June 29, 1965 R. P. VINCENT 3,191,680

METHOD OF SETTING METALLIC LINERS IN WELLS

Filed March 14, 1962 4 Sheets-Sheet 1

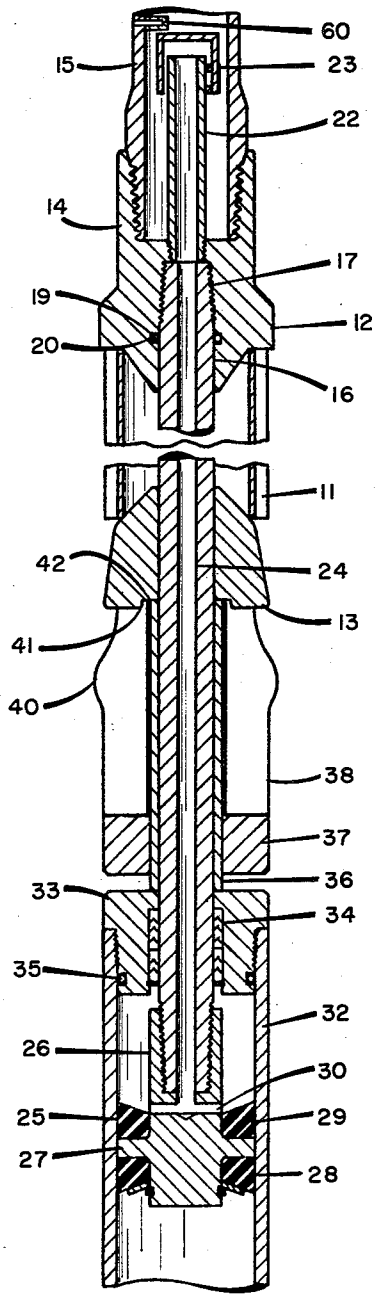


FIG. -1

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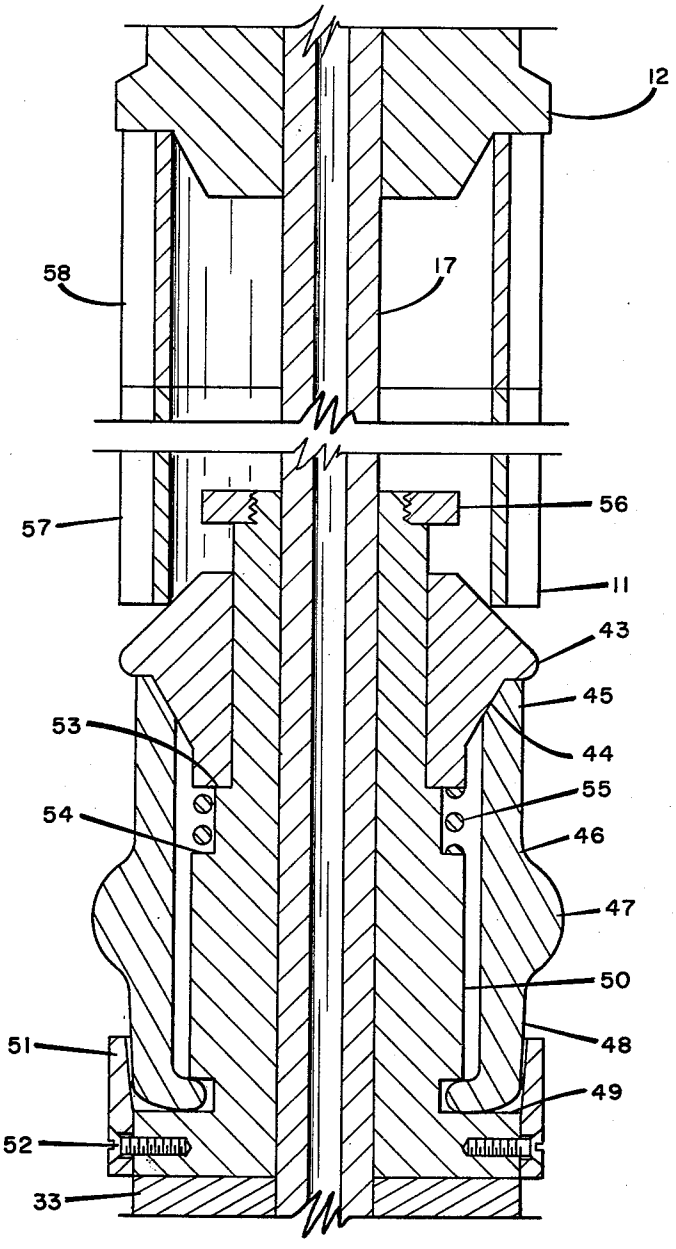


FIG. - 2

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METHOD OF SETTING METALLIC LINERS IN WELLS

Filed March 14, 1962 4 Sheets-Sheet 3

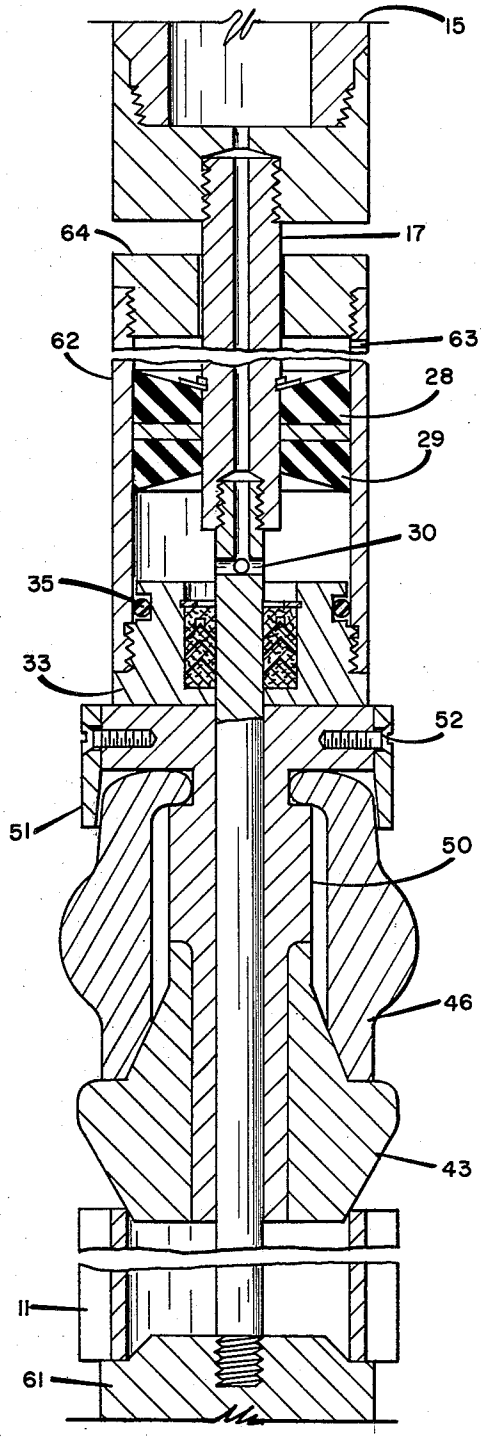


FIG. - 3

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June 29, 1965 R. P. VINCENT 3,191,680

METHOD OF SETTING METALLIC LINERS IN WELLS

Filed March 14, 1962 4 Sheets-Sheet 4

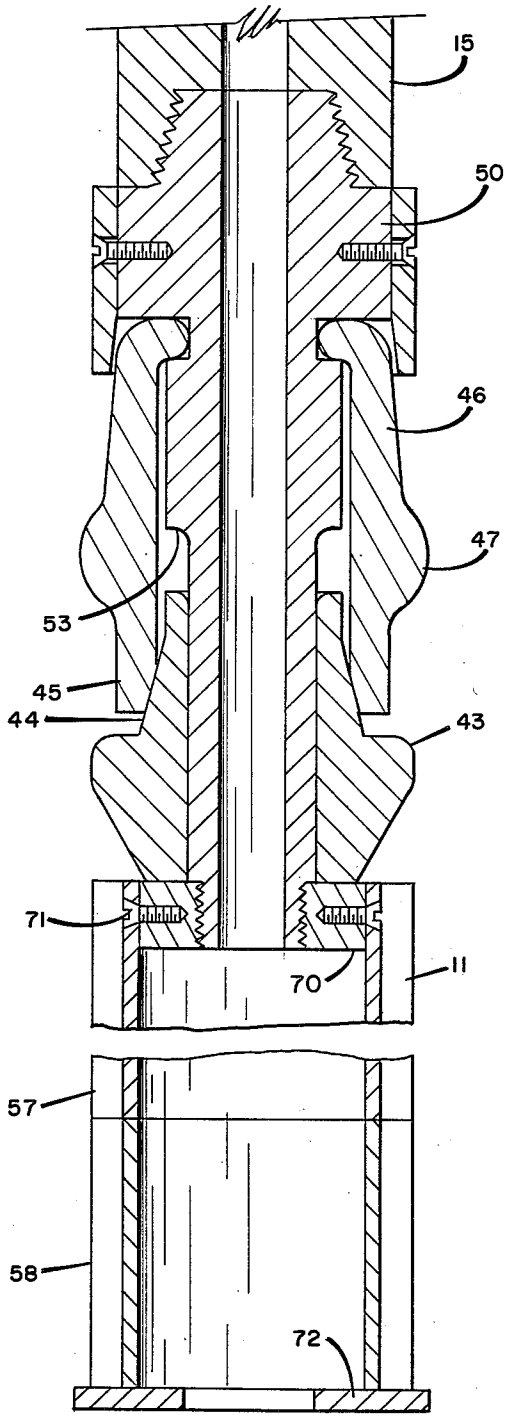


FIG. - 4

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United States Patent Office 3,191,680 Patented June 29, 1965

3,191,680

METHOD OF SETTING METALLIC LINERS IN WELLS

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Filed Mar. 14, 1962, Ser. No. 179,609
4 Claims. (Cl. 166—46)

This invention relates to setting metallic liners in wells. More particularly it relates to setting such liners in previously unlined portions of wells.

This is a continuation-in-part of my U.S. patent application No. 123,039, filed July 10, 1961, now abandoned. In that application a method and apparatus are described for placing a metallic liner in compressive stress within a section of casing in a well. I have now found that certain embodiments and variations of the method can be used for placing a very desirable form of liner in open hole to solve many of the problems in drilling, completing, and producing wells.

In drilling with liquid drilling fluids through vugular, cavernous, or fractured zones of earth formations, large volumes of the whole drilling fluid, not just filtrate, are often lost. A liner set over such a zone and sealed to formations above and below the zone would obviously stop loss of drilling fluids. For this application of a metal liner there are two principal requirements. First, the liner when set should have an internal diameter sufficient to pass a bit of the desired size, preferably the same bit used for drilling the unlined section of hole. This means the inside diameter of the liner should be no smaller than the inside diameter of the unlined hole. Second, a good seal must be established between the liner and the formation to avoid flow of drilling fluid behind the liner to the vugs, caverns, or fractures to which it was being lost before the liner was set.

Other possible applications of a liner during drilling operations with liquid drilling fluids include sealing off shales which tend to slough off into the well, and forming a conduit through enlarged well sections which tend to trap bit cuttings and then let these cuttings fall into the well at various inconvenient times.

When drilling a well with air or other gas, entry of water into the well sometimes compels abandonment of the gas with its advantage of rapid drilling rates. Again a liner which would seal off the water without reducing the well diameter would be very desirable. This application of a liner has the same two requirements as for those sealing-off zones to which whole mud is lost.

After a well has been drilled and is ready for completion, several possible uses of my liner exist. For example, a short section of liner can be set above the producing zone. The well can then be completed by running tubing or a small diameter casing and setting a packer between the liner and the tubing or casing. If desired, the space outside the casing or liner can then be filled with drilling fluids, oil, water or other materials frequently referred to as packer fluids.

In some cases it will be desirable to set a liner over the producing formation and then form openings through the liner by use of casing cutters, bullet perforators, jet perforators or the like. This is particularly desirable when an oil producing zone is thin and has water, gas or both closely associated with the oil. This technique is also particularly desirable as a method of placing a fracture only at exactly the desired level in a well by hydraulic fracturing technique. In these well completion operations, the liner need not be squeezed out until its internal diameter is the same as the well without the liner. The seal between the liner and the formation is

obviously even more important, however, than in drilling operations.

Even after a well has been drilled, completed, and produced for a time, use of a liner is often advisable. For example, a gas cap may have formed resulting in excessive gas production. In this case, a liner may be set through the top of the producing formation to decrease gas production. In case of an active water drive the production of water into a well may become excessive. In this case, a liner may be set opposite the bottom portion of the formation to decrease water production. These operations can probably best be considered as recompletion operations. Recompletion by one of the techniques mentioned above in connection with original completions may also be advisable.

All these cases are examples of instances in which a liner is required in a previously unlined section of the well. The term "previously unlined" as used here obviously means the formations are still exposed to the well bore and have not been isolated by steel casing, cement, or the like. A section of well having a filter cake deposited from drilling fluid should be considered to be unlined for my purposes.

The problems described above are long-standing ones in the art of drilling, completing, and producing oil wells. Several solutions to the problems have been proposed including that suggested in U.S. Patent 1,233,888, Leonard. Leonard proposed setting a metallic liner in open hole by forming longitudinal corrugations in the wall of a tube to reduce its outer diameter so it could be lowered through a well or well casing of the same size as the original internal diameter of the tube. After the tube was lowered into the well, a swage was driven through it to cause it to resume its original diameter and cylindrical shape. Small longitudinal cuts were formed in the bottom of the tube to divide the tube into a number of strips which were bent outwardly to act as anchors. Around the top of the tube a gasket was placed to form a more effective seal between the liner and formation.

The Leonard apparatus and method had several difficulties and was not accepted for general use. One problem was anchoring the corrugated tube so the swage could be driven through it. The tube could not be expanded anywhere except at the bottom of the well. Another problem in the Leonard system was getting the solid swage to the bottom of the well. In order for the swage to expand each section to the same diameter as the others, this swage had to be of the same external diameter as the internal diameter of the casing and well. As a result, running the swage to the new section of the liner was sometimes difficult.

Finally, it will be apparent that in expanding a section of liner to an internal diameter equal to the original internal diameter of the well, considerable crushing and cracking of the formation was necessary. The gasket provided by Leonard did not form an effective seal between the liner and this crushed and fractured formation.

The general plan of Leonard is excellent. Because of a few difficulties, however, the plan has not been used to any great extent in the 45 years since the Leonard patent issued. This is in spite of the continued existence of the problems outlined above, many of which Leonard recognized and described.

An object of this invention is to provide a method for setting a metallic liner in sealed engagement with the previously unlined wall of a well. More specifically, an object of the invention is to overcome the difficuties with Leonard's corrugated liner technique so this method and apparatus can be used to solve the problems which have existed for many years and which might be solved by a well-sealed, fully expanded metallic liner. Even more

specifically, an object of the invention is to provide a method for expanding a longitudinally corrugated tube into a substantially cylindrical shape to form a liner at any desired level in a well. Still another specific object is to provide a method for forming an effective seal between a metallic liner and the wall of a well in which it is set.

As previously noted, I have now found that certain embodiments and variations of the apparatus and methods described in my U.S. patent application 123,039 can be used to accomplish the objects of my invention. Some of these are shown in the drawing in which FIGURE 1 is the same as FIGURE 1 of my U.S. patent application 123,039 and shows a hydraulic means for expanding a liner using a double expanding head having a solid expanding cone and a collet spring head for making the final expansion. FIGURE 2 shows a modified section of FIGURE 1 in which the design of the expanding head is changed to provide a more positive final liner diameter of a desired preselected size. FIGURE 3 is a further modification of the design shown in FIGURE 2 but in which the hydraulic force is down rather than up. FIGURE 4 is a design for setting a liner in the bottom of a well using the weight of a string of pipe to expand the liner.

Referring now to the drawing in more detail, in FIGURE 1, the corrugated liner tube **11** is mounted between connector **12** and an expanding cone **13**. The connector **12** includes a top collar portion **14** which is internally threaded to receive standard well tubing **15** which serves to lower the entire liner setting assembly into the well. Other hollow conduit, such as drill pipe, can, of course, be used if desired. The main body portion of connector **12** includes a central passage **16**, the upper portion of which is threaded to receive and hold the top of a polished rod **17**. A complete seal between the polished rod and connector **12** is assured by use of O-ring **19** in peripheral goove **20** around passage **16**. In the top of passage **16** a short pipe **22** with loose cap **23** is provided to prevent scale, dirt, and the like from the inside wall of the tubing from falling into the hydraulic system below.

Polished rod **17** includes a central bore **24** which connects with the interior of pipe **22**. A piston **25** is mounted on the bottom of polished rod **17**. The piston includes an internally threaded cap **26** for attachment to the externally threaded bottom portion of polished rod **17**. The piston also includes flange **27** on which resilient cups **28** and **29** are mounted. Above top cup **29**, a passage **30** is provided in the piston which is connected to the inner bore **24** of polished rod **17**.

Piston **25** works in a cylinder **32** having a cap **33** through which polished rod **17** passes. Packing **34** is provided to form a seal between polished rod **17** and cap **33**. Preferably, an O-ring **35** is provided between the cylinder **32** and cap **33** to insure a good seal between these members. Sleeve **36** rests on the top of cap **33** and supports expanding cone **13**. Surrounding sleeve **36** is a collet head **37** with collet spring arms **38**. The arms have an inner surface which is spaced from sleeve **36** to permit inward movement of the arms. The arms also have slots, not shown, between them to permit this same action. Near the tops of arms **38** are outwardly enlarged portions **40** which perform the final forming action to force the corrugated liner into a substantially cylindrical shape as the cone and collet head are forced through the corrugated liner tube by the hydraulic piston and cylinder arrangement shown. Arms **40** are normally sprung out farther than shown in FIGURE 1. In this figure, the arms are shown as being restrained by projecting portions **41** which fit into a mating recess **42** in expanding cone **13**. This permits lowering the assembly more easily through the well to the desired location.

In operation, the liner setting tool is assembled at the surface, as shown in FIGURE 1 and glass cloth saturated with resin is wrapped around the corrugated tube. The assembly is lowered into the well in this condition to the location at which the liner is to be set. A liquid, such as oil, is then pumped into the tubing. The oil passes through the well tubing, pipe **22**, polished rod **17**, passages **30** and into the cylinder **32** above piston **25**. As the pressure increases, the pressure on cap **33** causes it to rise, carrying sleeve **36** and expander head **13** upwardly with respect to the polished rod. Upward movement of liner tube **11** is restrained by connector **12** attached to the top of the polished rod. Therefore, as expanding cone **13** rises, it expands corrugated liner tube **11**.

As cone **13** passes upwardly through liner tube **11**, the bottom of the tube eventually strikes the enlarged portions **40** of the collet head spring arms. When this happens, upward motion of the collet head is restrained and causes projections **41** to pull out of restraining recess **42**. The arms then spring outwardly. As cap **33** on the hydraulic cylinder continues to rise, the cap comes in contact with the bottom of collet head **37**, forcing it through liner tube **11**. The spring arms complete the expansion of the liner tube out against the well wall, except, of course, for the sealing layer of glass fibers and resin between the liner and well wall.

When the upward movement of cap **33**, collet head **37**, and expanding cone **13** causes cone **13** to come into contact with connector **12**, the upward motion must, of course, stop. This is indicated by an increase of pressure required to inject liquid into the tubing. The expanding cone **13** and collet head **37** may then be forced the remaining distance through the corrugated liner tube by simply lifting on the well tubing. This is possible because the frictional drag of the expanded portion of the liner against the well wall is sufficient to hold the liner down against the upward pull of the cone and collet head. In addition, if the liner is pressed back into the wall of the well, there will be a shoulder of the formation above the expanded liner to restrain upward movement of the corrugated tube. It will be apparent that after only a few inches of the liner have been expanded against and into the well wall, connector **12** is no longer needed to hold the liner down while the tube is being expanded.

An alternative procedure when cone **13** strikes connector **12** is to release the pressure on the tubing, raise the well tubing two or three feet, secure it firmly at the surface, and then resume injecting hydraulic fluid into the tubing. Raising the well tubing will lift connector **12** two or three feet above the top of the liner. Expanding cone **13** and collet head **37** can then be forced on through the liner tube by injecting hydraulic fluid through the tubing.

As soon as the cone and collet head have been pulled completely through the liner, the tubing and liner setting assembly are removed from the well. To avoid pulling a wet string, it is possible to inclue a break-off relief seal **60** in the well tubing **15** above cap **23**. This seal can be broken off by dropping a go-devil down the tubing. Breaking of the seal allows the liquid in the tubing to leak out as the tubing is pulled from the well.

The solid expanding element **13** in FIGURE 1 and similar elements in other figures are referred to as expanding cones for convenience. They are rarely actually cones, but are solids with surfaces which are surfaces of revolution about a central axis. The surface is tapered from a large end slightly smaller than the desired final diameter of the liner to a small end slightly smaller than the smallest diameter of the corrugated tube.

If a liner is to be set in a casing, the important factor is the pressure of the liner against the casing. It is important to have spring arms to apply this pressure regardless of minor variations in casing diameter. In a liner set in open hole, however, the most important factor is ordinarily the internal diameter of the liner. Therefore, a more positive means should be provided for insuring exactly the internal liner diameter which is desired. In addition, if the internal diameter of the liner is to be

about the same as the original diameter of the well, it will be apparent that spring arms capable of applying a radial force sufficient to expand the liner to this diameter will also exert approximately the same radial pressure on the well wall above the liner. This is not desirable. Therefore, use of the spring arms should ordinarily be limited to well completion operations where the final internal diameter of the liner is less than that of the well above the liner. In application of this sort, the spring arms move outwardly above the top of the liner. If properly designed with a large spring constant, the radial force on the well wall above the liner can be made very small.

Both the problem of insuring exactly the desired internal diameter of the liner and the problem of radial pressures on the well wall above the liner can be overcome by the design shown in FIGURE 2. In this design the expanding cone 43 is somewhat similar to the cone 13 in FIGURE 1 except for tapered surfaces 44 on the bottom. These surfaces are the faces of a truncated pyramid. The faces of this pyramid are all substantially congruent. The apex of the pyramid (formed by the extended faces of the truncated pyramid) lies substantially on the axis of sleeve 50 on which cone 43 is mounted. Tapered ends 45 of expanding arms 46 ride on tapered surface 44. These arms, preferably about 8 in number for a well 6 inches in diameter, have bulges 47 for the final expansion of the liner. Opposite the tapered end of each arm 46 is a hooked end which fits into an annular groove 49 in sleeve 50 which fits over polished rod 17 and carries the expanding cone and arms. The arms are prevented from falling off sleeve 50 by collar 51. This collar is attached to sleeve 50 by set screws 52. The bottom of sleeve 50 rests on cap 33. The arrangement below this cap is as shown in FIGURE 1.

Toward the middle of sleeve 50 there are shoulders 53 and 54. Shoulder 53 supports expanding cone 43 when this cone is pressing against corrugated tube 11 and the tube is against connector 12. When the cone is not pressing against the tube, spring 55 which rests on shoulder 54 and presses against the base of cone 43, forces cone 43 upwardly permitting inward movement of arms 46. The spring should be sufficiently strong to support the weight of expanding cone 43 and the corrugated tube. At the top of sleeve 50 is retaining nut 56 to hold cone 43 on sleeve 50.

The corrugated tube in FIGURE 2 is made up of two parts. One is the usual corrugated mild steel tube which is identified as part 57. The other is portion 58 above part 57. Portion 58 is made of drillable material such as brass, aluminum alloy, or the like, having approximately the same strength as the steel tube. This is for reasons explained later. Preferably the two parts 57 and 58 are attached together as by welding, brazing, soldering, or the like.

In operation, the apparatus of FIGURE 2 is made up at the surface as shown in FIGURE 1 except that cap 33 is lowered sufficiently to bring retaining nut 56 into contact with cone 43. Glass cloth saturated with liquid settable resin is wrapped around the corrugated tube and the assembly is lowered into the well to the desired level. This step is simplified by the action of spring 55. When cap 33 is lowered, sleeve 50 goes with it carrying arms 46 downwardly because of hooked ends 48. Spring 55 acting against the bottom of cone 43 lifts the cone and corrugated tube with respect to sleeve 50. Tapered ends 45 on arms 46 are thus able to move inwardly to avoid applying any radial force against the well wall.

When the assembly is in the desired location in the well, hydraulic pressure is applied through hollow polished rod 17. Upward motion of cap 33 on the hydraulic cylinder then forces sleeve 50 upwardly with respect to rod 17, cone 43, and tube 11, compressing spring 55 until the base of cone 43 contacts shoulder 53. This motion also causes tapered surface 44 of cone 43 to contact tapered ends 45 of arms 46, forcing the arms out to a definite predetermined position as shown in FIGURE 2. Further application of hydraulic pressure then causes cone 43 and arms 46 to move upwardly through corrugated tube 11, expanding it out against and into the well wall.

As explained in connection with FIGURE 1, the expanding cone and arms must be pulled through the last few inches of the corrugated tube by lifting on the tubing or by resetting the tubing at a higher level and again applying hydraulic pressure. The action of the tool in the last few inches of the corrugated tube should be particularly noted. The only thing which holds arms 46 out against the corrugated tube is tapered surfaces 44 on cone 43. As soon as cone 43 passes the upper edge of tube 11, there is no force to hold cone 43 down against the action of spring 55. Cone 43 rises, therefore, releasing arms 46 so they can move inwardly. This is a very desirable action since it permits the tool to be easily withdrawn from the well. However, the action leaves a length of corrugated tube only partly expanded. The length of the partially expanded portion of the tube is equal to the distance between the outermost points on cone 43 and bulges 47 on arms 46. The upper portion 58 of tube 11 is made of an easily drillable material such as brass, aluminum alloy, or the like, and is of a length greater than the length of the partly expanded portion of the tube. If desired, this portion can be drilled with an ordinary rock bit or mill to the same internal diameter as the fully expanded portion of the tube.

Of course, it is possible to mill out a partially expanded portion of a steel liner. This involves an extra trip into the well, however, so the operation should be avoided if possible. The drillable portion of the tube is particularly important if the liner is used in drilling operations. In this case the ordinary drilling bit can easily drill through the partially expanded portion of the liner if the liner is made of brass, for example. The bit can then continue drilling the earth formations. In the case of liners set in well completion operations, it is frequently unnecessary to remove the partially expanded portion of the liner, since the intended diameter in such cases is not so important.

If it is desired to leave the partially expanded portion of the liner on the bottom rather than the top of the tube, the apparatus shown in FIGURE 3 may be used. In this case the cone 43, arms 46, and sleeve 50 are much the same as in FIGURE 2 except that they are inverted. In addition spring 55 can be omitted since the force of gravity normally causes cone 43 to move away from arms 46, permitting the arms to move inwardly. In the apparatus of FIGURE 3 the corugated tube 11 is placed below cone 43 and is supported by plate 61 on the bottom of rod 17. The hydraulic pressure in this case is applied to a piston and hydraulic cylinder 62 above the tube-expanding assembly. A hole 63 may be provided in the wall of cylinder 62 above the piston to permit entry and escape of fluids from the space above the piston. Preferably a cover 64 is provided for the cylinder to prevent entrance of large pieces of dirt, sand, or the like, into the cylinder.

Application of hydraulic pressure to the cylinder and piston in the arrangement of FIGURE 3 causes the expanding heads to move downwardly to expand the tube which is supported by plate 61. When cone 43 contacts plate 61, the tubing should be lowered a short distance, after which hydraulic pressure is again applied to force the expanding cone and arms the remaining distance through the tube. Plate 61 must, of course, be small enough in diameter to pass upwardly through the partially expanded portion on the bottom of the tube. That is, it must be of at least slightly smaller diameter than the largest diameter of the expanding cone.

FIGURE 4 shows apparatus adapted to set a liner in the bottom of a well. In this case the sleeve 50, arms 46, and cone 43 are mounted much as in FIGURE 3, except that there is no central rod 17. In FIGURE 4 sleeve 50 is supported directly by the tubing or drill pipe 15. The

corrugated tube 11 is mounted in this case on a supporting plate 70 by means of shear screws 71. Plate 70 is in turn mounted on the bottom of sleeve 50 and serves the double purpose of supporting the corrugated tube and expanding cone 43.

The corrugated tube is made up of steel portion 57 and drillable metal portion 58. Supporting disc 72 of drillable metal such as brass, aluminum, cast iron, or the like, may be provided on the bottom of corrugated tube 11 to prevent excessive imbedding of the tube in the bottom of the well. Portion 58 should be long enough in this case to be sure that bulges 47 on arms 46 reach the bottom of portion 57 of the corrugated tube before supporting plate 70 strikes the bottom of the well or disc 72 if used.

In operation, the assembly of FIGURE 4 is lowered to the bottom of a well on tubing or drill pipe. When disc 72 reaches the bottom of the well, the weight of the tubing or drill pipe on sleeve 50 and plate 70 is transmitted to screws 71 causing them to shear. This permits cone 43 to contact tube 11. Further downward motion of the drill pipe and sleeve 50 causes tapered ends 45 on arms 46 to move outwardly on tapered surfaces 44 of cone 43 until shoulder 53 of sleeve 50 comes in contact with the base of cone 43. The weight of the string of tubing or drill pipe is then applied to cone 43 to force it downward through tube 11 to expand the tube partially. Further downward motion causes bulges on arms 46 to complete the expansion of portion 57 of the tube 11. If desired, several drill collars can be used above the expansion assembly to provide any desired amount of downward force to insure effective expansion of the tube.

When the string of tubing or drill pipe is lifted, cone 43 drops with respect to arms 46, permitting these to move inwardly so bulges 47 are not pressed against the well wall. The expansion assembly can then be easily removed from the well. An ordinary rock bit is then used to drill the partially expanded drillable portion 58 of the tube and drillable plate 72 after which drilling of the earth formations can continue.

It will be apparent that the apparatus shown in FIGURES 2, 3 and 4 have several advantages in drilling operations. One of the principal advantages is that the bulges on the expanding arms extend to an exact predetermined point and no more or less. Preferably, the design is such that the ends of the arms contact a shoulder on the solid expanding cone at the same time that the base of the cone contacts the shoulder on the sleeve. Both contacts thus control the relative positions of the cone and arms, thus determining the exact diameter to which the liner tube is expanded. Another advantage is that in spite of the ability to expand the liner to a diameter as great as that of the rest of the well, the expanding element does not press against the well wall when going into or coming out of the well.

In most operations the final diameter of the liner is definitely fixed by the apparatus shown in FIGURE 2, 3, and 4. One exception should be noted. If the radial pressure on the bulges on the expanding arms becomes excessive, this radial pressure is transmitted to the tapered ends of the arms and through these ends to the truncated pyramidal part of the solid expanding cone. It will be apparent that if the force on the arms becomes suffiiciently high, the solid cone will be displaced along the sleeve to releive some of the radial pressure. Thus, while the tool ordinarily insures a liner diameter of the exact size desired, it does have a safety mechanism which permits it to yield in case of unusual conditions. To insure this action, the angle of faces 44 to the axis of the pyramid should be between about 20 and about 40 degrees preferably about 30 degrees.

The designs shown in FIGURES 2 and 3 can be set at a level in a well other than at the bottom since the tools provide their own support for the end of the tube opposite the expanding elements. By using a drillable portion as the last part of the corrugated tubing to be expanded, no unexpanded or partially expanded steel portion need be left in the well. In this regard, two comments should be made. Many drillers do not mind drilling a small amount of mild steel with a rock bit. These drillers would not be worried as long as the liner was expanded to substantially its entire length, that is to within about a foot of the end. Therefore, in many cases it is possible to use an all-steel corrugated tube. The second comment is that in some cases it would be desirable to make the entire corrugated tube of a material such as brass, aluminum alloy, or the like. Corrugated tubes of such materials may be not only more easily expanded into cylindrical form, but may also be desirable to combat special corrosive conditions or the like. It is also simpler to remove all or any part of such easily drillable materials than is the case of the liner is steel. It will be apparent that when reference is made to a malleable metal, this is intended to mean either a substantially pure metal such as aluminum or an alloy such as brass or steel.

Another very important advantage of my liner is the seal which is formed between the liner and the formation. As previously noted, expansion of the liner into the well wall necessarily crushes and cracks the formation. As my liner is placed, however, the glass fiber mat, saturated with liquid settable resin, is squeezed between the tube and the formation. Some of the liquid resin is thus forced out of the glass mat and into the crushed and cracked formation, filling the cracks and the spaces between the crushed particles. When this resin sets to a hardened state, the crushed formation is consolidated into a solid impermeable mass and the cracks are sealed. Thus, there is little possibility of leakage through this crushed and cracked zone. If a resin such as an epoxy is used which bonds firmly to metals, there is no chance of leakage along the outside surface of the liner as often occurs when liners are sealed with Portland cement.

When my apparatus and method are used to complete or recomplete a well, as distinguished from use during drilling operations, the principal advantage is the nearly perfect seal between the liner and the well wall. This is particularly true if a fracturer is desired only at some exact level in the wall. In this case a short section, for example 20 feet, of liner can be set in the well. Perforations can be formed by bullet or jet perforators or a notch can be formed by abrasives or a casing cutter at exactly the desired level. Packers can be set above and below the opening and hydraulic pressure can be applied to form a fracture only at the desired level. The perfect seal avoids any danger that the fracturing liquid will flow up or down the well behind the liner to a naturally weak and, therefore, more easily fractured level of the formation. The same seal also prevents leakage of gas down along the liner to the opening opposite the fractured zone or upward along the liner and into the well if the liner ends a short distance above the gas zone. The same advantages also are present in case a water bearing zone is sealed off.

The possibility of setting the liner at any desired level above the bottom is also an essential element and an advantage of my apparatus and method as applied to well completions. Any of the embodiments of apparatus shown in FIGURES 1, 2, and 3 can be used for this purpose. It is true that the assembly shown in FIGURE 1 employs spring arms to expand the corrugated liner. This is permissible, however, in well completion operations since it is not necessary in this case for the inside diameter of the liner to be the same as, or larger than, the original diameter of the well. Therefore, the liner can be merely pressed firmly against the well wall to insure a good bond between the formation and the liner. The inside diameter of the liner in such a case will be somewhat smaller than the diameter of the unlined well. This permits the expanding arms to spring out as they pass the end of the liner, relieving most of the stress in

the arms so they do not exert a strong radial pressure against the unlined well wall. The spring arms have the advantage of expanding the entire liner to the end rather than leaving a short, partially expanded section as when the apparatus of FIGURES 2 and 3 is used.

The length of the corrugated tube can be any length which can be set in a well. A length of about 10 feet has been found to be a very convenient length for most purposes in open hole. Shorter lengths can be used in some cases; but in order to obtain a highly effective seal, a liner of at least about 6 feet is generally advisable. In some cases much longer liner sections should be used such as 20 or 30 feet. Lengths greater than this are difficult to handle due to the inconveniently long dimensions of the setting assembly.

Still longer lengths can be obtained by setting several shorter lengths separately end to end in the well. A single long length can be set by using a long polished rod through a long corrugated tube, but using a short hydraulic cylinder. A length of tube in then expanded equal to the length of the hydraulic cylinder. The cylinder position is then reset and the operation is repeated in the same way that the final few inches of the liner is expanded as explained previously. A longer length than 20 feet is sometimes needed to seal off all of an undesirable formation.

Still another technique for setting long sections of liner employs a casing packer such as the Baker Model E shown on page 576 of the Composite Catalog of Oil Field Equipment and Services, 1960–1961. Use of this packer makes possible the use of lighter tubing for manipulating the equipment in the well since part of the vertical thrust from the setting tool can be borne by the slips and packer element. The packer is ideally suited to setting long sections of liner since it can be raised and reset any number of times to permit use of a short hydraulic cylinder to expand almost any desired length of liner.

The thickness of the wall of the corrugated tube is ordinarily about ⅛ inch, particularly if the tube is made of mild steel. In the case of mild steel, the radius of curvature of the corrugations should be no less than about 3 times the thickness of the wall of the tube to avoid cracking of the steel when the tube is corrugated or expanded into cylindrical form. Steel liners should be well annealed after corrugation for the same reason. Steel walls thicker than ¼ inch make the corrugations very difficult to expand into cylindrical shape. In addition, if a liner is to have the same internal diameter as the original well, the formation must be forced back by an amount equal to the thickness of the liner plus the glass fibers on the outside. This may not be possible in very hard formations with any reasonable amount of force applied to the expanding elements if the thickness of the steel liner is more than about ¼ inch. A steel liner should be not much less than about 1/16 inch if it is to withstand the pressures and mechanical blows to which it will be subjected in a well. If a more malleable or ductile metal or alloy such as brass or aluminum is used, the thickness can be somewhat greater, particularly for well completions where the final internal diameter is not critical. The radius of curvature of the corrugations can also be somewhat less than when steel is used.

While the ridges and valleys of the corrugations are preferably parallel to the axis of the liner tube, it will be apparent that a tube in which the corrugations spiral around the tube to some degree may also be used. Preferably, however, the tube should be substantially longitudinally corrugated. That is, a ridge of the corrugations should not vary more than about an inch or two from a line parallel to the axis of the tube in a foot-long section of the tube.

The original internal diameter of the tube before corrugation should be at least about the desired final internal diameter for the re-expanded liner. The steps of corrugating and re-expanding to cylindrical form ordinary stretch the liner circumference by about 2 percent. Thus, the internal cross-sectional perimeter of the corrugated liner may be slightly smaller than the desired final internal liner perimeter. The tube perimeter should be at least about 98 percent of the desired liner perimeter, however. Making the corrugated tube internal perimeter at least 98 percent as large as the final desired liner circumference insures that the expanding operation will not stretch the liner and split it. The internal perimeter of the tube should not be less than the greatest circumference of the expanding tool at the bulges on the arms to avoid the possibility of splitting the liner. The internal perimeter of the tube should not be more than about 10 percent greater than the desired final internal liner circumference to avoid excessive remanent corrugations in the liner as finally placed. An advantage of the resin filled glass mat is that the resin can fill small channels left under remaining corrugations such as those at the partially expanded end of a liner. It is better, however, that this resin be available to penetrate the formation and insure a good seal and bond between the liner and formation. Therefore, the internal cross-sectional perimeter of the corrugated tube should be as near as possible to the final desired internal diameter. Certainly the perimeter should be no less than about 98 percent and no more than about 110 percent of the desired internal perimeter of the liner. In this connection it should be noted again that the desired internal perimeter of the liner may be either the original well or bit diameter or even slightly larger, or it may be something less than the well diameter as when a liner is set in a well for well-completion purposes and the absolute diameter is not particularly critical.

When a corrugated tube is said to be expanded to substantially cylindrical shape it will be understood that this term is intended to include cases such as where the internal periphery of the tube is about 10 percent greater than the original well diameter. In this case there will be some remaining corrugations, but the liner may be considered substantially cylindrical for my purposes. The same is usually true for the partially expanded end of a tube expanded by the apparatus of FIGURES 2 and 3. The solid cone in these cases expands the corrugated tube to within two or three tenths of an inch of the diameter established by the following arms. In such cases, the portion expanded by the solid cone alone can be considered for my purposes to be expanded to substantially cylindrical form or shape.

The glass fibers which are applied outside the liner and are saturated with liquid resin can be of several types. In selecting an appropriate type, the principal functions of the glass fibers should be borne in mind. The main function is to carry sufficient resin to fill the space between the liner and formation and to penetrate the formation as far as possible. The glass fibers best adapted to this purpose are obtained in the form of cloth, woven of threads which are, in turn, spun from very fine glass fibers, preferably less than 0.001 inch in diameter. Mats in which the threads are stuck together with an adhesive or plastic may also be used. The glass mats may be simply wrapped around the outside of the corrugated liner and held in place by bands, threads, or wires. Preferably, the glass mat is attached by means of an adhesive to the corrugated surface of the liner. In this case, the resin may be applied with a blade or wire brush after the glass mat is attached to the liner surface. If the mat is simply wrapped around the liner, the resin is most conveniently applied to the glass mat, again with a blade or wire brush, before the mat is wrapped around the liner. In any case, the glass mat should be thoroughly saturated with the resin.

Any resin which will cure or set hard, either naturally or artificially, in the well may be employed. Typically, these resins are thermosetting resins, i.e., resins which are capable of undergoing a permanent physical change under the influence of well temperature or an artificially

induced higher temperature. Polyester or epoxy resins are examples. Other suitable resins include urea, resorcinol, and phenol formaldehydes, and the like. Epon 828, an epoxy resin manufactured by Shell Chemical Company, is an example of a preferred epoxy resin. As is well known in this art, these resins may be combined and various catalysts or curing agents employed in various concentrations so that the setting or curing time or pot life for various well depths or various temperatures may be controlled. Versamid resin 140, a polyamide manufactured by General Mills, Inc., is an example of a preferred catalyst which, in the ratio of about 30 parts to 70 parts of the Epon 828 epoxy resin, has a pot life at room temperature of about 3 to 3½ hours. Such resins when set, i.e., when they are cured sufficiently to be self-supporting and relatively rigid, are referred to herein as plastics.

A lubricant should be applied to the inside surface of the corrugated liner tube to decrease frictional drag on the expanding cone and arms. Use of such a lubricant is not essential, but is recommended. The lubricant may be mineral oil, vegetable oil such as cottonseed oil, or animal oil such as sperm oil. It may also be in a more solid form, such as paraffin wax, beeswax, tallow, or the like. A preferred lubricant is made up of about 90 percent ozokerite, or its purified form ceresin wax, and about 10 percent of finely divided particles of malleable material, such as copper, lead, graphite, nutshells, or the like.

My invention will be better understood from the following example of setting a metallic liner in open hole. For this purpose a shallow well was drilled in the Oologah lime where it outcrops near Tulsa, Oklahoma. The well was drilled to a depth of 21 feet using a worn 4⅞-inch bit which resulted in a well of about 4¾ inches. The assembly shown in FIGURE 1 was used to set a steel liner 6 feet long from a depth of about 11 feet to a depth of about 17 feet in this well. The original external diameter of the tube before corrugation was 5 inches and the original internal diameter was 4¾ inches. Eight longitudinal corrugations were formed in the tube to reduce its maximum diameter to about 4½ inches. The corrugated tube was then carefully annealed. Before lowering the corrugated tube and expanding assembly into the well, a mat of glass fibers saturated with liquid resin was wrapped around the tube and fastened in place. The glass was a form known as woven roving. The liquid resin was an epoxy available under the trademark Epon 828. The catalyst was a polyamide known as Versamid 140. The outer unstressed diameter of the spring arms on the expanding head was about 4.7 inches.

To expand the tube in the well it was necessary to embed it into the well wall. This action plus the usual force required to expand the liner to its original cylindrical shape required a hydraulic pressure which varied between about 3,400 and about 7,000 pounds per square inch. Since the area of the piston was about 10 square inches, this pressure produced a total vertical force between about 34,000 and 70,000 pounds. This high pressure may have been due in part to the slightly crooked nature of the well which increased the difficulty of pulling the tool through the liner.

After the liner was set, a caliper survey of the well was made using a special caliper accurate to about 0.005 inch. The results of the survey are presented in Table I. The caliper actually measured the well circumference from which the diameter was then calculated.

TABLE I

Caliper survey stressed steel liner in open hole

Depth (ft.):	Hole size (in.)
5	4.765
6	4.740
7	4.745
8	4.740
9	4.755
10	4.753
11	4.750
12	4.755
13	4.770
14	4.800
15	4.755
16	4.730
17	4.725
18	4.750
19	4.760
20	4.775
21	4.765

Three points should be noted in Table I. The most important is that the internal diameter of the liner between 11 and 17 feet is almost exactly the same as the internal diameter of the rest of the well. Second, the center of the liner is slightly larger than the ends of the liner. This apparently is a characteristic of the system and has been observed in other cases. Third, the internal diameter of the liner seems to be slightly larger than the maximum diameter of the spring arms on the collet head. This observation also is not uncommon in the center of the liner. Apparently the expanding head applies a leverage action which expands the liner following the expansion head to a diameter slightly larger than the expanding head itself. After a liner has been expanded, the ends fit snugly against the expanding head when run a second time through the liner. Opposite the center of the liner, however, the expanding head fits loosely, there being several hundredths of an inch of clearance between the expanding head and the expanded liner. This does not, however, explain why the ends of the liner also seem to be slightly larger than the maximum unstressed diameter of the spring arms. A possible explanation is that caliper measurements were made only at one-foot intervals. The exact dimensions of the liner ends were not, therefore, measured. In any case, however, it is apparent that the liner was embedded into the formation to substantially its entire thickness. This is in spite of the very hard and strong nature of the Oologah lime.

After the liner had been set, the seal between the liner and the formation was tested. For this purpose two cup-type packers were mounted on tubing having an opening in the wall between the packers. The bottom packer opened upwardly and the top packer opened downwardly. The lips of the packers were set 19 inches apart in the well. The lip of the bottom packer was set 9 inches below the bottom of the liner. Water was pumped into the tubing to apply hydraulic pressure to the well between the packers. This pressure was increased in steps starting at about 500 pounds per square inch and increasing in steps of 250 pounds per square inch. No leakage was detected at any pressure up to and including 2,000 pounds per square inch. It was apparent, therefore, that any passages formed by crushing or cracking of the formation when the liner was expanded had been effectively sealed.

I claim:

1. A method for setting a metallic liner in sealed engagement with the wall of a previously unlined portion of a well comprising mounting a longitudinally corrugated tube of a malleable metal on a means for lowering said tube into said well, said tube having an internal cross-sectional perimeter between about 98 and about 110 percent as great as the final desired internal cross-sectional perimeter of said liner, applying around said corrugated tube a mat of glass fibers, saturating said mat with a liquid resin capable of being set to a hardened state, lowering into said well to the desired level for said liner said tube with its surrounding layer of resin-saturated mat of glass fibers, expanding said tube into substantially cylindrical shape in contact with the wall of said previously unlined portion of said well while said resin is in a

liquid state, curing said resin to a hardened state, and withdrawing from said well said means for lowering said tube into said well, whereby a metallic liner is formed and bonded securely to earth formations penetrated by said well.

2. The method of claim 1 in which said malleable metal is steel.

3. The method of claim 1 in which said resin is an epoxy resin.

4. The method of claim 1 in which the internal cross-sectional perimeter of said corrugated tube is substantially the same as the desired internal cross-sectional perimeter of said liner.

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