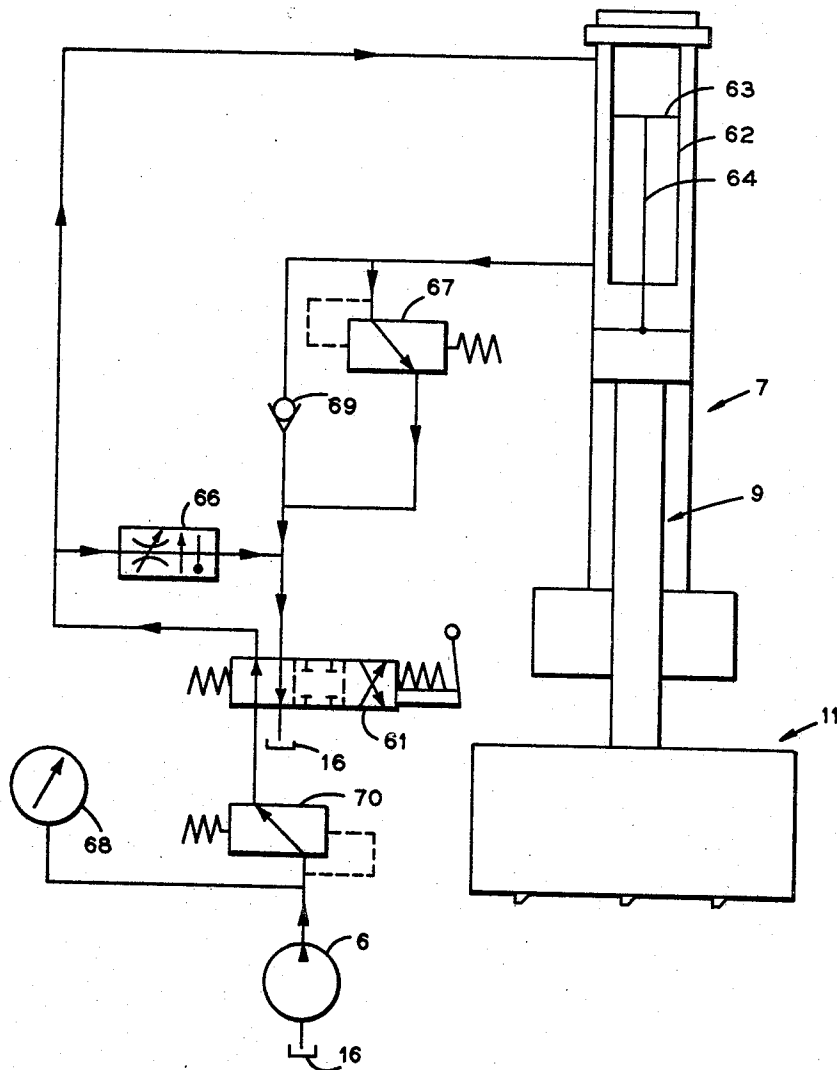


FIGURE 12

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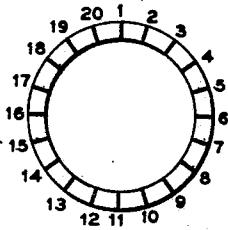
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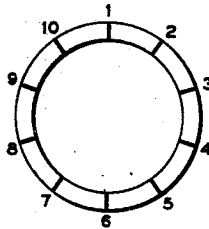
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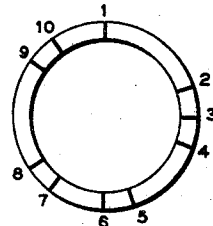
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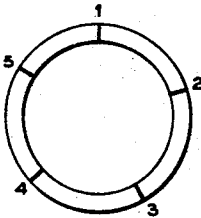
5'- 20T - EVEN
FIGURE 13a
PRIOR ART



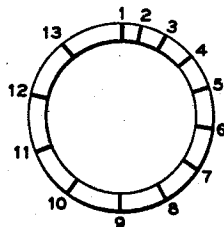
5'- 10T - EVEN
FIGURE 13b
PRIOR ART



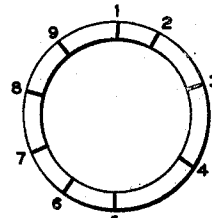
5'- 10T - ODD
FIGURE 13c



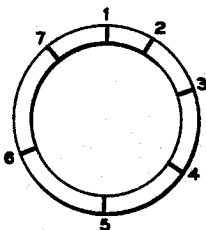
2'- 5T - ODD
FIGURE 13d



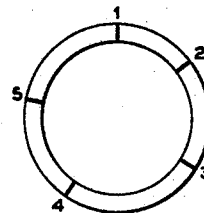
5'- 13T - ODD
FIGURE 13e



5'- 9T - ODD
FIGURE 13f



5'- 7T - ODD
FIGURE 13g



5'- 5T - ODD
FIGURE 13h

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U.S. Cl. 175—398

9 Claims

ABSTRACT OF THE DISCLOSURE

The basic drill is a core barrel having the general shape of a thick-walled cylindrical shell having a multiplicity of cutter blades secured to the barrel at substantially a common radius and depending from its lower end. The barrel is secured to a square kelly bar which extends up through a rotary table and has a hydraulic crowd cylinder secured to its upper end. The crowd cylinder is disposed within a vertical mast which is tilted down to the bed of a truck for movement between drilling sites. The entire drilling rig is slidable on a wiggle table which is pivotably secured to the truck bed.

The invention lies in the structural modifications to reduce or eliminate vibrations, in particular by using a number n of cutting blades spaced from one another by unequal pitches, defining a pitch as the angular spacing between any pair of cutter blades, including both non-adjacent pairs and adjacent pairs. Vibration is reduced as the number of different pitches S is increased to approach the maximum number of such different pitches, $n(n-1)$. The inventor has also discovered that vibration may be substantially eliminated with a lesser value of S , greater than

$$\frac{n^2}{5} - 1$$

and preferably greater than

$$\frac{n^2}{3} - 1$$

The present invention is appropriately classified with surface core drills which are rotated about the central axis of the drill but are not equipped with means to grip and retrieve the core.

Another name which could be used is kerf drill, as the cutters of the invention are mounted on an annular crown or barrel which is rotated to drill an annular kerf until the complete thickness of pavement is penetrated and the core portion is thus broken loose. Such drills have many uses, an outstanding one being the forming of access holes in roadbeds for maintenance work on various types of pipelines. A similar employment is repair work on the pavement itself, the drill being used to define and separate a core of damaged pavement which is then replaced with new concrete or similar paving material. It may also be used to harvest minerals, form foundation holes for piling, bore tunnels, ventilation holes, mine raises, and the like.

The present invention resulted from applicant's engagement to design a new type of pavement drill, one capable of drilling paved roadways to form openings of the order of 2 to 5 feet in diameter. Prior to the invention almost all such pavement drilling was done with the well known jackhammer, an air operated type of percussion drill, and those who must make holes in pavement de-

manded a drilling machine free from many of the objectionable characteristics of jackhammers. Since the drill was often to be used in metropolitan areas having high population densities, a prime requirement was that the drill operate at a low noise level, much lower than the almost deafening decibel level of a jackhammer. It was also to operate quickly, so that no individual street area would be preempted and no vehicular traffic thereover would be restricted or detoured more than a reasonably short time. Flexibility was also demanded, as the roadway area to be penetrated would sometimes be located adjacent a steep curb or next to a building. Mobility was also required, both to get maximum duty from the drill by moving it quickly from one site to the next and again to minimize the time when any one area is occupied by the drilling equipment, this object in turn to be aided by providing equipment requiring minimum times for both installation and removal.

Additional objects were to provide a pavement drill (1) capable of penetrating a paved area with a minimum of crack propagation into areas of pavement adjacent and outside the opening being formed, (2) operating with a minimum discharge of dust into the atmosphere but without releasing large quantities of drilling fluid onto the pavement, (3) equipped with cutters having an economical service life under even the most difficult conditions, the cutters to be mounted so that when they became worn they could be replaced in a matter of seconds, (4) so designed that the drill barrel could be quickly assembled or disassembled from the rest of the equipment, making it possible to execute with dispatch a decision to change from one hole size to another, (5) mounted on a truck of such weight that the total gross weight would permit the rig to travel over and be used on any paved street in a completely legal manner, i.e., without exceeding any maximum weight limit established by competent highway authority. This object implied a light weight drilling rig and met with considerable skepticism on the part of the inventor's colleagues, who predicted extremely rough operation and excessive vibration.

Such forecasts were rather fully borne out in an early prototype of a pavement drilling machine designed by the present inventor, who succeeded in eliminating the predicted vibrations only by the use of the invention to be described. The stated objects were obtained by providing a rotary drilling rig mounted on the bed of a medium size truck, together with its power supply, drive train, tiltable and swingable mast, and all auxiliary equipment such as jacks, hydraulic cylinders, and even a water tank and circulation lines to cool the drill and flush out the cuttings. Quiet operation and compactness were partially attained by using continuously cooled drag type cutting blades and a muffled internal combustion engine as the prime mover turning a hydraulic pump and providing hydraulic components to perform all secondary operations—rotate the drill stem, crowd the drill stem into the pavement, tilt and swing the mast, operate the jacks, etc. The mast lies flat on the truck in transport position, with the core barrel slightly overhanging the rear end of the truck, and is moved further to the rear and then tilted to a vertical position just behind the rear end of the truck when a drilling operation is to be started. Inaccessible areas of pavement are reached by swinging the mast approximately 10 degrees to either side of the center line of the vehicle. The time required for either set-up or breakdown is only about 5 minutes, thus insuring low down time on any one drilling site, and the truck mounting makes for a maximum of mobility.

The rotary equipment provided on this initial assembly

will turn the drill stem at 0 to 20 revolutions per minute (r.p.m.), a range sufficiently low so that high pitched noises are avoided and yet sufficiently high so that an average drilling rate of about one inch per minute may be maintained in drilling homogeneous concrete with the core barrel loaded to 18,000 pounds of force. With the usual quantity of spaced apart inclusions, an 18-inch pavement can be cored through in 30 minutes or less. The core barrel itself is simply a thick-walled cylindrical shell having its lower end notched at various circumferential locations to define pockets for the mounting of replaceable drag blades which extend below the barrel and somewhat overhang both its inner and outer surfaces.

The need for certain features of the present invention became apparent when the aforementioned prototype of the drilling equipment thus far described was given its initial field tests. In such tests the drill operated with a great deal of vibration, most of it in the vertical direction. This was not only noisy, but the vibrations were transmitted upwardly through the drill to cause tremendous shaking of the equipment mounted on the truck bed. Threaded connections became loose, some connecting members failed in shear, and in general the high amplitude vibrations threatened to tear up the whole assembly.

The concrete for such tests had the usual steel reinforcing ("rebars") embedded in it, and it quickly became apparent that the unwelcome vibrations had some causal relationship with such rebars and their interaction with the cutting blades. Just what this relationship was, however, was not immediately apparent, nor was it at all obvious that something could be done to eliminate the vibrations and save the equipment from destroying itself.

A general concept built into embodiments of the present invention to reduce such vibrations is that of increased structural rigidity. Two means contributing to such greater rigidity are known in the prior art but are described here because they are the exception rather than the rule in prior art drilling equipment. One of these means is disposing the four jacks which support the truck bed and drilling rig approximately under the corners of this bed. This disposition amounts to a maximum longitudinal spacing of the two sets of jacks (or the fore set and the aft set), and contrasts with the usual arrangement where the fore set, that nearer the cab, is located just forward of the rear truck or bogie. The effect of the usual jack disposition was a tendency of the entire rig to swing somewhat during operation, causing the drill barrel to rub against and bind with the sidewalls of the hole. Changing the jacks to the described maximum longitudinal spacing eliminated or sharply reduced such effect.

The other in this pair of features known in the prior art is the substitution of a wiggle table for a turntable as a swingable mount for the drill, to enable it to be moved to either side of the truck bed for cutting in relatively inaccessible areas. In the mounting of this wiggle table the fulcrum was moved forwardly to a point just short of its forward end (just behind the truck cab), as contrasted to the usual pivot location in the center of the ordinary table used in mounting such drilling equipment as augers. Substitution of the wiggle table also caused a weight decrease which brought the gross weight on the rear wheels within the legal limit.

One contribution of the present inventor to greater structural rigidity, now to be claimed in a divisional application, involves the connection between the drill barrel and the kelly bar, the central shaft through which torque and thrust are transmitted to the core barrel. The drill barrel itself is made quite rigid and true, preferably by casting it and making it in a relatively thick section, e.g., with a wall thickness of $\frac{3}{4}$ inch for a 5-foot diameter barrel. In the preferred embodiment to be de-

scribed, the lower end of the barrel, where the cutting blades are mounted, is made even thicker, e.g., $1\frac{1}{2}$ inches, over the lowermost six inches of length. The kelly bar itself is made square in cross-section so that it can gradually slide through the rotary table while being turned by the table through a sliding fit into a square central hole therein. In the preferred embodiment it is made as a hollow member, e.g., seven inches square with a $\frac{5}{8}$ inch wall, largely to serve as a conduit through which water is circulated down to the barrel and the drag blades. Although it has been postulated that the connection between the drill barrel and the kelly bar can be a relatively loose slip fit, in embodiments of the present invention it was found that the opposite approach of increasing the rigidity of the connection by making it a force or press fit reduced vibration and caused the drill barrel to cut a truer kerf.

Another novel aspect conceived by the present inventor, now to be claimed on the aforementioned divisional application, deals with the problem of making control adjustments when the drill encounters changed conditions. This contribution deals in particular with drilling through a section of homogeneous concrete and into a section containing reinforcing bars or other disparate inclusions. The word "disparate" is used because the only characteristic of such things as steel rebars and large pieces of hard aggregate which make them more difficult to drill is the fact that they are different from the bulk of the material in which they are embedded. They are not particularly harder or tougher to drill than concrete, and a block consisting entirely of steel or limestone presents no very great problem to a driller. The problem seems to lie solely in the fact that they are spaced apart in a fundamentally different matrix.

The usual prior art technique was to deal with the changed situation by varying the thrust load in response to a harder drilling condition, specifically by "drilling off" and then "bumping" (respectively the manipulation of the controls to lift the drill until the cutters are barely free of contact with the bottom of the annulus, and intermittently lowering the drill so that it contacts and cuts bottom in short spaced apart bursts of power application, being lifted off bottom between cutting bursts). In using this technique the operator accepts whatever penetration rate results, while by contrast in the present invention the opposite technique is employed, namely the penetration rate is controlled and the thrust magnitude is allowed to vary as required to maintain a penetration rate dictated to the controls by the operator. When more difficult drilling is encountered, the controls are set so that a lower penetration rate obtains. This approach was a significant departure from standard drilling practice, but resulted in successful drilling while the prior art practice caused rough drilling and frequent stalls.

The significant contribution claimed herein lies in another structural departure from the prior art aimed at reducing or eliminating rough running and excess vibration. This contribution lies in the spacing of the cutter blades about the circumference of the core barrel, a spacing aimed at minimizing or reducing the amplitude of the longitudinal movement of the barrel as it passes over inclusions such as reinforcing bars. In prior art drills such spacing is for the most part uniform, i.e., the angular distance or pitch between one pair of adjacent blades is equal to that between all other adjacent pairs. Embodiments of the present invention, on the other hand, utilize at least some unequal pitches and preferably all of the pitches so dimensioned that there is relatively little duplication. The ultimate in such unequal spacing is to select all of the pitches so that each pitch is unequal to all of the others and each possible sum of consecutive pitches up to one less than the total number of teeth is unequal to both each individual pitch and each other such sum of pitches. Total compliance with this criterion is not absolutely essential, but the more closely it is ap-

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proached the more certainly smooth running will be assured.

Another way of stating the invention is by thinking of a blade pitch as the angular spacing between any pair of blades, whether the members of the pair are adjacent or non-adjacent. Using this definition and measuring blade No. 1 of a 5-bladed drill, it will be apparent that there are 4 pitches—No. 1 to No. 2, No. 1 to No. 3, No. 1 to No. 4 and No. 1 to No. 5. Similarly, there are 4 pitches when blade No. 2 is used as a reference, 4 for No. 3, 4 for No. 4 and 4 when blade No. 5 is the starting point. In short the total number of pitches is $5 \times 4 = 20$, or $n(n-1)$. Each of these 20 pitches can be chosen to be different from the other 19, and the present inventor has found that vibration is eliminated as S, the number of unduplicated pitches, approaches $n(n-1)$. He has also found that smooth running is substantially insured when S is greater than

$$\frac{n^2}{5} - 1$$

and preferably greater than

$$\frac{n^2}{3} - 1$$

A subsidiary (and claimed) feature is the mounting of the cutter blades for ready replacement. To accomplish such replaceability the massive base of the cutter is formed with at least one laterally protruding lug or flange designed to engage a corresponding shoulder of the core barrel to prevent axial movement of the blade. With a single such flange the base of the blade has the general shape of an L. In one preferred embodiment, the cutter blade base is formed with a pair of oppositely extending flanges, giving it the shape of a T, and a similarly shaped slot is formed in the lower edge of the drill barrel, the T being formed so that an observer sees a T outline when looking inwardly along a radius of the barrel—with the cross bar above the central vertical leg. To hold the cutter in place against radial movement a pair of registering vertical holes are formed in blade and barrel, and a pin of appropriate size is disposed to extend through such aligned holes. The hole in the barrel is elongated vertically so that the whole of the pin may be pushed up into the hole during a changeover of blades, and it is preferably biased to a normally protruding position by a spring also disposed in the elongated opening. In a second embodiment the pin and spring are replaced by a machine screw extending through a hole in the blade and engaging a threaded hole in the barrel, vibrational loosening being prevented by a locking member in the threads, e.g., a plastic plug disposed in a transverse hole and extending into the threads. This embodiment has the advantage of lower cost resulting from the elimination of machining operations, the entire manufacture of the blades being by forging plus the brazing of the carbide cutting inserts.

These and certain other features of the invention will perhaps become more readily understood by a scanning of the attached drawing, in which:

FIGURE 1 is a left side perspective elevation of the entire drilling machine in a drilling attitude, complete with its truck support,

FIGURE 2 is a bottom end view of the core barrel, looking up into the barrel from its cutting end, only one cutter blade being shown in a slot,

FIGURE 3 is a sectional elevation of a preferred cutter blade assembly as disposed in the drill barrel, the sectioning plane passing through a circumference midway between the inner and outer surfaces of the barrel, as indicated by the lines and arrows 3—3 of FIGURE 2.

FIGURE 4 is a perspective view of the cutter blade of FIGURES 2 and 3,

FIGURES 5 and 6 are similar views of a second cutter assembly and blade, respectively, a vertical section and a perspective view, this cutter being secured to the core

barrel against lateral movement with an ordinary machine screw,

FIGURE 7 is a fragmentary plan view showing both a true cylindrical kerf cut by the apparatus of the present invention and a wavy kerf cut by drilling apparatus lacking the improvements of the invention,

FIGURE 8 is a fragmentary elevational section, somewhat schematic in form, showing both a smooth bottom as achieved with the present invention and a wavy or sinusoidal bottom which is likely to result from the use of prior art devices or methods,

FIGURES 9 and 10 are schematic plan views of drilling apparatus mounted on a wiggly table which in turn is mounted on a truck bed, respectively showing the conventional and unconventional locations of the pivotal member.

FIGURE 11 is an elevation, partly in section, showing the connection between the drill barrel and kelly bar,

FIGURE 12 is a schematic diagram of the hydraulic circuit for the crowd cylinder, and

FIGURE 13 is a group of schematic views of the cutter blade locations, some of which illustrate cutter spacings which resulted in rough running while other views show cutter spacings according to the concepts of the present invention which resulted in smooth operation, virtually without vibration.

Turning now to the drawing for a more detailed description of the invention, FIGURE 1 is a side view of the complete truck mounted drilling rig. The major components of the complete machine are cab 1, trailer or truck bed 2, the wiggly table 3 which supports all of the drilling equipment, the gasoline engine prime mover 4, the hydraulic fluid reservoir 6 which supplies fluid to the pump (not shown), the drilling mast 7 which contains the vertically disposed crowd cylinder (not visible) in its upper portion and the top part of the square kelly bar in its lower portion, the rotary table 8 through the center of which the kelly bar extends, kelly bar 9, and core barrel 11. Also shown in FIGURE 1 are water tank 16, control console 17, auxiliary hydraulic winch 18 for service line 19, forward jacks 21 and aft jacks 22, and a water pump 23 and swivel 24 for connecting water line 26 to kelly bar 9. Not visible are the main hydraulic motor which is coupled to the rotary table by appropriate gearing and the main hydraulic pump driven by engine 4. The water tank 16 supplies water to the core barrel for cuttings removal and dust suppression through pump 23, line 26, swivel 24 and kelly bar 9.

The wiggly table 3 (see FIGURES 1, 9 and 10) is essentially a pair of parallel rails 31, appropriately cross braced and pivotably supported on a fixed framework on the truck bed. As previously indicated, the vertical pivot point 36 is located just behind cab 1, giving the drill at the opposite end of the pair of rails the maximum linear travel for any given angle of rotation. The rails 31 act as ways for the drilling rig, allowing it to be slid rearwardly preparatory to raising the mast and forwardly preparatory to moving to another location. Ordinarily they are disposed parallel to the longitudinal axis of the truck, but a pair of hydraulic cylinders 32 are provided to permit their rotation in a horizontal plane through an angle of about 10 degrees from either side of center. Each such cylinder is normally disposed in a slanted position relative to the truck longitudinal axis with one end of the cylinder pivotably secured to the fixed framework on the truck bed at 33 and the piston rod 34 extending from such cylinder pivotably fixed to the adjacent rail 31. The two cylinders 32 and piston rods 34 are thus disposed to point rearwardly and inwardly so that their extended center lines would converge and meet approximately on the longitudinal center line of the trailer. To swing the table 3 (i.e., rails 31) to one side of center, one of the piston rods is extended further than normal from its associated cylinder while the other piston rod is at the same time retracted into its cylinder. In a swing to the opposite side

of center, of course, the directions of extension or retraction of the two piston rods are reversed.

The difference between the wiggle table mounting used with embodiments of the present invention and of the prior art will be apparent from a comparison of FIGURES 9 and 10, which respectively show a wiggle table 3' as pivotably mounted at 36' according to conventional practice and the wiggle table 3 mounted at 36 in drilling machines actually built and tested. In the two figures the core barrel 11 or 11' has been moved the same distance laterally from its normal position shown in dashed outline, but to accomplish this the usual prior art table 3' must be rotated through a larger angle than the wiggle table 3 used with the invention. In addition, the disposition of the employed structure is more stable because a greater reaction load up through the barrel is required to rock the rig in a vertical plane. To reduce the likelihood of such rocking the rear end of the wiggle table is provided with an overhanging lip (not shown) which projects beneath an adjacent member of the fixed framework of the truck bed.

A connection between core barrel 11 and kelly bar 9 is illustrated in FIGURE 11. Top plate 41 of the barrel terminates inwardly in a downwardly extending short cylindrical sleeve 40 which is tightly coupled to a similarly shaped adaptor 42 by a ring or circle of spaced apart machine screws 43 extending through the radial annular flange 44 of the adaptor and top plate 41. The recess 46 of adaptor 42 is square in cross section to receive the square kelly bar 9.

In the prototype model the fit of the kelly bar 9 into opening 46 was relatively tight, by comparison with the prior art, as a clearance X of about $\frac{1}{64}$ inch was provided. The connection was completed by a tightly fitting pin 47 extending horizontally through registering openings in the kelly bar and adaptor. The result was unsatisfactory, causing a rotation of the core barrel about pin 47 when hard inclusions were encountered. The kerf resulting from this condition is the wavy cut shown in the fragmentary plan of FIGURE 7. The present invention eliminated this undesirable condition and produced the smooth cut shown in the same figure by reducing the clearance X to zero, that is by making a press fit or force fit between the kelly bar and the core barrel.

With respect to the feature of the invention involving controlling the penetration rate of the drill rather than the magnitude of the thrust, it should be noted that many different means can be used to accomplish such control. An applicable hydraulic circuit is shown in FIGURE 12, but it should be understood that such circuit is only illustrative. In the circuit of this drawing figure hydraulic fluid is supplied by pump 6 through valve 61 to the upper end of crowd cylinder 62, and such fluid acts on piston 63 to exert downward thrust through piston rod 64 and kelly bar 9 on core barrel 11. The volume of fluid thus supplied determines the thrust rate (penetration rate), and is controlled by flow control or bypass valve 66. Fluid leaving the lower end of crowd cylinder 62 passes through relief valve 67 and main valve 61 to return to the pump through tank 16.

Relief valve 67 is set so that it will stay closed when the pressure in crowd cylinder 62 below the piston is less than that caused by the weight of the system pendent from the piston, i.e., the barrel 11, kelly bar 9, piston rod 64 and piston 62, and will open to permit flow out of the lower end at some preset higher pressure. This insures positive control when the required thrust is less than such suspended weight, i.e., the penetration rate is totally dependent on the rate at which hydraulic fluid is supplied to the upper end of the cylinder. For example, suppose the weight of the suspended system were 3200 pounds and the cross-sectional area below the piston were 16 square inches, indicating that a pressure of 200 p.s.i. is needed below the piston to support the suspended system. If valve 67 were to be set to permit flow out of the bottom of

crowd cylinder 62 at some reduced pressure less than 200 p.s.i., core barrel 11 would always have to sit on bottom during a drilling operation. This would prevent the operator from using the drill as a milling machine, a mode of operation necessary for such a condition as a broken-off rebar which has snapped back so that a considerable length of it at the broken end lies in the kerf. If the core barrel must remain on bottom, as it rotates a cutting blade over the concrete the blade plows into the frayed end of the rebar, very likely either breaking the blade, stalling the machine, or both. In the actual mode of operation employed, the cutting blades are held slightly off bottom so that they contact only the frayed rebar, and they drill or grind through it at a set rate of penetration.

Gage 68 is a pressure gage which enables the operator to read the thrust load and thus maintain a rate setting which the drill can maintain. If the drill were unable to maintain the rate demanded by such a setting, the piston 63 would nevertheless continue to move downwardly relative to cylinder 62, but the thrust would increase to cause crowd cylinder 62, mast 7, and the entire rig to be raised up and supported by the core barrel and kelly bar, a highly undesirable condition because when this occurs the operator loses control of both the rate of advance and the position of the machine. In practice the operator avoids such a result by adjusting valve 66 to bypass a larger fraction of fluid therethrough, thus reducing both the pressure at the top of cylinder 62 and the flow of fluid therethrough. The check valve 69 is provided to bypass valve 67 and permit the reverse flow of fluid through cylinder 62 to retract piston 63 and thus the kelly bar and core barrel. Valve 70 is a relief valve which protects pump 6, and is similar to valve 67 in operation. It will be apparent to one of average skill in the art that the setting of relief valve 70 can be such that the maximum pressure delivered to crowd cylinder 62 will be less than that required to lift the rig off the ground and thus prevent the undesirable condition mentioned above.

If the described circuit were to be modified to a system where thrust rather than thrust rate is controlled, valve 66 would be replaced by a pressure responsive valve having the effect of maintaining a particular pressure in the hydraulic line leading to the upper part of crowd cylinder 62 for a particular setting of the valve (rather than causing a particular flow rate in this line, according to the invention). Such a system is undesirable in drills of the present invention, characterized as they are by light weight and thus by a small number of cutting blades, because it produces frequent stalls. Since the material being cut is non-homogeneous, the thrust required at one elevation is greater than at another. When rebars are encountered the concrete between them is cut quickly but not the rebars themselves. The drill rides up and down over each rebar, causing longitudinal vibrations and frequent stalls. As an example of the control system of the invention, the valves of the described system were set to give a penetration rate of $\frac{3}{4}$ to 1 inch per minute in cutting through pavement having no rebars or other hard inclusions, using the 5-foot diameter core barrel and turning it at 12 to 14 revolutions per minute. For this part of the cutting the flow rate into and out of the crowd cylinder was about .085 gallon per minute (g.p.m.) and the pressure gage 68 read 1200 p.s.i. When the drill then encountered a rebar, as evidenced first by a screeching noise and then a regular thumping, the operator reduced the flow rate to .031 g.p.m. to obtain a penetration rate of about $\frac{3}{8}$ inch per minute and a pressure reading of 400-500 p.s.i. between intervals of contact with the rebar. With such reduced penetration rate, the rebar was cut through without appreciable vibration or other undesirable incident.

The cutting blades 71 mounted in the lower edge of core barrel 9 are shown in detail in FIGURE 4, and the manner in which they are mounted in the barrel is shown

in FIGURE 3. The blade itself is a massive bit of steel presenting a vertical leading surface 72 disposed approximately in a radial plane of the axis of the drill (actually with a 5 degree negative rake). The cutting tip of the blade is chisel shaped with apex 73 displaced only slightly from the center of the blade. While blades made entirely of steel may be used, the preferred and illustrated construction utilizes an insert 74 of such wear resistant material as cast or sintered tungsten carbide to define the cutting structure. The lower edges 76 of the insert are preferably formed with a small draft sloping away from leading surface 72, also as illustrated.

The base 77 of blade 71 is provided with the short tongues 78 extending outwardly below the leading face 72 and the trailing face opposite face 72, thus giving base 77 the general shape of a T. Slots 81 in the lower edge of core barrel 9 are formed with a similar shape, the clearances being such that blades 71 are generally inserted into slots 81 with a snug fit. Any movement parallel to the vertical axis is thereby prevented, and similarly the blade can not move in a circumferential direction, but to prevent radial movement of the cutters something additional must be provided. The securing means of the invention is a locking pin 82 disposed in the registering vertical holes 79 in the blade and 83 in the barrel. Movement of the pin during operation of the drill is prevented by the shoulder engagement of its oversize diameter portion 84 with the surface surrounding the upper end of hole 83, together with the action of spring 86 in urging the pin downwardly. The upper part 87 of opening 83 is made oversize to accommodate spring 86 as it surrounds the pin and seats at one end against the upper end of opening 87 and at the other end against the upper surface of the enlarged knot 84 on pin 82. In mounting or disassembling blade 71, locking pin or plunger 82 is pushed upwardly into openings 83 and 87 against the increasing compressive force of spring 87 until it clears opening 79 in the blade, whereupon the blade may be pushed radially inwardly or outwardly. Sleeve 88 is made as a separate piece simply because of the necessities of assembly, and is force fitted into the counterbored lower end 89 of the opening as a permanent assembly.

With respect to the tooth (blade) spacing improvement of the invention, it may be mentioned that in early prototypes having uniform spacings the core barrel bounced vertically with a frequency per revolution approximately equal to the number of blades used. The result was a wavy or sinusoidal bottom, as so drawn and labeled in FIGURE 8. It appeared that this type of bottom pattern was resulting from the drill's encountering and attempting to drill through disparate inclusions such as rebars. When the first tooth out of, e.g., 20, struck the rebar it would ride up over the inclusion, raising the entire barrel and rig and falling off the distant side of the rebar with a sharp blow that would cause all of the blades to make similar dents in the concrete at their individual spacings from the first tooth. During the rotation of the bit to bring tooth #2 up to the rebar a certain amount of concrete would be cut, but as tooth #2 engaged the rebar it too would ride up over to raise the entire rig and cause it and all blades to fall into contact with the pavement with a sharp blow as tooth #2 slipped off the far side of the rebar and into the dent or impression started by tooth #1. At that particular time, since the pitches for all teeth were equal, tooth #3 would fall into and deepen the impression started by tooth #2 when tooth #1 slid off the rebar, tooth #4 would fall into and deepen the impression started by #3, and so forth all the way around the circumference of the core barrel for a total of only 20 impressions. As the barrel was further rotated each blade would be raised from the trough of an ever deepening impression to pass through a crest until the next trough was encountered, and the result was the build-up of a bottom hole pattern with a continuous succession of troughs spaced apart by crests. As previously indicated,

running the drill over this type pattern resulted in a great deal of noise and such a large amount of vibration as to threaten to tear the machine apart.

There are several possible solutions to this vibration problem, but none of the alternate solutions appear attractive. One is to set the maximum penetration rate so that the thrust load available will permit uniform cutting of the hardest material anticipated, e.g., the rebars, but this would result in an unacceptably low average penetration rate. The same result would obtain if the unit load per tooth were decreased by increasing the number of teeth (more or less like converting the drill to a saw). The opposite approach of decreasing the number of teeth would be feasible for small drills, but would not work for core barrels as large as 5 feet in diameter because the cutter spacing could be so high that it would be too difficult to start cutting the kerf unless a guide collar were available. It is also not feasible to rely entirely on decreasing the penetration rate when hard material is encountered because of the high frequency of encounters between rebars and cutting blades.

The actual solution to the problem, and the major contribution of the present invention, was to so unevenly space the cutters that smooth running was obtained and excessive vibration was eliminated. The concept is to so space the cutters so as to minimize (or approach a minimum until smooth running obtains), during a complete revolution of the core barrel, the number of times the various teeth fall into impressions made by other teeth.

Another way of stating it is to say that the desired end is to maximize the number of separate impressions made by the teeth during a single revolution. Thus if there are 20 teeth the total number of falls of all teeth during one revolution over a single rebar is 20×20 or 400, but to arrive at the maximum possible number of separate impressions this total must be reduced by 19 or $(20-1)$ because nothing can prevent all 20 teeth from bouncing into a common impression as they slide over the rebar. Thus for 20 teeth the aim is to make 381 impressions per revolution, and for n teeth the maximum or ideal number of impressions is $n^2 - (n-1)$.

To compare the ideal number of impressions with the actual number resulting from an actual spacing, the ratio of the average number of falls per impression is utilized. This ratio is obtained simply by dividing n^2 , the total number of falls of all teeth in a revolution, by the actual number of impressions per revolution resulting from an actual spacing of the n teeth. The closer this ratio approaches unity, the more nearly is the ideal approached. It should be noted that such ratio is independent of the number of teeth, and thus affords ready comparison between various designs.

The number of falls per revolution caused by any single hard spot will be minimized if all the pitches between successive teeth and all possible sums of consecutive pitches up to and including one less than the number of teeth are unequal. For example, the number of blows per revolution will be minimized for a 3-tooth drill having pitches P_1 , P_2 , and P_3 if the following inequality holds:

$$P_1 \neq P_2 \neq P_3 \neq P_1 + P_2 \neq P_2 + P_3 \neq P_3 + P_1$$

For four teeth the inequality required would be:

$$\begin{aligned} P_1 \neq P_2 \neq P_3 \neq P_4 \neq P_1 + P_2 \neq P_2 + P_3 \\ \neq P_3 + P_4 \neq P_4 + P_1 \neq P_1 + P_2 + P_3 \neq P_2 + P_3 + P_4 \\ \neq P_3 + P_4 + P_1 \neq P_4 + P_1 + P_2 \end{aligned}$$

In general, satisfaction of this requirement will produce $n^2 - (n-1)$ separate impressions for n teeth and no impression is subjected to more than one fall per revolution except the one immediately adjacent to the hard spot.

In practice, absolute compliance with this spacing has not proved necessary. The following table summarizes the tooth arrangements actually tested and the running conditions that resulted from each.

TABLE I

Line	Barrel dia., ft.	No. of teeth	Consecutive pitches, degrees*	No. of impressions per rev.		Avg. No. falls per impression per rev.	Running condition
				Ideal	Actual		
a-----	5	20	18° (evenly spaced)----	381	20	20	Rough.
b-----	5	10	36° (evenly spaced)----	91	10	10	Do.
c-----	5	10	72, 18, 18, 54, 18, 36, 72, 18, 36.	91	20	5	Do.
d-----	2	5	75, 75, 75, 75, 60-----	21	9	2.78	Smooth.
e-----	5	13	13, 17, 20, 22, 24, 26, 28, 30, 32, 34, 36, 38, 40.	157	124	1.36	Do.
f-----	5	9	30, 42, 50, 58, 32, 34, 36, 38, 40.	73	62	1.31	Do.
g-----	5	7	30, 42, 50, 58, 66, 74, 40.	43	42	1.17	Do.
h-----	5	5	50, 72, 90, 70, 78-----	21	21	1.19	Smooth except when starting.

*Refer to Figure 13.

The cutting blade dispositions corresponding to those set forth in the above table are also illustrated in FIGURES 13a through 13h, the letters of the figures corresponding to the lines of the table. It will be apparent from the observed running conditions that smooth running results when the average number of falls per impression is something less than five, and preferably is less than three.

The invention can also be explained, without using functional expressions, by introducing the symbols P, S and I, where:

P=the angular or circumferential dimension between any pair of blades of cutters, whether adjacent or non-adjacent, excluding, of course, any pitch encompassing 360° or more;

S=the total number of different pitches between all the various pairs of blades of a complete drill; and

I=the total number of impressions made by all blades in one complete revolution, assuming all of them to fall with the drill as each blade rides over or passes a common index point (and each blade falling into the same impression at such index point).

It can be shown that

$I=S+1$, simply because an impression made by the blade used as a reference cannot be counted as a pitch.

Using the above criterion that the number of falls per impression in a single revolution should be something less than five, and preferably less than three,

$$\frac{\text{Falls}}{\text{Impression}} = \frac{n^2}{I} = \frac{n^2}{S+1} < 5, (S+1)5 > n^2, \text{ and } S > \frac{n^2}{5} - 1$$

Stated in words, the number of different circumferential pitches or spacings between the various combinations of pairs of blades, non-adjacent as well as adjacent, is greater than 1/5 the square of the number of blades less unity. For the less-than-three criterion, the number of different such pitches is greater than 1/3 the square of the number of blades, less unity.

To demonstrate the application of this principle, imagine the core drill projected as a clock, with each blade successively moving counterclockwise and momentarily stopping at a reference point normally used for the hour of 12:00. Designate the blade at the reference point for the first stop as #1 and, proceeding clockwise, designate the next blade #2, etc. Then draw up a table similar to the following for the 5-blade bit shown in line d of the above Table I, one line for each momentary position.

TABLE II

Adjacent pitches	Tooth at reference Pt.	Impressions made by teeth at degrees measured clockwise from reference point				
		Tooth No.				
		1	2	3	4	5
75° (1-2)-----	1	0 or 360	75	150	225	300
75° (2-3)-----	2	285	0	75	150	225
75° (3-4)-----	3	210	285	0	75	150
75° (4-5)-----	4	135	210	285	0	75
60° (5-1)-----	5	60	135	210	285	0
(As a check: Should be same as 1st line)-----	1	0	75	150	225	300

It can be seen from this table that when the drill is rotated so that blade #2 replaces blade #1 in the index position, the entire core drill must be rotated 75° and each new position (impression) of any blade is determined by subtracting 75° from the angular position of that blade in the previous line.

From the Table II it can be seen that the impressions are made at 0° or 360° (5 falls), 6° (1 fall), 75° (4), 135° (2), 150° (3), 210° (3), 225° (2), 285° (4) and 300° (1 fall). This yields

$I=9$ impressions
 $\text{Falls}=25=5^2=n^2$

$S=8$ because there are different pitches P of 75° (between blades 1-2, 2-3, 3-4, and 4-5), 60° (between blades 5-1), 150° (blades 1-3, 2-4, and 3-5), 225° (blades 1-4 and 2-5), 300° (blades 1-5), 135° (blades 4-1 and 5-2), 210° (blades 4-2, 5-3, and 2-5) and 285° (blades 2-1, 3-2, 4-3 and 5-4).

Thus $9=8+1$ or $I=S+1=9$ (for the 12:00 o'clock impression), and

$$\frac{\text{Average Falls}}{\text{Impression}} = \frac{n^2}{I} = \frac{25}{9} = 2.78$$

A table similar to Table II for the 5-bladed bit described in line h of Table I would show separate impressions at 0, 50°, 70°, 72°, 78°, 90°, 122°, 128°, 148°, 160°, 162°, 198°, 200°, 212°, 232°, 238°, 270°, 282°, 288°, 290°, and 310°, or $I=21$. By adding up the various pitches between adjacent blades it can be shown that $S=20$. In this case each impression except that at the reference point experiences only one fall of a blade during a revolution. Since each blade must necessarily fall toward the impression at the reference point, it can be readily seen that the maximum number of separate impressions is equal to $n^2-(n-1)$. In the example of line h such maximum is obtained, and is equal to $5^2-(5-1)=21$. For this situation the minimum average falls per impression is also obtained, being equal to $25/21$ or 1.19. For any given number of blades n such minimum average blows per impression is

$$\frac{n^2}{n^2-(n-1)}$$

for a 3-blade bit being

$$\frac{9}{9-2} = \frac{9}{7} = 1.3$$

and, for a 4-blade bit,

$$\frac{16}{16-3} = \frac{16}{13} = 1.23$$

FIGURE 2 shows a core barrel 11 provided with 13 blade-receiving slots 81, and corresponds to the arrangement shown in both line e of the table and FIGURE 13e. In addition to showing all of the pitches between successive blades in FIGURE 2, a second set of angle measurements have been marked therein, namely the an-

gular distance of each blade slot 81 from a common reference slot so marked at the top center of the circumference. It will be noted that each of the latter set of angles expressed in degrees is a prime number, another criterion which has been found to promote smooth running.

The cutting blade 71' of FIGURE 6 differs from that of FIGURE 4 primarily in having only a forwardly projecting base tongue 78, thus giving base 77' and L-shape in circumferential cross-section. In addition, vertical opening 79' has been modified to more of a semi-circular cross section and moved to the rear of base 77' so that it intersects the rear surface, making it more of a groove than a hole. As shown in FIGURE 5, blade 71' is then secured against radial movement by a cap screw 80 disposed in opening 79' and extending into and threadedly engaging hole 85 in barrel 11'.

It can also be mentioned that a very satisfactory blade cooling and dust laying system was provided by the water tank mentioned earlier and a water line running to the inside of the barrel. A circulation rate of less than 2 gallons per minute quite satisfactorily cooled the blades and flushed out the cuttings. This low rate caused no water overflow to surrounding paved areas, nor did it cause a pool of water to accumulate and run into the hole after the coupon (core) was cut. The water required simply mixed with the cuttings to form a thin paste which was easily disposed of by the drilling crew. Attempts to supply the water from outside the barrel did not cause adequate cooling and cleaning. As compared with dry operation, drilling with the water caused a tenfold increase in cutting blade life.

What is claimed is:

1. A core drill for reinforced pavement comprising a thick walled cylindrical core barrel and a multiplicity "n" of cutter blades secured to the core barrel to depend from the lower end thereof at substantially equal radii from the longitudinal axis of the barrel, said blades being spaced apart circumferentially so that the total number of different pitches S between pairs of said blades in a common circumferential direction, including pitches between both adjacent and non-adjacent pairs of blades, is greater than

$$\frac{n^2}{5} - 1$$

there being at least one instance where successive pitches between adjacent blades are unequal.

2. The core drill of claim 1 in which S, the number of different pitches, is also greater than

$$\frac{n^2}{3} - 1$$

3. The core drill of claim 1 in which there are at least 3 cutting blades.

4. The core drill of claim 1 in which the number of blades n is 5 or more.

5. A core drill for reinforced pavement comprising a core barrel having the general shape of a thick walled cylindrical shell and a multiplicity n of cutting blades secured in the bottom of said core barrel at a common radial distance from the center of said drill, said blades being spaced about the circumference of the core barrel so that there are S different circumferential spacings between the various pairs of cutter blades, non-adjacent pairs as well as adjacent pairs, the number of the blades n and their spacings S being selected so that $n^2/S + 1$ is less than 5, there being at least one instance where successive pitches between adjacent blades are unequal.

6. The core drill of claim 5 in which said blades are spaced so that the number of blades n and the number of different pitches S between the various pairs of blades are chosen so that $n^2/S + 1$ lies between 1 and 3.

7. The core drill of claim 5 having n blades spaced apart with S different circumferential spacings substantially equal to $n(n-1)$.

8. The core drill of claim 5 in which substantially all of the pitches between adjacent blades are unequal.

9. A core drill for reinforced pavement comprising a cylindrical shell core barrel and a multiplicity of cutting blades secured in the bottom end of said barrel at substantially the same radius with respect to the longitudinal axis of said core barrel, said cutting blades being spaced about the circumference of the barrel so that a substantial number of their angular distances from a common reference blade, measured in degrees, are prime members.

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