

Feb. 28, 1967

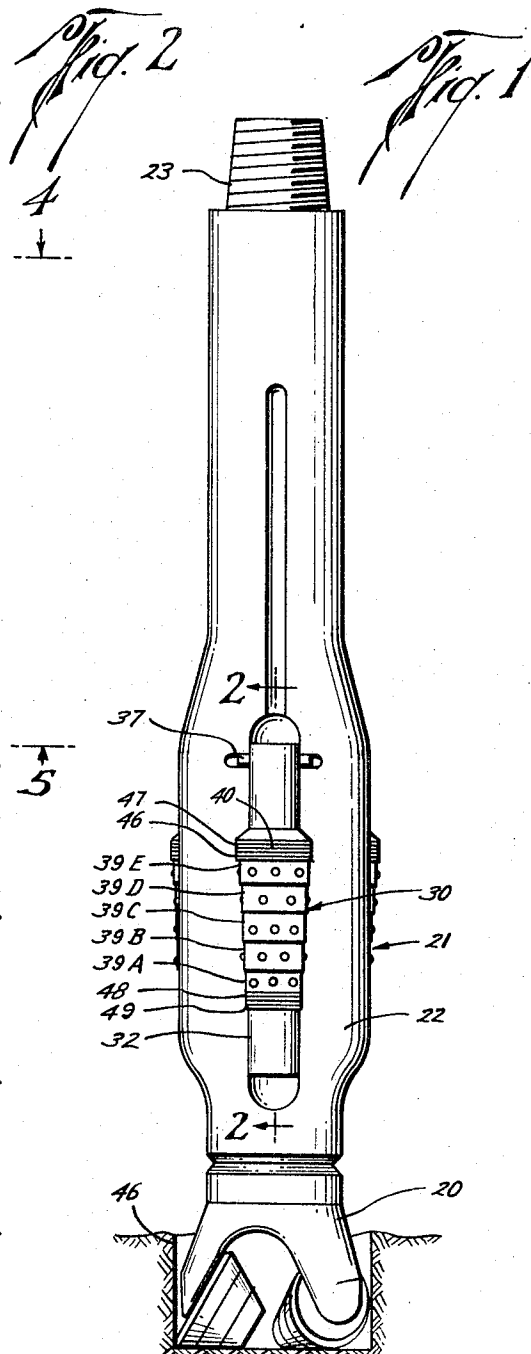
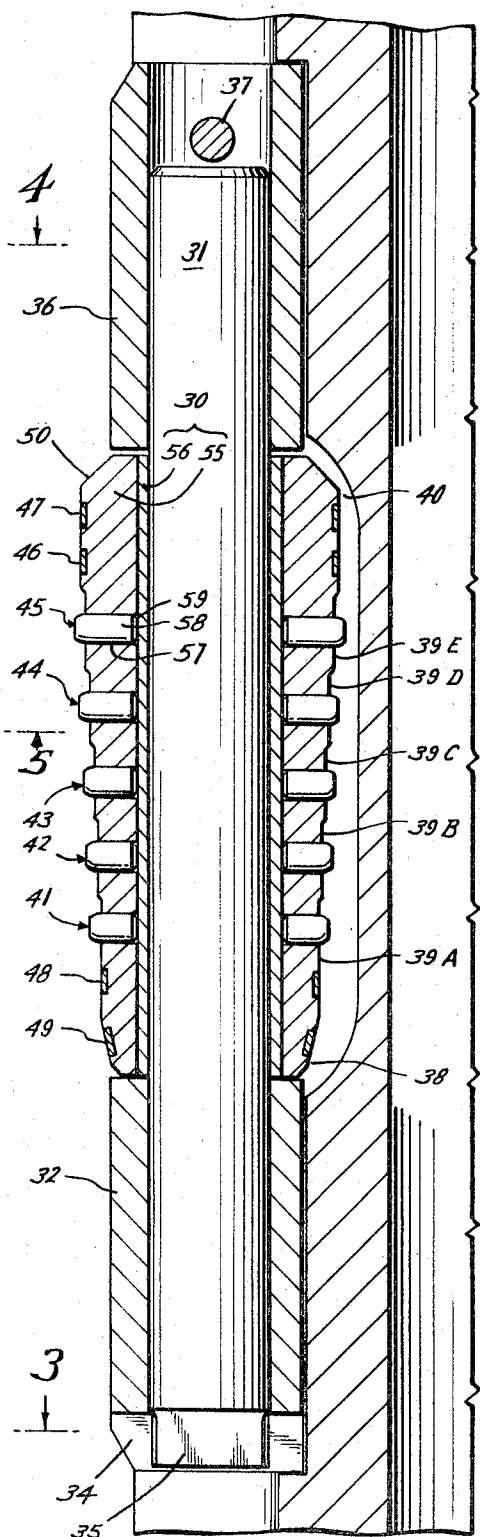
W. R. GARRETT ETAL

3,306,381

REAMING APPARATUS

Original Filed Jan. 11, 1960

5 Sheets-Sheet 1



William Robert Garrett
Stanley C. Moore
INVENTORS

BY *Murray Robinson*
ATTORNEY

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REAMING APPARATUS

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5 Sheets-Sheet 2

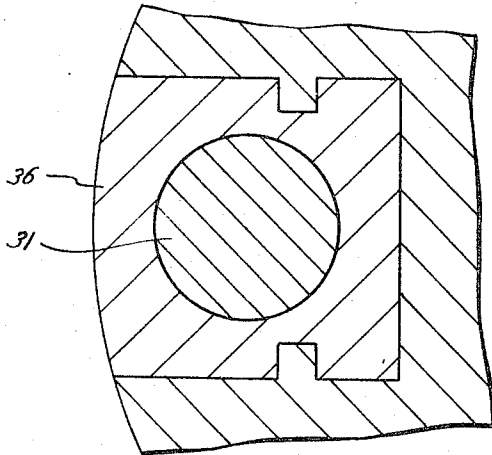


Fig. 4

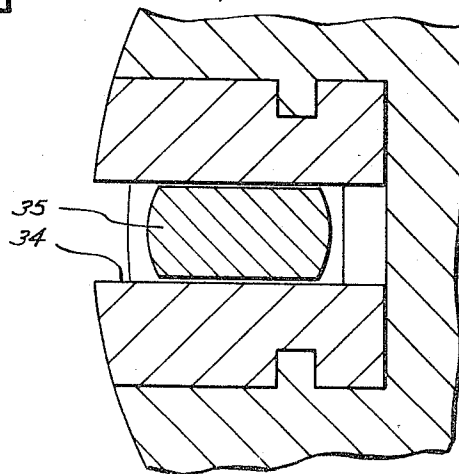
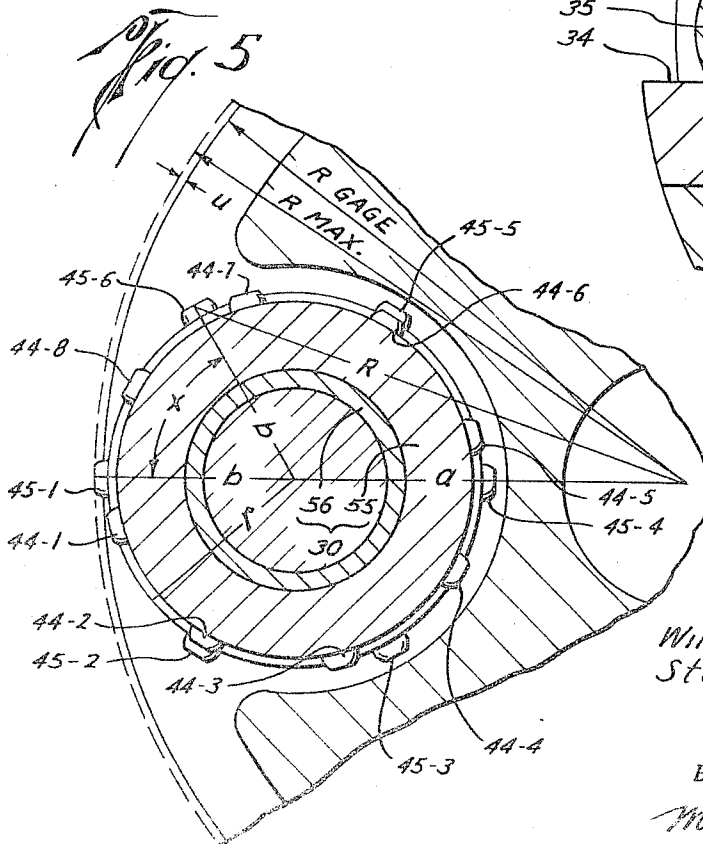


Fig. 3



William Robert Garrett
Stanley C. Moore
INVENTORS

BY

Murray Robinson
ATTORNEY

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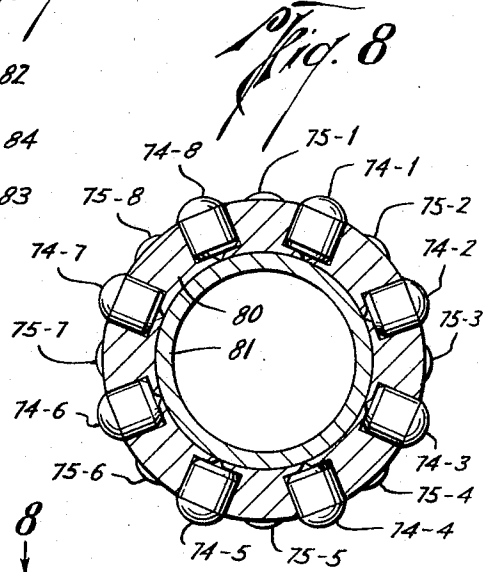
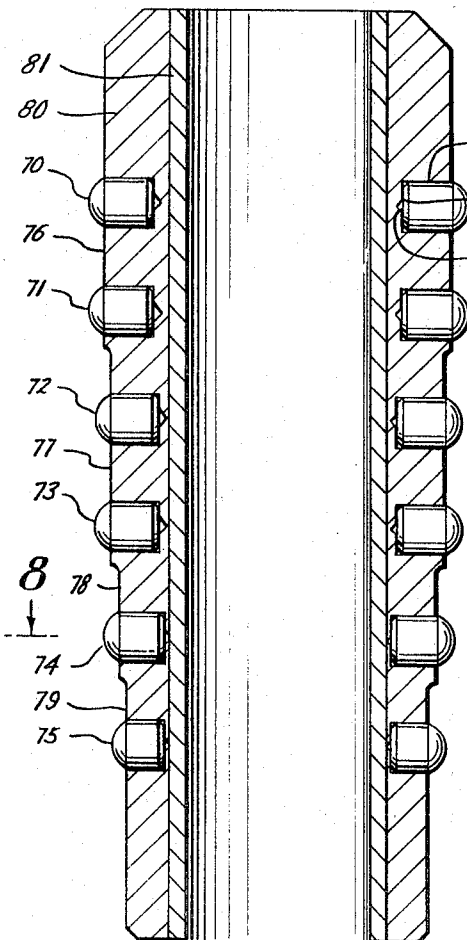
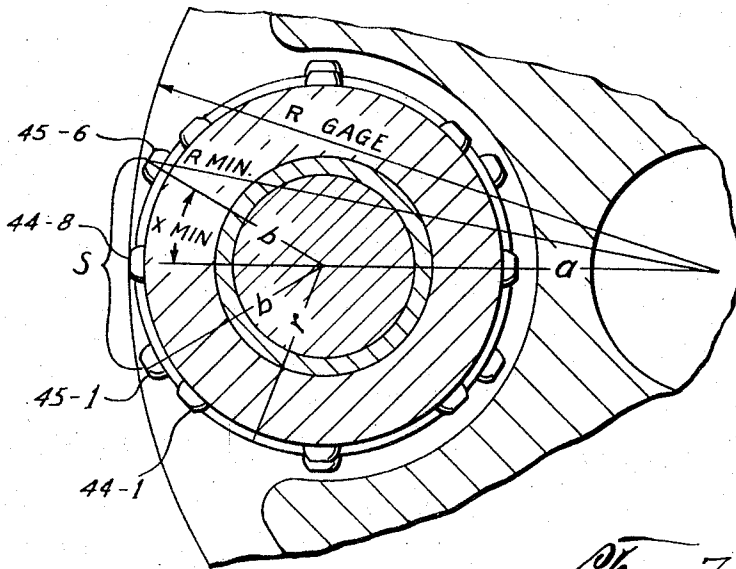
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REAMING APPARATUS

Original Filed Jan. 11, 1960

5 Sheets-Sheet 3



William Robert Garrett
Stanley C. Moore
INVENTORS

BY

Murray Robinson
ATTORNEY

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REAMING APPARATUS

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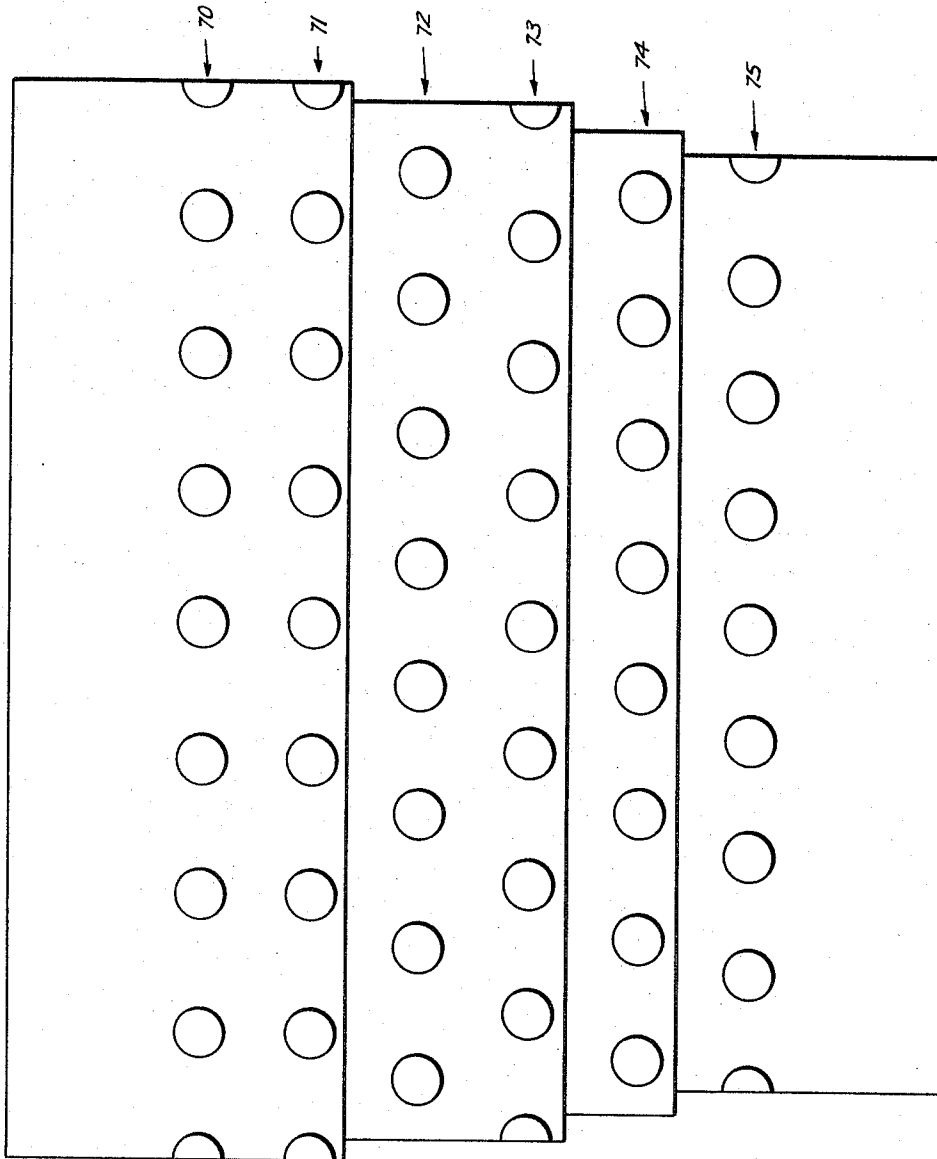


Fig. 9

William Robert Garrett
Stanley C. Moore
INVENTORS

BY

Murray Robinson

ATTORNEY

Feb. 28, 1967

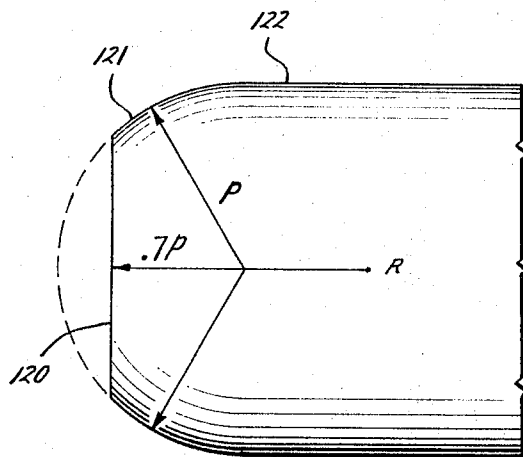
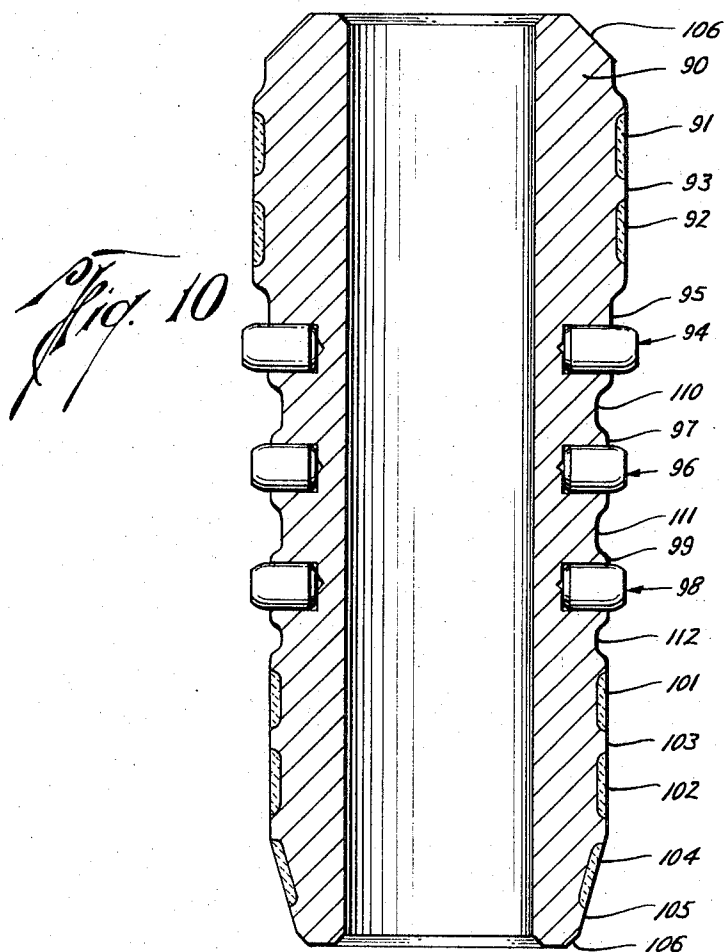
W. R. GARRETT ET AL

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REAMING APPARATUS

Original Filed Jan. 11, 1960

5 Sheets-Sheet 5



William Robert Garrett
Stanley C. Moore
INVENTORS

BY

Murray Robinson

ATTORNEY

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3,306,381

REAMING APPARATUS

William Robert Garrett and Stanley C. Moore, Midland, Tex., assignors to Drilco Oil Tools, Inc., Midland, Tex., a corporation of Texas

Continuation of abandoned application Ser. No. 1,556, Jan. 11, 1960. This application Dec. 16, 1963, Ser. No. 330,715

14 Claims. (Cl. 175—346)

This application is a continuation of our prior copending application Serial Number 1,556, filed January 11, 1960, now abandoned in favor of this application.

This invention pertains to rotary drilling apparatus and more particularly to a reamer used above a drill bit for reaming the side walls of an earth bore.

According to the invention a reamer is provided including a tubular body threaded at its ends for insertion in a drill string between the bit and drill pipe, normally just above the drill bit between the drill bit and lowest drill collar, although the reamer is also of use in other locations in the drill string.

The reamer body is provided with a plurality of rollers each having sintered tungsten carbide inserts protruding therefrom disposed in annular rows of increasing diameter progressing upwardly.

OVERGAGE INSERTS

The reamer radius, that is, the radius from the axis of the reamer body to the extremity of a carbide insert when its axis is aligned with a radius from the axis of the reamer body, at the uppermost row or rows of inserts is larger than the radius of the full gage hole that is desired to be drilled. The inserts in each overgage row are spaced far enough apart so that by turning the rollers to a position where no overgage insert projects straight out radially from the reamer axis the reamer can be moved axially through a full gage hole without obstruction. When the drill string is rotated these overgage inserts will underream the hole slightly and thus maintain it of at least full gage until the overgage inserts are worn down below full gage.

TORQUE UP BANDS

In certain embodiments of the invention on-gage hard facing bands may be provided above the overgage inserts to indicate when the overgage inserts are worn down by causing high torque in the drill string. Under-gage hard facing bands may be provided below the lowermost row of inserts to indicate by torque-up when the drill below the reamer has worn under gage to a predetermined amount.

OBLATE TIPPED INSERTS

The outer ends of the inserts are preferably rounded, e.g. hemispherical or approximately so, which has been found to provide a maximum active area with a minimum of failure although other shapes may be used and an insert tip having an approximately truncated hemispherical shape may be used with advantage.

BEARING SLEEVES

In certain embodiments of the invention the rollers may be provided with bearing sleeves and the inserts placed in radial holes extending clear through the roller bodies so that the inserts bottom on the bearing sleeves, thereby facilitating assembly, increasing the roller life, and making possible the easy salvage of used inserts from worn out reamers and rollers. The sleeved roller body construction makes it possible to provide both a very hard metal for the bearing shaft contact area and hard tough metal for the roller body to retain the inserts despite the severe service.

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For a detailed description of several preferred embodiments of the invention reference will now be made to the accompanying drawings wherein:

FIGURE 1 is an elevation showing a reamer embodying the invention in conjunction with a per se conventional three cone rock bit to the top of which the reamer is connected;

FIGURE 2 is a vertical section through one of the rollers of the FIGURE 1 reamer, together with immediately adjacent portions of the rest of the reamer;

FIGURES 3, 4 and 5 are horizontal sections taken on lines 3—3, 4—4, and 5—5 of FIGURE 2;

FIGURE 6 is a view similar to FIGURE 5 with the roller turned so as to pass through a full gage hole;

FIGURE 7 is a vertical section through another form of reamer roller embodying features of the invention;

FIGURE 8 is a horizontal section taken on line 8—8 of FIGURE 7;

FIGURE 9 is a flat layout of the outer surface of the roller of FIGURES 7 and 8;

FIGURE 10 is a vertical section through another form of reamer roller embodying features of the invention; and

FIGURE 11 is an axial section through the outer end of a roller insert showing to an enlarged scale the shape thereof according to the FIGURES 1-6 embodiment of the invention.

REAMER AND DRILL BIT ASSEMBLY

Referring now to FIGURE 1 there is shown a three cone rock bit 20 to the upper end of which is connected a reamer 21 embodying the invention. The reamer includes a tubular body 22 having a threaded pin 23 at its upper end and a threaded socket at its lower end for engagement with the rock bit pin.

The reamer body 22 is recessed to accommodate a plurality, e.g., three, rollers such as 30 (see also FIG. 2) each adapted to rotate on shaft 31. The lower end of shaft 31 is mounted in an apertured block 32. As best seen in FIGURE 3 the block is dovetailed into the reamer body and has a slot 34 in its lower end to receive the flattened end 35 of the shaft 31, thereby preventing the shaft from turning. Apertured block 36 (see FIG. 4) is dovetailed into the reamer body 22 to receive the upper end of shaft 31. Referring again particularly to FIGURES 1 and 2, a pin 37 holds the block 36 against vertical motion and likewise prevents axial motion of shaft 31.

REAMER ROLLER

Still referring to FIGURES 1 and 2, the lower outer edge of the roller is bevelled at 38 and the outer peripheral surface of roller 30 is stepped providing six annular lands 39A, 39B, 39C, 39D, 39E and 40. Disposed respectively on the lands 39A-E are five annular rows 41, 42, 43, 44, 45 of tungsten carbide inserts. Each row of inserts projects at least as far and preferably a little farther radially than the roller land just above it, thereby protecting such land against undercutting during use.

Thus, when the roller is turned to place one of the apertures or holes 57 (infra) receiving the inserts 58 (infra) into a position where such aperture, and the insert therein, are at a maximum distance from the reamer axis where the insert can perform its reaming function, the distance from the outermost tip of the insert to the reamer axis measured perpendicular to the reamer axis is at least as great as the distance from the reamer axis of the portion of the outer surface of the roller, i.e., the land, adjacent the aperture nearest thereabove. Compared to the diameter of the full gage hole 46 that is drilled by drill bit 20 when it is new, the reamer radius at rows 41, 42, and 43 is undergage but of progressively larger radius going up the roller. Insert row 44 is on gage. Insert row 45 is over gage.

Hard facing bands 46, 47 at the upper end of each roller are on gage. Hard facing band 48 at the lower part of each roller is a predetermined amount undergage, and hard facing band 49 is provided on the bevelled guide shoulder at the lower end of each roller. No hard facing is needed on the upper guide bevel 50.

The hard facing can be applied to the roller body surface, or as shown, to annular grooves formed therein. The hard facing may be tube metal (crushed cast tungsten carbide in a tubular steel jacket) welded in place on the roller body. If, as shown, the hard facing is flush with the roller surface, it will be apparent that upper land 40 which carries on gage bands 46, 47 will itself be on gage.

As shown in FIGURE 2, each roller 30 comprises a body 55 of tough steel, ductile enough to take shocks without cracking but hard enough, e.g. 25-30 Rockwell C scale, to wear well under abrasive service. For example AISI 8620 may be used. Press fitted into each roller body is a sleeve or bushing 56 of some hard steel such as high chrome bearing steel, ATS 52100 series, carburized stainless steel, or rock bit bearing steel. A hardness of 58-65 Rockwell C scale is appropriate.

CARBIDE INSERTS

Holes such as 57 are bored in roller body 55 to receive inserts 58 that make up the rows 41-45. The inserts are made of sintered tungsten carbide and are of generally cylindrical shape with preferably hemispherical outer or cutting ends. The inner ends are bevelled as shown at 59, to facilitate insertion into the holes 57, there being a mechanical interference or press fit of the order of one to three thousandths of an inch diameter difference. The inserts may be of the order of $\frac{3}{16}$ inch, or preferably $\frac{3}{16}$ inch in diameter. In order that all the inserts can bottom on the same uniform diameter sleeve 35 they are necessarily of different lengths, the inserts in the overgage row being longest. The drawing, being to scale, shows the various lengths of the inserts. The shortest inserts penetrate the sleeve a distance greater than their diameters. The inserts protrude beyond the outer periphery of the roller about $\frac{1}{8}$ inch.

The spacing of the inserts as measured around the periphery of the roller may be of the order of one inch apart on centers. The inserts in each row, though shown in FIGURE 2 by draftsman's license as being in register with those in adjacent rows, are preferably staggered so that only the inserts in every other row are in register and those in rows in between are circumferentially disposed half way between the inserts in adjacent rows. This increases the minimum distance between holes and strengthens the roller. With the aforementioned one inch spacing of the inserts in the roller, even with inserts of $\frac{3}{16}$ inch diameter the spacing between the nearest side surfaces of the protruding ends of adjacent inserts is at least as great as the diameter of the inserts. This is true not only of adjacent inserts in the same row but in adjacent rows. In this regard see also the layout of another embodiment of the invention shown in FIGURE 9 and described later on herein.

The inserts in the over gage row or rows usually will be somewhat farther apart, and if more than one row is used the inserts in each row will be in circumferential register with those in adjoining rows. This arises from the requirement that the roller can be turned to a position in which the greatest radial extent of any part of the roller from the reamer axis is no greater than the radius of a full gage hole.

OVERGAGE REAMING

Referring now to FIGURES 5 and 6, there is shown the circumferential disposition of the eight on gage inserts 44-1 . . . 44-8, and the six over gage inserts 45-1 . . . 45-6. In FIGURE 5 the roller 30 is turned so that over gage insert 45-1 is aligned radially with a reamer radius and therefore protrudes a maximum amount from the

reamer to cut an overgage hole. In FIGURE 6 on gage insert 44-8 is shown aligned with a reamer radius and hence in position to cut an on gage hole, while the bisector of the angle between overgage inserts 45-1 and 45-6 is aligned radially with a reamer radius and in this position the inserts do not protrude beyond the gage radius of the hole.

It will be understood that during drilling a new drill bit will initially cut a full gage hole and the over gage row of inserts will enlarge the hole to slightly over gage. The drill bit will wear faster than the reamer and as the drill bit becomes under gage the on gage inserts of the reamer will enlarge the hole to full gage and the over gage inserts will enlarge it still more. The hard facing bands 46, 47 will burnish the hole. When the bit becomes worn down still more the under gage rows on the reamer will come into action and enlarge the hole some in advance of the on gage row of inserts. The hard facing band 49 will protect the under side of the rollers from wearing away rapidly. The on gage inserts may be worn slightly undergage by this time but the overgage row of reamer inserts will enlarge the hole still farther to somewhat over gage. However the over gage inserts will also be worn somewhat by this time so that the hole radius will not be as large as when drilling with the new bit and reamer commenced. Therefore although the hole is still overgage at all points it is not of uniform radius.

Finally, when the bit and reamer wear down still farther, one of two things happens to warn the operator it is time to change tools. If the bit wears down to the diameter of hard facing band 48, the drill string torque will increase; if the reamer wears down to the point where over gage inserts 45 extend no farther radially than hard facing bands 46, 47, the drill string torque will increase; in both cases the torque increase is due to the engagement of the hard facing bands with the well wall. When the drill string torque is increased, the drill string is removed from the well and the bit or reamer or both replaced as need be.

During removal of the drill string for tool replacement, and during replacement of the drill string into the hole with new tooling, it is necessary for the over gage inserts to move axially up and down the hole which in some places may be no more than full gage in radius. This is possible by the rollers turning to the FIGURE 6 position, which they do automatically, being pushed to this position by the forces of reaction of the well wall thereon when the reamer is moved axially in the wall.

CRITICAL SPACING

Referring further to FIGURES 5 and 6, the radius R from the reamer axis to the tip of any insert is

$$R = [(b \sin x)^2 + (a + b \cos x)^2]^{1/2}$$

where a is the radius from the reamer axis to the roller axis, b is the radius from the roller axis to the tip of the insert, and x is the angle at the intersection of radius b with radius a . With inserts equally spaced about the circumference of a roller, the position of overall minimum reamer radius will occur when the bisector of the angle between the radius b of two adjacent inserts is in alignment with radius a . Then with n inserts in the row, the angle x will be

$$X_{\min} = \frac{1}{2} \left(\frac{360}{n} \right) = \frac{180}{n} \text{ degrees}$$

Let U = the underream produced by the subject reamer
 R_{gage} = the radius of an on gage hole, and
 R_{max} = the reamer radius with an over gage insert aligned with a reamer radius.

Then $U = R_{\text{max}} - R_{\text{gage}}$

The largest amount of underream that can be obtained under the limitation that the reamer can pass through an on gage hole occurs when $R_{\text{gage}} = R_{\min}$ and

$$U_{\text{max}} = R_{\text{max}} - R_{\min}$$

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where $R_{\min}$ is the reamer radius with the bisector of the angle between two over gage inserts aligned with a reamer radius. Then, since $R_{\max}=(a+b)$,

$$U_{\max}=(a+b)-\left[\left(b \sin \frac{180}{n}\right)^2+\left(a+b \cos \frac{180}{n}\right)^2\right]^{1/2}$$

so that the larger the value of n the smaller will be $U_{\max}$.

For given values of U , a and b , there will be a maximum permissible value of n determined from the above equation. Correspondingly there is a minimum value of the inter insert spacing $S_{\min}$ measured on the roller surface from insert axis to insert axis:

$$S_{\min}=\frac{2\pi r}{n_{\max}}$$

where r is the roller radius at the particular row of inserts. Such minimum spacing may be referred to in the claims appended hereto as the "critical spacing" of the inserts. Combining the last two equations, we obtain the single equation:

$$(U-a-b)^2=\left(b \sin \frac{180 S_{\min}}{2\pi r}\right)^2+\left(a+b \cos \frac{180 S_{\min}}{2\pi r}\right)^2$$

The values of r , a and b are immediately apparent on inspection of a reamer, and the value of U is determined or indicated in several ways, so that whether or not a reamer roller has its inserts spaced apart no less than the critical spacing is also determined.

DETERMINATION OF UNDERREAM

As for the determination of U it may be mentioned by way of example that it is usually only slightly less than $(b-r)$ since it is desired to support the inserts with the roller over as much of their lengths as possible. It is for this reason that the outer peripheral surface of each roller is preferably stepped. In other words, each insert projects from the roller an amount about equal to the maximum permissible wear contemplated for such insert. In the case of the over gage inserts this distance is U .

Assuming that $U=b-r$ and substituting this value in the last previous equation we may then define the critical spacing from the equation:

$$(r+a)^2=\left(b \sin \frac{180 S_{\min}}{2\pi r}\right)^2+\left(a+b \cos \frac{180 S_{\min}}{2\pi r}\right)^2$$

U may also be determined from the relationship

$$U=(a+b)-R_{\text{gage}}$$

since R_{gage} is the radius of the on gage hole which is equal to the initial radius of the rock bit, and of the reamer at upper land 40 and on-gage bands 46, 47 of hard facing. In such case the equation for $S_{\min}$, the critical spacing becomes:

$$(R_{\text{gage}})^2=\left(b \sin \frac{180 S_{\min}}{2\pi r}\right)^2+\left(a+b \cos \frac{180 S_{\min}}{2\pi r}\right)^2$$

Other criterion for the determination of U may be established in any particular case.

From an inspection of FIGURE 6 it will be apparent that

$$S>S_{\min}$$

since in the position shown

$$R_{\min}<R_{\text{gage}}$$

This is desirable so that there will be a slight clearance between the over gage inserts and the hole when the reamer rollers are in position to provide minimum reamer radius at the over gage inserts.

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MULTIPLE OVERGAGE INSERT ROWS

Referring now to FIGURES 7 and 8 there is shown a modified form of reamer roller in which there are two rows of overgage inserts 70, 71, both of the same radius, two rows of on gage inserts 72, 73, and two rows of under gage inserts 74, 75, row 75 being of smaller radius than row 74. The inserts of equal radius occupy a common land. Thus, insert rows 70, 71, are on the largest land 76, insert rows 72, 73 are on land 77, insert row 74 is on land 78, and insert row 75 is on land 79. The bands of hard facing of the first embodiment have been omitted in this modification in order to provide room for the extra row of over gage reamer inserts and to permit the use of larger diameter inserts without increasing the roller length.

A further feature of the embodiment of FIGURES 7 and 8 is the use of sockets for the inserts that do not go all the way through the reamer body 80 to the bearing sleeve 81. Although this presents additional work to ream the sockets 82 to near full diameter at the socket bottoms 83 to enable the inserts to be properly seated therein, bottoming the inserts in the solid body of the reamer provides a firm support for the inserts. The bevel 84 around the bottom periphery of the inserts also facilitates bottoming of the inserts.

As best shown in FIGURE 9, the inserts in alternate rows of inserts are actually staggered rather than aligned as would appear from FIGURE 7, except that the inserts in over gage rows 70, 71 are in register. There are the same number, eight, of inserts in each row, equispaced at 45 degrees. Six or eight inserts per row is usual although four to ten might be used. For the larger diameter tools, preferably larger diameter rollers with more inserts per row are used with the same number of rollers since three rollers per reamer is so much stronger than a larger number.

The sleeve and roller body of the FIGURES 7-9 embodiment of the invention may be made of materials the same as in the first embodiment except that the body of the roller is preferably case hardened to about 40-45 Rockwell C scale to provide firm support for the inserts at the bottom of the sockets. Although the sockets for the inserts are drilled and reamed after the machined blank has been hardened, it will be observed that the case hardening of the inside of the roller is of about the thickness of the roller at the socket bottoms.

SLEEVELESS ROLLER

Referring now to FIGURE 10 there is shown another form of roller embodying the invention. The roller 90 in this modification is integral instead of comprising a body with an internal bushing as in the previously described embodiments. This roller, like the bodies of the rollers in the previously described embodiment, may be made of a steel such as AISI 8620 carburized about one-tenth of an inch deep and case hardened and drawn. However in the absence of any bushing sleeve, the roller of FIGURE 10 is preferably brought to a greater hardness, e.g., 58-62 Rockwell C scale. This construction is less expensive than the composite rollers of the previously described embodiments to the extent that the bushing sleeve is eliminated, and will give satisfactory service where the tearing force on the rollers and inserts is not too large.

The FIGURE 10 embodiment employs two upper on gage bands 91, 92 of hard facing material, similar to the first described embodiment. These are provided in the upper land 93. A row of over gage inserts 94 is provided in land 95; a row of on gage inserts 96 is provided in land 97, and a row of under gage inserts 98 is provided in land 99. Hard facing bands 101, 102 corresponding to a reamer radius equal to the minimum permissible radius of a worn bit are disposed in lower land 103. A hard facing band 104 is disposed around bevelled portion 105. Both the upper and lower ends of the roller are provided with

further guide bevels at 106, 107. Undercut annular areas 110, 111, 112 may be provided between adjacent lands to insulate the lands from one another to prevent the spreading of metal failure around an insert in one row to the metal around an insert in an adjacent row.

The operation of the rollers shown in the FIGURES 7-9 and FIGURE 10 embodiments is substantially the same as those of the first embodiment, except that in the FIGURES 7-9 embodiment there will be no torque up of the drill string upon the reamer or drill bit reaching predetermined degree of wear since the hard facing bands are omitted in this embodiment. But the operation of the over gage, on gage, and under gage inserts will be the same in all cases. It will be apparent that it is not necessary to have any inserts exactly on gage since the reamer reams over gage until worn to the point of desirable replacement. The on gage inserts are just part of the series of inserts of graduated extents of projection leading up to the over gage inserts that bring the hole to its final diameter.

FLATTENED TIPPED INSERTS

It will be noted that in FIGURES 7-9 the inserts have been shown as having rounded ends that approximate hemispheres rather than the somewhat blunter shape shown in FIGURES 1-6 and 10. The latter shape is more clearly illustrated in FIGURE 11. Viewed from the top of the reamer as in FIGURE 11, the extreme tip 120 of the insert is cylindrical with a radius R going to the reamer axis. This is such a relatively large radius that a flat will do just about as well for tip portion 120, the purpose being to provide a large area of contact with the well wall that will not wear away too quickly. The annular portion 121 between tip 120 and the cylindrical surface 122 of the body of the insert is spherical with a radius P disposed about .7P from the tip 120 on the insert axis. P is also the radius of the cylindrical surface 122. This spherical area could also be conical, the purpose being to reduce breakage of the inserts by enabling them to wedge against the well wall prior to crushing it rather than striking it a lateral blow. The end shape just described may be called "truncated" and together with the rounded shape shown in FIGURES 7-10 forms a class of shapes known as "oblate," to be distinguished from shape or pointed.

INCLINED ROLLERS

While the invention has been described as applied to a reamer having rollers whose axes are parallel to the reamer axis, it will be apparent that it is also applicable to reamers whose roller axes are otherwise disposed, e.g., as shown in FIGURE 11 of said Patent 2,272,405 with the roller axis coplanar with reamer axis but not parallel thereto, or as shown in FIGURES 12 and 13 of said Patent 2,272,405 with the roller axis not coplanar with reamer axis. Since the distance S_{min} determining the critical spacing was measured in a horizontal plane for vertical rollers, obviously reference must be made to the horizontal component of S when the roller axis is inclined. In cases where the roller axes are not parallel to the reamer axis they must at least have a component of their axes parallel to the reamer axis in order to cause the rollers to turn as the reamer is rotated about its axis. This distinguishes reamer rollers from drill bit rollers or cones which contact the bottom of the hole and hence should have at least a component of their axes horizontal, i.e., 90 degrees to the vertical. To draw the distinction more precisely, reamers do not employ rollers whose axes make an angle of more than about 30 degrees to the vertical, or otherwise stated, the vertical component is at least 85% of the total.

In the foregoing statement vertical is intended to be synonymous with reamer axis since in normal use the reamer axis is desirably vertical. Thus, if a roller axis is inclined thirty degrees from the vertical, it makes a thirty

degree angle with a line parallel to the reamer axis, and if perpendiculars are dropped from the ends of a unit length of the roller axis onto said line that is parallel to the reamer axis (or the reamer axis itself if coplanar with the roller axis) the perpendiculars will cut off a portion of the line having a length of 0.866, since the cosine of 30 degrees is 0.866. The orthogonal (perpendicular) projection of the roller axis on the reamer axis or a line parallel thereto is thus 86.6% of the length of the roller axis. In the language of composition and resolution of vectors, the component of the roller axis that lies parallel to the reamer axis in such case has a length 86.6% of the roller axis length. It is in this sense that in the claims it is said that the roller axis must have at least an 85% component parallel to the reamer axis, this being one convenient way of stating the angular position of the roller axis relative to the reamer axis.

INSERT AXIS AND SECTION

Likewise it is to be noted that the tungsten carbide inserts forming the earth formation reducing means of the reamer rollers need not be disposed with the insert axis radial to the roller axis, nor need the inserts be of circular cross section, though such disposition and shape of the inserts is greatly to be preferred since the inserts will be more easily inserted and better retained with the preferred construction.

The tungsten carbide inserts and the hard facing bands provide means to reduce the earth formation during reaming of the well bore and may be referred to as such in the appended claims.

While a preferred embodiment of the invention has been shown and described, many modifications thereof can be made by one skilled in the art without departing from the spirit of the invention and it is intended to cover by Letters Patent all forms of the invention falling within the scope of the following claims.

We claim:

1. A side wall roller reamer comprising:

a tubular member having

means at its upper end for connecting the member to a rotary drill string whereby the reamer can be rotated about the axis of said tubular member which thus forms the reamer axis and

means at its lower end for connecting the member to a rotary drill string whereby torque and fluid can be transmitted by the reamer from such drill string at the upper end of the reamer to such drill string at the lower end of the reamer to rotate a drill bit connected to the lower end of the last mentioned drill string,

a plurality of rollers disposed around the outer periphery of said tubular member,

means mounting each of said rollers on said member for rotation about an axis which thus forms the roller axis, said roller axes being parallel to the reamer axis,

each roller having an outer surface that is a surface of revolution with respect to the roller axis,

each roller being larger in diameter at its upper end than at its lower end providing an outer surface having portions of increasing radius progressing upwards along the roller,

each roller including a plurality of cylindrical apertures in its outer surface disposed around the periphery thereof with their cylindrical axes perpendicular to the roller axis,

a number of said apertures being disposed in an annular row around each roller near the upper end thereof,

a generally cylindrical insert disposed in each of said apertures,

each insert including a portion at one end protruding from the aperture and forming a tip adapted to contact the sidewall of a bore hole,

each insert in the apertures below said annular row of apertures protruding a distance such that the distance of its tip from the roller axis measured perpendicular to the roller axis is at least as great as the distance from the roller axis of the portion of the outer surface of the roller adjacent the aperture nearest thereabove, and

each insert in the apertures in said annular row of apertures equally protruding from its aperture to place its tip at a distance (b) from the roller axis, said distance (b) being greater than the maximum distance (r) from the roller axis of the tips of inserts in apertures below said row,

the last said distance (r) added to the distance (a) of the roller axis from the reamer axis constituting the on-gage radius R_{gage} of the reamer adapted to ream the bore hole to the same radius as the on-gage radius of a new drill bit connected to a drill string below the reamer,

said distance (b) of the tips of the inserts in said annular row from the roller axis added to said distance (a) of the roller axis from the reamer axis constituting the underream radius R_{max} of the reamer,

each insert in said annular row being disposed with its axis spaced apart from those of the adjacent inserts on both sides thereof progressing around said row a distance at least equal to the critical spacing S_{min} determined by the equation:

$$(R_{\text{max}} - R_{\text{gage}} - a - b)^2 = \left(b \sin \frac{180 S_{\text{min}}}{2\pi r} \right)^2 + \left(a + b \cos \frac{180 S_{\text{min}}}{2\pi r} \right)^2$$

2. Method of boring a hole in the earth with a rotary drill string including a drill bit and a side wall roller crusher reamer above the drill bit having an annular row of oblate tipped crushers circumferentially spaced apart around each reamer roller a distance S_{min} and whose maximum extension from the reamer axis exceeds the on-gage radius of the drill bit but no more than by a distance U as determined by the equation:

$$(U - a - b)^2 = \left(a \sin \frac{180 S_{\text{min}}}{2\pi r} \right)^2 + \left(a + b \cos \frac{180 S_{\text{min}}}{2\pi r} \right)^2$$

where (a) is the radial distance from the roller axis to the reamer axis, (r) is the roller radius, and (b) is the radial distance from the roller axis to the crusher tip, comprising the steps of

lowering the string to the bottom of the hole with the reamer rollers turned to retracted position in which the roller radius bisecting the angle between roller radii to adjacent outermost crushers is aligned with a reamer radius when the string passes through on-gage portions of the hole,

rotating the drill string on bottom to cause the drill bit to bore further hole and the reamer to underream the previously drilled hole by the amount said maximum extension of the crusher exceed the on-gage radius, and

without rotation of the drill string withdrawing the drill string from the hole to cause the oblate tipped crushers to cam the rollers to the aforesaid retracted position.

3. Rotary drilling apparatus including

a drill bit adapted to drill an on-gage hole when new and an undergage hole when worn,

a roller crusher reamer above the drill bit adapted to ream the hole drilled by the bit to a diameter in the range of on-gage to overgage,

said reamer including rollers mounted for rotation about axes parallel to the reamer axis,

each roller including an annular row of crusher elements whose maximum protrusion from the reamer axis is overgage when new,

said crusher elements being spaced apart circumferentially about the roller by a distance at least equal to S_{min} as determined by the equation:

$$(R_{\text{gage}})^2 = \left(b \sin \frac{180 S_{\text{min}}}{2\pi r} \right)^2 + \left(a + b \cos \frac{180 S_{\text{min}}}{2\pi r} \right)^2$$

where

R_{gage} = on-gage radius of the hole as drilled by the drill bit when new

r = roller radius at the crusher elements

a = radius from roller axis to reamer axis

b = radius from tips of crusher elements to roller axis.

4. A roller reamer including a tubular body with a plurality of rollers mounted thereon for rotation about axes parallel to the body axis, each roller having earth formation reducing elements radially protruding therefrom and circumferentially spaced apart about the roller at least a distance S_{min} determined by the equation:

$$(r + a)^2 = \left(a \sin \frac{180 S_{\text{min}}}{2\pi r} \right)^2 + \left(a + b \cos \frac{180 S_{\text{min}}}{2\pi r} \right)^2$$

where

r = roller radius

a = radius from roller axis to axis of tubular body

b = radius from roller axis to tip of element.

5. An underreamer comprising a tubular body having a plurality of rollers rotatably mounted thereon for rotation parallel to the body axis, each roller having elements protruding therefrom adapted to underream by a radial distance U , the elements being circumferentially spaced about the roller by a distance at least equal to S_{min} as determined by the equation:

$$(U - a - b)^2 = \left(a \sin \frac{180 S_{\text{min}}}{2\pi r} \right)^2 + \left(a + b \cos \frac{180 S_{\text{min}}}{2\pi r} \right)^2$$

where

a is the radial distance from the roller axis to the body axis; r is the roller radius; and b is the radial distance from the roller axis to the tip of the element.

6. An underreamer comprising a tubular body having a plurality of rollers rotatably mounted thereon for rotation about axes having at least an 85% component parallel to the body axis, the upper end of each roller axis being at least as far from the reamer axis as the lower end thereof, each roller having elements protruding therefrom adapted to underream by a radial distance U , the elements being circumferentially spaced apart about the roller by a distance whose component in a plane perpendicular to the body axis is at least equal to S_{min} as determined by the equation:

$$(U - a - b)^2 = \left(a \sin \frac{180 S_{\text{min}}}{2\pi r} \right)^2 + \left(a + b \cos \frac{180 S_{\text{min}}}{2\pi r} \right)^2$$

where

a is the radial distance from the roller axis to the body axis; r is the roller radius; and b is the radial distance from the roller axis to the tip of the element.

7. Well apparatus for reaming a hole following a drill bit to maintain the hole at least full gage as drilling progresses and the initially full gage drill bit wears under-gage comprising

an underreamer in accordance with claim 6,

means at the upper and lower ends of the underreamer body for connecting the body in a rotary drill string whereby the body can be rotated about the axis of the body collinear with the drill string axis, and

means comprising oblate outer tips on the protruding underream elements of the underreamer rollers to cam the rollers into positions in which the midpoints between the elements nearest the underreamer outer periphery are coplanar with the body axis and the respective roller axis when said apparatus is moved

axially into a full gage portion of a hole without rotating said apparatus about said body axis, the radii from the extremities of the underream elements to the body axis being no greater than said full gage when said rollers are in said position, due to said spacing of at least S_{min} between said elements.

8. A reamer comprising

- a tubular member having means at its upper and lower ends for connecting the member in a rotary drill string whereby the reamer can be rotated about the axis of said tubular member which thus forms the reamer axis,
- a plurality of rollers disposed around the outer periphery of said tubular member, means rotatably mounting each of said rollers on said tubular member with its roller axis having at least an 85% component parallel to the reamer axis, each roller being of progressively increasing diameters all the way from adjacent the lower end to adjacent the upper end of the reamer, the diameter increasing stepwise along the length of the roller forming a plurality of annular lands each of uniform diameter, there being an annular band of radial sockets extending around each land, the sockets having sides that are straight in the direction progressing inwardly from the outer surface of the roller,
- earth formation reducing means at the outer peripheral surface of each roller, said earth formation reducing means comprising a plurality of tungsten carbide inserts disposed in annular bands in said sockets in the roller lands, each insert having a straight sided root portion making an interference fit within its socket and an oblate tip portion extending out of the socket, the tips of the inserts disposed in each larger radius land extending farther from the roller axis than the tips of the inserts in the next smaller radius land, the tips of the inserts in each land protruding therefrom to a distance at least as far from the roller axis as the periphery of the next larger land,
- said earth formation reducing means further including an annular bevelled area adjacent the smallest diameter land, said bevelled area being provided with a band of hard facing material therearound, said bevelled area having an annular groove thereon receiving said hard facing whereby the latter is flush with the surface of said area.

9. A reamer comprising

- a tubular member having means at its upper and lower ends for connecting the member in a rotary drill string whereby the reamer can be rotated about the axis of said tubular member which thus forms the reamer axis,
- a plurality of rollers disposed around the outer periphery of said tubular member, means rotatably mounting each of said rollers on said tubular member with its roller axis having at least an 85% component parallel to the reamer axis, each roller being of progressively increasing diameters all the way from adjacent the lower end to adjacent the upper end of the reamer, the diameter increasing stepwise along the length of the roller forming a plurality of annular lands each of uniform diameter, there being an annular band of radial sockets extending around each land, the sockets having sides that are straight in the direction progressing inwardly from the outer surface of the roller,
- earth formation reducing means at the outer peripheral surface of each roller, said earth formation reducing means comprising a plurality of tungsten carbide inserts disposed in annular bands in said sockets in the roller lands, each insert having a straight sided root portion making an interference fit within its socket and an oblate tip portion extending out of the socket, the tips of the inserts disposed

in each larger radius land extending farther from the roller axis than the tips of the inserts in the next smaller radius land, the tips of the inserts in each land protruding therefrom to a distance at least as far from the roller axis as the periphery of the next larger land,

said earth formation reducing means further including an annular band of hard facing material around the roller at the end thereof adjacent the smallest diameter land, the maximum radial extent of said hard facing from the reamer axis being a predetermined amount less than the on-gage radius of the hole to be reamed, whereby when the bit on the drill string has worn down to said predetermined amount below full gage said hard facing band will cause torque up of the drill string.

10. A reamer comprising

- a tubular member having means at its upper and lower ends for connecting the member in a rotary drill string whereby the reamer can be rotated about the axis of said tubular member which thus forms the reamer axis,
- a plurality of rollers disposed around the outer periphery of said tubular member, means rotatably mounting each of said rollers on said tubular member with its roller axis having at least an 85% component parallel to the reamer axis, each roller being of progressively increasing diameters all the way from adjacent the lower end to adjacent the upper end of the reamer, the diameter increasing stepwise along the length of the roller forming a plurality of annular lands each of uniform diameter, there being an annular band of radial sockets extending around each land, the sockets having sides that are straight in the direction progressing inwardly from the outer surface of the roller,
- earth formation reducing means at the outer peripheral surface of each roller, said earth formation reducing means comprising a plurality of tungsten carbide inserts disposed in annular bands in said sockets in the roller lands, each insert having a straight sided root portion making an interference fit within its socket and an oblate tip portion extending out of the socket, the tips of the inserts disposed in each larger radius land extending farther from the roller axis than the tips of the inserts in the next smaller radius land, the tips of the inserts in each land protruding therefrom to a distance at least as far from the roller axis as the periphery of the next larger land,
- said means rotatably mounting each roller including a sleeve bushing inside the roller, said bushing being harder than the outer part of the roller, the outer part of the roller being more ductile than said bushing in order better to retain said inserts,
- said openings in the roller extending all the way inwardly to said bushing and said inserts being bottomed against said bushing.

11. A reamer comprising

- a tubular member having means at its upper and lower ends for connecting the member in a rotary drill string whereby the reamer can be rotated about the axis of said tubular member which thus forms the reamer axis,
- a plurality of rollers disposed around the outer periphery of said tubular member, means rotatably mounting each of said rollers on said tubular member with its roller axis having at least an 85% component parallel to the reamer axis, each roller being of progressively increasing diameters all the way from adjacent the lower end to adjacent the upper end of the reamer, the diameter increasing stepwise along the length of the roller forming a plurality of annular lands each of uniform diameter, there being an annular band of radial sockets extending around each land, the sockets having sides that are straight

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in the direction progressing inwardly from the outer surface of the roller,

earth formation reducing means at the outer peripheral surface of each roller, said earth formation reducing means comprising a plurality of tungsten carbide inserts disposed in annular bands in said sockets in the roller lands, each insert having a straight sided root portion making an interference fit within its socket and an oblate tip portion extending out of the socket, the tips of the inserts disposed in each larger radius land extending farther from the roller axis than the tips of the inserts in the next smaller radius land, the tips of the inserts in each land protruding therefrom to a distance at least as far from the roller axis as the periphery of the next larger land,

said earth formation reducing means further including an annular band of hard facing material around the roller at the upper end thereof, the maximum radial extent of said hard facing from the reamer axis being the on gage radius of the reamer, inserts in the uppermost land of each roller having a maximum radial extent greater than said on gage radius so as to ream an overgage hole, said on gage band of hard facing serving to burnish the hole after the action of the inserts, said on gage band further serving to cause torque-up of the drill string when the overgage inserts are worn down to on-gage.

12. The combination of claim 11 in which the peripheral distance between the overgage inserts measured about the roller surface is at least equal to the critical spacing allowing the rollers to be turned into positions in which none of the overgage inserts extends radially from the reamer axis more than the on gage radius of the reamer.

13. The combination of claim 12 in which said overgage bits are disposed in a plurality of annular rows around the roller and the bits in one row are in register with those in an adjacent row.

14. A reamer comprising

a tubular member having means at its upper and lower ends for connecting the member in a rotary drill string whereby the reamer can be rotated about the axis of said tubular member which thus forms the reamer axis,

a plurality of rollers disposed around the outer periphery of said tubular member, means rotatably mounting each of said rollers on said tubular member with its roller axis parallel to the reamer axis,

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each roller being of progressively increasing diameters all the way from adjacent the lower end to adjacent the upper end of the reamer, the diameter increasing stepwise along the length of the roller forming a plurality of annular lands each of uniform diameter,

there being an annular band of radial sockets extending around each land, the sockets having sides that are straight in the direction progressing inwardly from the outer surface of the roller,

earth formation reducing means at the outer peripheral surface of each roller, said earth formation reducing means comprising a plurality of tungsten carbide inserts disposed in annular bands in said sockets in the roller lands, each insert having a straight sided root portion making an interference fit within its socket and an oblate tip portion extending out of the socket, the tips of the inserts disposed in each larger radius land extending farther from the roller axis than the tips of the inserts in the next smaller radius land, the tips of the inserts in each land protruding therefrom to a distance at least as far from the roller axis as the periphery of the next larger land,

said sockets in said land and said inserts therein having cylindrical sides with the cylinder axis radial to the axis of the respective rollers and uniformly spaced apart circumferentially around the rollers, the sockets and inserts in one land being staggered relative to those in an adjacent land,

said sockets terminating within each roller at points spaced radially outward from said means rotatably mounting the rollers on said tubular member so as to provide a solid bottom for each socket.

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CHARLES E. O'CONNELL, *Primary Examiner.*

J. A. LEPPINK, *Assistant Examiner.*