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Design of Downhole Pressure Isolation Device

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Reza Dashtpour

PROBLEM DESCRIPTION

Background:

Growing number of projects that involve harsh downhole conditions in one hand and increasing restrictions and safety requirements in other hand, have been the key driving factors for improving downhole tools. In this context, pressure isolation tools have been of prime importance and many research and developments have been carried out to improve the performance of these tools.

While some of these activities rely on refining existing technologies, others consist of radically new approaches. Therefore identifying limitations caused by conventional sealing technologies as well as recognizing potentials of novel approaches can be extremely valuable when development of new tool is considered.

Tasks:

1. Collect relevant data signifying the most commonly downhole pressure isolation tools used in the North Sea.
2. Collect related data illustrating the most significant failure reasons of downhole pressure isolation tools.
3. Study some of the recent developments containing novel technologies related to the downhole pressure isolation tools.

Based on findings in the previous tasks, develop a potential design that could offer some advantages compared to the current tools.

SUMMARY

In the petroleum industry, growing number of projects that involve harsh downhole conditions in one hand and increasing restrictions and safety requirements in other hand, have been the key driving factors for improving downhole tools. In this context pressure isolation tools, due to their profound impact on safety and efficiency of broad range of downhole operations, have been given special attention in the recent years.

Many research and developments have been carried out to improve performance of these devices. While some of these activities are focused on refining existing technologies, others consist of radically new approaches. In this master thesis existing technologies related to downhole pressure isolation devices are initially investigated and heir advantages and shortcomings are identified. Furthermore; with the aim of identifying potentials for developing a new design, number of most relevant patents and technologies are explored. Finally a novel design based on existing technologies and recent patents is developed and presented.

From investigation of plug operational failure rates from 1999 to 2012 it is observed that while number of plug runs has more than doubled, the failure rate has dropped from 30% in 1999 to approximately 12% in 2012. Developments in plug design and improvements in deployment methods over the years have played a significant part in this reduction.

At present state, wellbore debris is acknowledged to be a major concern. According to the Statoil evaluation 72% of plug failures are either directly or indirectly triggered by debris in well. Another source of limitations and failures, especially in high pressure high temperature wells, is identified to be associated with elastomer sealing elements.

To mitigate the problems associated with current technology, a new design based on metal to metal seals in combination with semi-solid metal processing technology and expanding characteristic of Bismuth is developed and presented in the final stage of this thesis.

Metal to metal seals have number of advantages over the traditional elastomer seals. However, because of the limitations caused by their design, establishing a satisfactory metal to metal seal at required microscopic level to provide a gas thigh seal is found to be challenging. To take advantage of metal to metal seal to overcome the limitations faced by traditional sealing

technology and at the same time guarantee formation of metallic gas tight seal at microscopic level, a secondary sealing element is considered in the suggested design. In addition to the main design two alternative modifications are also included.

Inclusion of the alternative designs is intended to broaden the application of the suggested plug. This is achieved by initially investigating the stress distribution at the seal's contact surfaces with tubing as the result of its geometry and subsequently providing an alternative geometry profile that could improve the plug performance in certain downhole conditions. In another alternative method expansion of Bismuth upon solidification was used for a creating self-energizing seal.

Finally to improve the possible applications of the suggested design several future work are recommended. Followings are the most important ones among these recommendations:

- A research study to identify a most suitable material that has expanding characteristics and is suitable for wide range of downhole conditions.
- A research study for identifying a modification of the suggested design to suit multiset applications.

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1. INTRODUCTION

Increasing energy demand in combination with limited resources has forced energy companies to consider developing increasingly more challenging reservoirs that are deeper and often consist of harsh high pressure high temperature environments. Such operations are costly and technically demanding which require special considerations as well as specially developed equipment.

As the industry moves towards developing more challenging fields, the necessity for using suitable tools to guarantee the safety and efficiency of the operations becomes increasingly more important. The industry has responded to this issue by introducing more strict and demanding standard verifications for wide ranges of operational equipment. Downhole isolation devices, as one of the most important safety barriers, are vital for safe and successful delivery of various drilling, completion and production operations. Therefore regulatory authorities have given special attention to improve the safety of these devices by introducing more demanding standards such as ISO 14310 V0.

Manufactures have responded to this issue by trying to improve the existing tools as well as exploring new technologies and novel approaches. Numerous patents and technology improvements related to downhole equipment is a valid proof for this claim. For instance metal to metal seals have been given special attention in the recent years. However despite number of successful operations, up to the present time the limitation caused by their designs and characteristics have prevented their widespread success.

This master thesis is an attempt to initially investigate the existing technologies related to downhole pressure isolation devices and identify their advantages and shortcoming. Furthermore, to present innovative technologies that are under development or commercialization and finally to propose a potential design that could address some of limitations of current devices.

2. PERMANENT AND RETRIEVABLE PLUGS

Plugs can be classified based on their design or characteristics. Based on downhole permanency, plugs can be divided into two major groups: Permanent and Retrievable plugs. Figure 1 demonstrates typical permanent and retrievable packers (Heriot Watt University, 2005).

2.1. Permanent Plugs

"Permanent plugs are designed in a way that sealing component will be locked in its set configuration by means of mechanical device. Usually, two opposite sets of slips; one on top and other one on the bottom of the seal, seize any movement (Dashtpour, 2012)." Permanent plugs are run and set by various methods including: electric wireline, tubing/drillpipe and by mechanical manipulation-rotation or run on tubing and set by internal hydraulic pressure. In contrast to retrievable packers, permanent types cannot be removed easily and removal process includes milling operation.

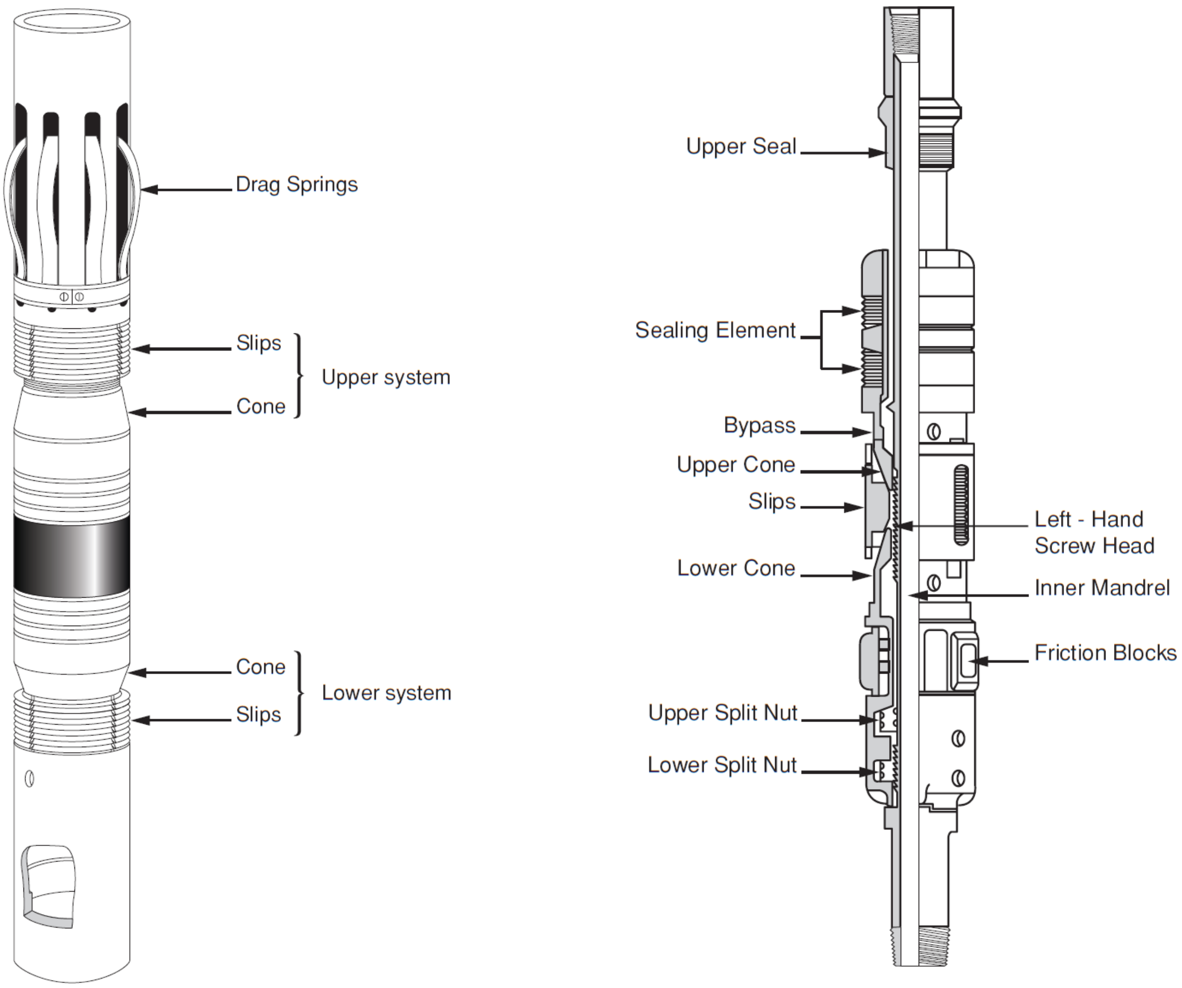


Figure 1 Permanent Packer vs. Retrievable Design

A wide range of permanent plugs with competitive characteristics are available from several vendors. Some of these tools that are widely used in the Norwegian continental shelf will be discussed in more details in the chapter 3.

2.2. Retrievable Plugs

Retrievable plugs are easier to remove and milling operation is usually not required for retrieval process. Compared to permanent plugs, usually designs of these tools are more versatile and may or may not include resettable feature. Low pressure/Low temperature versions are typically very basic while High pressure/High temperature models could be very complex. As the result, these tools are more expensive compared to permanent plugs. Nevertheless, the ease of removal process and in some cases resettable capability most often justify the added cost (Larry W. Lake, Joe Dunn Clegg, & Ruddock, 2006).

Similar to permanent plugs, retrievable models can also be set by mechanical setting tools, hydraulic devices or by using wire-line technology. However, especially in deviated wells, hydraulic setting systems are preferred. Unsetting and retrieval is typically performed by tubing manipulation and applying tensile force through a retrieving tool. More detailed explanation could be found in “Development Study of Downhole Packers and Bridge Plugs” (Dashtpour, 2012).

3. PLUGS PERFORMANCE IN THE NORTH SEA

In order to exemplify the performance of the downhole sealing devices used in petroleum industry, track records for plugging operations from Statoil, a major operator in the Norwegian sector of the North Sea, is presented below. Statoil is among the largest international energy companies with operations in more than 30 countries. However the company's main focus is on the Norwegian part of the North Sea and the company is the largest operator on the Norwegian continental shelf with 60% of the total production. Therefore it is reasonable to suggest the company's experience in plugging operations is an acceptable representative of such operations in the North Sea.

3.1. Main Downhole Mechanical Isolation Plugs

Downhole mechanical isolation plugs can be subcategorized into three major groups:

- Retrievable completion plugs
- Retrievable drilling plugs
- Permanent plugs

According to the data provided by Statoil (Statoil ASA, 2013), while usually there are large numbers of plugs available in each class from different vendors, only few models are preferred. In this chapter the most common plugs in each category are presented and selections of these tools are discussed in more detail to highlight their advantages and limitations.

3.1.1. Retrievable completion plugs

"Retrievable plugs are designed in a way that they can be easily disengaged and pulled out from the hole and may include resettable feature that allows them to be reset in different location. Despite advantages, their sealing capability is lower than permanent plugs and therefore they are not very suitable for high pressure wells (Dashtpour, 2012)."

Figure 2 shows the main retrievable completion plugs used by Statoil in 2012. As it can be noticed from the figure Interwell and Halliburton were the two main plug providers in this category. It is also evident from the figure that, the number of plug runs including ME and EVO plugs were considerably more than other plugs.

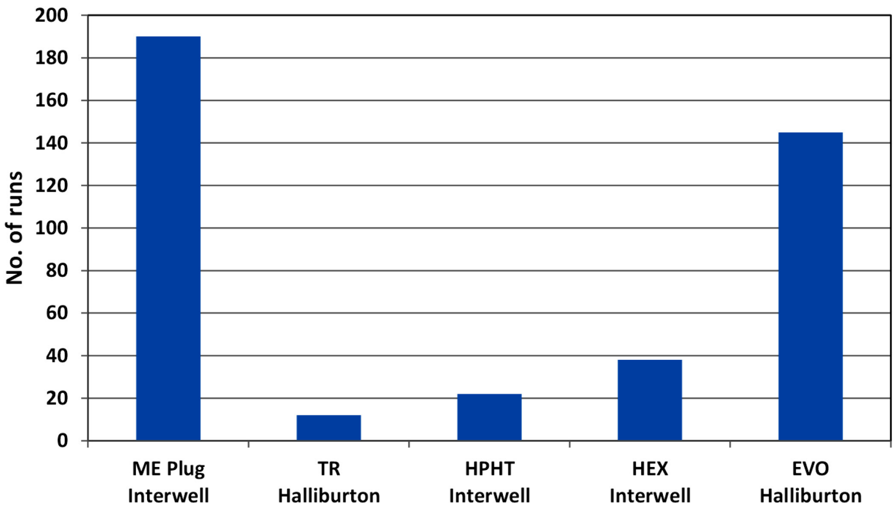


Figure 2 Main Retrievable Completion Plugs 2012. (Statoil ASA, 2013)

Medium Expansion Retrievable Bridge Plug (ME)

The ME plug provided by Interwell, Figure 3, is an ISO 14310 V0 approved bridge plug/packer which can be used as a temporary or a permanent barrier. The plug is a high performance model with a very reliable elastomeric sealing element and an optional internal junk extension. In addition, it can tolerate bi-directional pressure and therefore it can be set in a cross flow condition. The ME plugs are tested to 5000 psi (345 bar) differential pressure and temperatures up to 121°C (250°F). This plug is used in many operations such as workover applications: well control barrier, packer for injection valve, fixed choke etc. Different models which cover various casing sizes from 2 3⁄8” up to 9 5/8” are available.

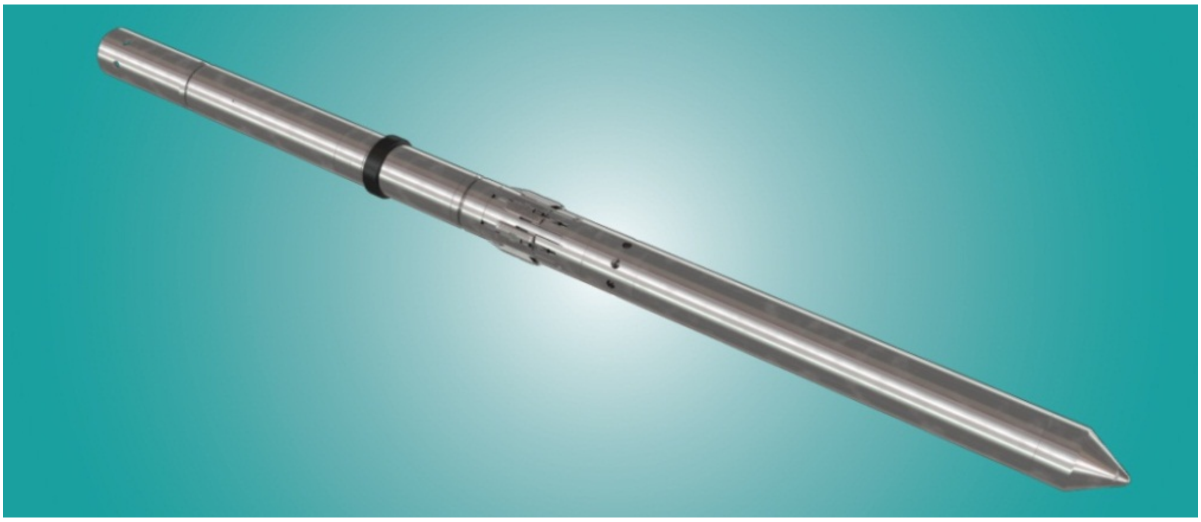
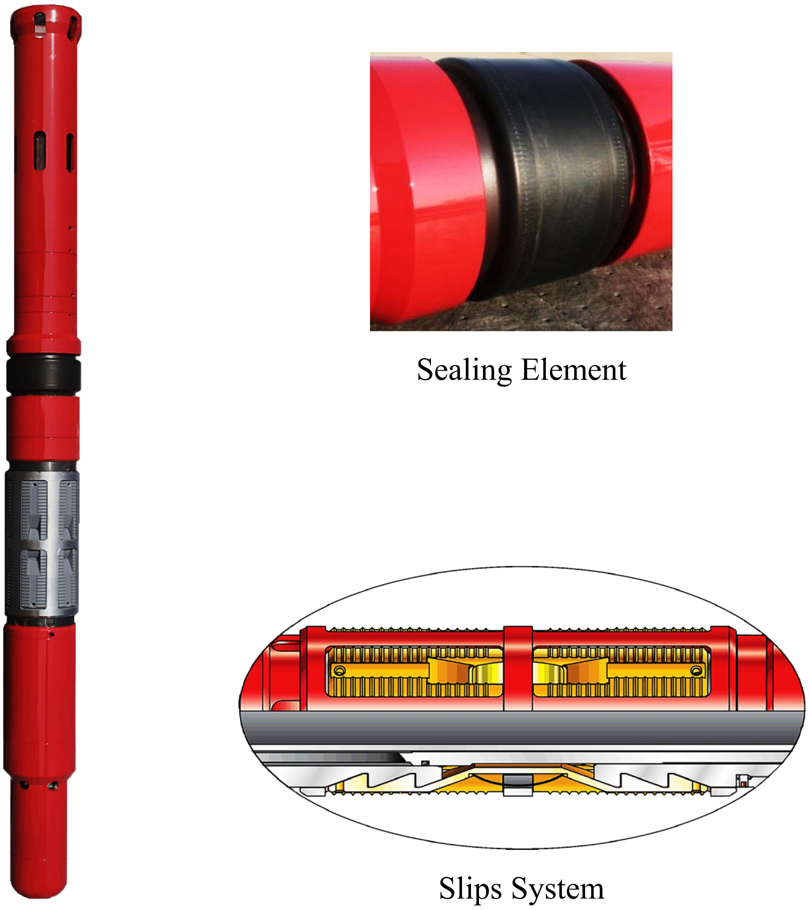


Figure 3 Medium Expansion Retrievable Bridge Plug

EVO plug

EVO-Trieve plug, shown in Figure 4, is one of the Halliburton's retrievable monobore bridge plugs. The plug construction is based on Halliburton's HE3, TR0/TR and Monolock bridge plugs. It is a high performance model and does not require a predetermined setting arrangement for locating or sealing. This plug is also certified for V0 applications based on ISO 1430 up to 7500 psi (517 bar) and 325°F (163°C).



Sealing Element

Slips System

Figure 4 EVO-Trieve Bridge Plug (EVO-Trieve Halliburton, 2013).

Several improvements in EVO design compared to previous models have resulted in a more robust tool. For instance, element is positioned above the slips, which in conjunction with a large diameter pressure equalizing passage, resulted in improved debris tolerance capability. Moreover, concerning pressure reversal, improved body lock ring system helps holding element pack off force better than previous models. The manufacturer also claims that the success rate in retrieval operations has improved through inclusion of top guide mechanism which facilitates the retrieving tool engagement in highly deviated wells.

3.1.2. Common retrievable drilling plugs

Figure 5 shows the common retrievable drilling plugs used by Statoil in 2012. The VMB plug is manufactured by Archer Well company while RTTS and GTV are provided by Halliburton and Baker Hughes respectively. As it can be noticed from the figure, the number of plug runs containing VMB plugs is considerably more the other two drilling plugs used by Statoil and therefore this plug is presented in more details.

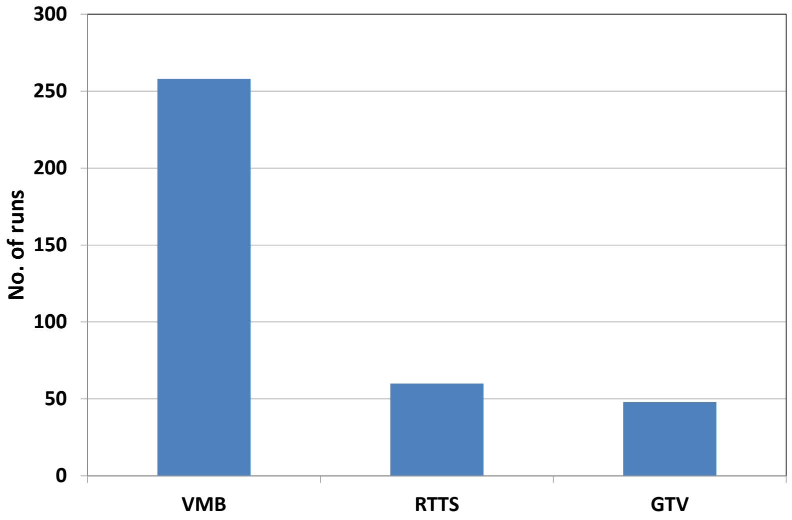


Figure 5 Main Retrievable Drilling Plugs 2012 (Statoil ASA, 2013).

VMB Plug

The VMB plug, illustrated in Figure 6, is a multi-set retrievable suspension plug with a mechanical setting device. The plug is ISO 1430 V0 approved and therefore it can also be used in operations where gas tight sealing is required. The VMB plug has been used in industry as a primary and secondary barrier for temporary or permanent isolation since 2005 and it is available in various sizes from 9 5/8” to 14”.

Running tool assembly

Ball valve assembly; high differential pressure capability and 3 inch through bore; ISO 28781 certified

Figure 6 VMB Plug Complete Tool Assembly (Aarcher Well, 2013)

According to Archer Well, the retrieval operations of VMB plug have never failed in over one thousand deployments. Safe and effective pressure equalization before unseating is achieved through an ISO certified ball valve. If for any reason a milling operation is proved to be necessary for releasing the plug, the mill certified design of the plug allows it to be milled and released without producing large quantity of debris.

Because of VMB plug features, operators can reduce operations time and therefore reduce the operational cost. For instance, unlike many other plugs in the similar class, it is not required to install drill pipes below the plug for setting process. In addition, 3 inch through bore design provides a large flow area and therefore faster tripping speeds without surge and swab are possible. Furthermore, the large through bore also enables active washing to clean the setting area and therefore improves the success rate of setting operation. The large 3 inch bore also provides an easy access to the lower sections via wireline tools and coiled tubing.

3.1.3. *Common permanent plugs*

"In contrast to retrievable plugs, permanent types cannot be removed easily and removal process usually includes milling operation. These plugs are designed in a way that sealing component will be locked in its set configuration by means of mechanical device. Usually two opposite sets of slips; one on top and other one on bottom of the seal, seize any movement. As the result of their robust design and decent sealing capability, permanent plugs are widely used in well completion operations where high pressure fluctuations, which could cause unplanned unseating, are expected. Permanent plugs are also ideal choice for deep and high pressure wells (Dashtpour, 2012)."

Figure 7 shows the common permanent plugs used by Statoil in 2012. Even though the number of plug runs from this class recorded by Statoil is considerably less than those of retrievable plugs, these plugs are equally important. In this category, EZSV manufactured by Halliburton is usually preferred while N1/K1 Baker Hughes are only favored in few occasions. It is interesting to note that high degree of drillability is a common feature between all these plugs. A brief description of EZSV plug is presented in the following paragraphs.

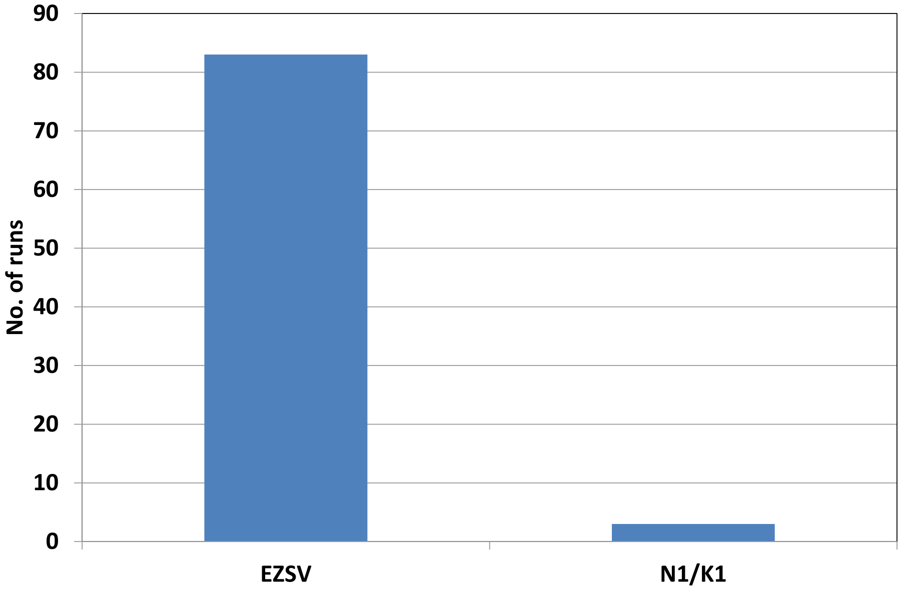


Figure 7 Common Permanent Plugs 2012 (Statoil ASA, 2013).

EZ Drill SV Squeeze Packer

EZSV plug belongs to Halliburton’s drillable tools which include number of tools such as EZ Drill Squeeze Packer, EZ Drill Bridge Plug or EZ Drill Frac Plug. EZ Drill SV (sliding valve), illustrated in Figure 8, is a highly drillable squeeze packer. The plug is made of cast iron, brass, aluminum and rubber. The design and the material choice provide unsurpassed drillability in general oilfield service operations.

“The tool’s sliding sleeve valve allows it to operate as a bridge plug up to the squeezing operation. When the pressure-balanced, sliding-sleeve valve maintains squeeze pressure on the perforations when closed. Operated by pipe reciprocation, the valve seals the packer against fluid movement in either direction. Sliding the valve down to open allows fluid movement through the tool. Side ports in the tool allow unobstructed fluid flow (Halliburton, 2013)”.

The tool’s components are specially designed to set and seal at high pressures and at the meantime produce minimal resistance to drillout. Therefore the tool can be set and seal in different pressure directions. Moreover, due to packer’s small diameter it can be deployed in broader range of casing sizes. As the result of increased clearance between casing ID and the tool, due to the tool’s small OD diameter, the risk of unintended setting is also reduced.

EZSV is mainly employed in squeeze cementing operations however it has also been successfully used as a bridge plug in various operations such as zonal isolation or abandonment.

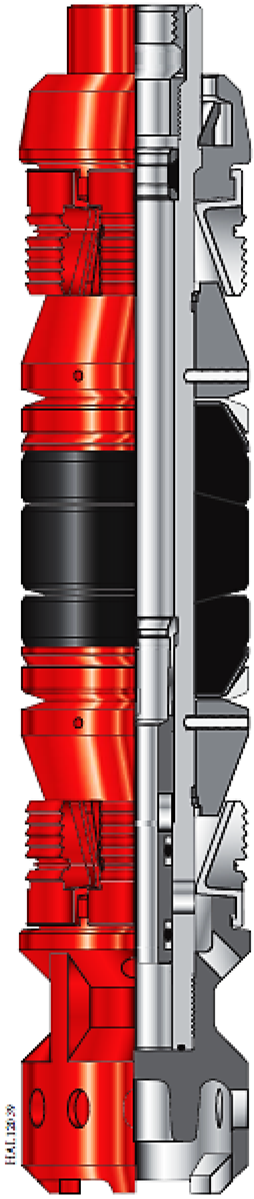


Figure 8 EZ Drill SV Squeeze Packer (Halliburton, 2013)

3.2. Deployment Methods

According to Statoil's statistics, in this company, approximately one thousand plug runs are performed each year. Figure 9 shows the conveying methods used for installing sealing plugs.

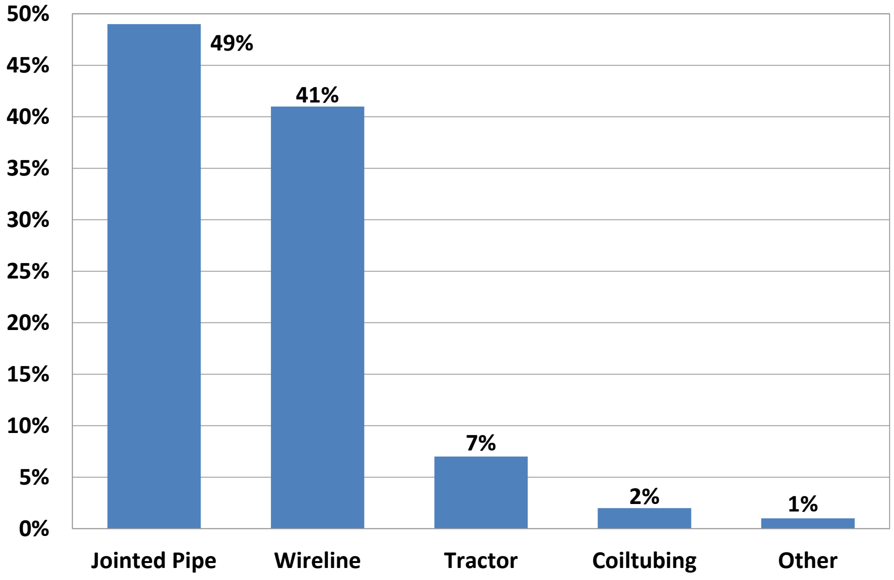


Figure 9 Plug Deployment Methods (Statoil ASA, 2013)

With reference to Figure 9, while various methods are used to deploy plugs; joined pipe and wireline deployment methods are still the most preferred methods and together account for 90% of the operations.

3.3. Plug Operational Failure Rates And Failure Types

Figure 10 illustrates plug failure rates over the last twelve years in the Statoil. While number of plug runs has more than doubled over this period, the failure rate has decreased from nearly 30% in 1999 to approximately 12% in 2012. Developments in plug design and improvements in deployment methods over the years have played a significant part in reduction of failure rates.

The main causes of plug failure are illustrated in more details in Figure 11. As it can be noticed, unsuccessful attempts to reach the desired depth together with not being able to latch on the packer account for nearly half of the failures recorded in 2012. Other significant information that can be drawn from Figure 11 is the effect of debris on plug failure. Wellbore debris is a major concern and many problems with significant costs are associated with unclean wellbore. According to the Statoil's evaluation (Statoil ASA, 2013), 72% of plug failures are either directly or indirectly triggered by debris in well. Failures that are affected by debris are presented in red in Figure 11.

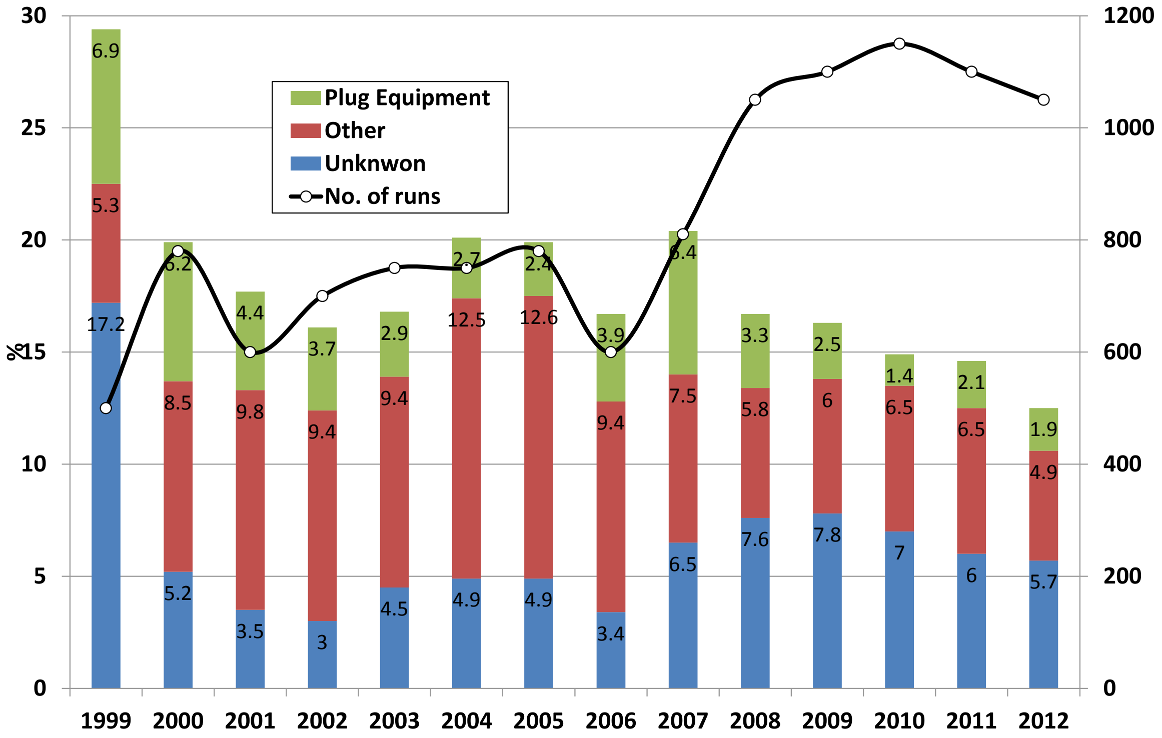


Figure 10 Plug Operational Failure Rates and Failure Types 1999 -2012 (Statoil ASA, 2013)

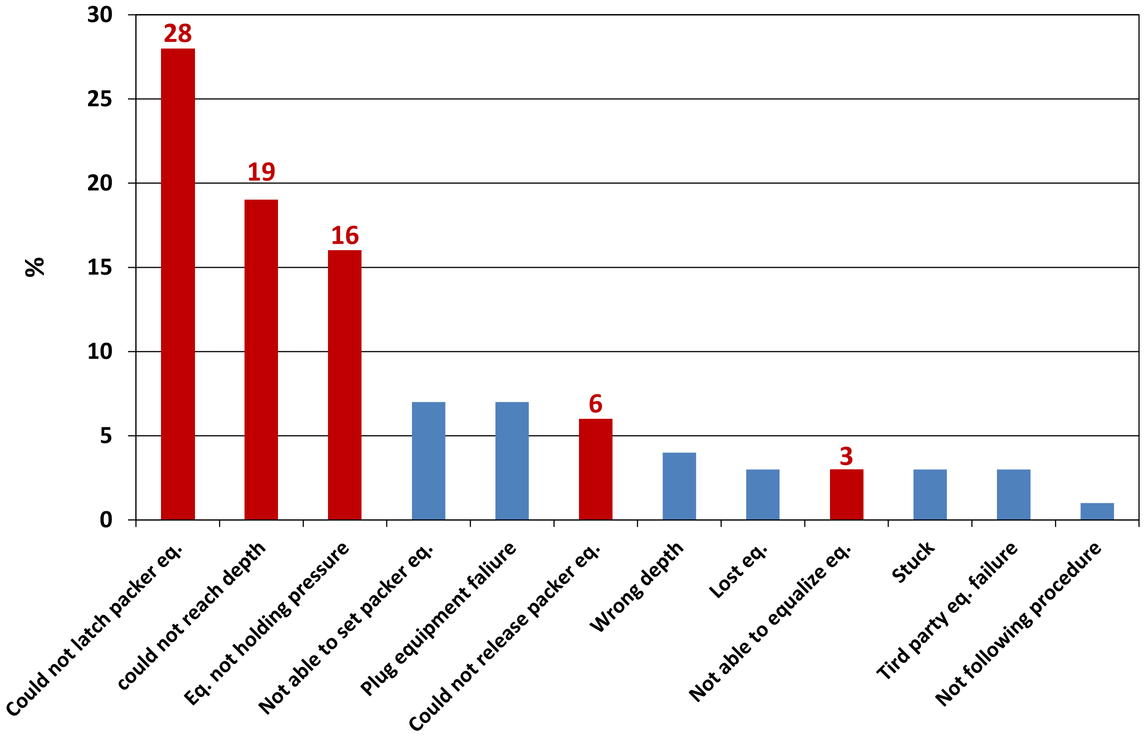


Figure 11 Main Causes of Plug Failure in 2012 (Statoil ASA, 2013)

Wellbore debris can be the result of various factors including but not limited to: drilling and completion operations, well fluid composition and its density, bottomhole pressure and temperature, wellbore configuration and completion arrangement. In the drilling stage number of issues can result in future problems with debris in the well. Among these issues loss of bit cons and accidentally dropped tools as well as residual fragments remaining after drilling out float equipment are the most common ones. In order to avoid further problems, various tools are used to clean the wells from debris. For instance, typically tools with reversing type flow system are employed to lift lost cons and other debris into a finger type catcher and clean the well (Haughton & Connell, 2006).

Usually in the completion stage, debris is formed due to perforating operation. Multiple zone perforation is a common practice and during these operations retrievable bridge plug or packers are used to create isolation between the zones. Typically due to the firing perforation guns, a large amount of debris is generated and settles around the retrieving section of the plug. This in turn makes the retrieving operation challenging or in some cases impossible. Even though packers retrieving tools typically include milling teeth and fluid passage to clean any debris around the retrieving head, metal shavings and junks are proven to be problematic and do not allow the J-Pin to be completely engaged in the internal slot (Haughton & Connell, 2006). Figure 12 shows a selection of debris retrieved from various wells.

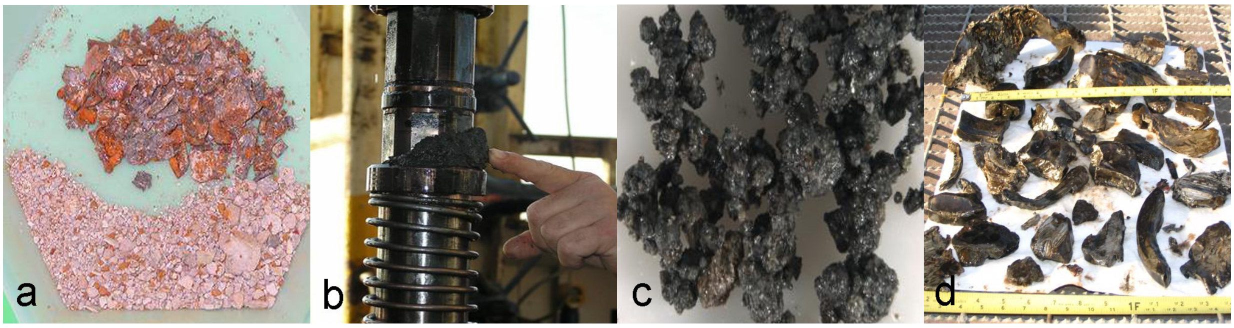


Figure 12 Selection of Debris Retrieved from Various Wells

a) Combination of magnetic and non-magnetic, mainly Quartz and Barite, debris (Javora, Sanford, Qu, Robinson, & Poole, 2008).
b) Very solid debris made of several non-magnetic components, Zinc being the major component, and small magnetic portion (Javora, Sanford, Qu, Robinson, & Poole, 2008).
c) Dense debris recovered from well which is covered by thin layer of wax like material (Javora, Sanford, Qu, Robinson, & Poole, 2008).
d) Small pieces of metal and PDC button recovered from well (Haughton & Connell, 2006)

4. COLLECTION OF APPLICABLE PATENTS

Isolation devices consist of a number of interlinked technologies which must work in harmony to deliver the required isolation under certain downhole conditions. It is difficult to see the whole picture and recognize potentials when individual patents are presented separately. To make this task easier, various techniques and noble ideas which could be implemented to improve current sealing technologies are selected and presented in this chapter.

4.1. Well Sealing Method And Apparatus EP 1339943 B1 (Eden & Eden, 2006)

The patent reveals a description of a method to form a plug in a well by using molten material that expands upon solidification. The patent includes description of procedures and tools which could be employed to fill a length of a well with molten metal which has a melting point higher than the well's temperature and has the characteristic to expand as it cools down and solidifies. The patent is mainly focusing on the advantages of such plugs compared to cement or resin plugs for well plugging and abandonment or other similar operations.

Normally, cement or resin injection is used to form a plug in a length, typically 50 meters, of the well. However for several reasons such as pressure build up over time, contraction of plug materials upon solidification and existence of debris and hydrocarbon film on contact surfaces, often these methods of well plugging are found to have leakage potential over time. Re-plugging leaking wells is a costly and time intensive operation; therefore, a solution that could offer a more reliable seal is highly attractive.

Forming a temporary seal by utilizing expanding characteristics of freezing water is a well-known technology in chemical plants. Even though an ice plug forms reliable seal, it demands constant cooling. The patent presented here is designed based on similar fundamentals however it consists of plug materials with much higher melting point than ice. Here, metallic materials such as Bismuth alloys which expand during solidification process are suggested to be used to form a plug in wells and to avoid pressure communication between layers.

Figure 13 illustrates a graphical representation of typical well plugging contrasted with the patented method. Compared to the conventional well plugging method, plug with a length of order of magnitude shorter would be sufficient to provide the necessary seal. In conventional methods, hydrocarbon film contaminated surfaces of casing 1 and tubing 2 in combination with contracting plug materials, usually cement, impose leaking risk through micro cracks and micro annuli shown as arrow 5. In contrast, material such as Bismuth alloy that expands upon solidification with a right plugging arrangement completely eliminates or significantly reduces such risks.

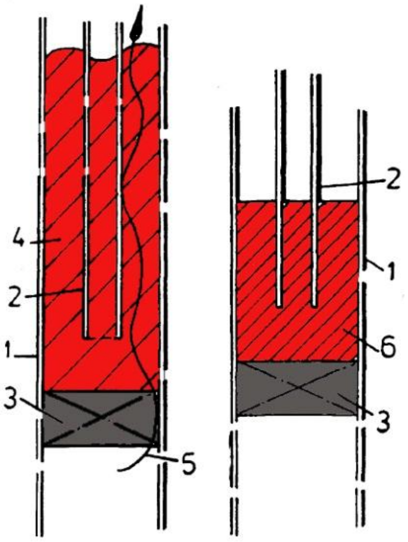


Figure 13 Conventional Plugging Method (Left) Vs. The Patented Method (Right)

Bismuth and number of Bismuth containing alloys such as: Rose's metal (melting point 93°C), Kraft's alloy (melting point 104°C) or Homberg's alloy (melting point 122°C) from printing industry or any other alloy which could be developed to have characteristics suitable for certain downhole conditions can be used as plugging material. These alloys have a higher density in liquid form than in their solid state and therefore expand upon solidification. Plug material needs to have a higher melting point than casing temperature at plugging depth. The material can be delivered to the setting depth in solid form and melted downhole or delivered in molten state. For the first case, the assembly needs to include a heating mechanism for melting plug material when the intended setting depth is reached. The following alternative solutions have also been suggested for this case:

- Delivering the material by carrier fluid in granular form and then melting it through heat generated from chemical reaction of delivery fluid with secondary fluid. For instance, inhibited hydrochloric acid can be an option for the delivery fluid and caustic soda for the secondary one.

- Another method for delivering plug material is using a carrier along with "Thermite" mixture. Material can be delivered to the desired depth in solid form and then a thermite mixture can be ignited to provide the required heat for melting process. Carrying container can also include anchoring mechanism to avoid any upward movement during setting process.

Several other methods for generating and delivering the required heat has also been proposed in this patent such as: heating with steam, electrical resistance heating, frictional heating, sonothermic (sound generated) heating and cavitational (pressure generated) heating.

In addition to the suggested methods for transferring plug material in solid form, the material may also be delivered to the desired depth in liquid form. Plug material can be melted at surface and delivered to the plugging zone in a canister or similar container and then poured into the plugging zone by simply opening the canister through a remote control system or by rapturing a preinstalled diaphragm. Moreover, as an alternative, the plug can also be designed to consist of two parts; first quantity with melting temperature lower than well temperature at the plugging depth, allowing it to be delivered in molten state, and the second part which when added, form a mixture with a melting temperature higher than downhole temperature.

To avoid losing molten metals into lower sections and bound it in a way that facilitates radial expansion rather than axial growth, a basket or a device that engages to the casing and collects the molten material is also considered in the suggested design.

Figure 14 demonstrates an exemplified method for delivering plugging material to the intended depth and an arrangement for providing required heat for subsequent melting process. Brief description of the design and procedure of the proposed method is included in the following text however detailed description of the method can be found in in appendix B.

With reference to Figure 14a**,** plug material is transferred into the casing 1 in solid form and positioned above the packers 3 by using a carrier spool. Figure 14b shows the carrier spool. The carrier spool includes tubular mandrel 10 which is open at the top and has a closed head at 11. The tapered lower end is intended to serve as a wedge that would push the plug into the casing when plug is set and exposed to the reservoir pressure from below. Several circular flanges 12 are designed along the length of mandrel 10. These fins are designed to limit axial expansion of solidifying molten plug material and instead promote radial expansion, increase heat transfer capacity from the core to the plug material and provide a backup mechanism which could reduce creep. Packer 3, mounted below the closed head, is designed to provide a base to avoid losing molten material to the lower section of the well. As an example of heat generating device for melting plug material a thermite mixture heater is also shown in Figure 14d. The heater is to be positioned inside the mandrel 10 and designed as a cylinder with an ignition source 13 and lower heater element 14.

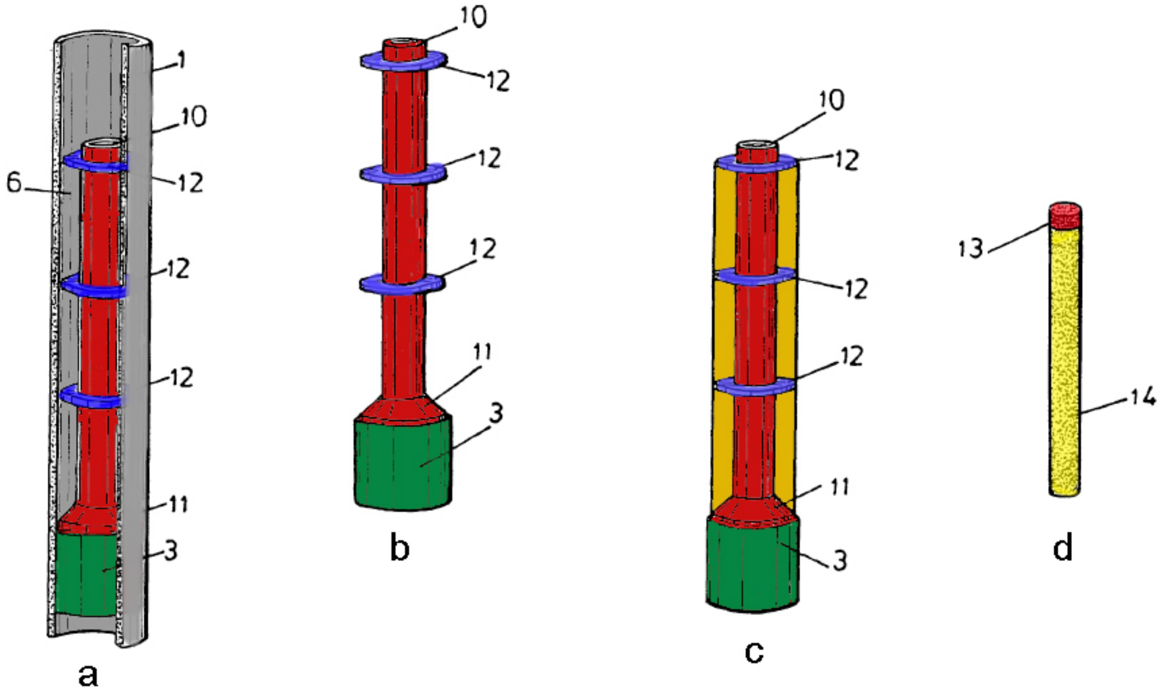


Figure 14 An Example of the Patented Plug Arrangement.

Solid plug material, shown in dark yellow in Figure 14c, will be positioned between the lower head and upper fins 12. By activating the heater, plug material melts and falls into the space above the packer 3 and casing wall 1 in Figure 14a. As the temperature of plug alloy decreases, it returns to its solid form and expands during this process. As long as local temperature remain above the plug’s melting point, solidified and expanded plug will form a reliable sealing plug in the well with a continuous energizing load on the casing wall.

4.2. Deformable Member US 7134506 B2 (Moyes, 2006)

Elastomer seals have been widely used in the petroleum industry. However, searching for difficult oil in increasingly harsh downhole environment with high pressure and high temperature has shown some limitation associated with these seals. Another alternative material that can be used for sealing without those limitations is metal. Tough ductile non-ferrous metals or metal alloys such as carbon steel or stainless steel are suitable for this purpose. Metal to metal seals have been used in various industries such as surface pipelines and automotive industries for several years. However conventional metal to metal seals are complex and expensive. In addition, setting operations of metal to metal seals consist of plastic deformation of the seal material and therefore they can only be used once.

This innovation describes several methods for providing a reliable seal that can be used in a variety of downhole tools. The methods comprise a deformable member that could form a metal to metal seal on its own or it could be used as a backup system in conjunction with traditional elastomer seals to form a reliable and robust barrier.

Due to the limitation of this paper, only the most important variations of this patent are selected and brief descriptions of these are included here. Several other variations are omitted; however, few additional alternative designs with figures are included in appendix C. Due to the importance of this patent, readers are encouraged to study the full text of this patent to gain additional information and insight into other designs and possible applications.

The simplest form of the patent is presented in Figure 15 and Figure 16. The element consists of hollow cylinder 48 which has two circumferential V shaped grooves (52, 54) on the external surface with the grooves depth equal to half of the wall thickness and one 58 on the inner surface that has a groove depth greater than half of the wall thickness. The grooves form lines of weaknesses where the deformation takes place and the hollow cylindrical shape allows the tool to be installed on supporting parts such as inner mandrel or sleeves. During setting process, deformation of the element will be restricted to the zone 62 that is located between groove 52 and 54.

Generally there are four distinctive methods that could be used to set the deformable member: axial force, axial force in conjunction with spring load, differential piston area and finally relative degree of freedom. In addition, combination of these methods can also be utilized to deform the member.

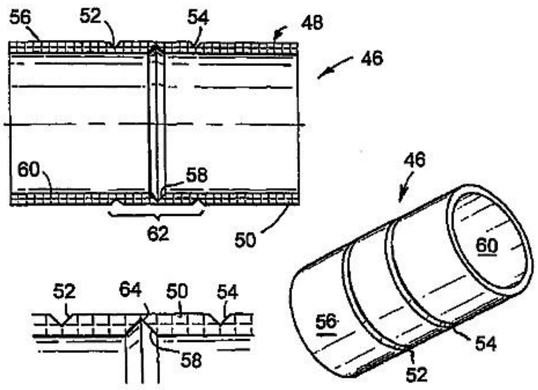


Figure 15 Seal Element in Un-Deformed Position

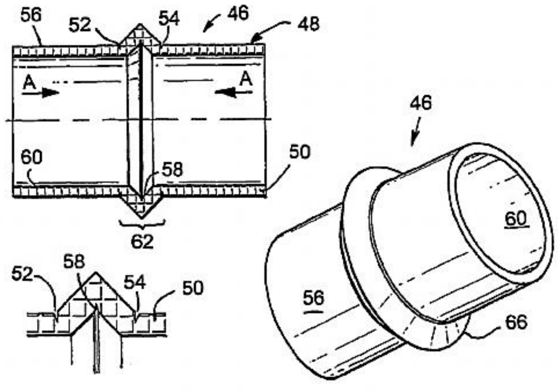


Figure 16 Seal Element in Deformed Position

Figure 16 shows deformation of the element as the result of an applied axial force in the direction shown by arrows A. The compression force generates high stress concentration at the tips of the grooves which in turn causes the member to fold and deform perpendicular to the direction of the applied force. As a result of deformation process, grooves 52, 54 and 58 are closed and therefore element 46 protrudes outward and comes in contact with the surrounding tube. If the member is elastically deformed then compressive force must be maintained to hold the deformed configuration. In the case of plastically deformed member even though the member holds its configuration, energizing force is required to hold the sealing characteristics of the deformed member. It is worth mentioning that the deformed member can be returned to its un-deformed configuration by applying an appropriate axial tensile force. Detailed description of the remaining methods for providing the necessary force can be found in the original paper.

The simple form of the patent presented above can be used in a wide range of applications. For instance, the member can be used as a static seal in construction of bridge plugs and packers or it could be employed as a flow control device in construction of variable annular venturi. By deforming the member to provide a light contact with the casing wall the patent can also be used as a casing scraper tool for removing debris in well or as a part of junk catcher tool.

Figure 17 is an illustration of another embodiment of the present patent. The deformable member 46e shown here differs from the previous version due to inclusion of two grooves 86 and 88 in the inner surface of the member. The grooves are V shaped and machined into the inner wall with a depth greater than half of the wall thickness.

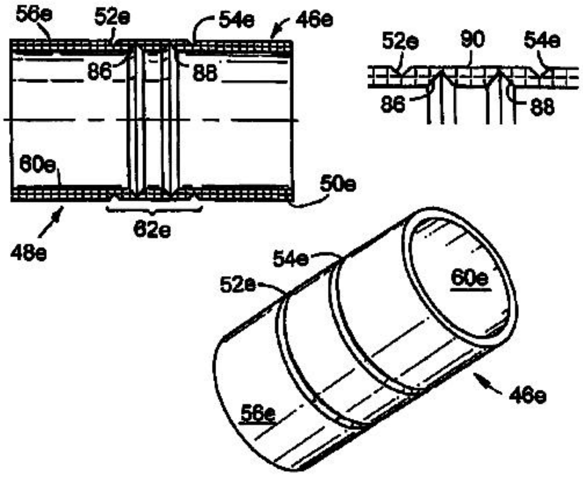


Figure 17 Alternative Design of Seal Element in Un-Deformed Position

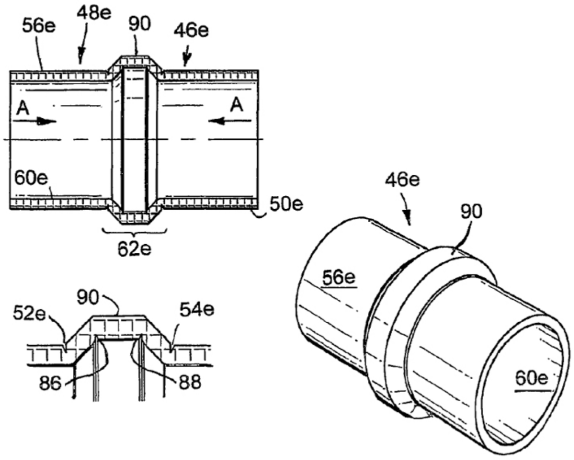


Figure 18 Alternative Design of Seal Element in Deformed Position

Figure 17 shows the same embodiment after the deformation process. Compressive force, shown by arrows A, causes the member to collapse into the shape illustrated in Figure 18. As the result, section 90 of the deformable member's wall comes in contact with the surrounding casing. The arrangement forms a greater contact area compared to the previous variation which results in smaller force per unit area which in turn reduces possibility of damage to the tubing.

To increase the sealing capability of the member and provide a V0 gas tight seal, the flat surface of section 90 could be coated with known sealing materials such as Nitrile, Viton, Teflon or soft metallic material. This will additionally reduce the energizing force needed to maintain the sealing which could make the seal particularly suitable for high pressure high temperature applications.

Figure 19 shows yet another variation of this patent. The deformable member 46k is made of two main sections. The first section is a typical cylinder with a constant wall thickness. The second section is in the shape of bulbous with varying thickness having a minimum thickness at the largest diameter.

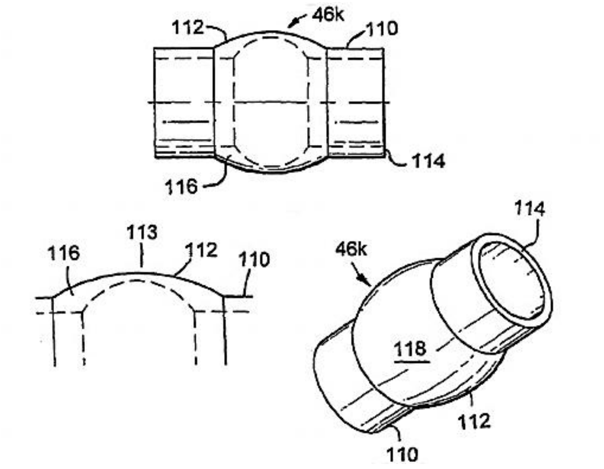


Figure 19 Alternative Design of Seal Element in Un-Deformed Position

The deformed configuration of the tool is shown in Figure 20. Axial force in the direction of arrows A, forces the member to compress axially while at the same time it bulges radially. As the result, the outer surface 118 engages with the surrounding casing wall and forms a pressure tight seal.

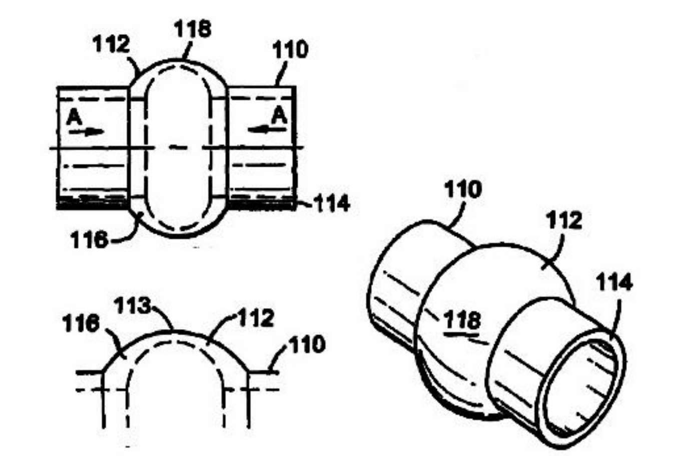


Figure 20 Alternative Design of Seal Element in Deformed Position

The curved contact surface produces a progressive and distributed load on the tool during the deformation process which avoids formation of high stress concentration points that could cause tools failure. This design can be implemented in construction of the tools where dynamic metal to metal seal is required such as reciprocating pistons or tubing expansion joints.

Finally, to characterize the loading regime in the deformation process and the consequent response of the deformable member in each loading zone; a graph of axial load against corresponding deformation is presented in Figure 21. Even though a particular deformable member (member 46s in appendix C) was tested to generate the graph, the figure represents typical response of all alternative designs when loaded in similar manner.

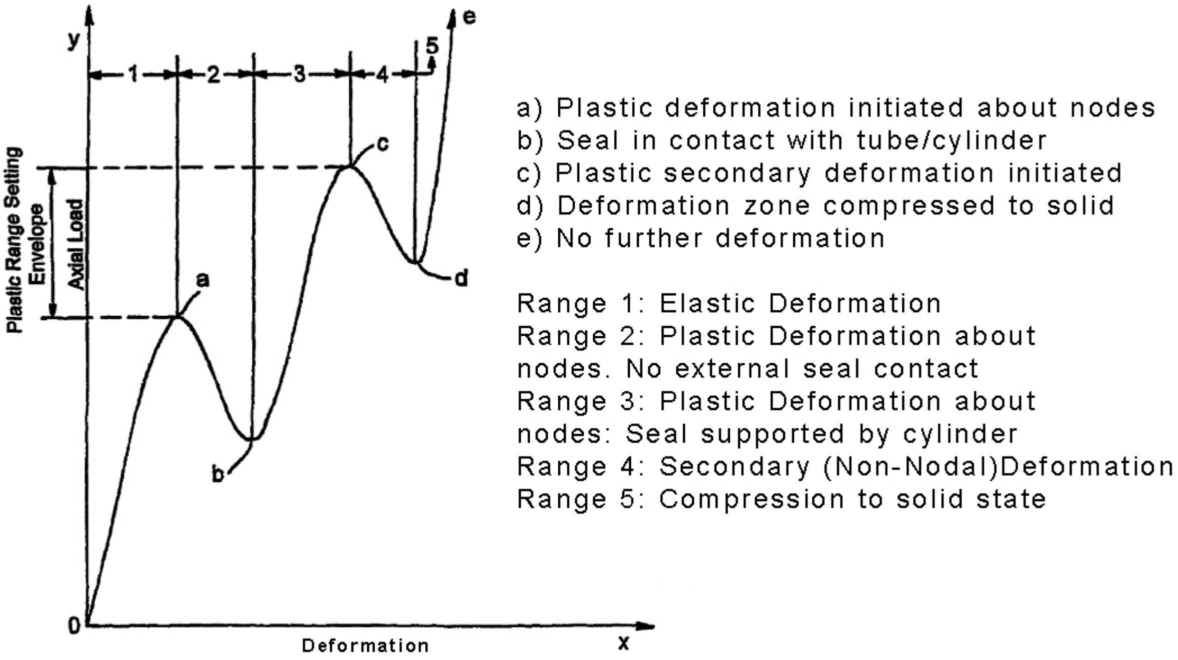


Figure 21 Graphical Representation of Test Results for a Load vs. Deformation Test

In response to loading, the member shows elastic characteristics in the first stage up to the point “a”. The second zone which is bounded by points “a” and “b” indicates the first plastic deformation zone where the member is deformed and comes in contact with the surrounding wall. Zone three shows deformation about nodes. In this stage, load is increased and seal is bounded by the confining cylinder. Additional load after point “c” causes the member to experience the secondary plastic deformation which terminates at “d”. Point “d” represents the point where member is permanently plastically deformed and additional load causes only negligible deformation.

The desirable operating range for the deformable member is up to point “b”, however this window can be extended up to the point “c” just before the initiation of secondary deformation. The Secondary deformation, zone four, is undesired and has to be avoided. To avoid undesired loading the following three methods may be utilized.

The first method is to prevent loading the member beyond the required value. Shear release system with the required loading limit can be used to achieve this goal. The second method includes a device which can limit the deformation range by setting the required travel limit. For this method prior knowledge of the amount of member's compression in each stage is essential. Finally, the secondary deformation can be avoided by expanding the operating window such that the load necessary to initiate the secondary deformation increases. This can be satisfied by including internal or external support features such as shaped metal inserts or purposely designed ledges.

4.3. Plugging Device WO2012079913 A2 (Georgsen, Hiorth, & Malvik, 2012)

Interwell is one of the companies that are active in developing new and innovative technologies related to barrier equipment. One of the latest patent applications by Interwell in downhole mechanical barrier design is described here. The patent refers to a sealing tool that comprises two cone shaped backup systems with a sealing elastomer in between. The innovative plug design offers a high expansion sealing device which also includes a novel backup system that provides an excellent barrier surface against extrusion and ensures longer operating time.

Typically, high expansion sealing devices can pass through narrow restrictions because of their small diameter compared to the conventional plugs. However these plugs can accommodate considerable expansion compared to the normal tools. Whenever a high expansion plug is employed in a well with high pressure high temperature conditions, due to elevated stress state in these conditions and large expansion ratio of the tool, the risk of losing sealing capability is increased significantly. In addition, due to operational considerations it is often required to utilize retrievable devices. Packer elements, when exposed to the harsh downhole conditions in conjunction with high expansion ratio, could deform permanently. As the result, retrieving the tool through narrow restrictions may become impossible.

The patent described here involves a high expansion sealing tool which is suitable for high pressure high temperature conditions and at the same time has a versatile design that allows it to be unset and retracted safely and efficiently at the end of its service.

Figure 22 shows the patented plug assembly in run and set configuration. The tool assembly comprises an anchoring mechanism 2, packer system 4 and connection sub 3 for engaging running and retrieving tools. Since the anchoring device and the connection sub are typical to any plug assembly, they are not discussed here. However detailed description of such devices can be found from many plug suppliers.

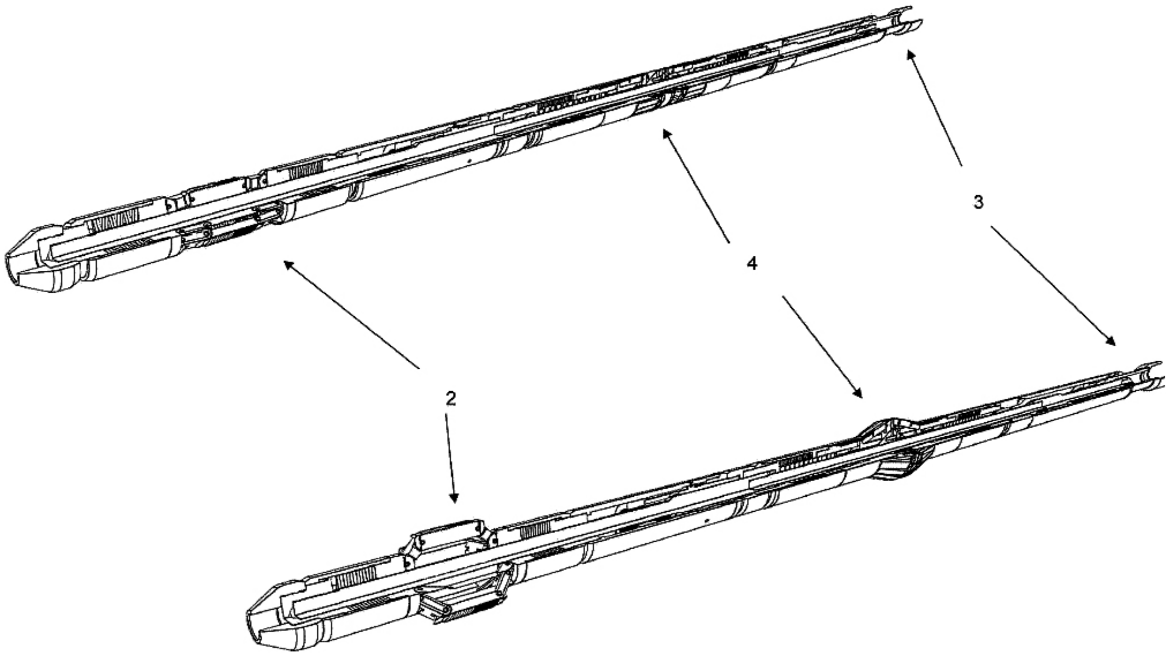


Figure 22 Plugging Device WO2012079913 A2

Figure 23 and Figure 24 on the next page show detailed views of the packer unit in retracted and expanded configurations respectively. The packer consists of ductile packer element 15, packer elements 50a, cone section 10 and packer supporting systems 20 and 22 on each side. In order to expand the packer, initially anchoring device is set and the plug is expanded by applying compressing force to the upper section which causes the packer supporting systems to slide down the tapered surfaces of the cone (12a, 14a) and expand the packer elements. In this process cone 12 is also forced towards cone 14 which causes axial compression of element 15 which in turn results in radial expansion of the same. Consequently, element 15 is pressed against the packer body and forms a continuous ductile seal. The system is designed to be retracted through a reverse procedure by applying tension force through a retrieving tool.

As it can be noticed from these figures, packer elements 50a are alternatively attached to supporting device 20 and 22. In the expanded configuration, packer elements 50a create a circular packer around the tool and form a continuous seal.

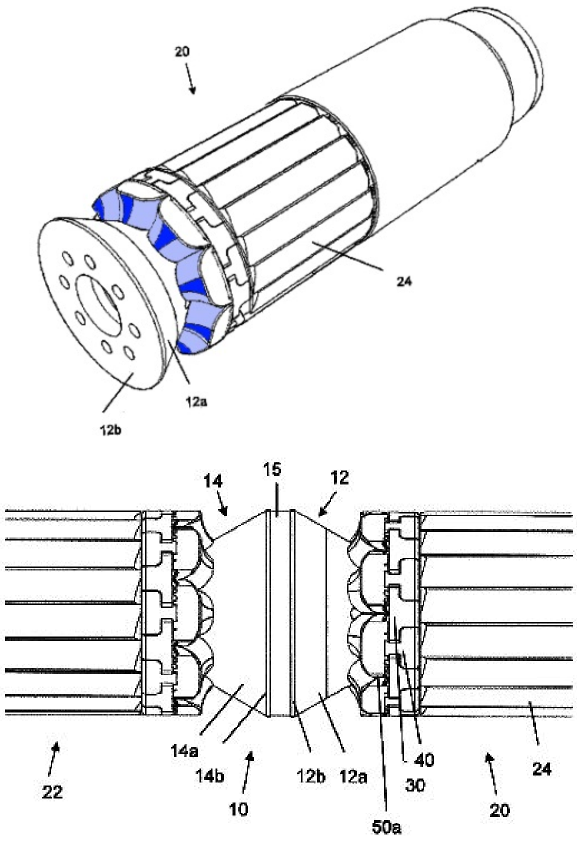


Figure 23 Plug in Retracted Configuration

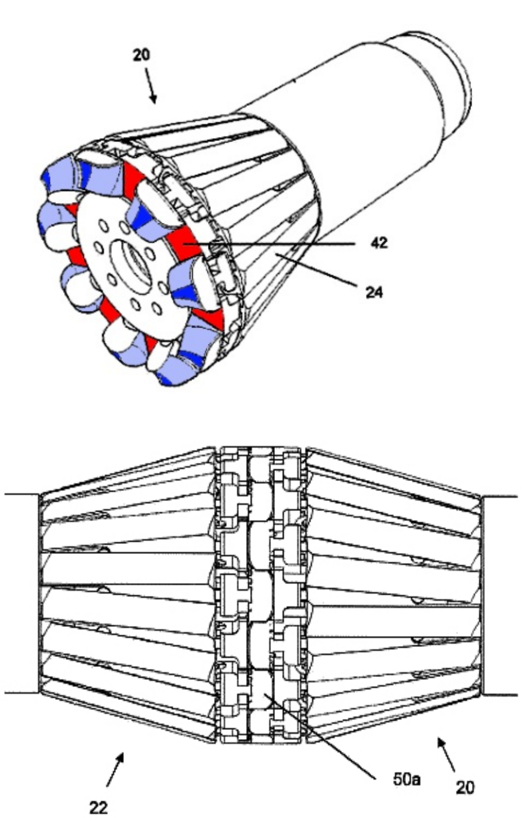


Figure 24 Plug in Expanded Configuration

Figure 25 shows the support elements (30, 40) in the contracted and expanded views. As the tool expands the elements of supporting device slide down the conical surfaces of components 12 and 14 which increases the space between these elements. However, as it demonstrated in Figure 25b and Figure 25c, even in fully expanded configuration the connection between front surfaces of elements 40 and rear surfaces of elements 30 remains.

It is also important to note that in the expanded position, the combination of sliding surfaces 31 and 41 of supporting elements form a continuous circular surface in the inner part of the packer section, which is shown by the dashed line A in Figure 25c. In addition, a continuous circular outer surface shown by the dashed line B is also formed during the expansion by combination of outer surfaces of elements 30 and 40. Therefore, despite high expansion ratio, sealing characteristic of the plug is not compromised in these areas.

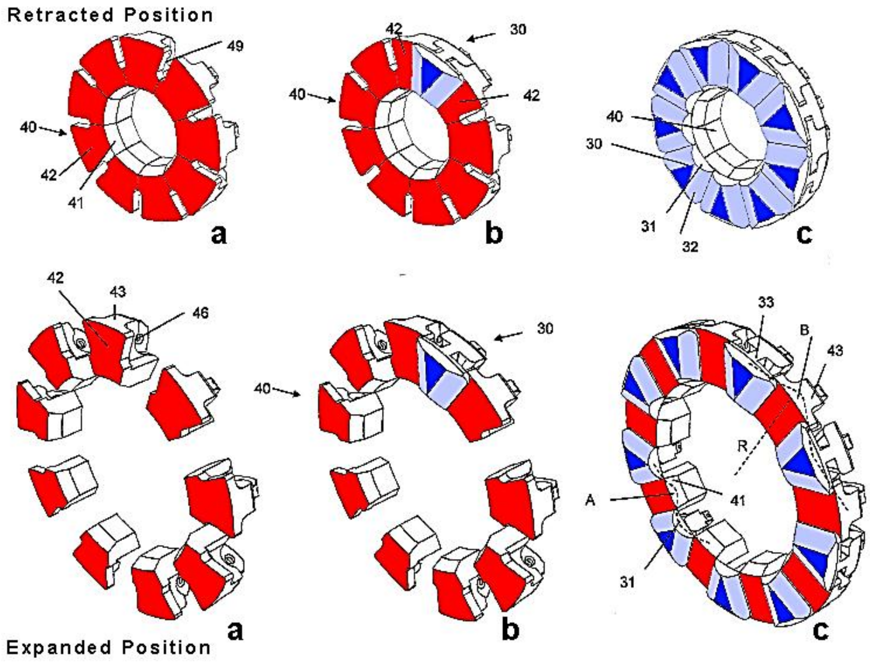


Figure 25 Configuration Of Supporting Elements In Retracted And Expanded Positions

Furthermore, undesirable extrusion is avoided because the packer element is reinforced by supporting faces (32, 42) of supporting elements (30, 40) that are forming a circular ring which is perpendicular to the base of the cones (12, 14).

4.4. Retractable Downhole Backup Assembly For Circumferential Seal Support US8307891 B2 (Bishop, Doane, & Kroll, 2012)

The innovation comprises detailed drawings and descriptions of a unique downhole seal backup system. The backup device described here is particularly relevant to retrievable and multiset plugs especially those that suffer from failures associated with debris. This patent along with the previous patent described in chapter 4.3 could also be particularly important for reference for future work which can include modification of the design described in chapter 6 to suit multiset plug applications.

As it stated in previous chapters and also discussed in “Development Study of Downhole Packers and Bridge Plugs” (Dashtpour, 2012), a typical design of downhole plugs include a cylindrical sealing element that is compressed axially to result in radial expansion of the same and seal the annular space.

One of the problems with elastomer seals that are set by compression force is undesired extrusion of the sealing element. Backup systems, usually in form of single or sets of metallic backup rings, are typically used to limit this issue. These rings are plastically deformed during the setting process and form an anti-extrusion surface at each end of the sealing element.

Since backup rings are plastically deformed they remain in their deformed shape even when the load is removed. This issue can create problems during plug retrieval or resetting process. Generally, during retrieving process the sealing element is extended by applying tensile force which causes the sealing element to retract and disengage from casing. However, because backup ring are usually plastically deformed, they may remain in contact with casing. Retrieving a plug in this situation can cause swabbing and result in associated problems such as formation damage or potential kick and loss of well control. In addition un-retracted backup rings can jam up the plug assembly during retrieval operation and in severe cases subsequent milling process may become necessary.

Another serious issue is settling of debris on top of anti-extrusion backup systems which can also create difficulties in the retrieving process. Conventional designs of plugs with slips above and below the sealing element can also lead to additional problems. When plug is installed downhole and subjected to differential pressures, there will be a transmission of applied differential pressure to wickers of slips. This issue leads to added stress on casing which can cause a failure.

The patent presented here focuses on an alternative design which is less affected by debris in well and also minimizes the transfer of forces created by differential pressure to the casing. The design also includes an arrangement that protects seal elements from moving parts which can damage the seal during setting process or while in service.

The packer design consists of sets of sealing elements with an anti-extrusion system between them. The innovated extrusion barrier system creates a complete circular anti-extrusion ring or rings. Due to unique position of the extrusion barrier, the system is protected from debris when the packer is set. The system is made of wedge shaped elements that are arranged in a way that cause it to change diameter when mandrel components are moved relative to each other.

Figure 26 and Figure 27 illustrate perspective and section views of the patent. As it can be seen the main parts of the system are mirrored components 10 and 12 of the mandrel assembly 14.

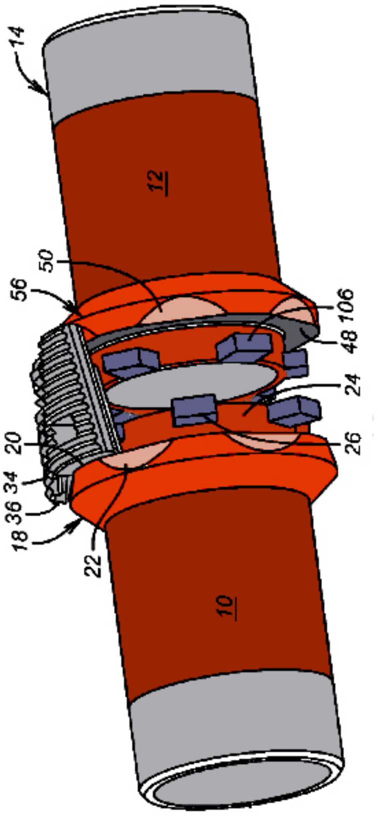


Figure 26 Perspective View Patent US 8307891 B2

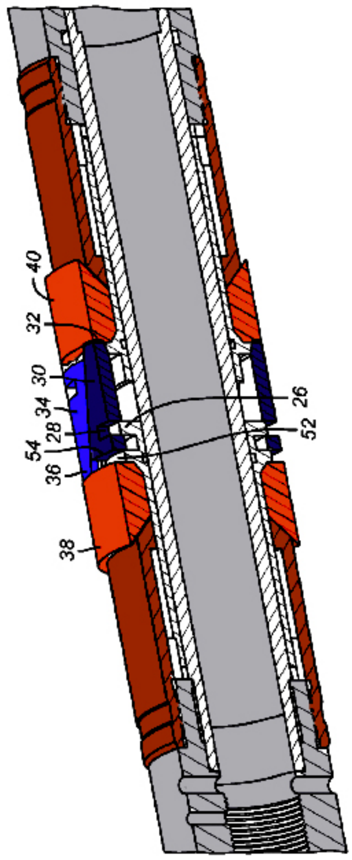


Figure 27 Cutaway View Patent US 8307891 B2

Component 10 is equipped with a ring 18 which has a pushing surface 20 and tapered flats 22. The lower core 24 extends past ring 18 and has outward rectangular projections 26 which are spaced in a way that they match up with the cut outs 28 in the tapered elements 30. These projections permit relative axial movement of the tapered elements while keeping the complete circular shape of the tool. Segments 30 and 34 are arranged alternatively with their noses 32 and 36 facing opposite directions. In order to change the tool’s diameter, segments 30 and 34 are forced to slide axially against each other while their noses 32 and 36 are pivoted in their position. This is achieved by relative axial movement of components 10 and 12. When components 10 and 12 are compressed towards each other, noses 32 and 36 trip over tapered flats 50 and 22 respectively. Subsequently, the other end of the segments 30 and 34 move outward which result in radial expansion of the tool. For an added advantage, exterior faces of these segments could be equipped with carburized teeth to dig into the metal of the casing and act as slips. To reduce the risk of undesired seal extrusion, the gaps between the noses (32, 36) and respective angled flat surfaces (50, 22) are kept to minimum values, for example 0.015 inches.

Figure 28 illustrates an alternative design with two backup systems and three mandrel segments. Seals 80, 82 installed on parts 74 and 78 respectively, the component 76 in addition to backup rings 70 and 72 are located between these seals.

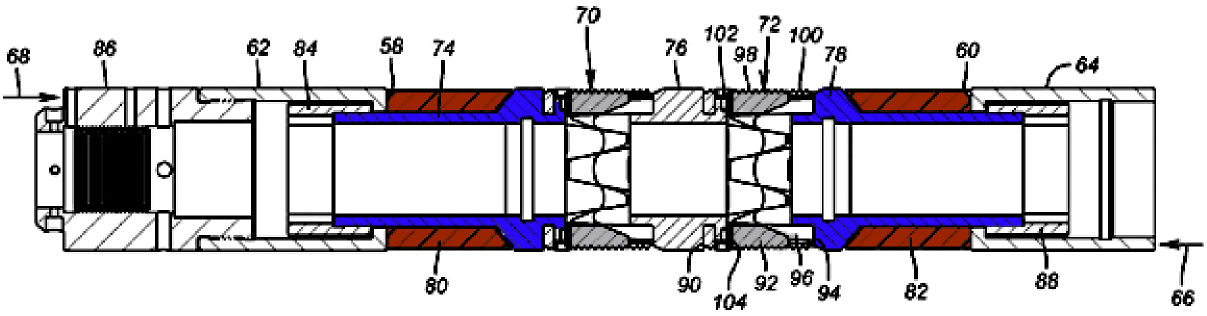


Figure 28 Alternative Design Patent US 8307891 B2

When the setting tool is activated, a compression force, shown by arrows 66 and 68, is applied to the plug and end faces 58 and 60 are forced toward each other. To avoid extrusion in this section during setting process, the relative movement of sleeves (62, 64) is limited by stop arrangement. Two travel stops are required for setting the tool. The first travel stop is reached when top of 86 comes in contact with sleeve 84. When the sleeve 88 runs into a component at the other end, not shown in the figure, the second stop is also completed.

As it can be noticed from Figure 28, in this variation the backup system is located between the seals and equipped with carburized teeth to function as a slip assembly. It is claimed that this arrangement eliminates the transfer of additional stresses, caused by well pressure, to the casing.

5. PRESENTATION of RELEVANT TECHNOLOGIES and MATERIALS

In chapter 6 a possible new approach to plug design is suggested. The proposed design is based on the current plugging technologies used in petroleum industry in conjunction with some of recent patents, known manufacturing techniques and unique characteristics of certain materials. Different designs of current plugging technologies are covered very briefly in chapter 2 and discussed in detail in “Development Study of Downhole Packers and Bridge Plugs” (Dashtpour, 2012). Applicable patents are also covered in chapter 4. This chapter is intended to briefly introduce related technologies and discuss the characteristics of certain materials which will be used in the proposed design.

5.1. Plastic Injection Molding

Injection molding technology has been known for more than a century. However the current manufacturing process is mainly based on the technology introduced in 1960s. Reciprocation screw injection molding machines (IMM), an illustration is shown in Figure 29, are the main equipment used today. The IMM can be divided in two main sections: the injection part and the clamping part. Process materials are prepared in the injection unit and the clamping part is where the injected material is held in mold under certain process conditions, namely temperature and pressure, to form a final product.

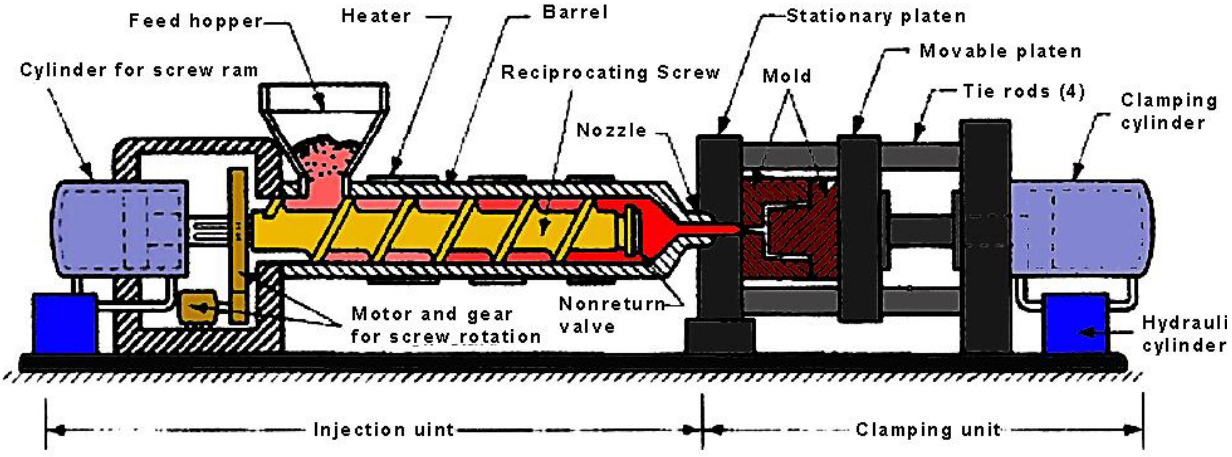


Figure 29 Typical Injection Molding Machine (Frizelle, 2011)

Injection molding process includes several consecutive stages which can be can be followed by monitoring the pressure changes inside the cavity with respect to time. The event timeline illustrated in Figure 30 is obtained by measuring the pressure at a point close to the mold's cavity (Frizelle, 2011). Injection unit prepares the shot and, the followings common stages are performed during a typical injection molding process: (the numbers given to each stage correspond to the event timeline shown in Figure 30)

1. Mold closes.
2. Filling stage: Screw moves forward and forces molten plastic to flow into the mold cavity. To reduce heat loss to the surroundings, this stage is performed in a relatively short period of time.
3. Packing the cavity: This stage includes increasing pressure and thus compressing the plastic inside the mold to achieve the required characteristics.
4. The packing pressure is held until the material in the molds gates solidifies. Thereafter, the packing pressure is reduced and screw rotation initiates for preparing the next shot.
5. Mold opens and part is ejected.

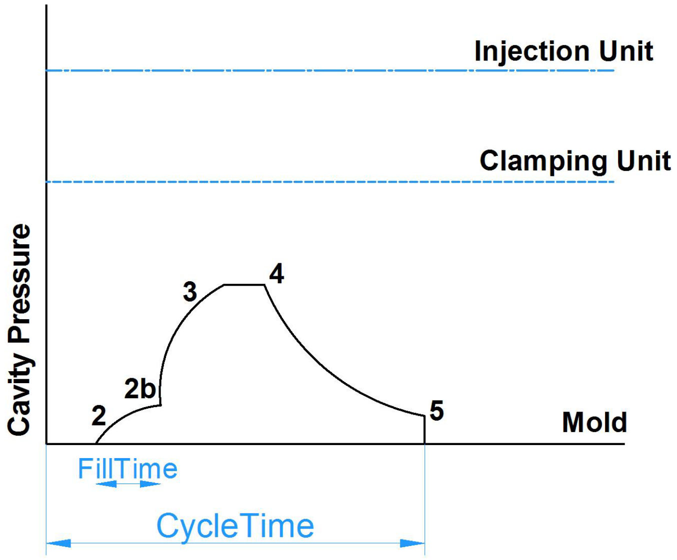


Figure 30 Injection Molding Event Timeline (Frizelle, 2011)

It is important to note that in injection molding process, the necessary heat for melting is not solely supplied by thermal conduction. Rather this objective is mainly fulfilled through frictional heating via rotation of reciprocating screw. A motor drives the screw and as the result of screw geometry, injection material are squeezed and at the same time mixed together. This approach results in rapid heating, uniformly distributed heat and produces smooth molten material that has homogenous properties. Such method could also be advantageous in semi-solid metal processing discussed in the next chapter.

5.2. Semi-Solid Metal Casting

Semi-solid metal casting (SSM) is a relatively new technology which is an alternative method of die casting. The process is based on “thixotropy” property of certain alloys. Thixotropic fluids define the type of fluids that are shear thinning, which means their viscosity is affected when shear rate is altered. As the result of increase in shear stress; thixotropic fluids show reduction in viscosity. The opportunity to use thixotropy phenomenon for producing metallic components was first acknowledged in the beginning of the 1970s (Lowe, Ridgway, & Atkinson, 1999). The semi-solid processing method developed since then and the technology was further divided into four primary methods: Thixocasting, Rheocasting, Thixomolding, and Strain Induced Melt Activated (SIMA) methods.

Thixocasting method

The Thixocasting manufacturing method consists of a die casting process that uses specially made pre-cast billets. Billets are produced through a process consisting of vigorous stirring of materials while the billet is being casted. This results in production of billets that have a non-dendritic[1] microstructure. In the component manufacturing stage, using induction heating and die casting machines, the pre-cast billets are reheated and injected into dies. Final components have exceptionally high quality owing to the material homogeneity which in turn is due to the quality of pre-cast billets that are produced in a similar condition used in producing forging or rolling stock (Midson, Sept. 2008).

Rheocasting method

This technique differs from thixocasting method by the way the feedstock is prepared. In this approach, semi-solid slurry is produced from molten metal provided from ordinary die casting furnace. With this approach the cost of raw material can be substantially reduced.

Thixomolding method

This production method follows a comparable technique seen in the plastic molding process. Feedstock is supplied in form of chips and fed into a molding machine through a hopper which is connected to a heated barrel. A screw feeder inside the barrel carries the material forward while it is heated. The combination of heating and shearing force supplied by rotation of injection screw

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[1] A dendrite in metallurgy is a characteristic tree-like structure of crystals growing as molten metal freezes, the shape produced by faster growth along energetically favorable crystallographic directions. This dendritic growth has large consequences in regards to material properties (Dantzig & Rappaz, 2009).

transforms the material into a semi-solid form. When required volume of semi-solid material is produced, screw pushes the semi-solid slurry into die to produce a desired component.

Strain induced melt activated method (SIMA)

SIMA is a method for forming semi-solid slurry by storing residual strain in billets which causes the formation of spherical structure after reheating (Sirong, Dongcheng, & Kim, 2006). Originally cold worked bar is brought into semi-solid temperature. Then, when the material approaches the solidus[2] temperature, recrystallization occurs and fine equiaxed[3] grain structure forms. When this temperature passes, grains boundaries melt and SSM microstructure forms. Wide range of alloys that can be turned into bar by extrusion or cold drawing are suitable for this process. To guarantee a successful recrystallization response, sufficiently uniform cold worked stock is essential. Therefore the process is limited to bars with the maximum thickness of 36mm.

Products that are manufactured through SSM show characteristic advantages of both casting and forging. Nonferrous metals such as copper, aluminum and magnesium and their alloys are commonly used in this process. Figure 31 shows an alloy in its semi-solid state. “A 3-inch diameter aluminum alloy semi-solid billet being sliced by a knife at 50% solid - 50% liquid. This SSM material has the consistency of modeling clay (Young, 2006).”

Figure 31 Semi-Solid Billet (Young, 2006)

Ideal materials for SSM process need to reach low viscosities that allow them to flow. To satisfy this condition, the process is performed when the solid potion of process material accounts for 30 to 65% of the total mass and the globular primary of solid particles are surrounded by liquid

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[2] Solidus: In chemistry and geology, a solidus is the set of temperatures below which a substance is completely solid or crystallized. The solidus defines the temperature at which a substance begins to melt, but not necessarily when the substance is completely melted (Encyclopedia of Astrobiology, Volume 1, 2011).

[3] Equiaxed crystals are crystals that have axes of approximately the same length.

phase (Young, 2006). The ideal temperature range to produce SSM material varies and it is governed by the alloys constituents. For instance aluminum alloy can be processed through SSM method at a wide temperature range between 5-100°C[4]. (Vinarcik, 2003)

As it is mentioned, semi-solid metal casting method is proven to have several advantages compared to other production methods. Some of these benefits are listed below:

- It is possible to produce parts that are net or near net shaped and therefore subsequent finishing process is minimized.
- Close temperature monitoring linked to the SSM manufacturing processes offers a potential for enhanced tolerance control as well as reducing thermal cycling stress of dies.
- Reduction in volume contraction in the solidification process, lower thermal fatigue and longer mold life due to lower feedstock temperature.
- Solidification defects such as gas entrainment, porosity, shrinkage and hot tearing can be reduced considerably as the result of decrease in turbulent flow in the mold and die which in turn is the consequence of viscosity control in SSM processing methods.
- Superior mechanical properties due to finer and more homogenous microstructure produced in SSM processes.
- Reduction in casting time compared to liquid processing method due to lower heat demands on the dies.

While semi-solid manufacturing method offers valuable advantages over conventional methods, it also introduces some defects that are unique to this processing technique. In addition to common defects in conventional die casting such as cold shuts, flash, warping and gas entrapment, components produced through SSM method can also suffer from containment veins and phase separation (Vinarcik, 2003).

Contaminant veins are due to the planar filling characteristics of semi-solid process or squeeze casting. During the filling process, material front can become contaminated as the result of oxidation and by coming in contact with any potential debris or other sort of impurities in the die. Typically, this type of contamination is found at the last section of die that is filled with material

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[4] This refers to the freezing range not the actual process temperature. For instance Aluminum alloy 319 freezing temperature range in common die casting process is 604–516 °C.

or in some cases, where the front separates and then rejoins on the other side of a core. Contaminant veins can accumulate close or attach to cores opposite to flow direction. The contaminant vein defect can be difficult to detect when trapped under component's surface. However processes such as machining or trimming can unveil the faults. Contaminant veins can become stress concentration points and as a result the component can fail because of unacceptable leak tightness or poor mechanical properties. Preventive measures can reduce the risk of encountering contaminant vein; these measures include but are not limited to: improved die design by for instance minimizing the distance which molten metal should travel to fill the cavity, use of inert gas to avoid surface oxidation and improved gating design such as utilizing fan gates layout (Vinarcik, 2003).

Phase separation, illustrated graphically in Figure 32, is another defect unique to the semi-solid metal production. As discussed earlier, semi-solid metals are made of both solid and liquid phases. Relative velocity of the two phases varies during injection and if the flow travel distance is excessively long and has to pass multiple cores, this can result in phase separation. Phase separation can result in the production of components with spheroidal microstructure near the gates and dendritic structure further away from the gates. Non-uniform mechanical properties as well as solidification shrinkage in the dendritic zone can lead to costly failures. The disparity in mechanical properties, resulted from phase separation, can be a severe issue when the affected components are subjected to high stresses. Moreover, solidification shrinkage is typically associated with undesired porosity in the final product which can result in early failure in pressure vessels. Phase separation can be avoided or minimized by appropriate gating, shortening the distance that the semi-solid metal should flow to fill the cavity and reducing turns in the mold cavity (Vinarcik, 2003).

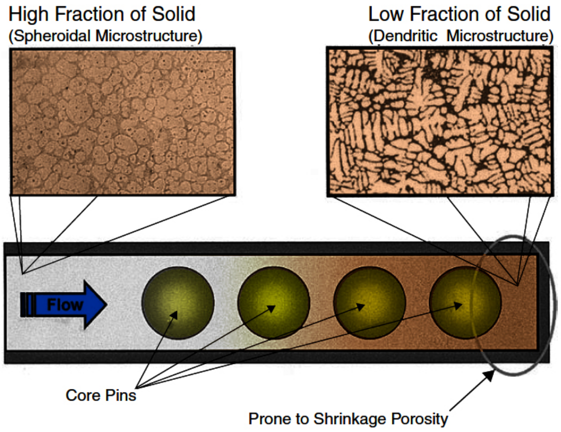


Figure 32 Phase Separation in Semi-Solid Metalworking.

5.3. Bismuth

Bismuth represented by the symbol Bi is a metal with silvery white color but due to surface oxidation is often seen in light pink color. Bismuth melts at 271.4°C and because of its low melting points compared to most metals, Bismuth alloys are frequently used in application such as low melting point solders, electric fuses and safety devices (Hammond, 2004). Bismuth is a dense but brittle metal with low shear modulus (12.8Gpa) which offers great machinability properties (Martienssen & Warlimont, 2005), therefore it also has applications in free machining steels and free machining aluminum alloys where the precision machining properties are required (David Llewellyn, 1998). Therefore if this metal is used in a plug design which has to be drilled out for any reason, the machinability property of Bismuth may offer great advantages by reducing required operation time. The most significant characteristic of Bismuth however, is its expansion upon solidification. Molten Bismuth has higher density (10.05 g/cm^3) compared to its solid state (9.8 g/cm^3) which means it expands during solidification. The expansion of Bismuth through solidification can be advantageous and may offer an opportunity to build a plug that has self-energizing feature. In this thesis, it is intended to utilize Bismuth in construction of plug design therefore some of the physical and mechanical properties of this element at a wide temperature ranges is presented in this chapter.

Mechanical properties

Figure 33 on the next page illustrates the temperature effect on the mechanical properties of bismuth at different strain rates. In this figure ψ is specific elongation, δ represents reduction in section of specimen, ε is strain rate and σ represents the associated stress.

As mentioned above, Bismuth is very brittle at normal temperatures. This fact can also be concluded by referring to Figure 33 where it shows the value of zero for specific elongation and reduction in section at the temperature range of -196 to 0°C. However, as the temperature elevates, a sharp increase in values for both of these characteristics is noticeable which is an indication of improved plasticity. Plasticity reaches its maximum at temperatures between 50-100°C and a further increase in temperature result in sharp reduction in plasticity (Skudnov, Sokolov, Gladkikh, & Solenov, 1969). It is also interesting to note that the strength of Bismuth improves with temperature which is typical for brittle metals.

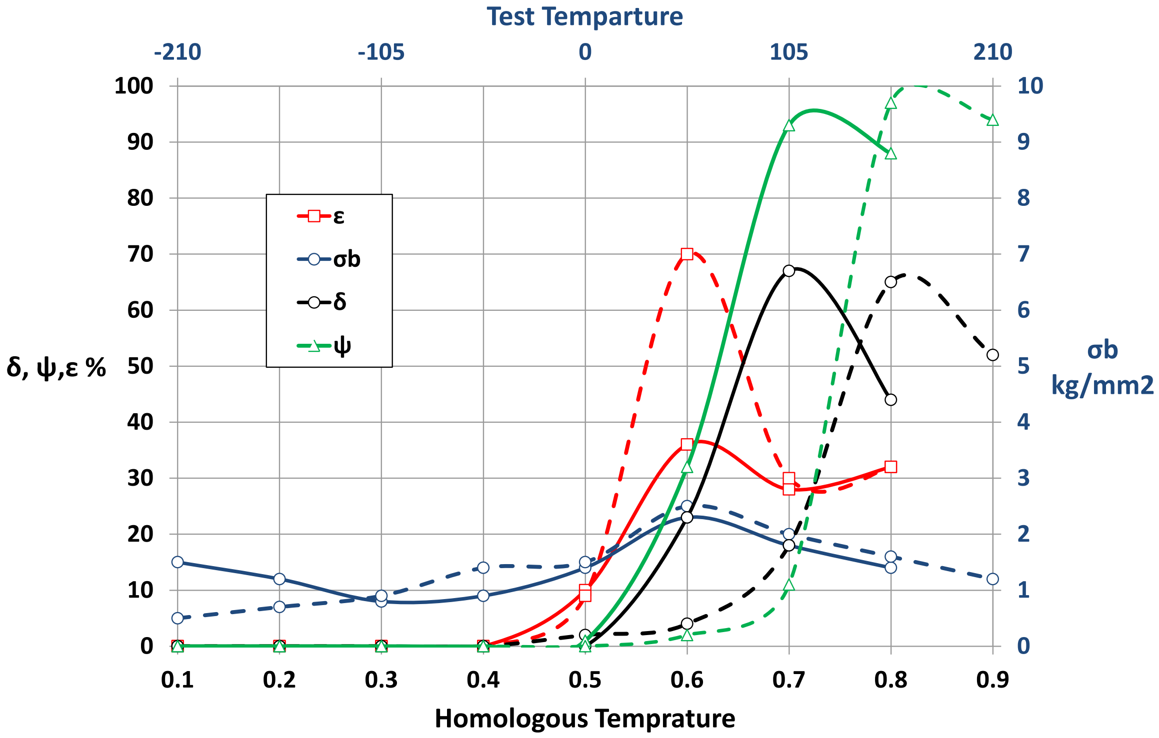


Figure 33 Bismuth Mechanical Properties
Temperature dependency of the mechanical properties of bismuth at different strain rates. ~(1.5-2.0)$10^{-2}$$sec^{-1}$, broken line; (1.5 -2.0) 10^{-1} sec^{-1}, dashed line.
Reproduced from: (Skudnov, Sokolov, Gladkikh, & Solenov, 1969)

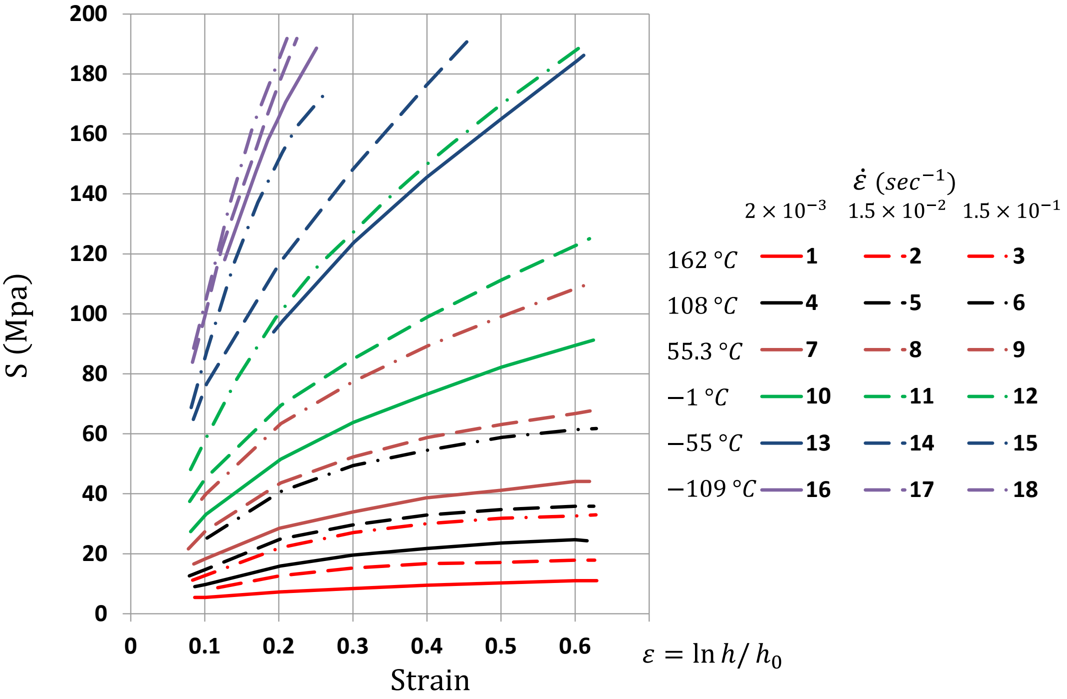


Figure 34 Bismuth Stress-Strain Relationships at Different Temperatures and Strain Rates
Reproduced from: (Skudnov, Sokolov, Gladkikh, & Solenov, 1969)

Ultimate strength of materials in general and metals in particular is greatly affected by stain rate as well as temperature and therefore is not a reliable value for analyzing temperature dependency of deformation resistance. However compression stress – strain experiments provide reliable data for such purpose. Result of compression stress – strain test at different temperatures carried out by (Skudnov, Sokolov, Gladkikh, & Solenov, 1969) is reconstructed for clarity and presented in Figure 34. It is evident from this figure that the "true" stress is directly proportional to the strain rate while it is inversely correlated with temperature.

Density

Figure 35 illustrates change of Bismuth density over a wide temperature range along with its expansion with respect to its liquid phase at melting point. Similar to a wide range of materials, the density of Bismuth is temperature dependent. As it can be noticed, with increasing temperature, Bismuth expands in both solid and liquid phases. However, there is an important discontinuity in the Bismuth expansion curve during the phase change and unlike most materials; Bismuth shows increase in volume during solidification.

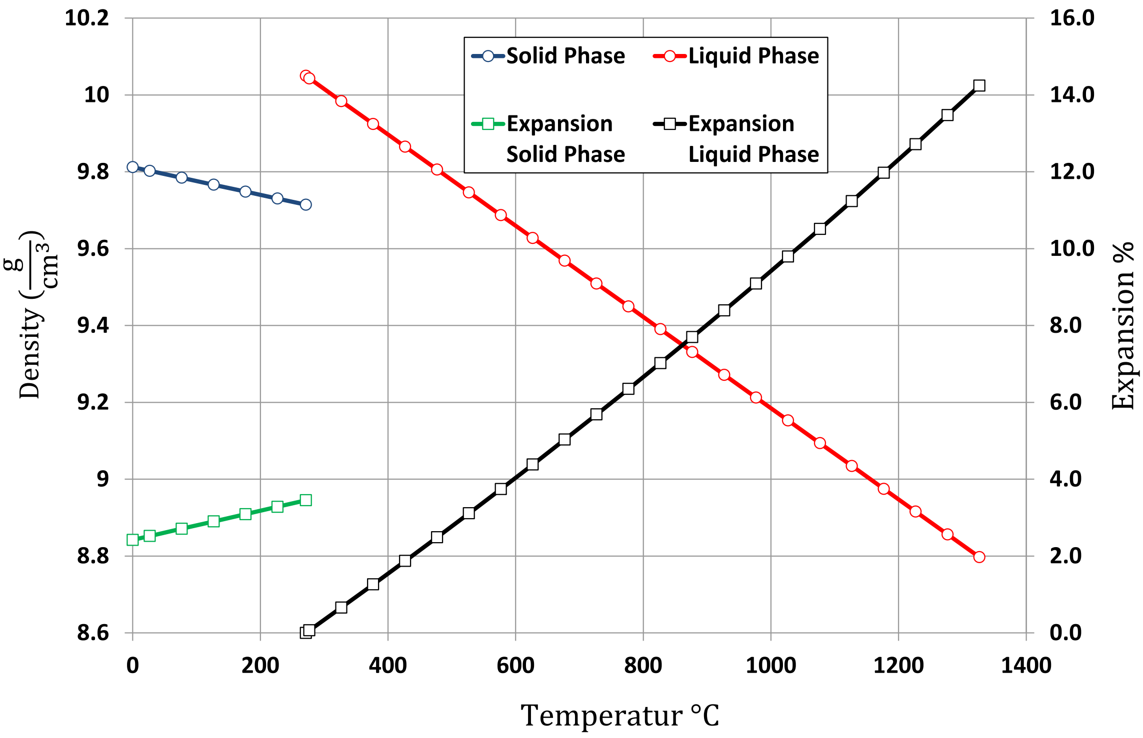


Figure 35 Density and Expansion of Bismuth at Different Temperatures
The expansion values are with respect to Bismuth liquid phase volume at the melting point.
Constructed based on data from: (Stankus, Khairulin, Mozgovoi, Roshchupkin, & Pokrasin, 2005)

With reference to Figure 35, the expansion rate; the difference between liquid and solid phase expansions, varies and depends on the initial and final temperatures of the liquid and solid phases respectively. For example, by converting molten Bismuth into solid state at its melting point, 3.5% expansion can be achieved. If molten Bismuth is injected into a confined space, such expansion is most likely to be adequate to insert the necessary force for energizing the plug and sealing any microscopic voids.

Compressibility

It is mentioned above that the expansion of Bismuth during the phase change may be used for creating a reliable seal at microscopic level or for providing an energizing force for an alternative seal. This is achieved by restricting Bismuth in a confined container while it is expanding which in turn results in pressure increase inside the container.

The expansion values presented in Figure 35 are obtained at atmospheric pressure. However, volume of materials is also pressure dependent. Therefore, to verify whether this pressure increase will result in the compression of Bismuth rather than exerting the expected energizing force; it is also important to present volume variation of Bismuth with respect to pressure. Figure 36 illustrate the Bismuth compressibility curve at 25°C.

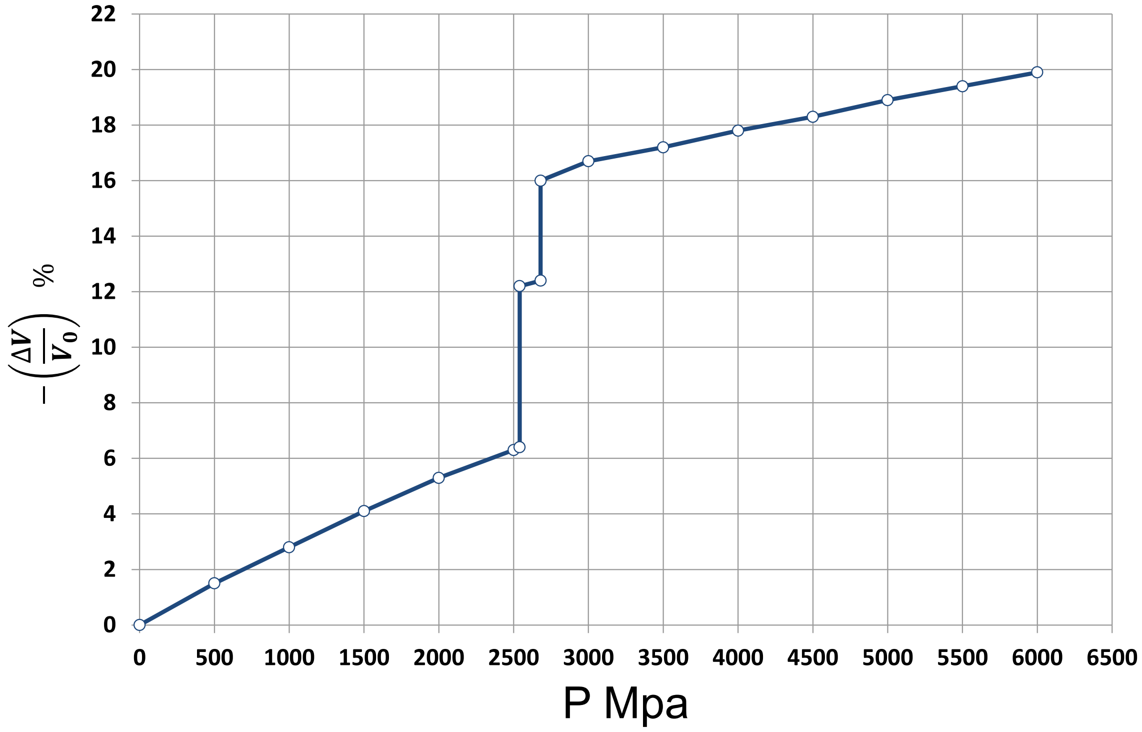


Figure 36 Compression curve of Bismuth at 25°C.
Constructed based on data from: (Giardini & Samara, 1965)

As it can be noticed from Figure 36 two transition points exist on this curve. For pressures up to 2540 Mpa, the compressibility of Bismuth is linear. At this pressure the first transition occurs where the compression value jumps from -6.4% to -12.2%. The second transition takes place at 2680 Mpa where the compressions value changes from -12.4% to -16%. Above this pressure once again the compressibility shows a linear trend.

Considering the yield strength of typical structural steel (250 Mpa), high strength alloy of steel (690 Mpa) or the burst strength of a typical 9 5/8" API casing (10,000 psi or 69 Mpa); the values for Bismuth compressibility will be too small to pose any limitation for the suggested idea.

6. DESIGN SUGGESTION

In this chapter a novel approach to downhole plug design which has the potential to offer number of advantages over the existing designs is explored. The method revealed here is mainly based on some of the applicable patents presented in chapter 4 and the relevant technologies and materials discussed in chapter 5.

Figure 37 illustrates a typical well with casing arrangements, production tubing and a packer. The packer shown in red maintains pressure isolation by sealing the annular space between casing and production tubing. In order to achieve reliable sealing, typically the annular space above the packer is also filled with an appropriate length of cement plug.

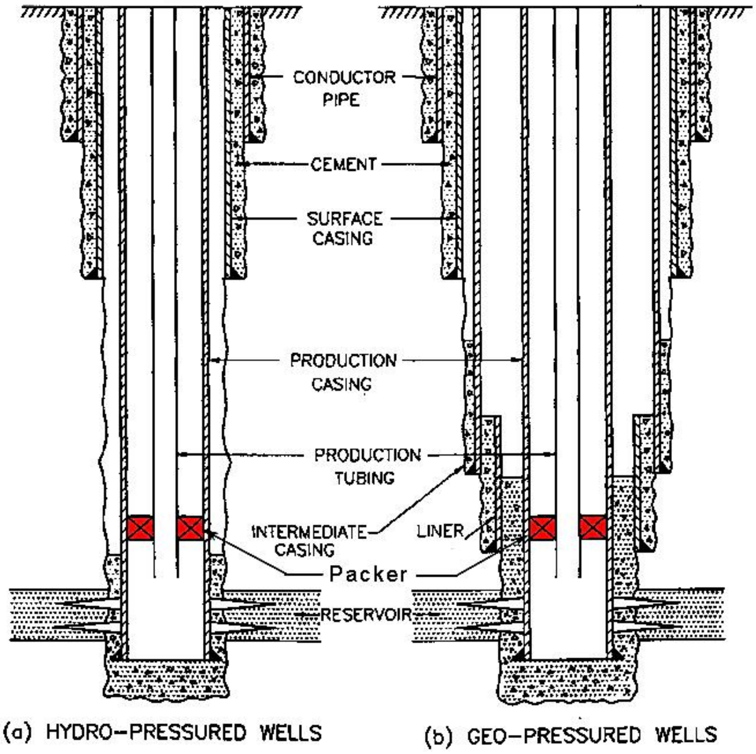


Figure 37 Typical Casing Program (Rahman & Chilingarian, 1995)

However, in many cases a mechanical plug without a cement barrier is used to provide the necessary isolation. In such cases the reliability of the plug is of prime importance. As discussed in previous chapters, successful setting operation and maintaining the required sealing is greatly influenced by several downhole factors. For instance, contaminated contact surfaces of casing and tubing at the setting depth or excess casing ovality could result in unsuccessful setting or it could compromise the sealing integrity in the long term even when the initial setting and pressure testing is successful.

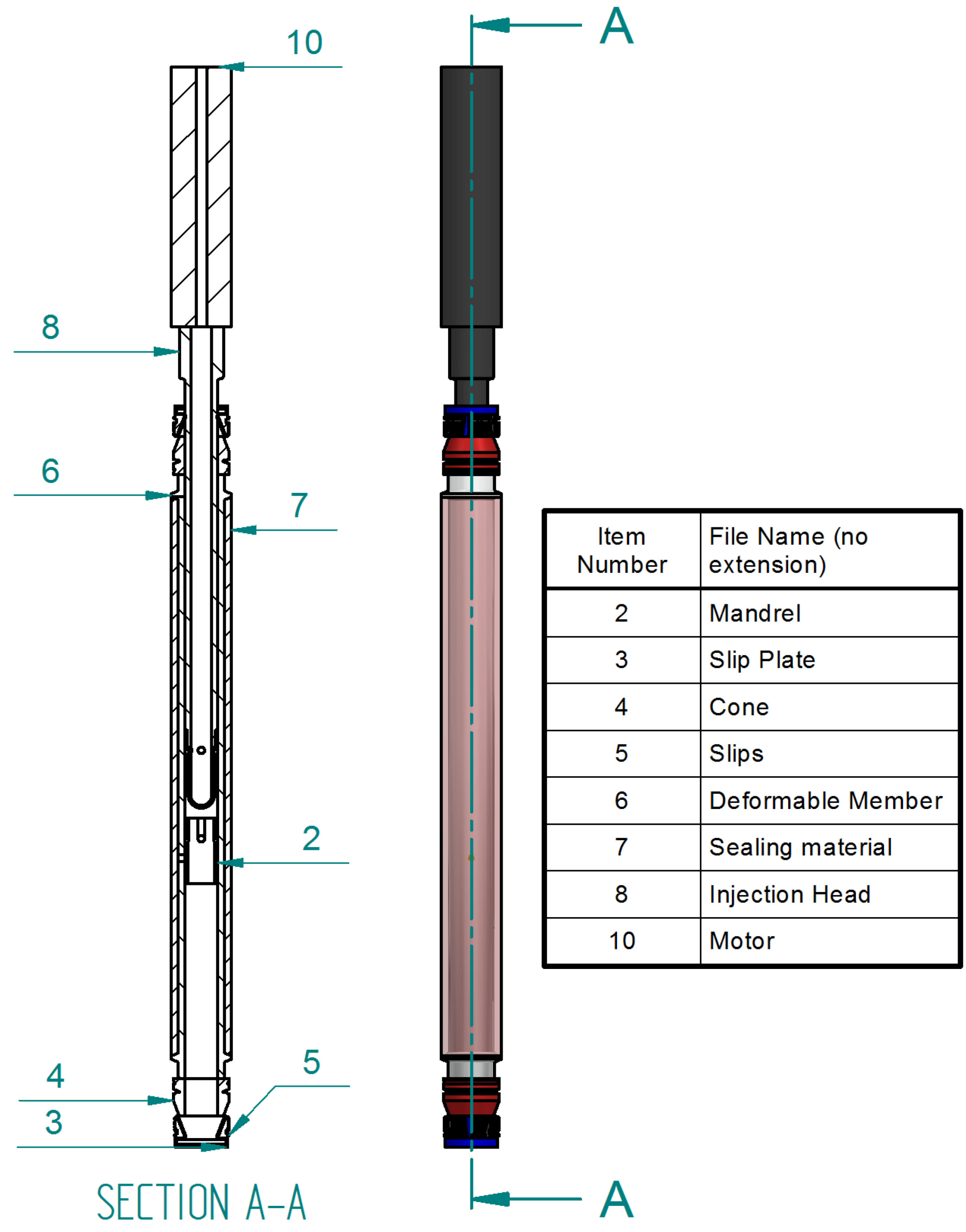
Figure 38 on the next page shows the first embodiment of the proposed design. The design is made of a sealing mechanism that consists of two parts; a deformable member plus a sealing material. The deformable member is fitted to provide a solid metal to metal seal and also to function as a backup system while the secondary sealing element is included to provide superior sealing capability and to increase possible applications of the proposed design by providing a reliable gas tight sealing element. With the aid of detailed drawings, various component of the concept design are described in the following subchapters. For simplicity, only small sizes of the figures are included in the main body of the thesis, however same drawings with larger size are also provided in appendix A.

6.1. Slips And Cone Systems

The assembly includes two sets of slips and cone systems on top and bottom of the deformable member. The slips and cone mechanisms are used to set the plug via a typical setting tool and they are also intended to serve as anchors to support the weight of any subsequent tubing. The slips and cone systems are assumed to have a standard design and therefore are expected to be known by those who are familiar with downhole plug technologies, thus this part of the assembly is not discussed any further in this paper. However, detailed description of such units can be found in “Development Study of Downhole Packers and Bridge Plugs” by the same writer (Dashtpour, 2012). Description of these tools can also be found in catalogues of downhole setting tools from various manufacturers.

6.2. Deformable Member

The metallic deformable member (6), shown in Figure 38, is making the first part of sealing mechanism. The member is designed in accordance with the patent discussed in chapter 4.4. The component consists of two identical deformable sections. Through the setting process the deformable member is subjected to an axial force, as the result the component is deformed and expanded radially to come in contact with surrounding casing (not shown) forming two metal to metal seals. The effect of setting process on the component, obtained from FEM simulation, is illustrated in Figure 39.



Item Number	File Name (no extension)
2	Mandrel
3	Slip Plate
4	Cone
5	Slips
6	Deformable Member
7	Sealing material
8	Injection Head
10	Motor

Figure 38 Assembly of the Proposed Design

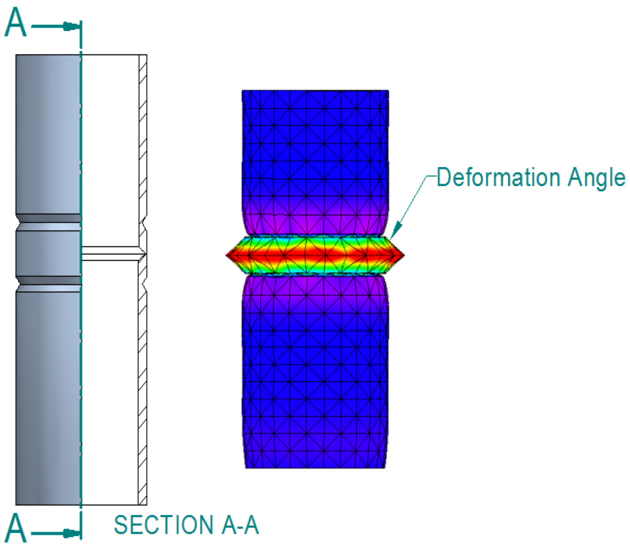


Figure 39 Deformable Member

Despite several advantages of metal to metal seals, due to the limitations caused by their structure, they are not widely used in petroleum industry. Typical rough surface finishes of casing and tubing; possible solids contain of circulation or production fluids as well as casing or tubing ovality, can pose challenges in establishing a satisfactory metal to metal seal at required microscopic level to provide a gas thigh seal.

Unlike elastomer seals, metal to metal seals are rigid and cannot easily enter in all microscopic voids between two surfaces. If the microscopic voids are sufficiently large and adequate differential pressure exists across the seal, there will be a great risk of seal failure due to gas or liquid leakage through these microscopic channels. To prevent such problems, sealing must be achieved at microscopic level meaning that a metal seal has be deformed plastically into the mating surfaces by application of a large force, which has proven to be a difficult operation. Therefore many operators still prefer proven elastomer seal technology that offers greater flexibility over relatively new metal to metal seals.

6.3. Secondary Sealing Element

Noting the drawbacks of metal to metal seals and to overcome such limitations, a secondary sealing element is included in this design. As described above, the presented design contains a deformable member which, after being set, forms two metal to metal seals. The zone between these two seals which is marked as sealing material in Figure 38 and shown in red in Figure 40, forms an empty annular space that could be used to resolve the drawbacks of metal to metal seals discussed above.

To form a reliable seal that is robust enough to avoid any possible leakage through microscopic voids, this space can be filled with molten metal and allowed to be solidified to form a secondary barrier. While various metals may be used to serve this purpose, a metal or an alloy which expands upon solidification can offer additional advantages. As stated in chapter 4.1 and 5.3, Bismuth and its alloys offer such characteristics.

A number of methods for producing downhole metal plugs made of Bismuth or Bismuth alloys and advantages of such methods were discussed in chapter 4.1. An innovative approach that offers several advantages over those techniques will be discussed herein. For simplicity, both Bismuth plug and Bismuth alloys plug will be referred to as Bismuth plug in the following paragraphs.

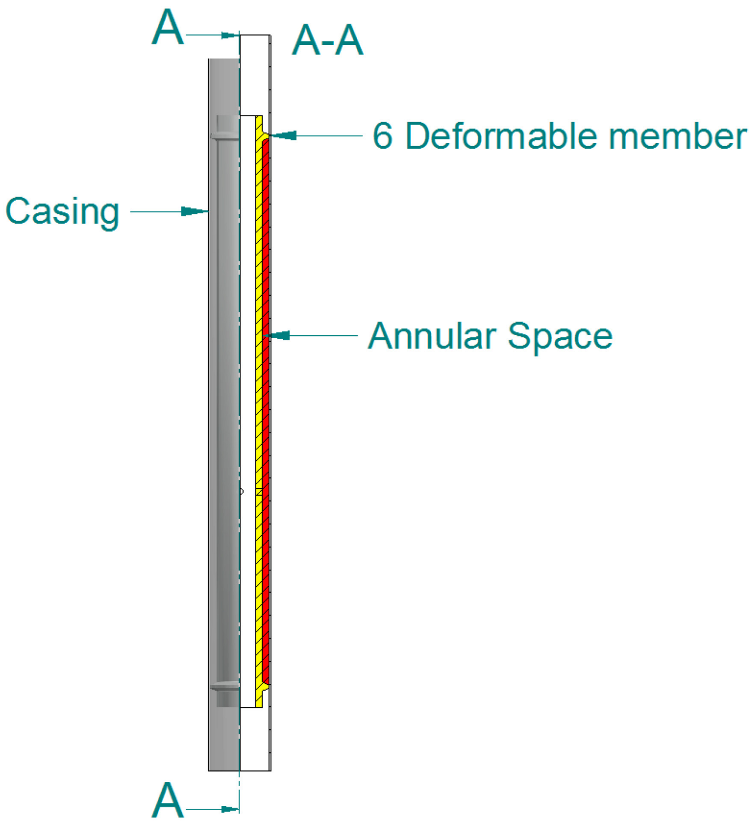


Figure 40 Annular Space

In the suggested design, Bismuth or Bismuth alloy is delivered to the required depth in semi-solid state and injected by means of a specially built injection machine into the annular space between the casing and the deformable member. The injected metal is then allowed to solidify to form a self-energized metal plug. With reference to Figure 40, unlike the patent presented in chapter 4.1, the plug will be bounded radially by casing and tubing and also from the top and the bottom by two metal to metal plugs formed by the deformable member. As Bismuth solidifies it expands and since the plug is bonded in all directions, increased volume forces the plug into any microscopic void in contact surfaces forming a robust plug.

The plug material consisting of Bismuth or one of Bismuth alloys, some examples are presented in Table 1, could be prepared for semi-solid processing through one of the method discussed in chapter 5.2. As it can be noticed from Table 1, apart from pure Bismuth these alloys have very low melting points which may cause serious limitations when typical downhole temperature ranges are considered.

Table 1 Bismuth Alloys

Metal Alloy	Melting T	Eutectic	Bismuth	Lead	Tin	Indium	Cadmium	Thallium
Bismuth	271.4 °C	-	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Rose's metal	93.0 °C	no	50.0%	25.0%	25.0%	0.0%	0.0%	0.0%
Cerrosafe	74.0 °C	no	42.5%	37.7%	11.3%	0.0%	8.5%	0.0%
Wood's metal	70.0 °C	yes	50.0%	26.7%	13.3%	0.0%	10.0%	0.0%
Field's metal	62.0 °C	yes	32.5%	0.0%	16.5%	51.0%	0.0%	0.0%
Cerrolow 136	58.0 °C	yes	49.0%	18.0%	12.0%	21.0%	0.0%	0.0%
Cerrolow 117	47.2 °C	yes	44.7%	22.6%	8.3%	19.1%	5.3%	0.0%
Bi-Pb-Sn-Cd-In-Tl	41.5 °C	yes	40.3%	22.2%	10.7%	17.7%	8.1%	1.1%
Kraft'salloy	104 °C	yes	62.5%	25.0%	12.5%	0.0%	0.0%	0.0%
Hombergs alloy	122 °C	yes	33.3%	33.3%	33.3%	0.0%	0.0%	0.0%

The yield strength of materials is temperature dependent. While there are some exemptions[5], as a general rule, the yield strength is reduced as temperature increases. Thus, the yield strength of Bismuth plug made of such alloys may be reduced considerably and may present extrusion risk at high temperature environments. As the result, preparing specially developed alloys with characteristics required for specific downhole conditions, especially pressure and temperature could be a superior choice. For instance, addition of Antimony[6] increases the melting temperature and improves the hardness and the mechanical strength of alloys or adding a small percentage of sodium in Bismuth alloys can be used to reduce creep (Eden & Eden, 2006).

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[5] Yield strength anomaly: The yield strength anomaly refers to the phenomenon that the yield increases with temperature (Liu, Johnson, & Smirnov, 2005)

[6] Antimony is a chemical element with symbol Sb and atomic number 51.

Semi-solid Bismuth/Bismuth alloy can be prepared at the surface and delivered to the intended depth in a canister equipped with an internal diaphragm. At plug depth, the diaphragm can be raptured by increasing pressure or via a mechanical device to allow the injection machine to force the material into annular space.

Alternatively, the material could be delivered to the intended injection depth in a granular form and turned into the required semi-solid state by allowing it to be subjected to heating and stirring. The necessary heating could be provided through different methods such as an exothermic reaction between two fluids separated with a pressure activated valve or by using a thermite pyrotechnic composition.

6.4. Heating Arrangement

Figure 41 shows an example of delivery method with a heating arrangement. The unit consists of two concentric cylinders. Plug materials are located inside the inner unit and an annular space between the two cylinders is reserved for the heating system.

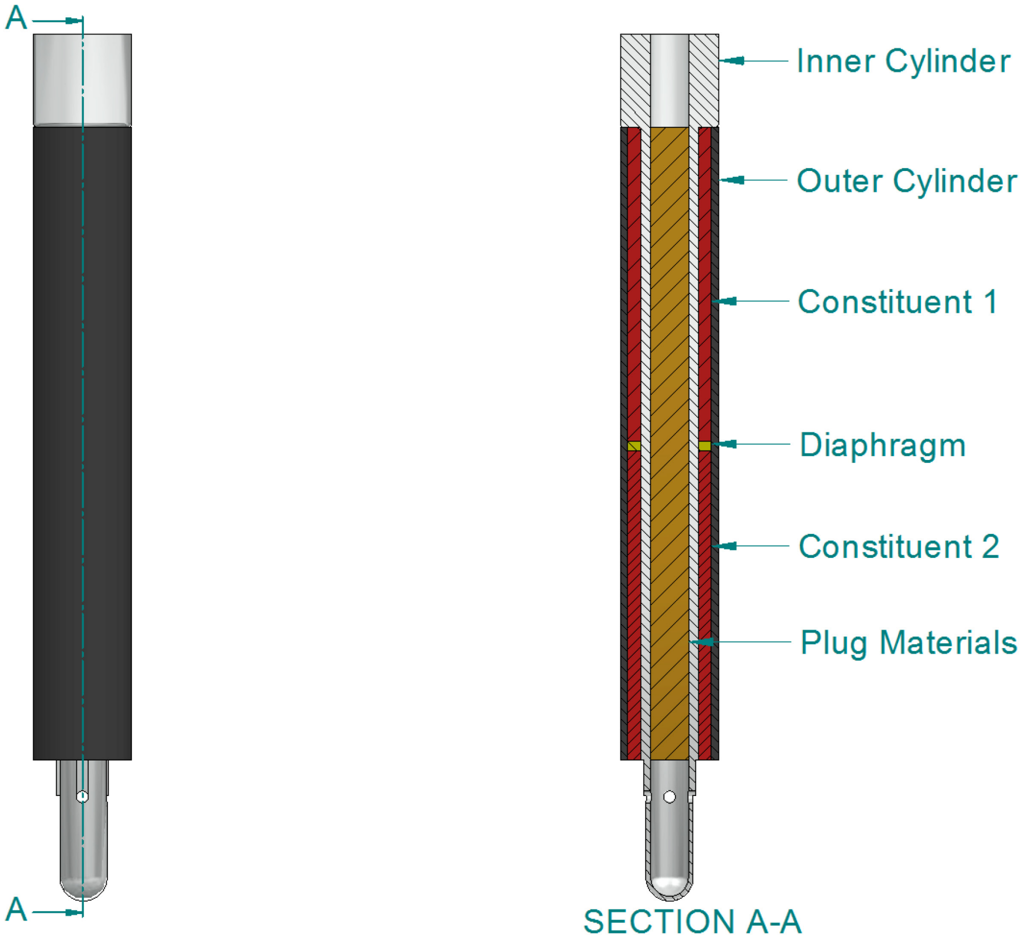


Figure 41 Heating Arrangement

As illustrated in the Figure 41, annular space is further separated into two sections with a dividing partition. Each of these sections is filled with one of the constituents necessary for an exothermic reaction. When heating is required the partition is removed or raptured through a mechanical arrangement or by exerting predetermined pressure on the diaphragm. As a result of an exothermic reaction between constituents, heat will be generated and transferred to plug material through the cylinder's wall by thermal conduction.

Alternatively the necessary heat could be provided by using a modified version of existing technologies. For instance, electrical downhole heaters used in enhanced oil recovery such as the one produced by PetroTrace systems (PENTAIR, 2013) may be adapted to fit the purpose. Currently such devices are capable of delivering the necessary power to achieve temperatures up to 300°C (PENTAIR, 2013). With reference to Table 1 and considering Bismuth melting point 271.4°C, even current downhole electrical heating devices are capable of supplying the heating requirements. Another alternative method may consist of heat delivery by flow of high pressure steam. However, in these types of systems, typically steam has to be generated at the surface and delivered to the required depth through tubing which may complicate the operation.

6.5. Injection Assembly

Injection assembly of the presented design is illustrated in Figure 42. The assembly consists of four main components: mandrel (2), injection head (8), motor (10), heater (not shown) and injection screw (9).

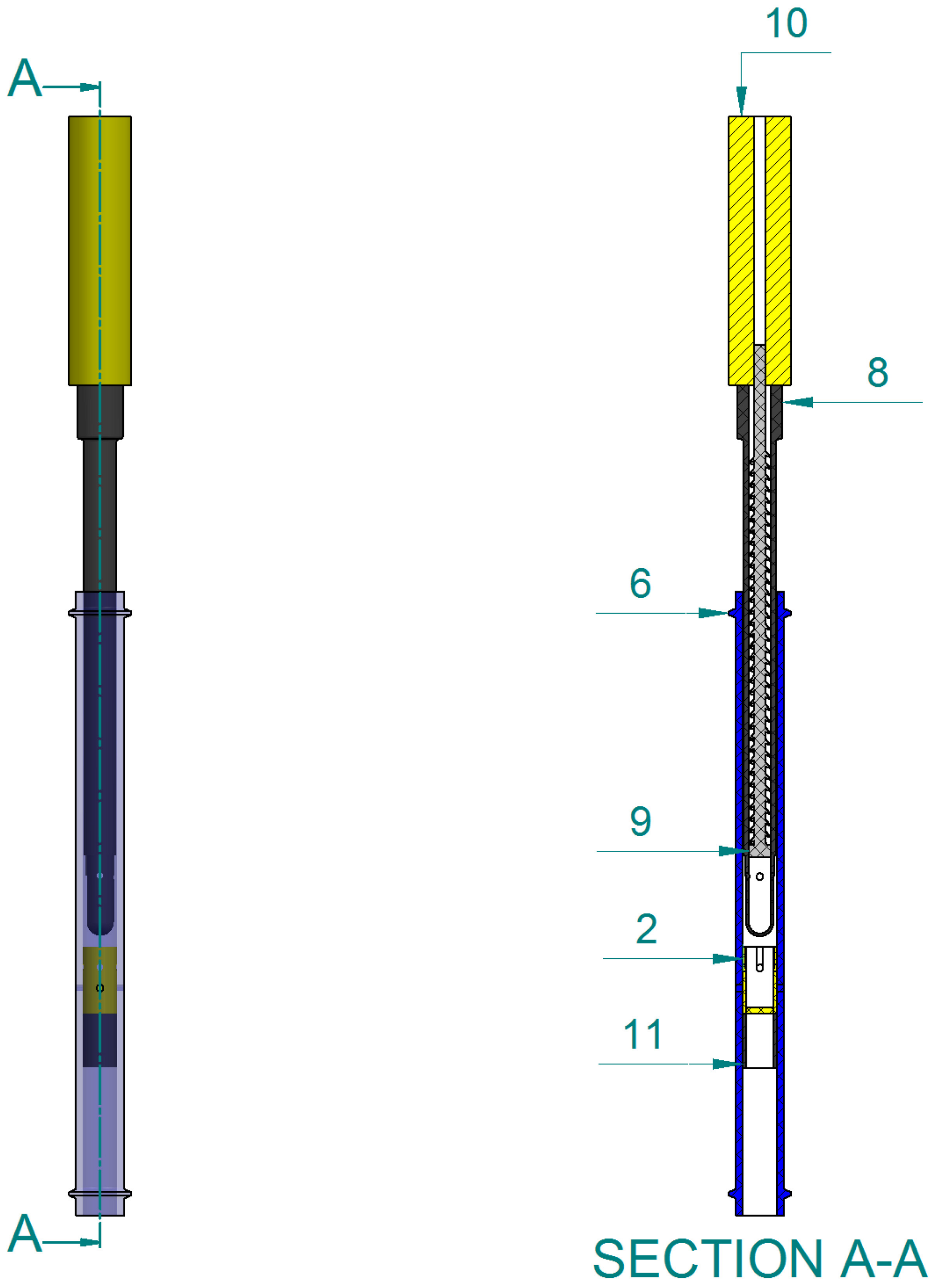


Figure 42 Injection Assembly
(2) Mandrel (6) Deformable Member (8) Injection Head
(9) Injection Screw (10) Motor (11) Spring Mechanism

6.5.1. *Mandrel component*

As seen in Figure 42 and Figure 43, showing detailed view of the mandrel component and associated devices in the assembly, the mandrel (2) is installed inside the deformable member (6) and equipped with a spring loaded linear traveling mechanism (11), linear slots, circumferential holes in its wall and through bore with an optional valve.

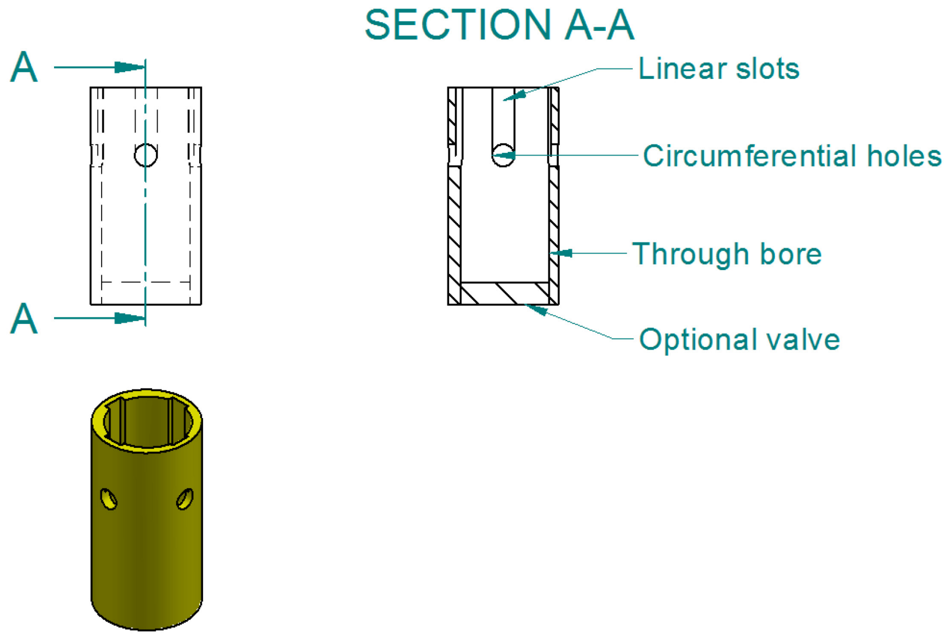


Figure 43 Mandrel

As the result of applying sufficient amount of axial force to the mandrel, the spring loaded system moves and retracts the mandrel between two predetermined positions; an illustration of this operation is presented in Figure 44. Several holes that are machined into the deformable member’s wall are passageways that allow annular space to be filled with semi-solid metal. In the absence of compression force, the mandrel is positioned in a way that it blocks these access holes. However in the loaded position, circumferential holes in mandrel’s wall line up with holes in the deformable member’s wall from one side and holes in the injection head from the opposite side, allowing flow of semi-solid metal into the annular space between the upper and lower metal to metal seals. The optional valve could be used to control the access to the lower sections of the well.

The axial load required to push the mandrel into intended position is to be applied through the injection head. In addition, as illustrated in Figure 43, several slots are machined into the inner surface of the mandrel’s wall. These slots are designed to match up with corresponding tongues in the injection head. When the semi-solid material is ready for injection, the injection heads moves down and tongs and grooves mechanism engages. The injection head and mandrel coalesce and move further down until all three sets of holes line up. When this position is reached, injection begins and annular space fills up with already processed semi-solid metal. Finally, once the required volume of the material is injected, the arrangement moves back into its original position resulting in permanent closure of the access holes. It needs to be understood since the annular space is filled with metal during setting and injection process, the access holes do not pose any leakage risk during plug's operation.

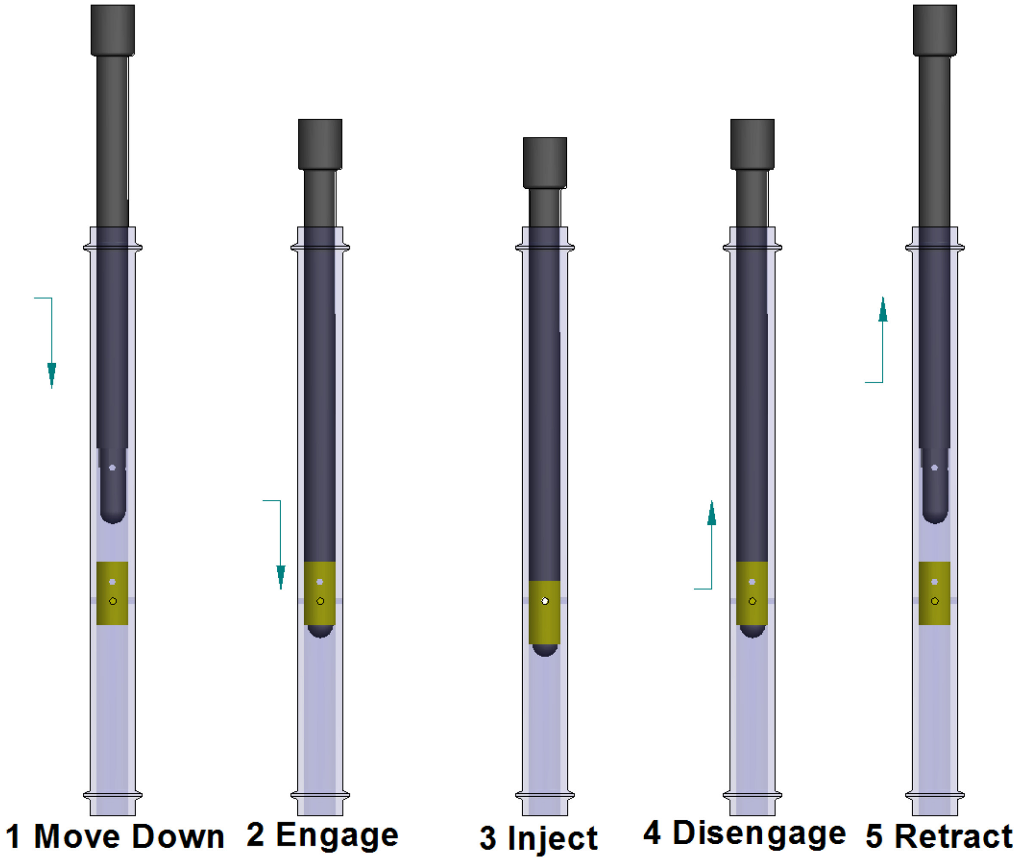


Figure 44 Injection Procedure

It should be emphasized that simple linear arrangement that is shown here serves as a clear demonstration tool. In practice, a more refined arrangement such as J slot system may be employed to guarantee perfect engagement between components and facilitate process monitoring through associated feedback signals.

6.5.2. *Injection head and injection screw*

Turning now to Figure 45 which presents a detailed view of the injection head and the injection screw, the various features of these units are described in the followings. For simplicity, the heating system is omitted in the drawing; however the detailed description of the same is already covered in chapter 6.4.

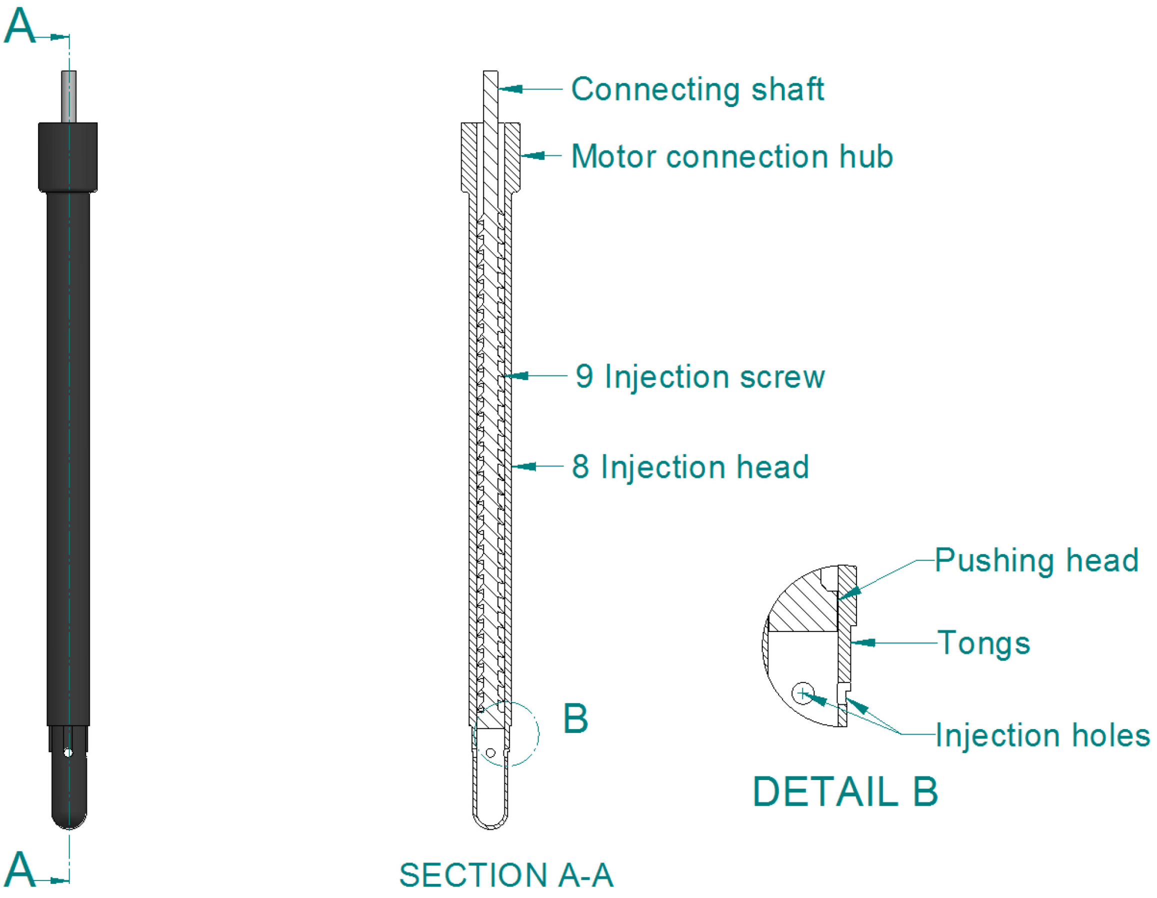


Figure 45 Injection Head and Injection Screw

The injection screw (9) can be divided into three main parts: Connecting shaft, Screw section and Pushing head. The connecting shaft is simply designed to connect the screw system to a driving mechanism which may consist of a downhole motor or another similar device. The screw section is designed to serve two purposes: to push materials towards the end of the injection head and at the same time to shear the material while it is heated in order to achieve the required semi-solid state. Finally, when the necessary volume of semi-solid material is prepared, the pushing head drives the material through the injection holes and into the annular space.

It is important to note that in here it is assumed that thixomolding method, discussed in chapter 5.2, is the preferred method for processing semi-solid materials and therefore the screw system is used to perform shearing and driving duty at the same time. However, as mentioned earlier other methods for semi-solid processing could be used instead of thixomolding. In such cases a simple piston and cylinder mechanism could be considered as an alternative device.

Referring back to Figure 45, some of the injection head's main characteristics are discussed herein. The injection head could be divided into three main sections. The upper section with the largest external diameter is intended to be used as a connection hub for attaching the injection head to the driving mechanism. The thick walled design of this section shown in Figure 45 is to provide a robust structure at the connecting point. However, if it becomes necessary to carry extra volume of feed stock for the semi-solid process, an alternative thin walled design illustrated in Figure 46, could be preferred. This design variation offers additional internal volume that could be used for storing extra volume of feedstock.

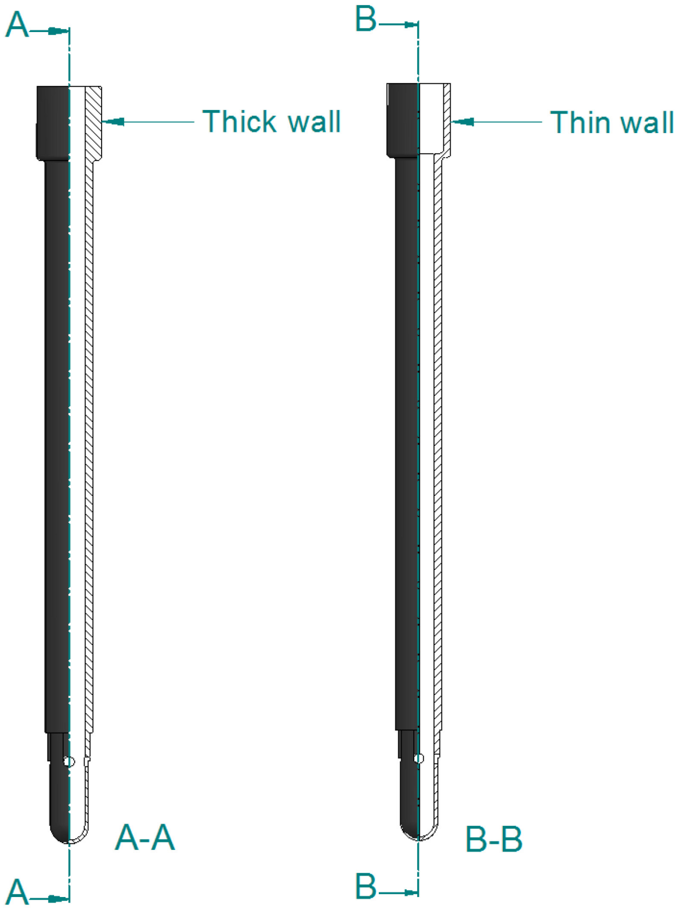


Figure 46 Injection Head Alternative Design

The middle section of the injection head is designed to perform as a semi-solid processing unit. As demonstrated in Figure 41, the outer wall of this section is surrounded by the heating system. Since the heat generated by the heating unit will be transferred through the wall, high conduction heat transfer coefficient of the wall material is of prime importance for this section. Feedstock stored inside the main barrel and connection hub, will be heated and at the same time sheared by the injection screw to form the semi-solid metal ready for injection.

The lower section of the injection head consists of hemispherical end, set of tongues and injection holes. The hemispherical end is chosen for two main reasons: first, to reduce the surge effect while running into the hole and second, to ensure smooth engagement between the injection head and mandrel. Set of tongues are simply designed to match the grooves in the mandrel’s inner wall and therefore guarantee precise orientation of these two parts relative to each other. The holes that are machined at the end of each groove are to provide passage for semi-solid metals. Each hole may include a check valve or a similar device to prevent inflowing of well fluid or return of injection material into the injection head. Alternatively, a single check valve can be installed inside the injection head above the set of holes to prevent inflow from all holes simultaneously. Finally, even though only four equally spaced injection holes are shown here, the number and orientation of these holes may be adjusted to improve flow of semi-solid metal during the injection process.

7. DESIGN ALTERNATIVES

The design solution discussed in the previous chapter may be adapted to suit different applications and various downhole conditions. Two design variations including modification of deformable member geometry and reconstruction of the secondary sealing element; to obtain self-energizing seal, are presented in this chapter.

7.1. Modification Of Deformable Member's Geometry

The geometry of the deformable member discussed in chapter 6.2 consists of two identical deformable sections in top and bottom of the deformable member. Each section is made of three V shaped grooves. One of these grooves is machined into the inner wall and has a groove depth extending slightly over half of the wall's thickness. Other two groves are machined partially into the outer wall and spaced equally on each side of the first groove. As discussed earlier, under sufficient compressive force, this arrangement result in over centered stress concentration which causes deformable sections to collapse perpendicular to the main axis of deformable member and wrap symmetrically about the middle groove. The exact position and direction of deformation is primarily determined by the location of these three grooves relative of each other. In addition the profile, depth and number of grooves have influence on the deformation direction and final shape of the deformed member.

The simple geometry of the deformable section presented in the previous chapters has several advantages such as relatively simple manufacturing and setting processes as well as capability to achieve high expansion ratios. However geometrical variations of these sections can offer various advantages which could be more important in certain downhole conditions. One of these variations is presented in this chapter. The alternative embodiment discussed here demonstrates a variation that offers advantages over the original geometry by offering a curved contact surface which result in reduction in high stress concentrated regions.

Figure 47 compares original geometry of one of the deformable sections with the modified version in normal and deformed configurations. As it can be noticed, the modified version has a larger maximum diameter in the initial un-deformed shape. Therefore the expansion ratio will not be as high as the deformable member with the original geometry. However, modified geometry offers several advantages compared to the original form which will be discussed in the following paragraphs.

In comparing these alternatives, the first thing to notice is the different contact surface profiles. While a sharp contact surface is resulted from the original V-shaped grooves configuration, the alternative geometry results in a curved surface.

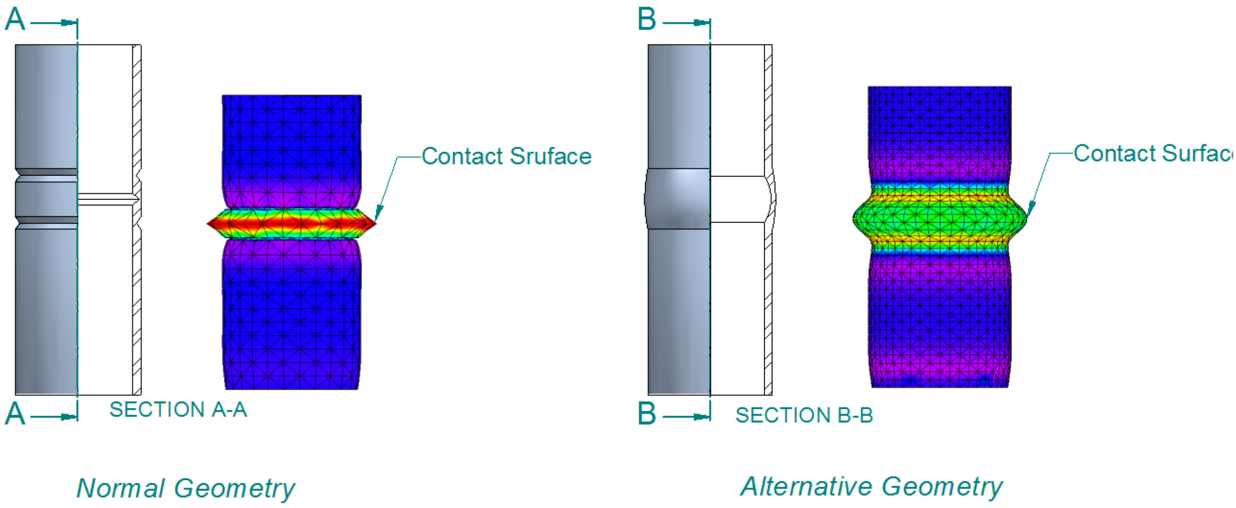


Figure 47 Deformable Member Alternative Geometry

As it can be seen from finite element analysis results, presented in Figure 47, in contrast to the original geometry, stress is no longer concentrated on a small contact surface. Therefore, the risk of seal failure due to excessive or cyclic loads and any unplanned axial movement is substantially reduced. Significance of this minor variation on reliability of the seal in certain downhole conditions could be better understood when loading conditions and possible movement of seal due to various reasons and subsequent effects are described in more details.

Unplanned seal movement could be caused by one or a combination of different phenomena including but not limited to:

- Temperature changes: Due to temperature changes in well and tubing, tubing length can alter. Considering typical length of tubing this phenomenon can produce enough force to result in the seal's movement. The issue is usually more of concern when the seal is installed in old corroded casing or in casing that is made of hard grade steel where slips do not tend to have sufficient grip.
- High differential pressure: Following setting a pressure isolation device in tubing, the device can be compared to a piston in a cylinder. Therefore, very high differential pressure across the seal in operations such as well simulation can cause some minor seal movements. Typically set of slips are used to provide sufficient support to avoid any

undesired movements. However generated force may also result in tubing ballooning and buckling effect. In such cases minor seal movement is almost inevitable.

- Setting force: The force applied to the device during setting operation to engage slips and deform the metal to metal seals is stored in the body of the deformable member. This force, if not released in a controlled manner, can spring back and result in minor seal displacement.

Due to narrow contact surface area of the metal to metal seal with casing and high stress concentration in this region of seals with the original deformable geometry, any minor displacement may cause the seal's material to bend in this sector and cause leakage failure. In addition, during deformation process; under considerable force, contact surface of metal to metal seals tend to deform in such way that it matches the contour of surrounding casing. Unfortunately, even between two very close points along the length of casing, cross section's contour may vary slightly. As the result a metal to metal seal that may have established a perfect seal at the setting point, may no longer provide a gas tight seal after slight seal movement.

Another area of concern is fatigue. Fatigue is one of the major failure mechanisms which is considered when materials are subjected to cyclic loads. In high stress concentrated regions, fluctuating loading can create localized slip bands in the materials. Over time, a growing number of these bands results in microscopic cracks that can spread through the seal's wall and cause failure. Considering the narrow contact area with high stress concentration of seals with original geometry, the original design would be unsuitable for wells with cyclic load. Therefore, a method to avoid fatigue failure could be highly important in such downhole conditions.

With reference to Figure 47, the presented alternative geometry offers larger contact surface with the surrounding casing. Therefore, following deformation, a larger portion of the seal's contact surface matches the contour of the surrounding casing which could reduce the risk of seal failure due to slight movements. In addition, as can be observed in the same figure, generally stress concentration is significantly reduce and transferred away from the seal's contact point with casing. Therefore risk of seal failure as the result of undesired bending, due to seal movement, in combination with narrow stress concentrated region at contact surface is reduced. Finally, because high stress concentrated regions are substantially reduced, the risk of fatigue failure is also decreased.

7.2. Self-Energized Seal Using Bismuth Expansion

In previous chapters it is mentioned that Bismuth possesses a distinct characteristic which causes its expansion upon solidification. In the original design in order to create robust seal it was suggested to use Bismuth as a secondary sealing material, filling the annular space between the two metal to metal seals. However the design could be restructured to take advantage of Bismuth expansion for creating self-energized metal to metal seals. An alternative design covered here presents a method which could be used to fulfill this objective.

Figure 48 illustrates a purposely designed mandrel and a deformable member for this method. For clarity other associated parts of the assembly are omitted and assumed to have similar design and characteristics to those discussed in chapter 6.

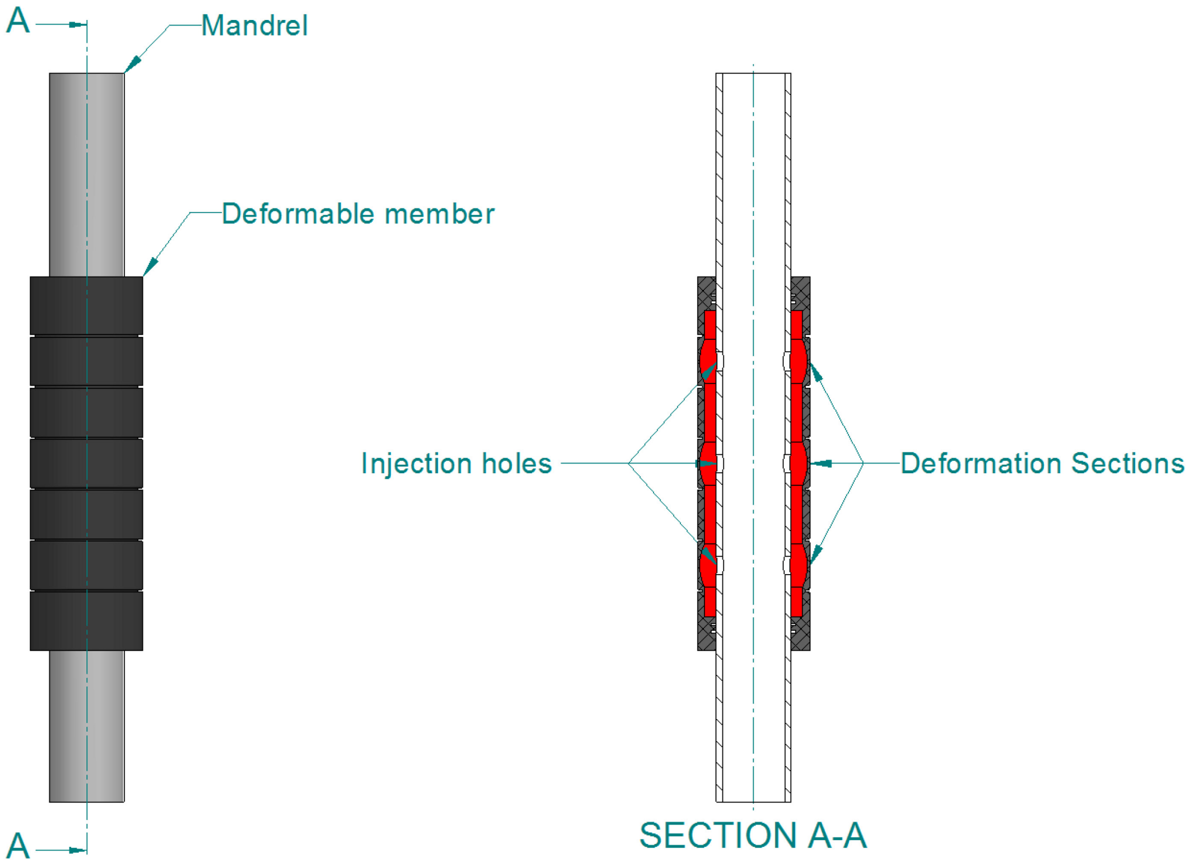


Figure 48 Self-Energized Seal

With reference to Figure 48, the deformable member is installed on a mandrel which is equipped with several injection holes to allow injection of bismuth inside the seal's cavity. Depending on manufacturing and assembly processes, the deformable member may either be welded on mandrel at both sides, fixed using sets of O-rings at each side or a combination of the two. Since the cavity between the deformable member and the mandrel will be filled with Bismuth, the designed seal will form a complete metal to metal seal in three planes. Therefore, any of the arrangements mentioned above will not pose leakage risk during the seal's service life.

The deformable member, shown in Figure 49, is made of ductile material and consists of three deformable sections. These sections are designed based on the fourteenth embodiment of the patent US 7134506 B2 which is discussed in chapter 4.4 and included in appendix C. The deformable member illustrated here consists of shoulder, three deformable sections, two optional grooves for O-rings on each side and sets of force distributing grooves.

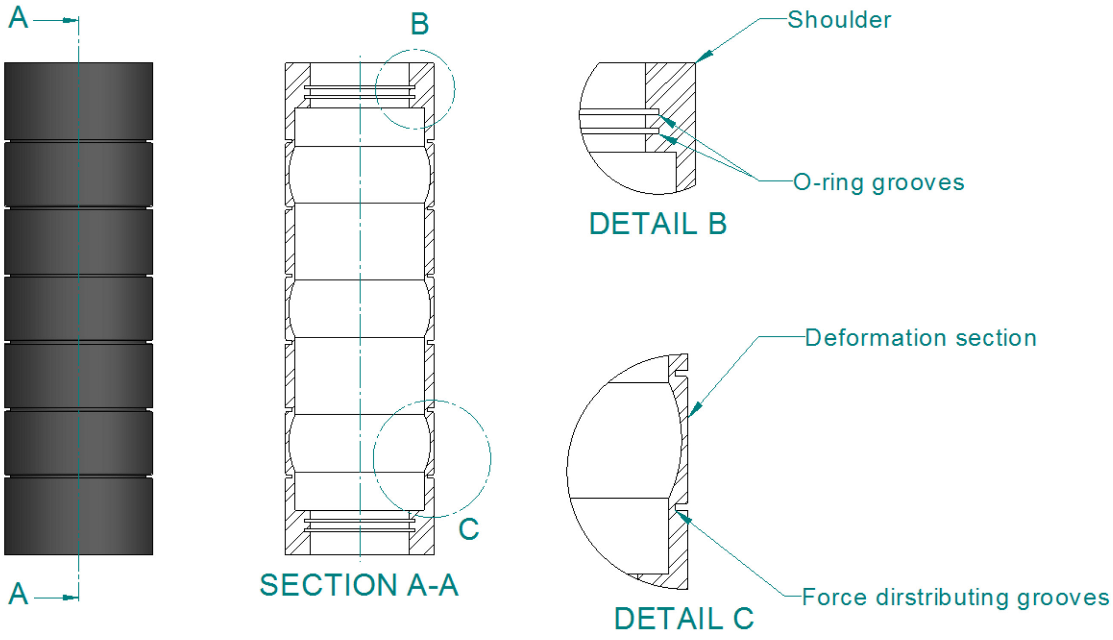


Figure 49 Self-Energized Seal: Deformable member

Each deformable section is designed with varying wall thickness to achieve deformation in the desired direction. The wall thickness is thicker at each side and has the smallest width in the middle. Therefore, as a can be seen in Figure 50; illustrating the result of setting process, when the member is subjected to an axial force over centered stress concentration forms and forces the deformable sections to bulge outward and to come in contact with the surrounding casing forming a metal to metal seal. The flat segments with constant wall thicknesses located between deformable sections are included to obtain controlled deformation at each section. Finally, the force distributing grooves machined on each side of the deformable section are intended to improve force distribution during setting process and to ensure optimum deformation.

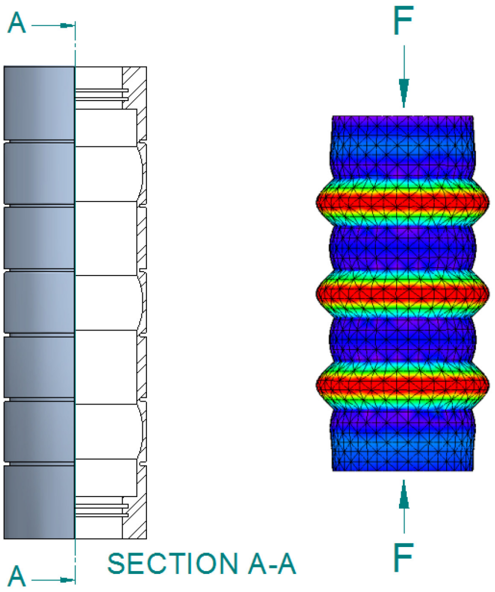


Figure 50 Self-Energized Seal: Deformable Member at Set Configuration

Even though a typical setting process involving application of compression force is shown here, the member may also be set by increasing pressure inside the deformable member by injecting Bismuth via injection holes. Such a procedure could be advantageous when transferring the required axial force to the setting device is difficult.

Following the setting process, the cavity between the deformable member and the mandrel, shown in red in Figure 48, is filled with semi-solid Bismuth alloy through a similar procedure explained in chapter 6. Expansion of Bismuth upon solidification creates an energizing force that holds the deformable member in its set configuration without requiring any additional energizing device. This method could be extremely valuable for establishing reliable seal in wells where high risk of unplanned unsetting is expected.

Another advantage of this method is the option for simplifying setting process compared to the original design discussed in chapter 6. In the original design it is necessary to form a confined space for Bismuth injection by initially setting the metal to metal seals. However, in the method presented above, the semi-solid metal will be injected inside the seal’s cavity which is bonded form all directions. Therefore, setting the metal to metal seals and injection of the semi-solid metals could be performed in a single stage.

8. DISCUSSION

The main goal of this master thesis was to provide a method and an apparatus for plugging the well which prevents or mitigates the problems associated with the current pressure isolation devices. The main challenges were identified to be associated with debris in the well along with the limitations caused by the conventional elastomer seal designs. Therefore, for finding a suitable solution, the effort was concentrated on the methods and materials which most likely do not pose the similar drawbacks. The metal to metal seal with a secondary metallic sealing element offered in this thesis contains features which can fulfill these requirements. Some of the advantages and limitations of the proposed design are discussed here and some recommendations for future work are offered in the subsequent chapter. It is important to note that, because the design proposed here is in the concept stage of the development, it is difficult to be absolutely certain about its performance. Therefore, the advantages and the limitations discussed here must be treated with care and further thorough evaluations with the aid of computer simulations and eventually physical model are highly recommended.

8.1. Advantages

In some cases, to allow bypassing restrictions and to set a tool in a large diameter tubing, high expansion plugs are required. While there are few plug deigns such as HEX from Interwell which allow these types of operations, they contain elastomer sealing element which could suffer from the typical elastomer seal failures. In addition, these devices are not suitable for high temperature applications where the bottomhole temperatures are above 150°C. For instance, HEX plug is only been certified for temperatures up to 110°C at 4000 psi differential pressure. For such cases, a metallic seal with a high expansion ratio could offer obvious advantage. However, as discussed earlier, a metal to metal seal alone may also not be a reliable substitute. The presented design could offer a valid solution by taking advantage of the metal to metal seals in combination with the secondary sealing element, to enables bypassing narrow restrictions and set in large ID tubing without the limitations associated with the metal to metals seal.

Another major advantage of the proposed design, which is inherited from metal to metal seals, is possibility to operate in very wide range of downhole environments. Typically, elastomer seals are designed to suit certain downhole conditions and expansion ratios. Similarly, ordinary metal to metal seal may not be deployed in certain downhole conditions and loading regimes. In contrast the suggested design could be used for various applications and in a wide range of downhole environments.

Yet another advantage of the suggested design; which is associated with the second alternative design discussed above, is the possibility of setting through hydrostatic pressure. In some cases due to well trajectory or other reasons, transferring the required compression force for the setting operation is challenging. Ability to set the plug with the pressure applied by injection of semi-solid Bismuth in the annular space, as discussed in chapter 7.2, could offer a valuable advantage. Once more it is important to emphasis that even though a screw injection machine was shown as an example, other injection methods such as a piston and cylinder arrangement may be used for injecting semi-solid material into the annular space. In this case, well pressure could also be used to force Bismuth behind the metal to metal seals and set the plug.

Expansion of Bismuth upon solidification could offer a great advantage compared to typical plugs. While in the case of traditional plugs; it is almost always necessary to sustain energizing force on the sealing element, self-energizing feature of the presented design automatically fulfill this requirement. This can be advantageous in avoiding de-energizing as a result of backlash or creep.

Finally, number of advantages which are inherited from the ordinary metal to metal seals may also be claimed. These advantages include but are not limited to:

- Possibly faster running speed due to smaller initial seal diameter and therefore greater annular space for flow passage which also reduces surging effect.
- With elastomer seals, the running velocity is also limited due to the risk of seal damage as a result of flow pass over the seal. By excluding elastomer from the suggested design this risk is also eliminated.

8.2. Limitations

Despite the advantages mentioned above, the design may not be suitable in certain conditions. For instance the design is only suitable for the permanent plug applications and lacks the resettable feature. Due to huge costs associated with well operations, this may indicate a serious limitation. If for any reason the setting operation fails, the plug may have to be retrieved from the well, repaired or replaced; and re-run in a subsequent operation which can be very costly.

Furthermore, removing the plug includes milling operation which may produce considerable amount of debris. Despite the fact that the proposed plug consist of materials with high machinability characteristics; in some situation, milling operation is not an ideal choice and operators try to avoid such operations.

Finally; as indicated in previous chapters to benefit from all features of the suggested design, the secondary sealing element's material should contain Bismuth or another similar material with expansion characteristic. Taking melting point of Bismuth (271.4 °C) and other typical Bismuth alloys into account and considering the fact that the typically strength of metals reduces at increased temperatures, this may limit the applications of the suggested design.

9. CONCLUSION

Without comprehensive verification through relevant experiments and computer simulations, it would be difficult to give an exact conclusion regarding the performance of the suggested design. However based on the data presented in the main text the following points could be concluded.

- The main sources of plug failure are well debris and limitations caused by the traditional elastomer seals.
- Due to their construction and setting process and despite few successful operations, current metal to metal seals are not very reliable substitution for elastomer seals when gas tight isolation is required.
- Some metals and metal alloys, such as Bismuth, expand upon solidification. This characteristic is considered for creating a gas tight self-energizing downhole seal.
- It is proven that semi-solid processing technique produces components with superior mechanical properties. Therefore, using this technology in combination with expanding metallic alloy can be advantages for producing a reliable gas tight plug.
- The lack of resettable feature as well as low meting temperature of known Bismuth alloys may limit the applications of the proposed design.
- Further investigation through computer simulations and ultimately building a physical model are highly recommended to verify the suggested advantages of the purposed design.

10.RECOMMENDATIONS FOR FUTURE WORK

Development of new products is usually complex and time intensive task which involves number of stages. The list below indicates typical stages of a new product development:

1. Idea
2. Research
3. Frist concepts
4. Patents
5. Development
6. Models (usually computer generated models)
7. Concept confirmation
8. Final design
9. Pre-production prototype
10. Testing
11. Tooling and manufacturing setup
12. Sample production
13. Full production

Due to the time constrains, only initial stages of the new plug design were covered in this master thesis and considerable amount of work, which has be carried out before this product could be introduced to the market or sold as a basic design to an industrial product developer, still remains. The following list contains suggestions for future works that could take the design to the next stage.

- Computer models produced in this thesis could be used directly or altered slightly to suit computer aided manufacturing software (CAM) where the model can be further tested.

- Simulation software such as finite element methods (FEM) could be used to simulate typical load conditions and test the model under different scenarios.

- Computational fluid dynamics (CFD) software could be used to simulate downhole flow and pressure regimes during running into the hole or while the plug is set and to verify its performance under relevant conditions.

- A research study to identify a most suitable material that has expanding characteristics and is suitable for a wide range of downhole conditions could be highly beneficial.

- A research study for identifying a modification of the suggested design to suit multiset applications could be highly beneficial. Patents WO2012079913 A2 and US8307891 B2 presented in chapters 4.3 and 4.4 are highly recommended for this purpose.

11. REFERENCES

Aarcher Well. (2013). *VMB Plug.* Retrieved 01 07, 2013, from Aarcher Well: http://www.archerwell.com/documents/archer_vmb_productguide_screen.pdf

Baker Hughes. (2012). *Liner Tieback Equipment.* Retrieved 11 05, 2012, from Baker Hughes: http://www.bakerhughes.com/products-and-services/completions/wellbore-construction/liner-solutions/liner-tieback-equipment

Baker Hughes. (2012). *Packer Systems Catalog.* Retrieved September 10, 2012, from Baker Hughes: http://www.bakerhughes.com/news-and-media/resources/brochures/packer-systems-catalog

Baker Hughes Incorporated. (2010). *Patent No. US 20100294485.* US.

Baker Oil Tools. (1986). Considerations in the Design and Selection of Dynamic Tubing to Packer Seals. *Engineering Tech Data Paper Number CS003*.

Bishop, D. S., Doane, J. C., & Kroll, D. E. (2012). *Patent No. US8307891 B2.*

Blizzard, W. A. (1990). Metallic Sealing Technology in Downhole Completion Equipment. *Society of Petroleum Engineers*.

Dantzig, J. A., & Rappaz, M. (2009). *Solidification.* London : EPFL Press.

Dashtpour, R. (2012). *Development Study of Downhole Packers and Bridge Plugs.* Trondheim.

David Llewellyn, R. H. (1998). *Steels : Metallurgy and Applications.* Oxford: Butterworth-Heinemann.

Donnelly, J. (2005, December 11). *Price rise and new deep-water technology opened up offshore drilling.* Retrieved September 22, 2012, from Boston.com: http://www.boston.com/news/world/articles/2005/12/11/price_rise_and_new_deep_water_technology_opened_up_offshore_drilling/

Eden, D. R., & Eden, H. R. (2006). *Patent No. EP1339943 B1.*

Ernest P. Fisher, J. C., & William G. Boyle, D. T. (1984). *Patent No. US 4483543.* USA.

EVO-Trieve Halliburton. (2013). *EVO-Trieve® Bridge Plug.* Retrieved 03 02, 2013, from Halliburton: http://www.halliburton.com/ps/default.aspx?pageid=2056&navid=109&prodid=PRN::K9KRRZ15

Finke, S., Wei, W., & Feenstra, F. (1999). Extrusion and Deposition of Semi-Solid Metals. *Solid Freeform Fabrication (SFF)*, (pp. 639-646). Austin.

Frizelle, W. G. (2011). Injection Molding Technology. In M. Kutz, *Applied Plastics Engineering Handbook 1st Edition (Processing and Materials)* (pp. 205-214). Elsevier.

Garfield, G., & Gordon Mackenzie, B. O. (2007). Metal-to-Metal Sealing Technology: Bridging the Gap Between Conventional and High-Expansion Zonal Isolation Applications. *SPE/ICoTA Coiled Tubing and Well Intervention Conference and Exhibition.* The Woodlands, Texas, U.S.A.: Society of Petroleum Engineers.

Garfield, G., & Mackenzie, G. (2007a). Wellbore Isolation Intervention Devices Utilizing a Metal-to-Metal Rather Than an Elastomeric Sealing Methodology. *Society of Petroleum Engineers.* California, U.S.A.: Society of Petroleum Engineers.

Garfield, G., & Mackenzie, G. (2007b). Zonal Isolation Applications Utilizing New Metal-To-Metal Sealing Technology Demonstrates Potential for Offshore and Deepwater Environments. *Offshore Mediterranean Conference and Exhibition.* Ravenna, Italy.

Georgsen, S., Hiorth, E., & Malvik, C. (2012). *Patent No. WO2012079913 A2.*

Giardini, A., & Samara, G. (1965). The compressibility of bismuth and its upper transition pressure. *Journal of Physics and Chemistry of Solids,Volume 26, Issue 9*, 1523–1528.

Halliburton. (2013). *Drillable Tools Books and Catalogs.* Retrieved 03 07, 2013, from Halliburton: http://www.halliburton.com/ps/Default.aspx?navid=87&pageid=58&folderid=MSE%3a%3a1044301114463853

Hammond, C. R. (2004). The Elements. In D. R. Lide, *Handbook of Chemistry and Physics 81st edition.* CRC press.

Haughton, D., & Connell, P. (2006). Reliable and Effective Downhole Cleaning System for Debris and Junk Removal. *Society of Petroleum Engineers*.

Heriot Watt University. (2005). *Production Technology (Part of petroleum course series).* Heriot Watt University.

I.C. Chapman, S. K., N.M. Nor, S. R., & G.R.J. Mackenzie, S. G. (2008). Wireline Deployed Metal Sealing Bridge Plug System: Operational Learning Curve and Subsequent Redevelopment. *SPE/ICoTA Coiled Tubing and Well Intervention Conference and Exhibition.* The Woodlands, Texas, USA: Society of Petroleum Engineers.

International Energy Agencey. (2012, September 12). *IEA's Oil Market Report.* Retrieved September 22, 2012, from Internationl Energy Agency: http://omrpublic.iea.org/

ISO14310. (2008). *Petroleum and natural gas industries, Downhole equipment, Packers and bridge plugs.*

Javora, P. H., Sanford, J., Qu, Q., Robinson, D., & Poole, G. (2008). Understanding the Origin and Removal of Downhole Debris: Case Studies From the GOM. *Society of Petroleum Engineers*.

John Fothergill, B. O. (2003). Ratings Standardization for Production Packers. *SPE Production and Operations Symposium.* Oklahoma City, Oklahoma: Society of Petroleum Engineers.

KARL, W. J. (2012). *Patent No. US2012043074 (A1).* US.

Larry W. Lake, E.-i.-C., Joe Dunn Clegg, E., & Ruddock, D. (2006). *Petroleum Engineering Handbook.* Society of Petroleum Engineers.

Liu, J., Johnson, D., & Smirnov, A. (2005). Predicting yield-stress anomalies in L12 alloys: Ni3Ge–Fe3Ge pseudo-binaries. *Acta Materialia, Volume 53, Issue 13*, 3601–3612.

Lowe, A., Ridgway, K., & Atkinson, H. (1999, September). Thixoforming. *Materials World Vol. 7*, pp. 541–543.

Martienssen, W., & Warlimont, H. (2005). *Handbook of Condensed Matter and Materials Data.* Berlin: Springer.

Midson, S. P. (Sept. 2008). Semi-Solid Casting of Aluminum Alloys: An Update. *Die Casting Engineer*.

Moyes, P. B. (2006). *Patent No. US7134506 B2.*

NORSOK Standard D-010 Rev 3. (August 2004). *Well integrity in drilling and well operations.*

PENTAIR. (2013). *Petrotrace Electric Downhole Heating Systems.* Retrieved April 15, 2013, from Pentair Thermal Management: http://www.thermal.pentair.com/Images/GB-PetroTraceOilfieldheatingsystemsNAM-SB-H58453_tcm432-26180.pdf

Rahman, S., & Chilingarian, G. (1995). *Developments in Petroleum Science, Volume 42, Casing Design Theory and Practice.* Elsevier.

Ricardo Amils, José Cernicharo Quintanilla, Henderson James Cleaves, William M. Irvine, Daniele Pinti, Michel Viso, Muriel Gargaud. (2011). *Encyclopedia of Astrobiology, Volume 1.* Springer.

Robb, T., Valentine, E., & Halliburton. (2101). New 9-7/8-in. HPHT Permanent Packer With New Back-Up System Provides North Sea Operator With Effective Solution For Damaged Or Worn Casing. *SPE Deep Gas Conference and Exhibition, 24-26 January 2010, Manama, Bahrain.* Manama, Bahrain: Society of Petroleum Engineers.

Rubbo, R. (1987). What to consider when designing downhole seals. *World Oil - Volume: 204:6*, 78-83.

Schlumberger. (2009). *Schlumberger - Sealing System.* Retrieved October 30, 2012, from Schlumberger: http://www.slb.com/~/media/Files/completions/catalogs/packers/sealing_systems.pdf

Sirong, Y., Dongcheng, L., & Kim, N. (2006). Microstructure evolution of SIMA processed Al2024. *Materials Science and Engineering A 420*, 165–170.

Skudnov, V. A., Sokolov, L. D., Gladkikh, A. N., & Solenov, V. M. (1969). Mechanical properties of bismuth at different temperature and strain rates. *Metal Science and Heat Treatment, Volume 11, Issue 12*, 981-984.

SPE PetroWiki . (2012, September 5). *Elastomers.* Retrieved November 6, 2012, from PetroWiki (Socirety of Petroleum Engineers): http://petrowiki.spe.org/Elastomers

Stankus, S. V., Khairulin, R. A., Mozgovoi, A. G., Roshchupkin, V. V., & Pokrasin, M. A. (2005). An Experimental Investigation of the Density of Bismuth in the Condensed State in a Wide Temperature Range. *High Temperature. Vol. 43, No. 3*, 368–378.

Statoil ASA. (2013). *Plug information from Statoil.* Provided by Sveinung Robertsen, Senior Advisor and Specialist Downhole mechanical isolation.

Torre, A. S., Schmidt, Z. U., Blais, R. U., Doty, D. U., & Brill, J. U. (1987). Casing Heading in Flowing Oil Wells. *SPE Production Engineering*, 297-304.

Vaucher, D., Brooks, R., & TAM International. (2010). Advantages of Inflatable Packer Technology for Temporary or Permanent Well Abandonment in the Gulf of Mexico. *International Oil and Gas Conference and Exhibition in China, 8-10 June 2010.* Beijing, China: Society of Petroleum Engineers.

Vinarcik, E. J. (2003). *High integrity die casting processes.* New York: Wiley.

Young, K. P. (2006). *Semi-Solid Metal Casting: Reducing the Cost of Copper Alloy Parts.* Massachusetts Office of Technical Assistance.

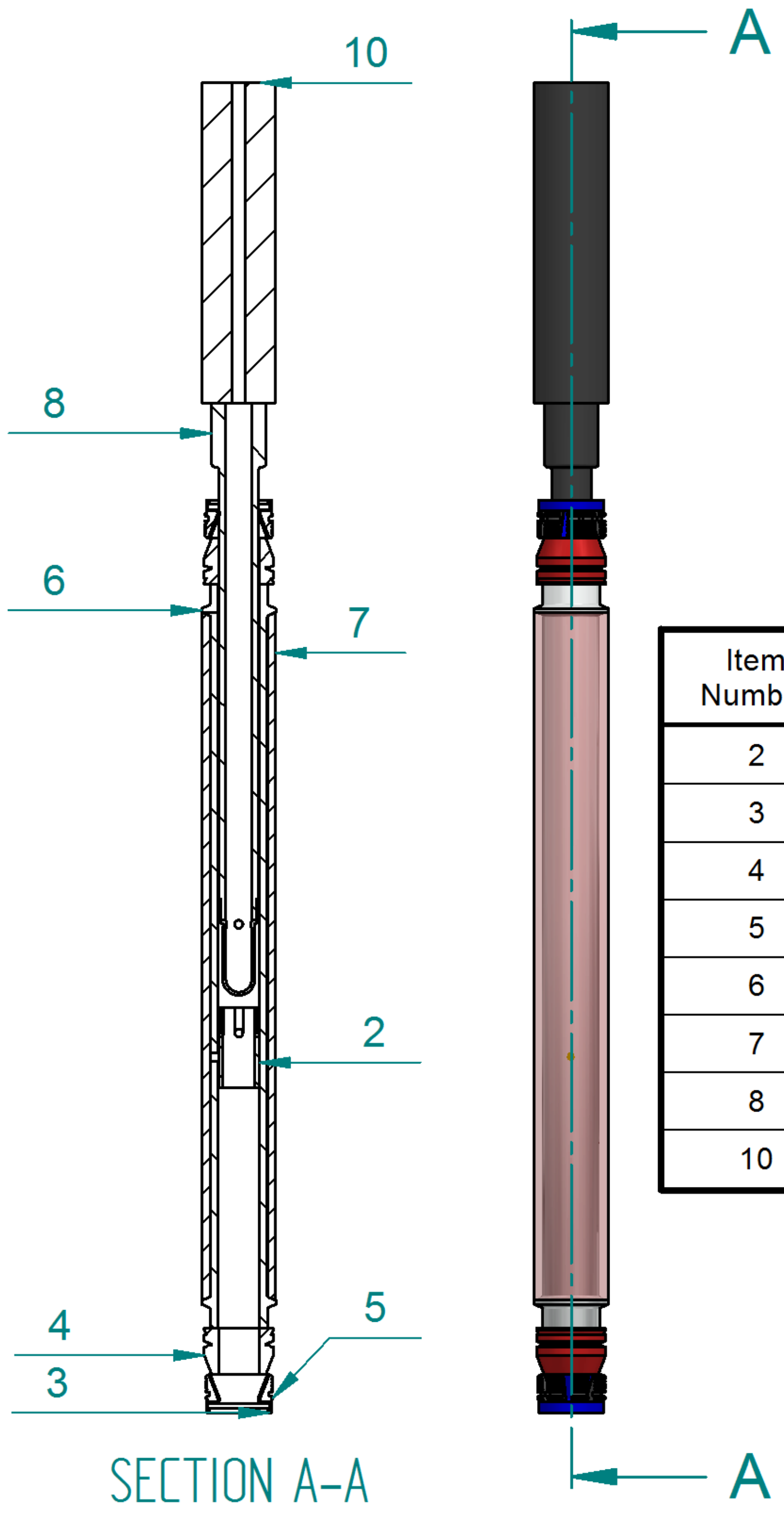
APPENDICES

- A Design Figures
- B Patent EP 1339943 B1
- C Patent US 7134506 B2 (Selected Pages)

APPENDIX A

Design Figures

APPENDIX A



Item Number	File Name (no extension)
2	Mandrel
3	Slip Plate
4	Cone
5	Slips
6	Deformable Member
7	Sealing material
8	Injection Head
10	Motor

Figure 38 Assembly of the Proposed Design

APPENDIX A

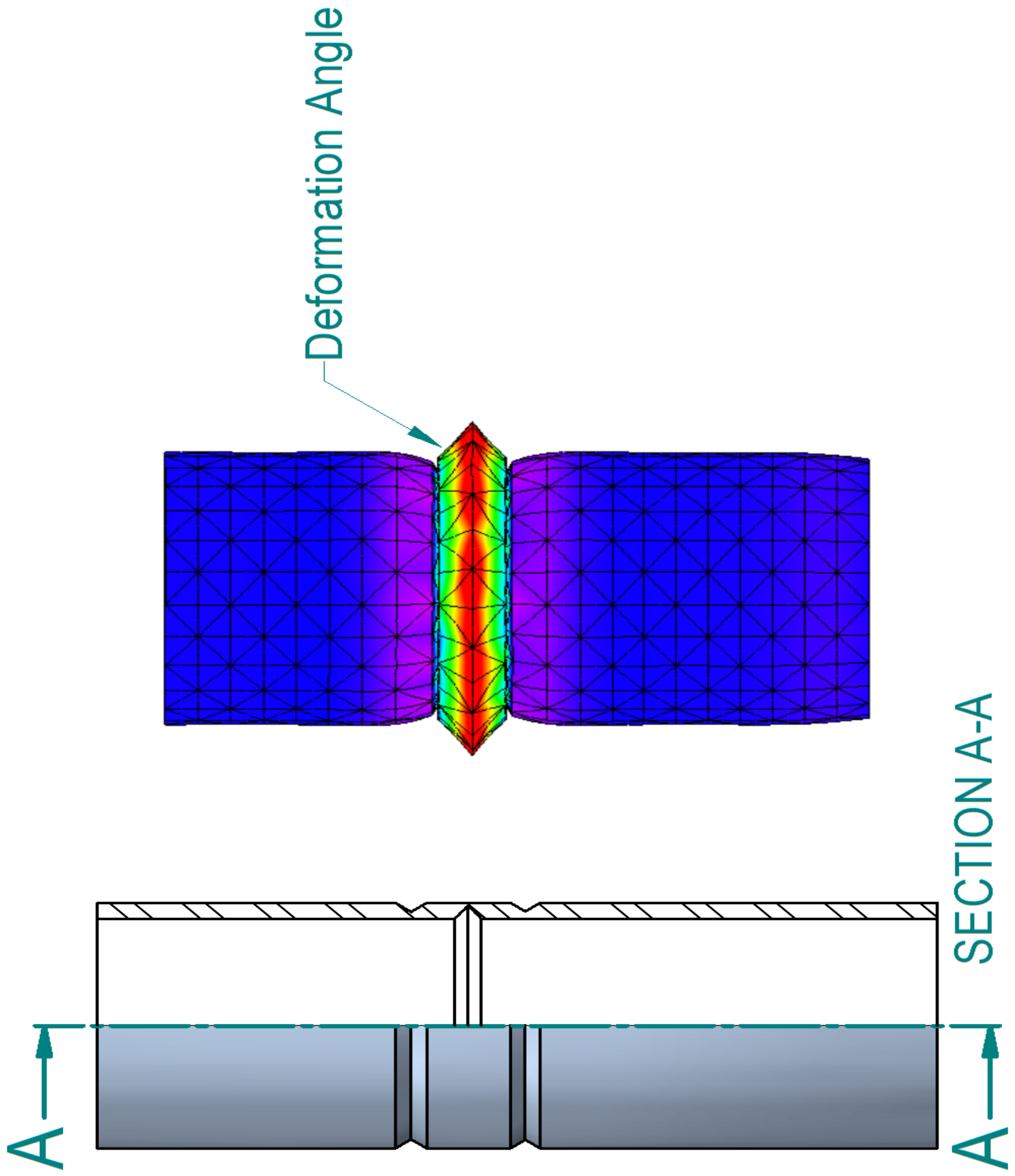


Figure 39 Deformable Member

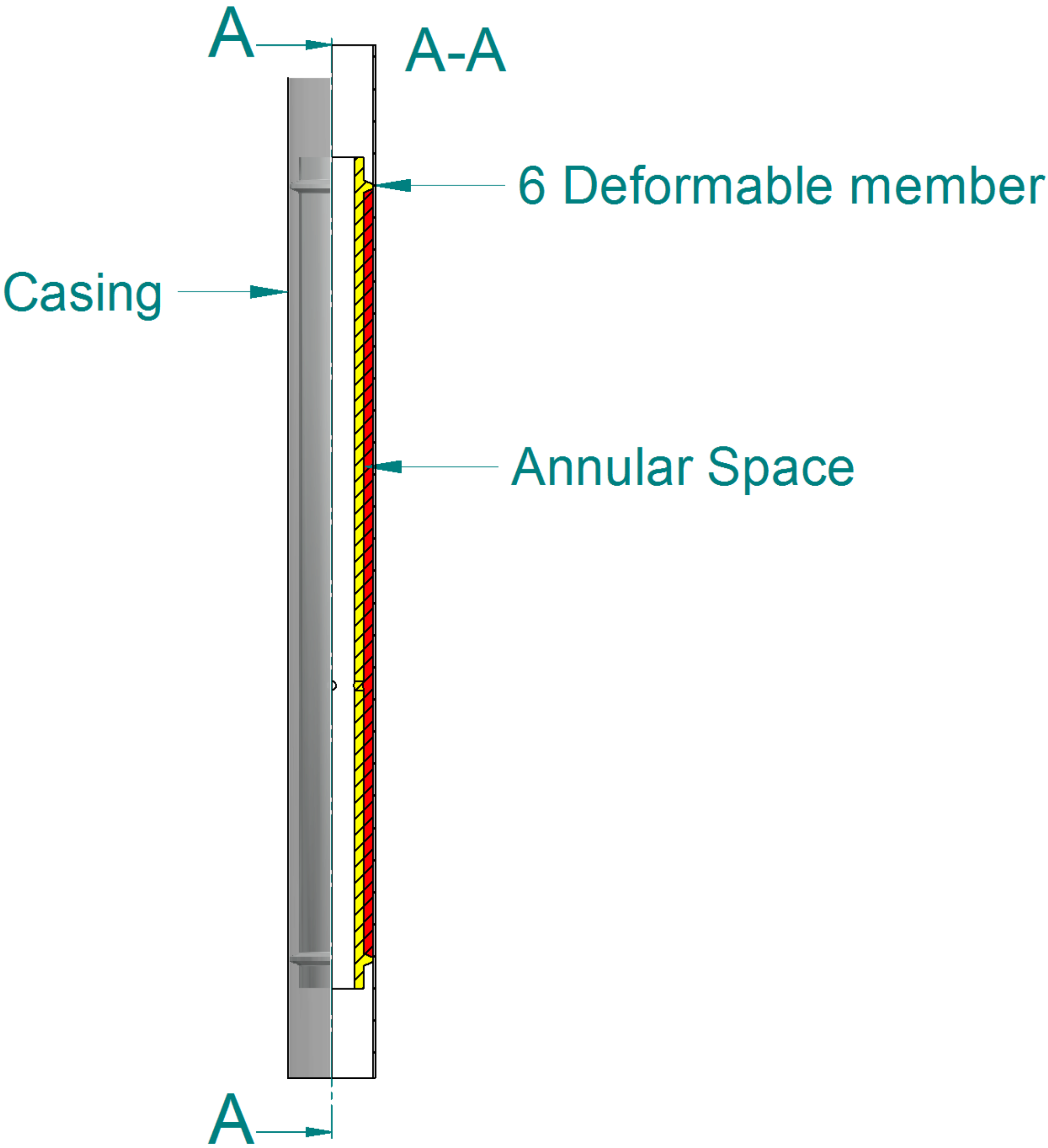


Figure 40 Annular Space

APPENDIX A

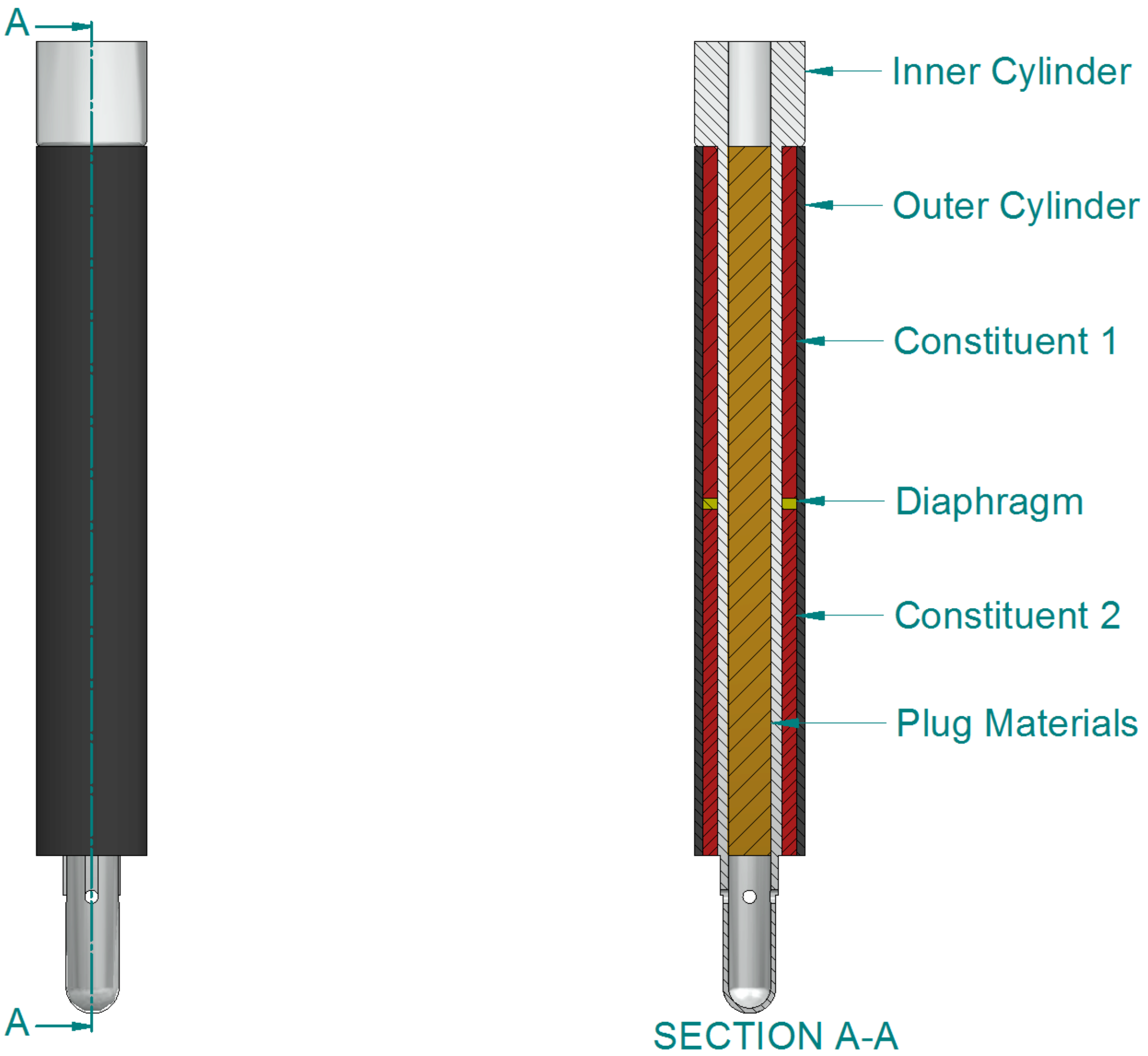


Figure 41 Heating Arrangement

APPENDIX A

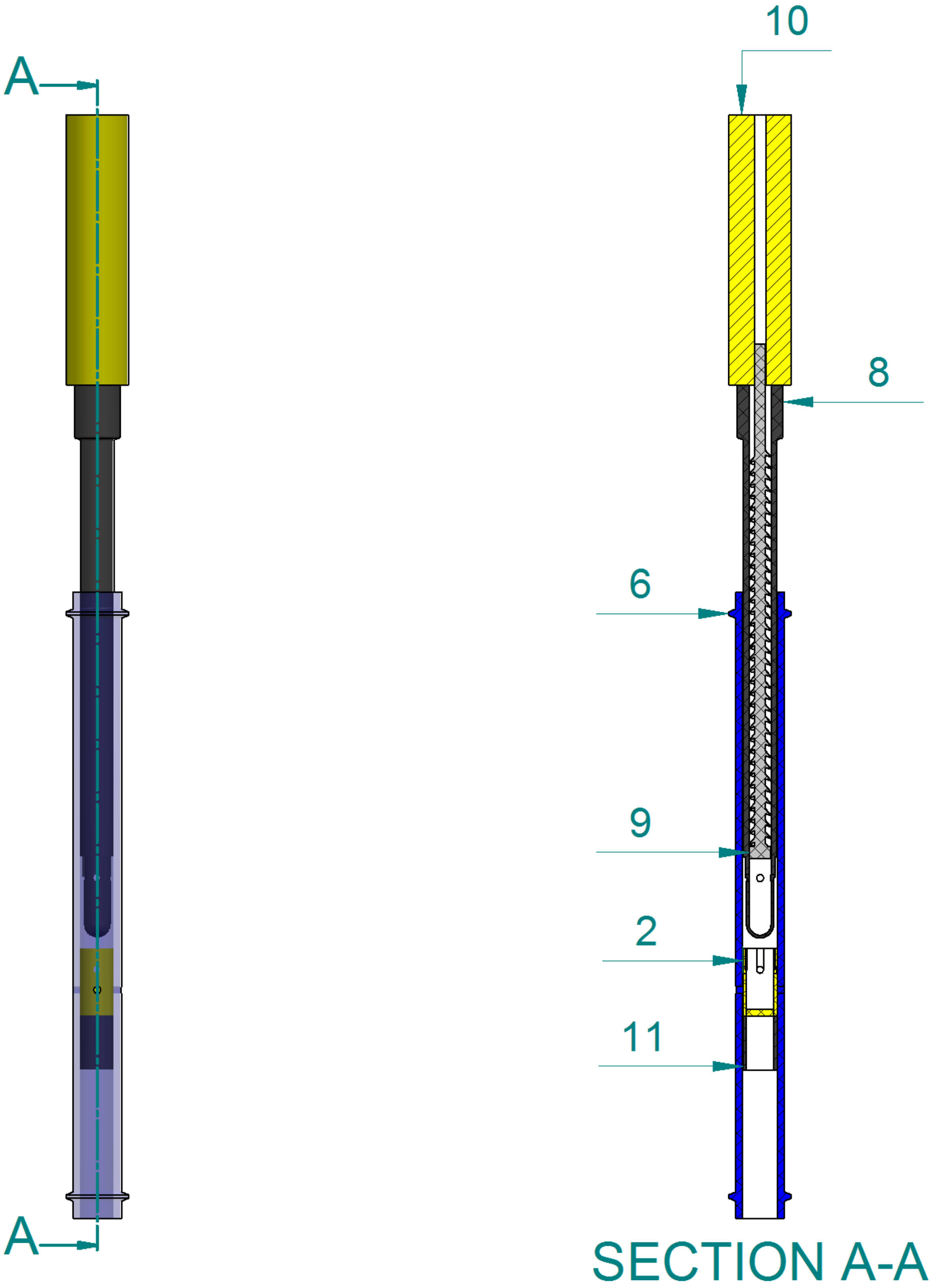


Figure 42 Injection Assembly
(2) Mandrel (6) Deformable Member (8) Injection Head
(9) Injection Screw (10) Motor (11) Spring Mechanism

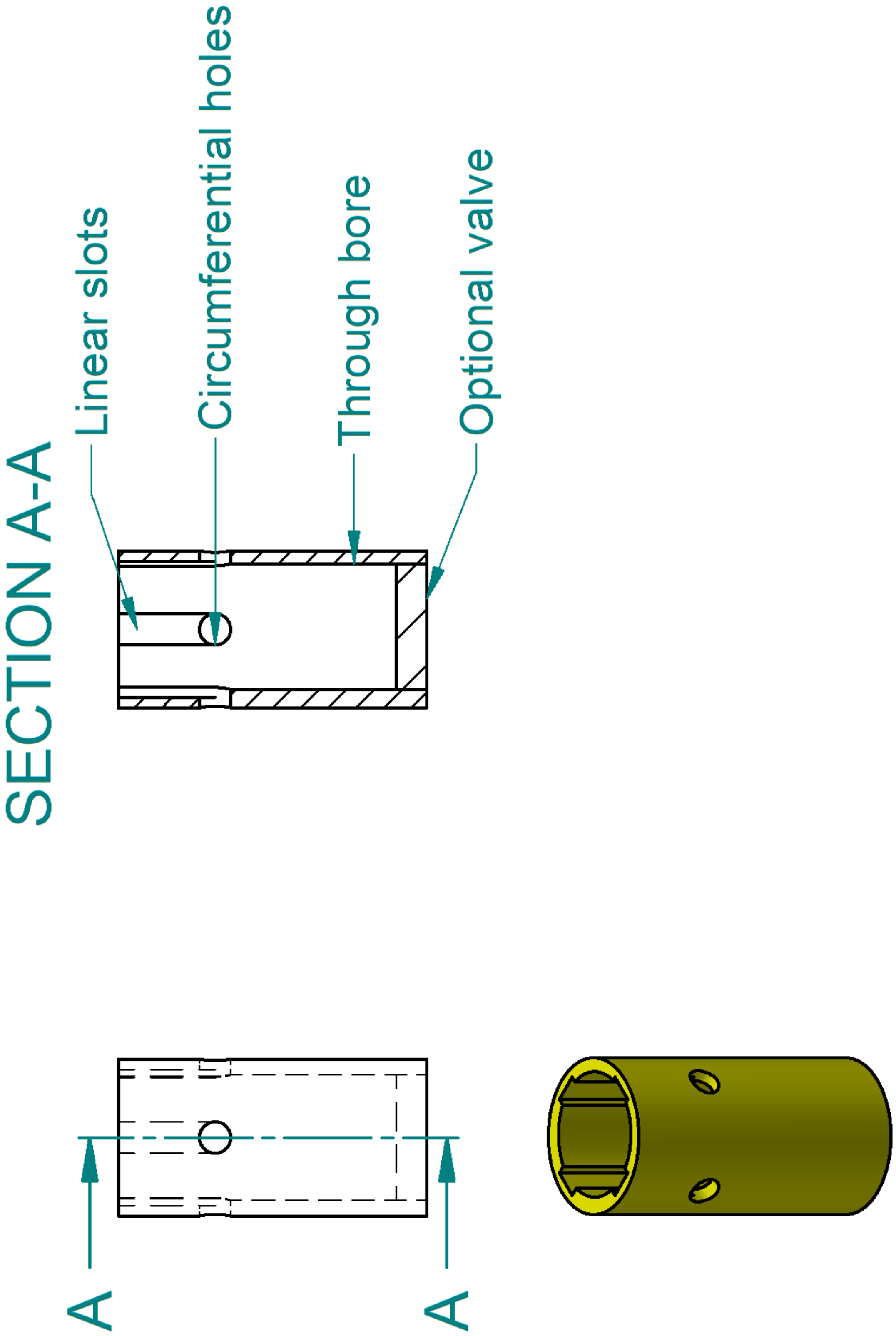


Figure 43 Mandrel

APPENDIX A

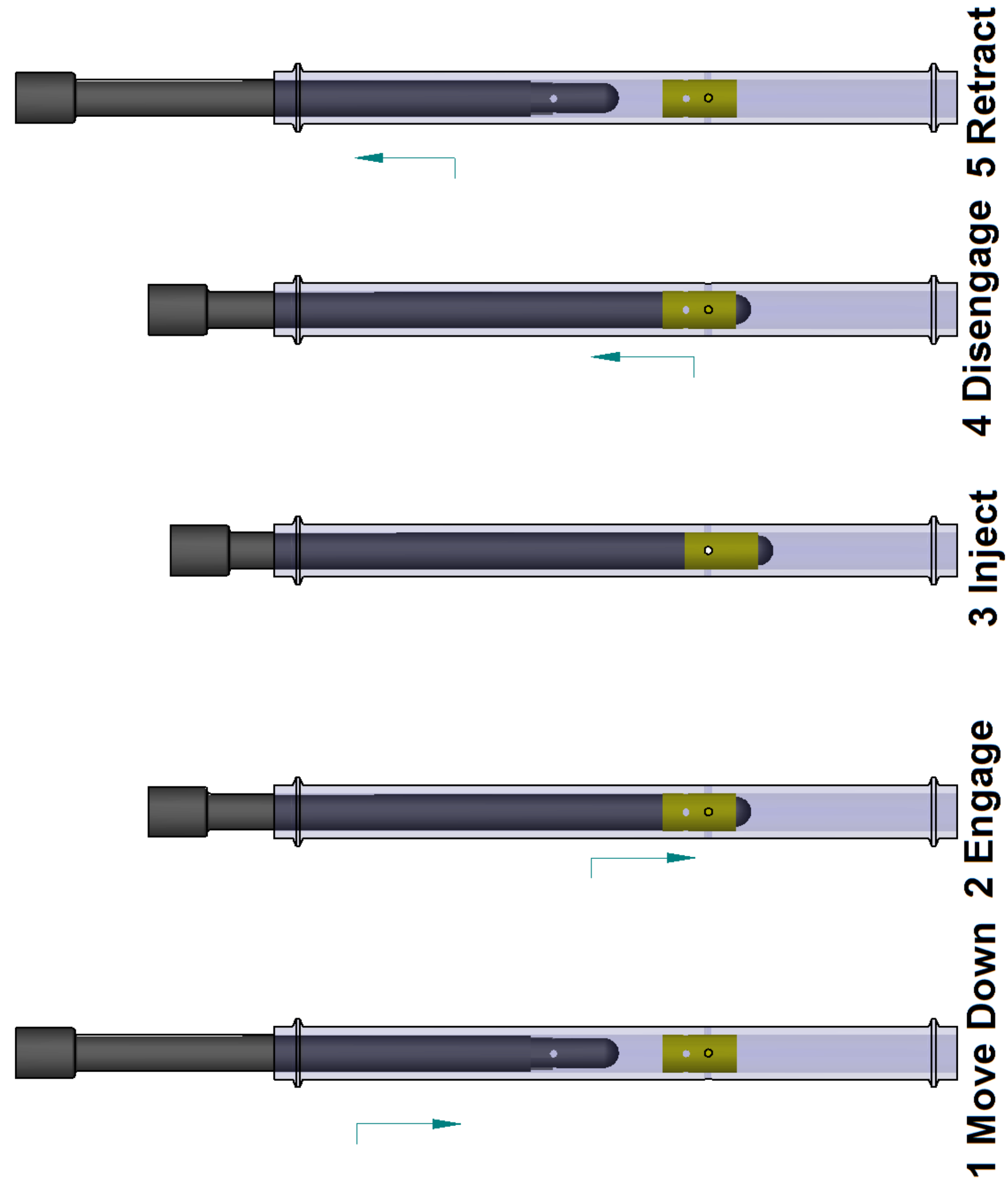


Figure 44 Injection Procedure

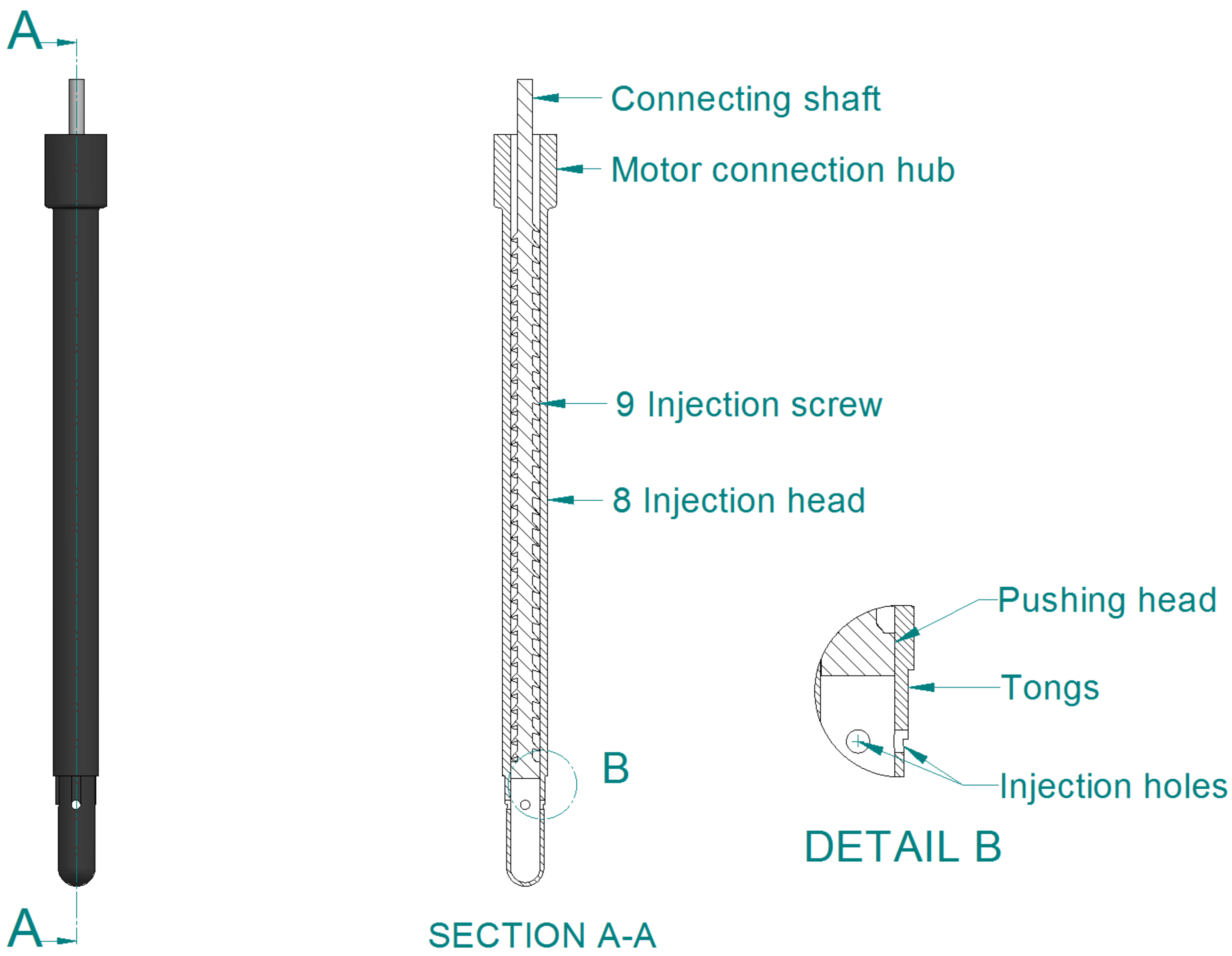


Figure 45 Injection Head and Injection Screw

APPENDIX A

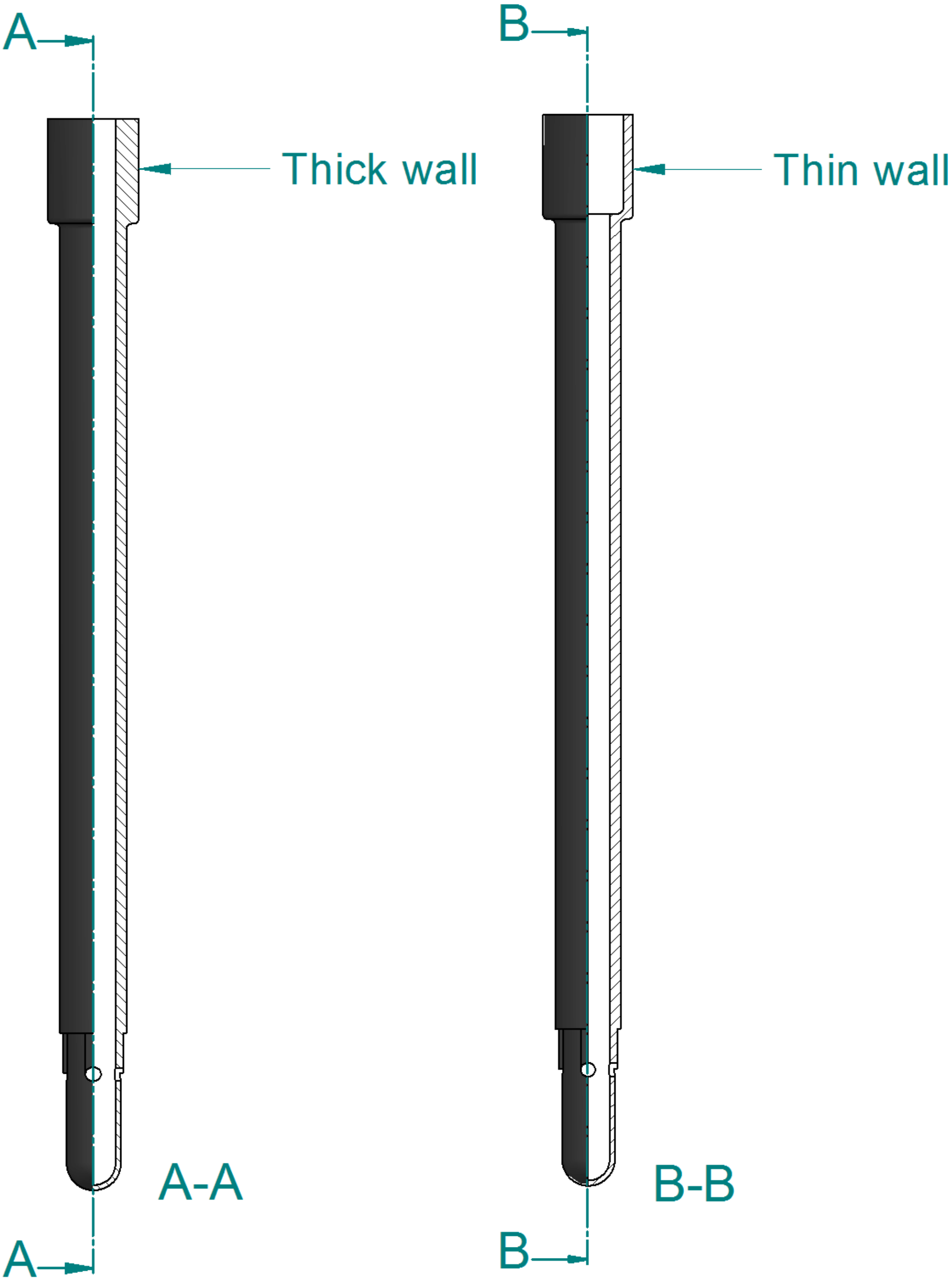


Figure 46 Injection Head Alternative Design

APPENDIX A

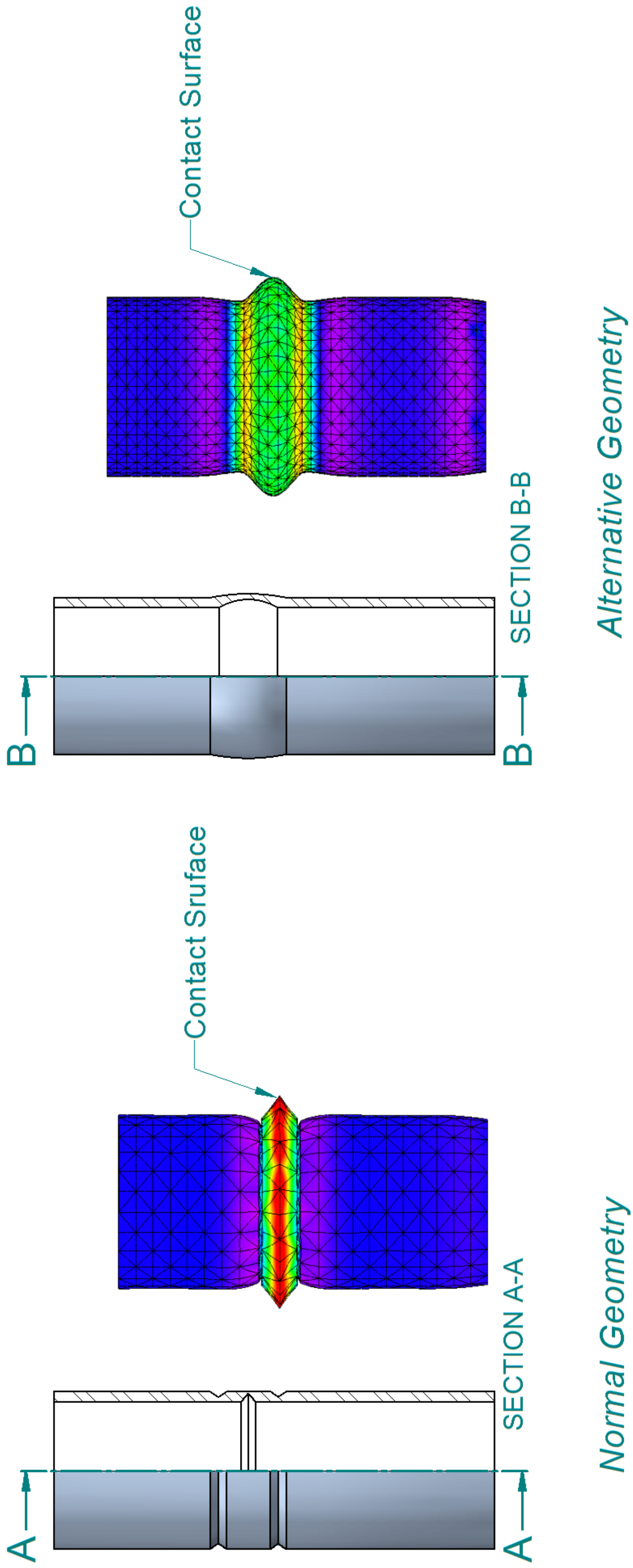


Figure 47 Deformable Member Alternative Geometry

APPENDIX A

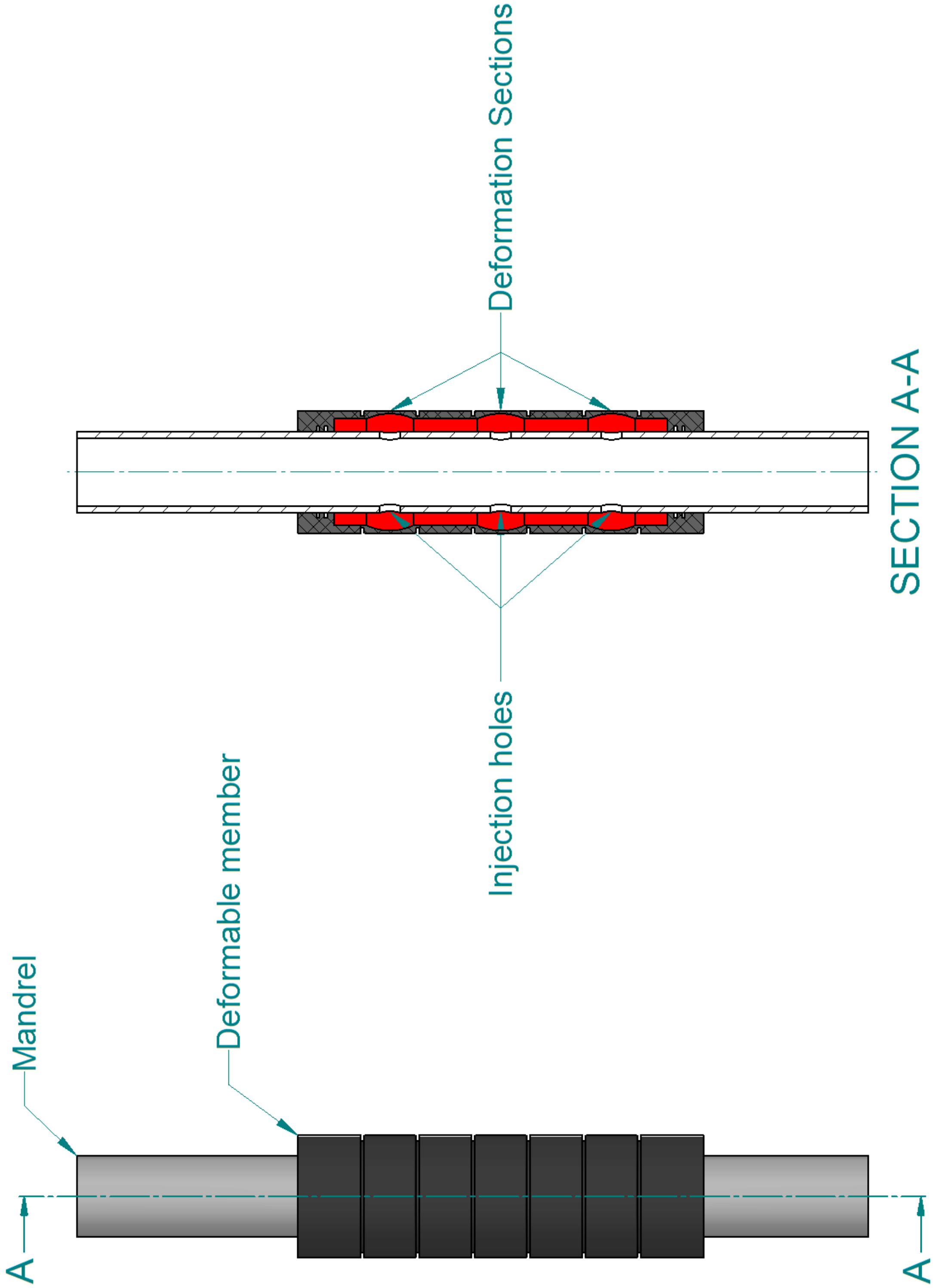


Figure 48 Self-Energized Seal

APPENDIX A

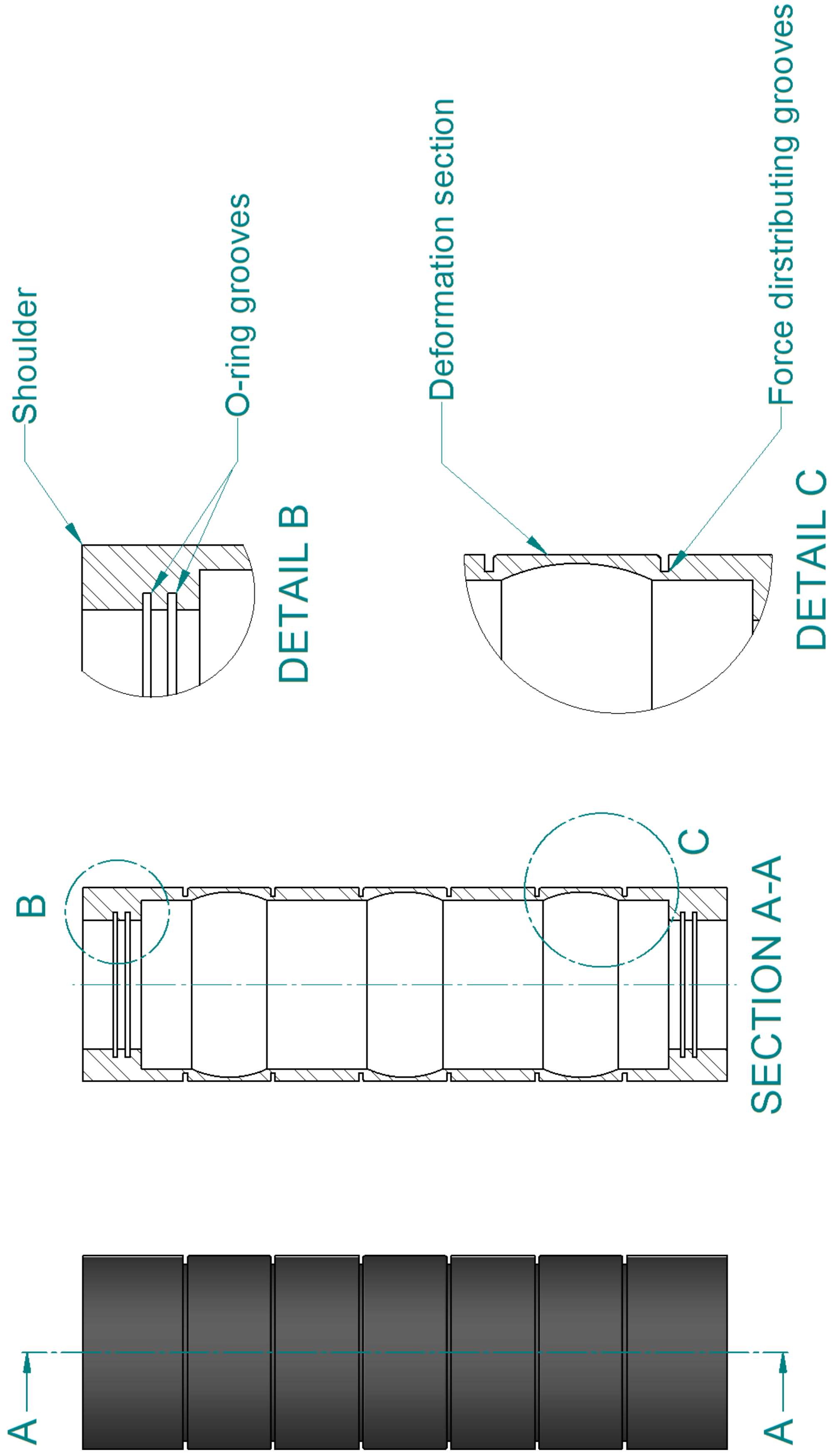


Figure 49 Self-Energized Seal: Deformable member

APPENDIX A

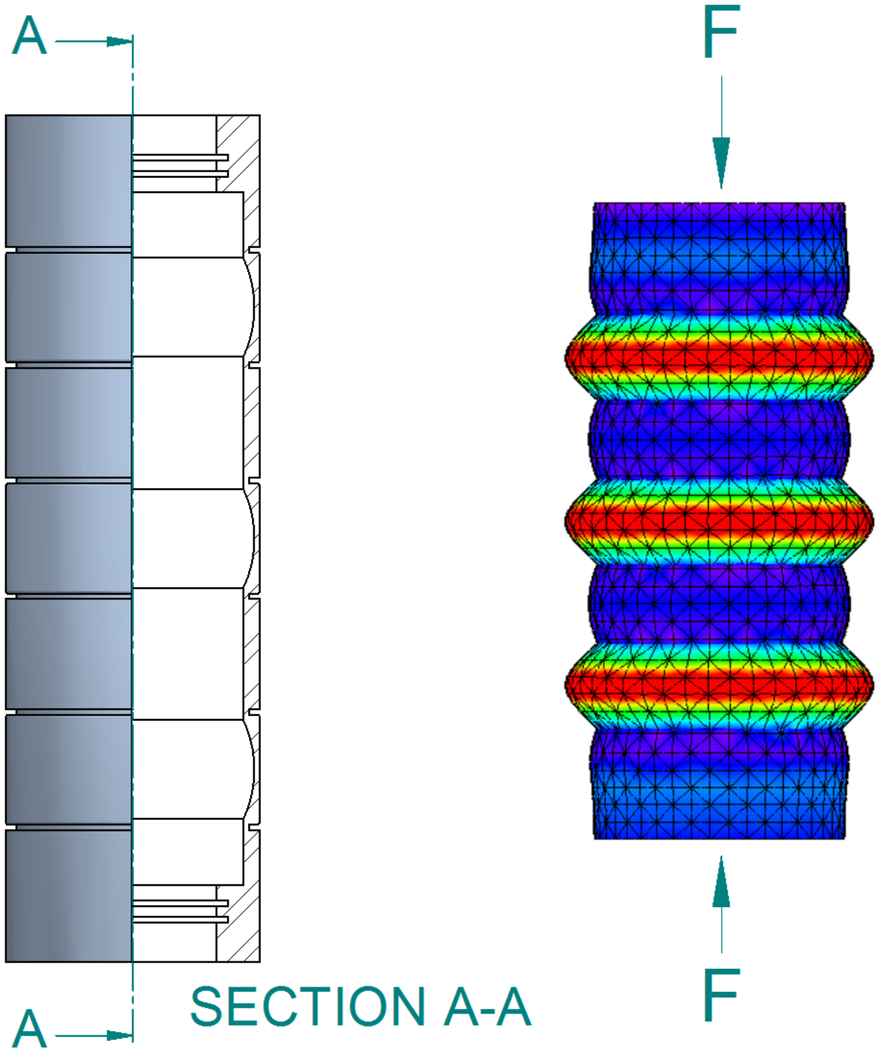


Figure 50 Self-Energized Seal: Deformable Member at Set Configuration

APPENDIX B

Patent EP 1339943 B1

APPENDIX B

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Office européen des brevets

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(54) WELL SEALING METHOD AND APPARATUS

VERFAHREN UND VORRICHTUNG ZUM ABDICHTEN EINES BOHRLOCHES

PROCEDE ET APPAREIL D'OBTURATION D'UN PUITS

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(56) References cited:
US-A- 1 631 419 **US-A- 2 298 129**
US-A- 3 208 530 **US-A- 3 273 641**
US-A- 3 333 635 **US-A- 3 419 074**
US-A- 3 420 928 **US-A- 3 738 424**
US-A- 3 891 034 **US-A- 4 275 788**
US-A- 4 489 784

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Description

[0001] The present invention relates to a method and apparatus for sealing underground components to prevent leakage of for example hydrocarbon fluids from those components.

[0002] In the oil and gas extraction industries, abandoned wells have to be plugged to keep the contents of deep high pressure environments which communicate with those wells from invading levels at or adjacent the surface. Plugs can be inserted at any point in a well, for example adjacent the surface or at a substantial depth. Typically, plugs are formed by injecting cement or resin into the well so as to fill for example a fifty metre length of the well. Experience has proved however that such plugs are not particularly reliable and often leak.

[0003] The known plugs tend to leak for a variety of reasons. Firstly, as the well wall is typically not particularly clean and is also covered with a hydrocarbon film, it is difficult to produce a reliable contiguous seal. Often a contiguous seal of only a metre or so in length is formed with a plug fifty times that length. Furthermore, as cement and resin based plugs solidify they contract which tends to open up a gap between the plug and the well wall. Although when a plug is initially inserted there may be little dynamic pressure in the well, after the plug is in situ substantial pressures can build up and as a result a plug which appears initially to be working satisfactory may subsequently be found to leak. If hydrocarbons leak past the plug contamination of the surface environment or for example a sub-surface aquifer can result. It is well known in the industry that a significant proportion of abandoned wells leak. As a result leaking abandoned wells often have to be re-plugged which is an expensive and time consuming operation.

[0004] It is known to form temporary seals in chemical plants by freezing water or other fluids in the plant. Such plugs are used for example to seal pipes whilst work is conducted upon systems connected to those pipes. The advantage of this approach is that the system does not need to be drained prior to work being initiated. Ice plugs do form reliable seals but require continuous cooling given that the sealed pipe will normally be at a temperature above melting point of ice.

[0005] Document US 3 208 530 discloses a method for plugging a casing using a body of plug material inserted into the casing on a carrier, said plug material having a melting point higher than the temperature of the casing to be plugged, and being formed of a bismuth alloy. The carrier incorporates a heater for melting the plug material, which is collected by a basket expanded to engage the casing walls. The accumulation of molten material in the basket forms the casing plug.

[0006] US 2,298,129 describes a method of sealing an earth or rock formation penetrated by a well bore. A quantity of metal is introduced into the well bore, the metal having a relatively low but higher melting point than the temperature of the earth or rock formation. Heat is applied to heat the metal in the well bore, and molten metal displaced from the well bore into the earth or rock formation by application of fluid pressure. A relatively cold fluid is introduced into the well to bring about solidification of the metal.

[0007] US 4,489,784 describes a method of controlling or terminating the flow of fluid from an uncontrolled well penetrating a subterranean formation. Metallic balls are introduced into the active string, such that they melt. Alternatively, liquid is introduced into the active string, which will cool and solidify in the well to form a plug of solid in the string to stop the flow of fluid.

[0008] US 3,273,641 describes a method of completing an oil and gas well by positioning in the well, a well screen having fusible means temporarily closing a plurality of transverse openings therein, placing a permeable cement in said well around the exterior of said screen and melting the fusible means to temporarily close the openings.

[0009] US 3,891,034 describes a method of emplacing a bridge plug through tubing in a well penetrating subterranean formations, by using a covered expansible centralizer, packer and dogs run downwardly through tubing to a predetermined depth. The dogs are released for holding against the casing.

[0010] US 1,631,419 describes an apparatus for plugging wells comprising a rupturable container, a plug of expansible material in the lower portion of the container providing an upper space for sealing material and having a chamber for containing a charge of explosive, and fulminating means comprising a cap located in the chamber.

[0011] It is an object of the present invention to provide a method and apparatus for plugging a well which obviates or mitigates the problems outlined above.

[0012] There is described herein methods for forming a plug in a well, wherein a length of the well is filled with a molten material the melting point of which is higher than the temperature within the well and which expands as it solidifies.

[0013] The material may be a metal alloy, for example a low-melting point bismuth-containing alloy such as "Rose's metal", "Kraft's alloy" or "Homberg's alloy". The bismuth-containing alloy may be doped with sodium. Such alloys expand upon solidification and thus once deposited in a well they lose heat into the surrounding environment, solidify, and in solidifying expand to form a secure plug within the well.

[0014] The material may be delivered to the well in a molten state. For example a canister of molten material may be lowered to the intended site of the plug and opened either by remote control or deliberate rupture of the canister. For sodium doped material the doping may be achieved by adding an ingot of sodium to the material when in a molten state when the alloy is first prepared. The sodium is added when the alloy is first manufactured, not "down-hole" when it is used to form the plug.

[0015] Alternatively, the material may be delivered to the well in a solidified state, subsequently melted in the well, and then allowed to solidify. For example, the material could be delivered in granular form, for example in a carrier fluid. The granular material could then be melted in any suitable manner, thereafter cooling to form a solidified plug. The granular material could be melted by delivering it in a first fluid, then adding a second fluid which when mixed with the first elevates the temperature to above the melting point of the granular material. The granular material then melts, and subsequently cools to form a solidified plug. The first fluid could be for example inhibited hydrochloric acid whereas the second could be for example caustic soda.

[0016] As a further alternative the plug material may be delivered to the well and located therewithin mounted in solid form on a carrier. Such a carrier may comprise a chemical heater, for example a "Thermit" mixture, which when ignited provides thermal energy to melt the plug material when it is located at the required well depth. The carrier may incorporate an engagement means to engage the well casing when in position. Such engagement means may be arranged to allow insertion of the carrier into the well and movement in a down-hole direction therein but prevent up-hole movement. This may be achieved by coupling the engagement means to the carrier via a hinge.

[0017] Non-chemical methods of melting the plug material could of course be used, for example steam, heated water, electrical resistance heating, frictional heating, sonothermic (sound generated) heating, cavitational (pressure generated) heating, or even simply introducing a solid high thermal capacity mass from which heat is transferred into the previously deposited granular material.

[0018] As a further alternative, a first component of the material which has a melting point lower than the temperature within the well may be delivered in a molten state, and a second component may then be added to the first, the second component mixing with the first and the resultant mixture having a melting point which is higher than the temperature within the well. Thus the first component could be accurately positioned in situ, visually inspected and then converted into a solid plug simply by pouring the second component into the well so that it mixes with the first component.

[0019] Once the molten material has solidified and formed a plug it may be capped with a coating material. A preferred example of a suitable coating material is concrete.

[0020] According to the present invention, there is provided a method for forming a plug in a well as claimed in claim 1.

[0021] Embodiments of the present invention will now be described, by way of example, with reference to the accompany drawings in which;

Figure 1 is a schematic representation of a conventional well plugging method;

Figure 2 is a schematic representation of a method for plugging a well;

Figure 3 is a schematic representation of another method for plugging a well;

Figure 4 is a schematic representation of a first method for plugging a well in accordance with the present invention;

Figures 5, 6 and 7 are side views of components used in the method of Figure 4;

Figures 8, 9 and 10 are schematic cross-sections (viewed from the side) of components used in the method of Figure 4;

Figure 11 is a schematic representation of a further method for plugging a well in accordance with the present invention; and

Figures 12 and 13 are side views of components used in the further method.

[0022] Referring to figure 1, an oil well has a casing 1 within which production tubing 2 extends axially. In order to plug the well, it is necessary to block both the annular passageway between the casing 1 and the production tubing 2 itself. Conventionally this is achieved by blocking the casing 1 beneath the production tubing 2 by inserting a packer 3. The space above the packer 3 is then filled with cement 4 to a depth typically of 50 metres. The cement then solidifies, forming the required plug.

[0023] The surface of the casing 1 and the surface of the production tubing 2 contacted by the cement are not ideal for forming sealing interfaces. Those surfaces are contaminated with hydrocarbon components and other deposits. Furthermore, as the cement hardens, it tends to contract so that in the absence of adhesion between the cement 4 and the casing 1 an annular gap can develop between the cement 4 and the casing 1. Although at the time the well is plugged generally there will be little upwards flow through the well because the seal is initially adequate, over time the seal can fail so that fluids will migrate up the gap created by seal failure. As a result unwanted fluid can leak past the plug 4 (shown by arrow 5), risking contamination of the local environment.

[0024] Referring now to figure 2, this illustrates a method for plugging a well. The same reference numerals are used for equivalent components as in figure 1. In contrast to the cement plug 4 of figure 1 however in figure 2 a bismuth alloy plug 6 is formed within the casing 1 above the packer 3. The length of casing 1 filled with the plug 6 is relatively small as compared with the length of casing filled by the cement 4 as shown in figure 1. Typically the length of casing 1 filled with the plug 6 is an order magnitude less than that often encountered with cement plugs (typically 50 metres). Nevertheless, the arrangement of figure 2 provides a reliable plug 6 because the bismuth alloy is initially molten within the casing 1 but subsequently solidifies and during solidification expands to tightly engage the casing 1 and the production tubing 2. Thus a solid plug 6 of expanded metal seals the casing 1 and locks together and components contracted by the plug 6.

[0025] The bismuth alloy plug 6 could be formed from one of the low-melting point bismuth containing alloys known from the printing industry, for example "Rose's metal" (melting point 93°C), "Kraft's alloy" (melting point 104°C), "Homberg's alloy" (melting point 122°C) or any alloy which may be developed to have characteristics suitable for the down-hole conditions. For example antimony could be used to form higher temperature melting point alloys.Such alloys increase in volume upon solidification and thus are sometimes referred to as "expanding metal alloys". The unusual property of expansion upon solidification has been used to advantage in the printing industry to lock printing blocks into printing frames. In the environment to which the present invention relates, once installed the bismuth alloy plug 6 will be a permanent fixture given that the stable temperature of the local environment ensure that it remains in a solid state. As the plugs expand on solidification, they form reliable seals along their entire length.

[0026] The solid plug 6 of figure 2 can be formed by delivering molten bismuth alloy in a canister or the like which is lowered to just above the packer 3 and then opened or ruptured as convenient. The released molten alloy flows to form a solid plug 6 above the packer 3 and then cools to the local temperature (typically 40-100°C). Thus the plug 6 solidifies and expands. Alternatively, the alloy could be delivered via a coiled tubing placement system.

[0027] Optionally the bismuth alloy may be doped with sodium. This may be achieved by adding an ingot of sodium to the bismuth alloy when it is molten during the manufacturing process. It will be appreciated that as sodium melts at a low temperature (98°C) it will melt in the molten alloy and become dispersed. Other methods of doping such as ion bombardment and pre-doping of the bismuth alloy before it is located in situ are not hereby precluded. The doping of the bismuth alloy may be such that around 1% of the alloy is comprised of sodium. It is postulated that doping with sodium serves as an aid in preventing creep of the bismuth alloy plug 6.

[0028] As an alternative to delivering molten alloy to the space above the packer 3, it would be possible to deliver a solid alloy in for example granular form and then to melt the alloy in situ using any convenient heating system. Figure 3 illustrates one arrangement in which the necessary heating is delivered by an exothermic reaction.

[0029] Referring to figure 3, this illustrates another method for plugging a well. Once again the same reference numerals are used as in figure 1 where appropriate. The space above the packer 3 however is filled with a layer of bismuth alloy granules 7 immersed in a carrier fluid of for example inhibited hydrochloric acid 8. The acid 8 cleans the surfaces of the down hole components above the packer 3 but does not attack the metal of the down hole components nor the bismuth alloy granules 7. All of the introduced materials will warm up to the local ambient temperature. This is too low to cause the granules to melt. A further component can then be added, that is caustic soda (illustrated by arrow 9), which reacts with the hydrochloric acid 8 in an exothermic reaction that elevates the local temperature to above the melting point of the alloy granules 7. The granules 7 thus melt and coalesce. In most applications, the local pressure will be sufficiently high to prevent the reactants from boiling and dissipating the generated heat. The end reaction products of the cooled acid 8/alkali 9 reaction are sodium chloride and water which are benign to the natural environment. It will of course be appreciated that other exothermic reactions could be used. It will also be appreciated that any other convenient method for melting the alloy granules 7 could be used.

[0030] Referring now to figures 4-10 an embodiment of the invention is illustrated using the same reference numbers as above where appropriate. Once again a bismuth alloy plug 6 is formed within the casing 1 above the packer 3. In contrast to the methods illustrated in Figures 2 and 3, the solid bismuth alloy plug 6 (shown in figure 4) is formed from an amount of bismuth alloy delivered in solid form on a carrier spool to the required depth within the casing 1.

[0031] The carrier spool may comprise 1% manganese steel. The carrier spool comprises a tubular mandrel 10. The mandrel 10 has an upper open end. The lower end of the mandrel 10 terminates in a head 11, upon which a cylindrical packer 3 (preferably comprising vulcanised rubber including 40% acrylonitrile) is mounted. The packer 3 may be mounted on the head by a method which includes a bonding step, thus forming a metallelastic bond. The head 11 defines a frustocone the base of which has a lower diameter than that of the packer 3 and which tapers from the upper surface of the packer 3 to the mandrel 10. The mandrel 10 has a plurality of circular flanges 12 in the form of fins distributed at intervals along its length. The diameter of each fin 12 is approximately equal to the diameter of the base of the frustocone 11.

[0032] In delivery form (shown in figure 6) the solid metal locates along the length of the mandrel 10 between the head 11 and an upper fin 12, defining a cylinder extending as far as the peripheral edge of the upper fin 12. The metal may comprise, for example, pure bismuth, an admixture of 95% bismuth and 5% tin or an admixture of 52% bismuth and 48% tin, in each case the metal may be doped with sodium. In this form the carrier spool is inserted into the casing I (packer end first) and lowered to the required depth.

[0033] Thus positioned the bismuth alloy is melted in situ by a heater which normally locates within the mandrel 10 (but which is illustrated for clarity in figure 7 outside the mandrel 10). The heater defines a cylinder, an upper portion of which comprises an ignition source 13 and a lower portion of which comprises a heater element 14. The heater element 14 may comprise an admixture of aluminium and iron oxide (thermit mixture). The ignition source 13 may comprise a barium peroxide fuse and an electrical heater. It will be appreciated that other forms of both ignition source 13 and heater element 14 could be used.

[0034] Commonly the ignition source 13 is activated using a fuse 15. The fuse 15 is preferably disposed in a bore 16 in a threaded cap 17 which engages a threaded portion 18 of the mandrel 10. The cap 17 may define a simple hollow plug (as shown in figure 8) or may include features such as incisions 19 (as shown in figure 9) which allow the cap 17 to be engaged by other equipment (not shown) such as a deployment tool. The cap 17 may define a stab connector.

[0035] Activation of the detonator 13 triggers the heater element 14. Heat produced from the heater element 14 causes the bismuth alloy supported on the mandrel 10 to become molten. Combustion/waste gases which may be produced from the heater element 14 are allowed to be vented by the open end of the mandrel 10 and the cap 17.

[0036] The molten bismuth alloy thus slumps into the volume defined by the upper surface of the rubber packer 3 and the casing wall I (as shown in figure 6).

[0037] The frustocone 11 is able to serve as a wedge that drives into the expanded bismuth alloy plug 6. Thus pressure from the reservoir serves to force the plug 6 against the casing wall 1.

[0038] The fins 12 serve three purposes. Firstly the fins 12 aid in forcing the expanding metal against the casing 1 by minimising axial and promoting lateral expansion. Secondly the fins 12 aid the transfer of heat from the heater element 14 to the bismuth alloy. Thirdly the fins 12 aid in reducing creep of the bismuth alloy plug 6 up hole.

[0039] Referring now to figures 11 to 13 a further embodiment of the invention is illustrated. Once more a bismuth alloy plug 6 is formed within the casing 1 above a packer 3. The bismuth alloy is delivered using a carrier spool as in the third embodiment. The further embodiment differs from the first embodiment in that casing engagement means are coupled to a fin 12 on the carrier spool.

[0040] The casing engagement means comprises arms 18a and 18b coupled by a hinge (not shown) to an upper surface of a fin 12. Although two arms 18a, 18b are illustrated coupled to one fin 12 it will be appreciated that additional arms may be included, either coupled to the same or other fins 12. The non-coupled ends of arms 20a and 20b have one or a plurality of casing engagement members (not shown), which may comprise for example a spike, a tooth, a chisel or another engagement member.

[0041] In delivery form the arms 18a, 18b are retained within the bismuth alloy so that the carrier spool carrying the bismuth alloy may be located at the required depth in the casing 1. Activation of the heater element 14 causes the bismuth alloy to be melted and thus the arms 18a, 18b are free to fall into engagement with a portion of the casing 1.

[0042] As the bismuth alloy solidifies and expands the arms 18a, 18b are urged into a pressured engagement with the casing 1. Thus deployed the arms 18a, 18b act as an aid in preventing reservoir pressure induced creep of the plug 6 along the well. Indeed any increase in reservoir pressure will merely cause stronger engagement of the engagement means with the casing 1.

[0043] In a further method for plugging a well which is not specifically illustrated, an alloy could be introduced the melting point of which is lower than the ambient temperature immediately above the packer 3. The composition of the alloy could then be changed to raise its melting point above the local ambient temperature. For example, alloys are known which have melting points below 40°C but into which lead can be introduced to form a mixture the melting point of which is well above 40°C. Thus one could envisage the formation of a plug by pouring a first component into the well so as to form a body of liquid alloy immediately above a packer, inspecting the deposited liquid alloy to ensure that the alloy is safely retained in place, and then simply pouring lead granules into the well such that the granules become immersed in the liquid alloy, causing the combined liquid/alloy lead granule mixture to form a solid plug.

[0044] In a yet further embodiment of the invention which is not specifically illustrated a further plug may be formed above the plug of solidified material. Such a further plug may be used to provide additional resistance against creep of the plug of scheduled material caused by pressure from the reservoir. As the further plug is not being used to provide a seal for the well its length need not be of the same order of magnitude as conventional plugs described in the prior art. For example the further plug may be of the order of 5-10 metres long. A preferred material for the further plug is concrete.

Claims

1. A method for plugging a casing (1) using a body of plug material (6) inserted into the casing on a carrier (10), the body of plug material (6) having a melting point higher than the temperature of the casing to be plugged and expanding on solidification, the plug material being supported on a mandrel (10), **characterised in that** a plurality of circular flanges (12) are spaced apart along the mandrel (10), the mandrel (10) carrying the body of plug material (6) being inserted into the casing, the mandrel (10) is heated to a temperature higher than the melting point of the plug material (6) such that the body of plug material (6) melts and slumps into the casing between the circular flanges (12), and the molten plug material (6) is cooled to solidify between the circular flanges (12), the circular flanges (12) forcing the expanding solidifying plug material against the casing (1), aiding the transfer of heat between the mandrel (10) and the plug material (6), and reducing creep of plug ma-

terial (6) along the casing (1).

2. A method according to claim 1, wherein a packer (3) is supported on the mandrel (10) beneath the circular flanges (12) to prevent molten plug material flowing away from the circular flanges (12).

3. A method according to claim 1 or 2, wherein the plug material (6) is a metal alloy.

4. A method according to claim 3, wherein the plug material (6) is a bismuth-containing alloy.

5. A method according to claim 3 or 4, wherein the plug material (6) is doped with sodium.

6. A method according to any one of the preceding claims, comprising adding a further plug above the plug material when solidified.

7. A method according to claim 6, wherein the further plug comprises concrete.

8. An apparatus for forming a plug in a casing (1), comprising a carrier (10) for insertion into the casing, the carrier supporting a body of plug material (6), the carrier comprising a mandrel (10), **characterised in that** the carrier further comprises at least two circular flanges (12) spaced apart along the mandrel (10), and a heater (13,14) for heating the mandrel (10), the plug material (6) having a melting point higher than the temperature within the casing (1) and lower than a temperature to which the heater (13,14) heats the mandrel (10), the plug material (6) being such that it expands when it solidifies, and the plug material being carried on the mandrel (10) such that if the mandrel is heated within the casing (1) to a temperature above the melting point of the plug material (6) the plug material slumps into the casing (1) between the circular flanges (12), the circular flanges serving to force expanding solidifying plug material (6) against the casing (1), aiding the transfer of heat between the mandrel (10) and the plug material (6), and resisting creep of solidified material along the casing (1).

9. An apparatus according to claim 8, comprising a packer (3) supported on a bottom end of the mandrel (10).

10. An apparatus according to claim 8 or 9, comprising arms (18a,18b) retained within the plug material (6), the arms being arranged to fall into engagement with a casing (1) within which the plug material is melted.

11. An apparatus according to claim 8, 9 or 10, wherein the plug material (6) is a metal alloy.

12. An apparatus according to claim 11, wherein the plug material (6) is a bismuth-containing alloy.

13. An apparatus according to claim 11 or 12, wherein the plug material (6) is doped with sodium.

14. An apparatus according to any one of claims 8 to 13, comprising a frustoconical head (11) at a lower end of the mandrel beneath the circular flanges (12), the frustoconical head (11) tapering upwards.

15. An apparatus according to any one of claims 8 to 14, wherein the mandrel (10) is tubular, and the heater (13,14) is received within the tubular mandrel.

Patentansprüche

1. Verfahren zum Verstopfen eines Futterrohres (1) bei Verwendung eines Stopfenmaterialkörpers (6), der in das Futterrohr auf einem Träger (10) eingesetzt wird, wobei der Stopfenmaterialkörper (6) einen Schmelzpunkt aufweist, der höher ist als die Temperatur des zu verstopfenden Futterrohres, und wobei er sich bei der Verfestigung ausdehnt, wobei das Stopfenmaterial auf einem Mantelrohr (10) getragen wird, **dadurch gekennzeichnet, dass** eine Vielzahl von kreisförmigen Flanschen (12) längs des Mantelrohres (10) beabstandet ist, wobei das Mantelrohr (10) den Stopfenmaterialkörper (6) trägt, der in das Futterrohr eingesetzt wird, wobei das Mantelrohr (10) auf eine Temperatur höher als der Schmelzpunkt des Stopfenmaterials (6) erwärmt wird, so das der Stopfenmaterialkörper (6) schmilzt und in das Futterrohr zwischen den kreisförmigen Flanschen (12) rutscht, und wobei das geschmolzene Stopfenmaterial (6) abgekühlt wird, um sich zwischen den kreisförmigen Flanschen (12) zu verfestigen, wobei die kreisförmigen Flansche (12) das sich ausdehnende, sich verfestigende Stopfenmaterial gegen das Futterrohr (1) drücken, wobei die Übertragung der Wärme zwischen dem Mantelrohr (10) und dem Stopfenmaterial (6) unterstützt und das Kriechen des topfenmaterials (6) längs des Futterrohres (1) verringert wird.

2. Verfahren nach Anspruch 1, bei dem ein Packer (3) am Mantelrohr (10) unterhalb der kreisförmigen Flansche (12) getragen wird, um zu verhindern, dass das geschmolzene Stopfenmaterial von den kreisförmigen Flanschen (12) weg fließt.

3. Verfahren nach Anspruch 1 oder 2, bei dem das Stopfenmaterial (6) eine Metalllegierung ist.

4. Verfahren nach Anspruch 3, bei dem das Stopfenmaterial (6) eine wismuthaltige Legierung ist.

5. Verfahren nach Anspruch 3 oder 4, bei dem das Stopfenmaterial (6) mit Natrium gedopt ist.

6. Verfahren nach einem der vorhergehenden Ansprüche, das das Hinzufügen eines weiteren Stopfens über dem Stopfenmaterial aufweist, wenn es verfestigt ist.

7. Verfahren nach Anspruch 6, bei dem der weitere Stopfen Beton aufweist.

8. Vorrichtung zum Bilden eines Stopfens in einem Futterrohr (1), die einen Träger (10) für das Einsetzen in das Futterrohr aufweist, wobei der Träger einen Stopfenmaterialkörper (6) trägt, wobei der Träger ein Mantelrohr (10) aufweist, **dadurch gekennzeichnet, dass** der Träger außerdem mindestens zwei kreisförmige Flansche (12), die längs des Mantelrohres (10) beabstandet sind, und einen Heizkörper (13, 14) für das Erwärmen des Mantelrohres (10) aufweist, wobei das Stopfenmaterial (6) einen Schmelzpunkt aufweist, der höher ist als die Temperatur innerhalb des Futterrohres (1) und niedriger als eine Temperatur, auf die der Heizkörper (13, 14) das Mantelrohr (10) erwärmt, wobei das Stopfenmaterial (6) so ist, dass es sich ausdehnt, wenn es sich verfestigt, und wobei das Stopfenmaterial auf dem Mantelrohr (10) getragen wird, so dass, wenn das Mantelrohr innerhalb des Futterrohres (1) auf eine Temperatur über dem Schmelzpunkt des Stopfenmaterials (6) erwärmt wird, das Stopfenmaterial in das Futterrohr (1) zwischen den kreisförmigen Flanschen (12) rutscht, wobei die kreisförmigen Flansche dazu dienen, das sich ausdehnende, sich verfestigende Stopfenmaterial (6) gegen das Futterrohr (1) zu drücken, wobei die Übertragung der Wärme zwischen dem Mantelrohr (10) und dem Stopfenmaterial (6) unterstützt wird, und wobei dem Kriechen des verfestigten Materials längs des Futterrohres (1) ein Widerstand entgegengesetzt wird.

9. Vorrichtung nach Anspruch 8, die einen Packer (3) aufweist, der an einem unteren Ende des Mantelrohres (10) getragen wird.

10. Vorrichtung nach Anspruch 8 oder 9, die Arme (18a, 18b) aufweist, die innerhalb des Stopfenmaterials (6) gehalten werden, wobei die Arme so angeordnet sind, dass sie mit einem Futterrohr (1) in Eingriff fallen, innerhalb dessen das Stopfenmaterial geschmolzen wird.

11. Vorrichtung nach Anspruch 8, 9 oder 10, bei der das Stopfenmaterial (6) eine Metalllegierung ist.

12. Vorrichtung nach Anspruch 11, bei der das Stopfenmaterial (6) eine wismuthaltige Legierung ist.

13. Vorrichtung nach Anspruch 11 oder 12, bei der das Stopfenmaterial (6) mit Natrium gedopt ist.

14. Vorrichtung nach einem der Ansprüche 8 bis 13, die einen kegelstumpfförmigen Kopf (11) an einem unteren Ende des Mantelrohres unterhalb der kreisförmigen Flansche (12) aufweist, wobei sich der kegelstumpfförmige Kopf (11) nach oben verjüngt.

15. Vorrichtung nach einem der Ansprüche 8 bis 14, bei der das Mantelrohr (10) rohrförmig ist und der Heizkörper (13, 14) innerhalb des rohrförmigen Mantelrohres aufgenommen wird.

Revendications

1. Procédé d'obturation d'un tubage (1) par l'intermédiaire d'un corps de matériau de bouchon (6) inséré dans le tubage sur un support (10), le corps du matériau de bouchon (6) ayant un point de fusion supérieur à la température du tubage devant être obturé et se dilatant lors de la solidification, le matériau de bouchon étant supporté sur un mandrin (10), **caractérisé en ce que** plusieurs brides circulaires (12) sont espacées le long du mandrin (10), le mandrin (10) étant chauffé à une température supérieure au point de fusion du matériau de bouchon (6), de sorte que le corps du matériau de bouchon (6) est fondu et s'affaisse dans le tubage entre les brides circulaire (12), le matériau de bouchon fondu (6) étant refroidi en vue de sa solidification entre les brides circulaires (12), les brides circulaires (12) poussant le matériau de bouchon en cours de solidification et de dilatation contre le tubage (1), facilitant ainsi le transfert de la chaleur entre le mandrin (10) et le matériau de bouchon (6) et réduisant le fluage du matériau de bouchon (6) le long du tubage (1).

2. Procédé selon la revendication 1, dans lequel une garniture d'étanchéité (3) est supportée sur le mandrin (10), au-dessous des brides circulaires (12), pour empêcher l'écoulement du matériau de bouchon fondu à l'écart des brides circulaires (12).

3. Procédé selon les revendications 1 ou 2, dans lequel le matériau de bouchon (6) est constitué par un alliage métallique.

4. Procédé selon la revendication 3, dans lequel le matériau de bouchon (6) est constitué par un alliage à base de bismuth.

5. Procédé selon les revendications 3 ou 4, dans lequel le matériau de bouchon (6) est dopé au sodium.

6. Procédé selon l'une quelconque des revendications précédentes, comprenant l'addition d'un bouchon additionnel au-dessus du matériau de bouchon après la solidification.

7. Procédé selon la revendication 6, dans lequel le bouchon additionnel comprend du béton.

8. Dispositif de formation d'un bouchon dans un tubage (1), comprenant un support (10) en vue de l'insertion dans le tubage, le support supportant un corps de matériau de bouchon (6), le support comprenant un mandrin (10), **caractérisé en ce que** le support comprend en outre au moins deux brides circulaires (12) espacées, le long du mandrin (10), et un dispositif de chauffage (13, 14) pour chauffer le mandrin (10), le matériau de bouchon (6) ayant un point de fusion supérieur à la température dans le tubage (1) et inférieur à une température à laquelle le dispositif de chauffage (13, 14) chauffe le mandrin (10), le matériau de bouchon (6) étant tel qu'il se dilate lors de sa solidification, le matériau de bouchon étant supporté sur le mandrin (10) de sorte que lorsque le mandrin est chauffé dans le tubage (1) à une température supérieure au point de fusion du matériau de bouchon (6), le matériau de bouchon s'affaisse dans le tubage (1) entre les brides circulaires (12), les brides circulaires servant à pousser le matériau de bouchon en cours de solidification et de dilatation (6) contre le tubage (1), facilitant ainsi le transfert de la chaleur entre le mandrin (10) et le matériau de bouchon (6) et résistant à un fluage du matériau solidifié le long du tubage (1).

9. Dispositif selon la revendication 8, comprenant une garniture d'étanchéité (3) supportée sur une extrémité inférieure du mandrin (10).

10. Dispositif selon les revendications 8 ou 9, comprenant des bras (18a, 18b), retenus dans le matériau de bouchon (6), les bras étant destinés à s'engager par retombée dans un tubage (1) dans lequel le matériau de bouchon est fondu.

11. Dispositif selon les revendications 8, 9 ou 10, dans lequel le matériau de bouchon (6) est constitué par un alliage métallique.

12. Dispositif selon la revendication 11, dans lequel le matériau de bouchon (6) est constitué par un alliage à base de bismuth.

13. Dispositif selon les revendications 11 ou 12, dans lequel le matériau de bouchon (6) est dopé au sodium.

14. Dispositif selon l'une quelconque des revendications 8 à 13, comprenant une tête en tronc de cône (11) au niveau d'une extrémité inférieure du mandrin, au-dessous des brides circulaires (12), la tête en tronc de cône (11) étant effilée vers le haut.

15. Dispositif selon l'une quelconque des revendications 8 à 14, dans lequel le mandrin (10) est tubulaire, le dispositif de chauffage (13, 14) étant reçu dans le mandrin tubulaire.

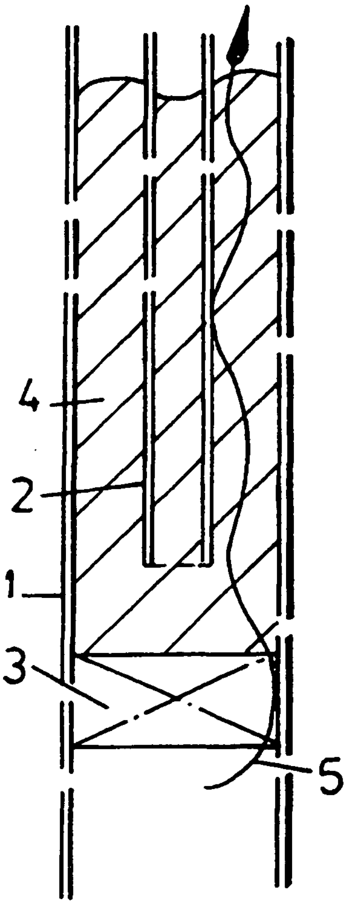


FIG. 1

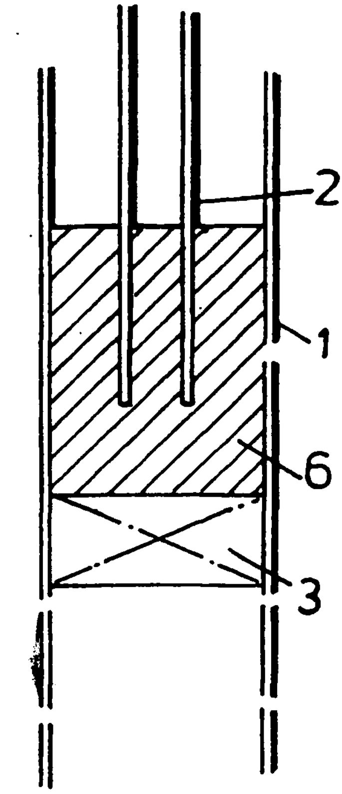


FIG. 2

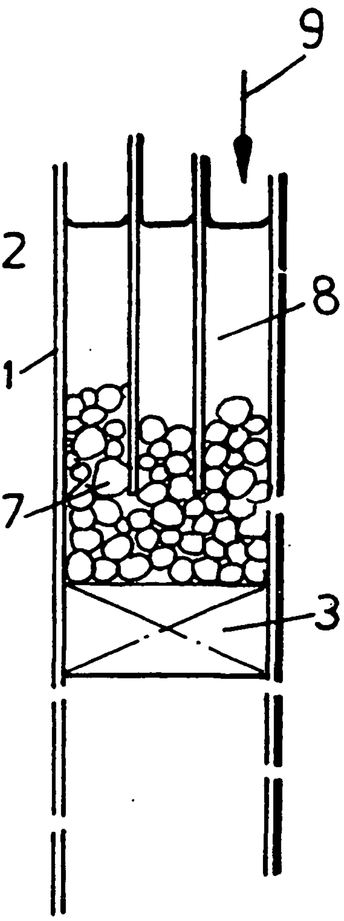


FIG. 3

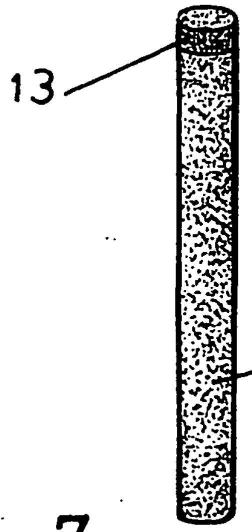


FIG. 7

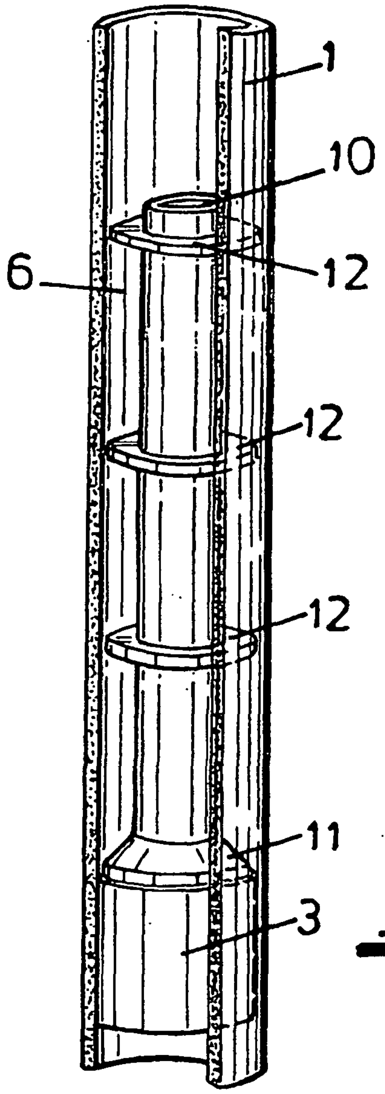


FIG.4

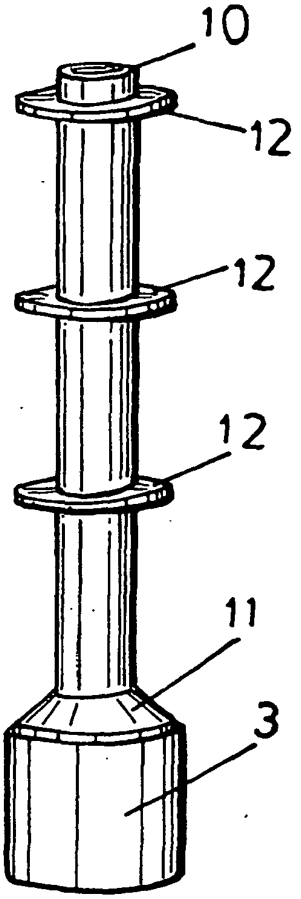


FIG.5

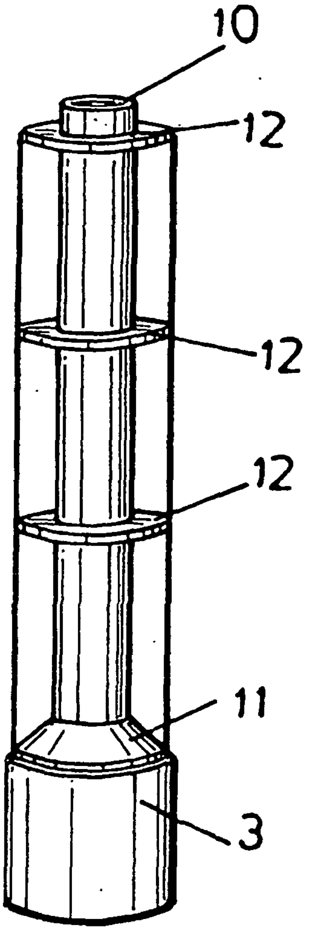


FIG.6

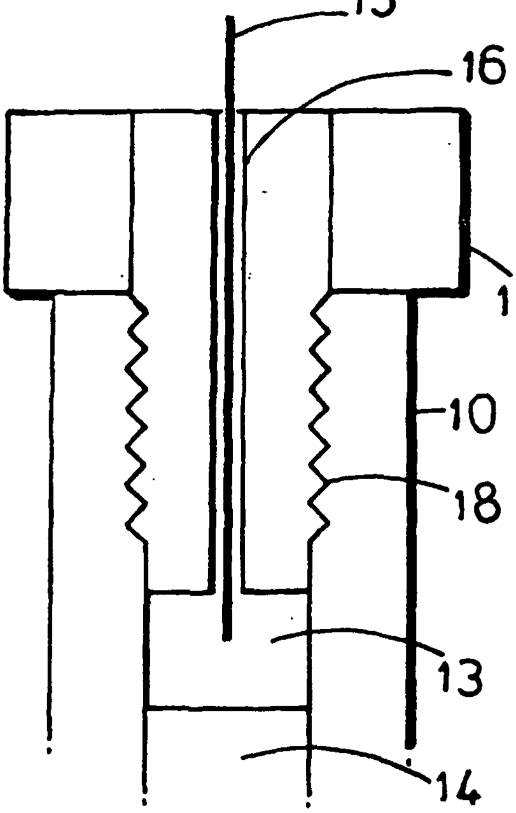


FIG.8

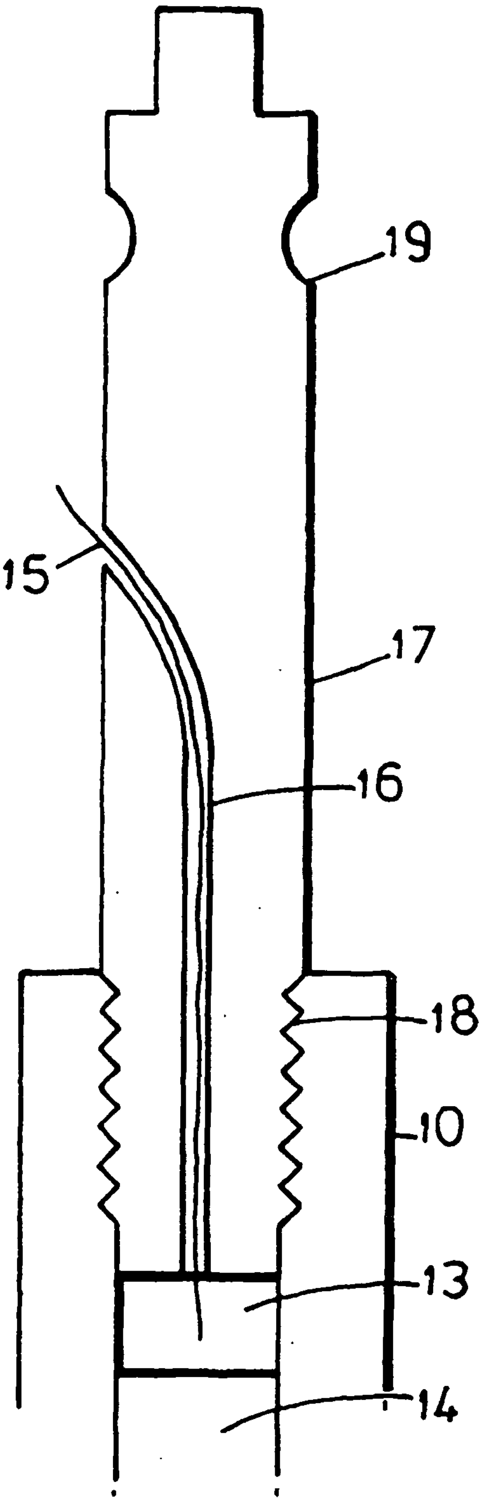


FIG.9

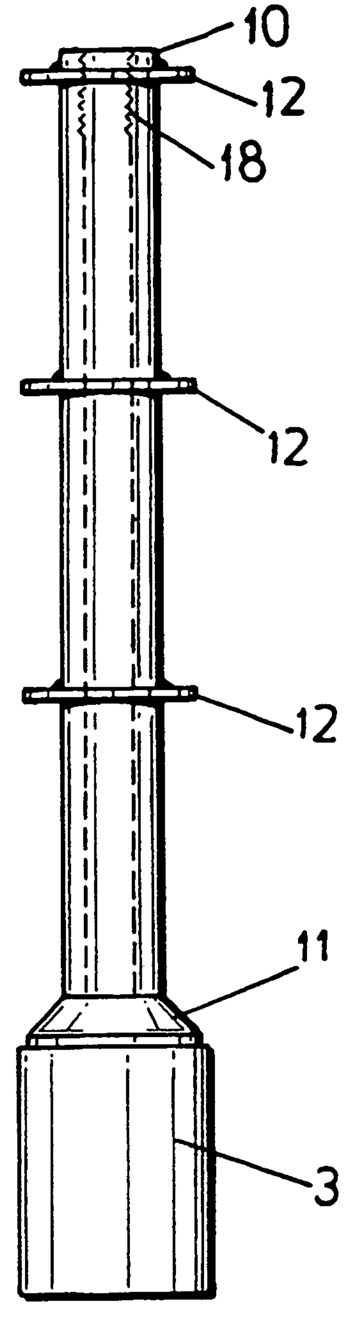


FIG.10

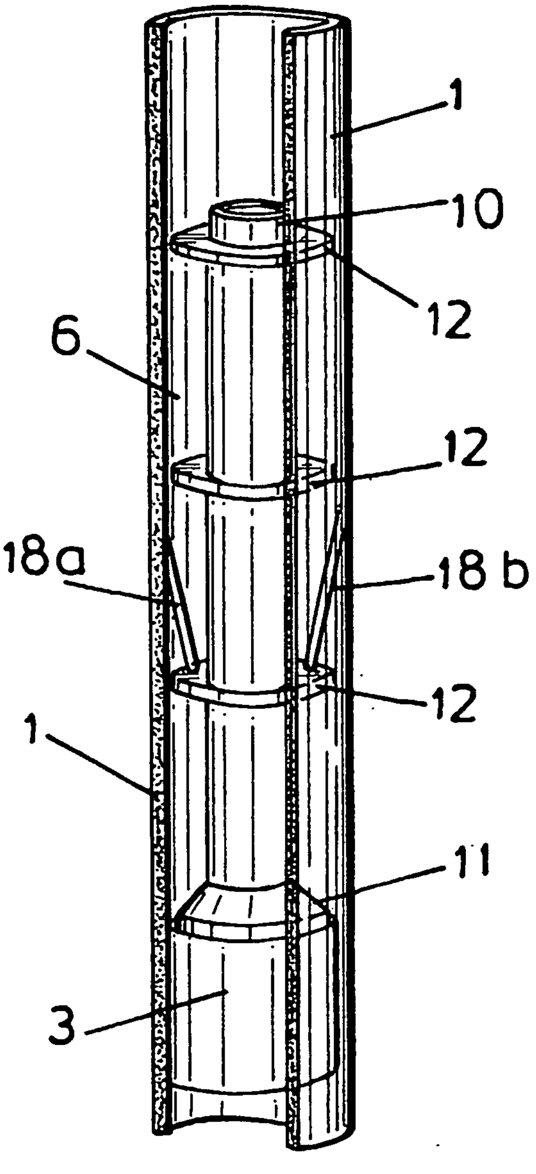


FIG.11

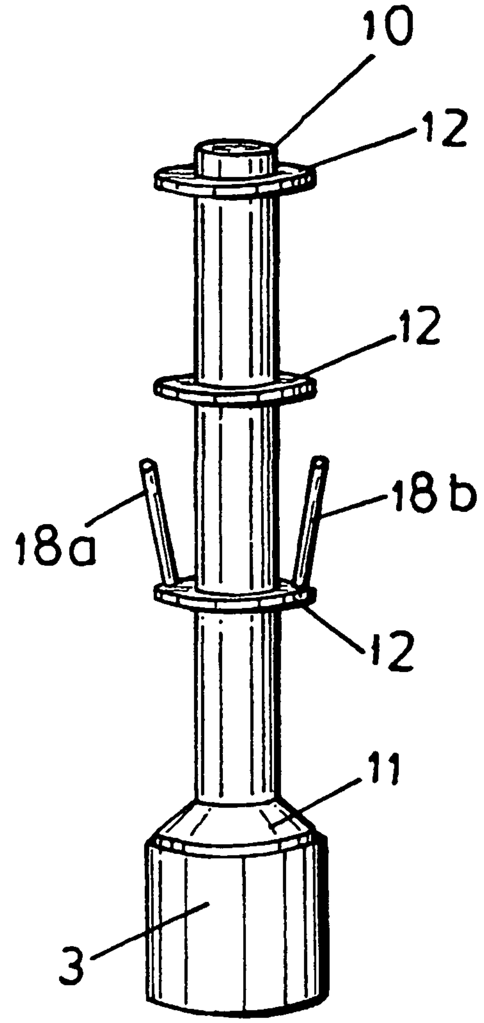


FIG.12

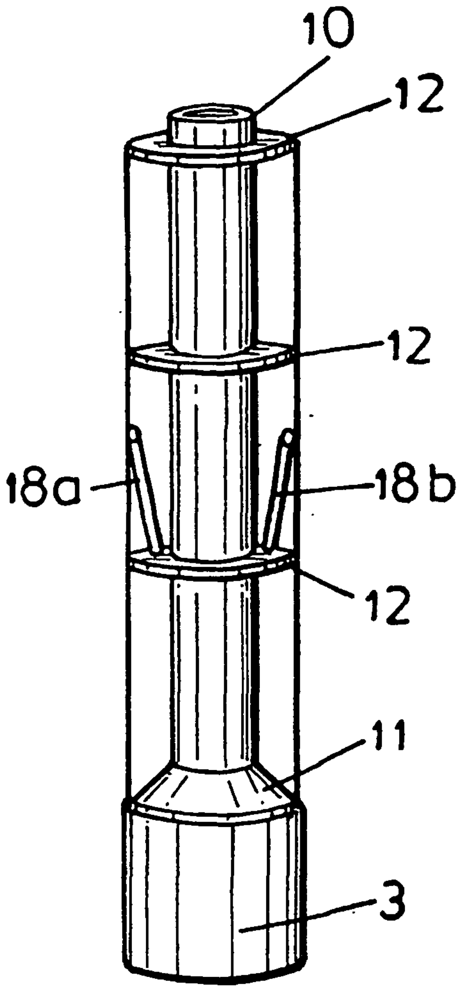


FIG.13

APPENDIX C

Patent US 7134506 B2

Selected Pages

APPENDIX C

US007134506B2

(12) United States Patent
Moyes

(10) **Patent No.: US 7,134,506 B2**
(45) **Date of Patent: Nov. 14, 2006**

(54) **DEFORMABLE MEMBER**

(75) Inventor: **Peter Barnes Moyes**, Aberdeenshire (GB)

(73) Assignee: **Baker Hughes Incorporated**, Houston, TX (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **11/114,488**

(22) Filed: **Apr. 26, 2005**

(65) **Prior Publication Data**

US 2005/0263296 A1 Dec. 1, 2005

Related U.S. Application Data

(60) Division of application No. 10/336,848, filed on Jan. 6, 2003, now Pat. No. 6,896,049, which is a continuation of application No. PCT/GB01/03072, filed on Jul. 9, 2001.

(30) **Foreign Application Priority Data**

Jul. 7, 2000 (GB) 0016595.1

(51) **Int. Cl.**
E21B 33/13 (2006.01)

(52) **U.S. Cl.** **166/387**; 166/313; 166/52

(58) **Field of Classification Search** 166/82.1, 166/118, 387, 191, 195, 217; 277/322, 327, 277/342, 343, 627
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

2,683,928	A	7/1954	Carson
4,482,086	A	11/1984	Wagner et al.
5,211,226	A	5/1993	Hendrickson et al.
5,988,276	A	11/1999	Oneal
6,032,958	A	3/2000	Fowler
6,425,444	B1	7/2002	Metcalfe et al.
6,431,282	B1	8/2002	Bosma et al.
6,530,574	B1	3/2003	Bailey et al.

FOREIGN PATENT DOCUMENTS

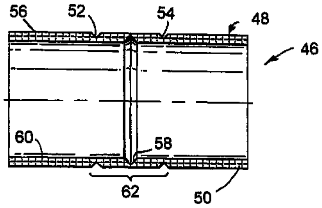
DE	87026	1/1895
EP	0 029 380 A1	5/1981

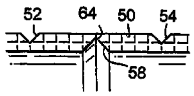
Primary Examiner—Frank S. Tsay
(74) *Attorney, Agent, or Firm*—Cantor Colburn LLP

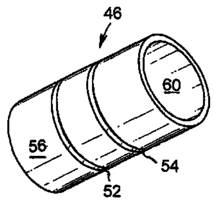
(57) **ABSTRACT**

A deformable member can be used in a well tool for use in downhole oil/gas wells. In one embodiment, a deformable member (**46**) is described which is deformable between undeformed and deformed positions, and comprises a generally hollow cylindrical body (**48**) defining a wall (**50**). The wall (**50**) includes three circumferential lines of weakness in the form of grooves, with two grooves (**52**, **54**) provided in an outer surface (**56**) of the member wall (**50**), and the other groove (**58**) provided in an inner surface (**60**). The member (**46**) is deformed outwardly by folding about the lines of weakness (**52**, **54**, **56**) and is used in particular to obtain sealing contact with a tube in which the member (**46**) is located.

14 Claims, 43 Drawing Sheets







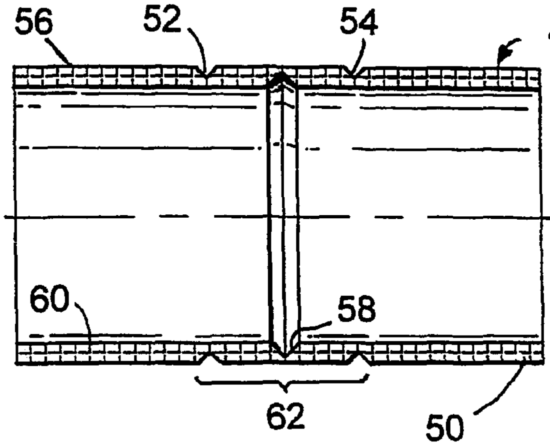


Fig.2A

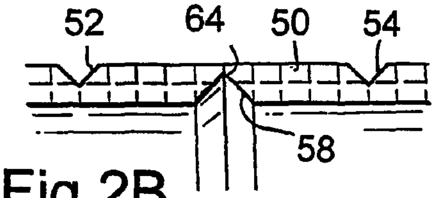


Fig.2B

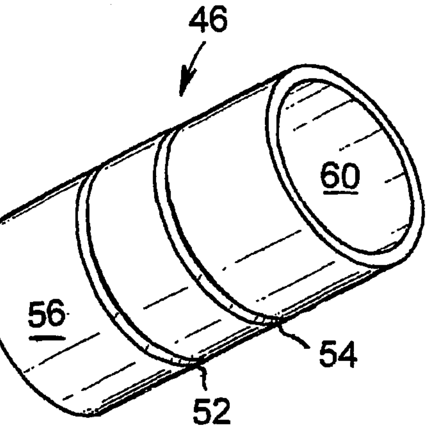


Fig.2c

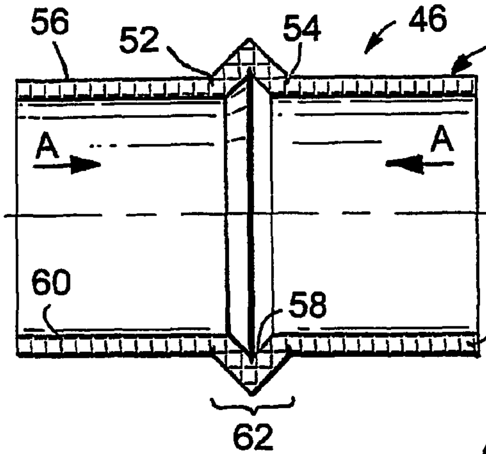


Fig.3A

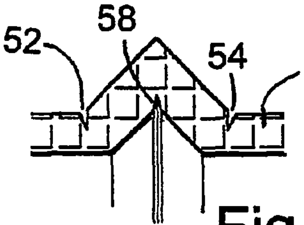


Fig.3B

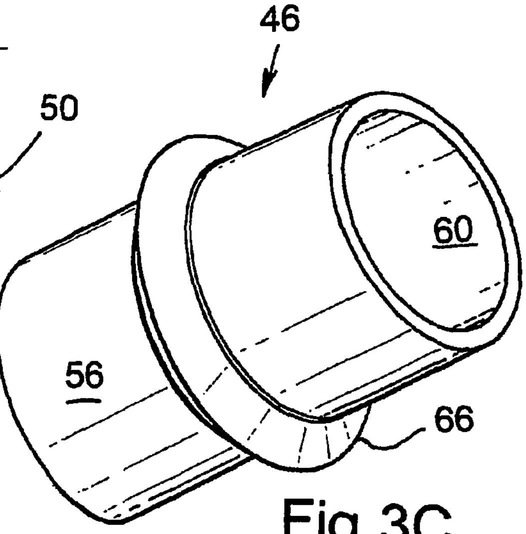


Fig.3C

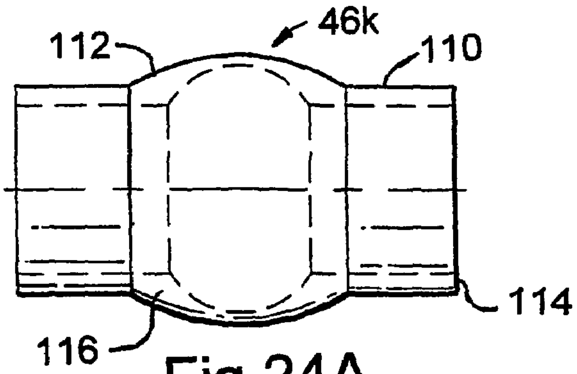


Fig.24A

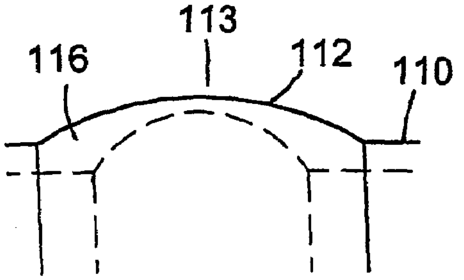


Fig.24B

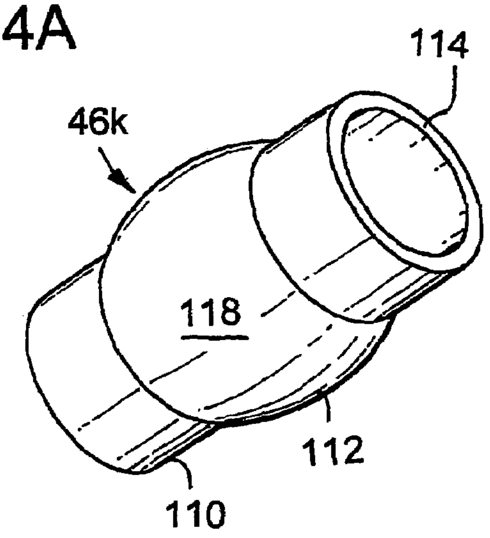


Fig.24C

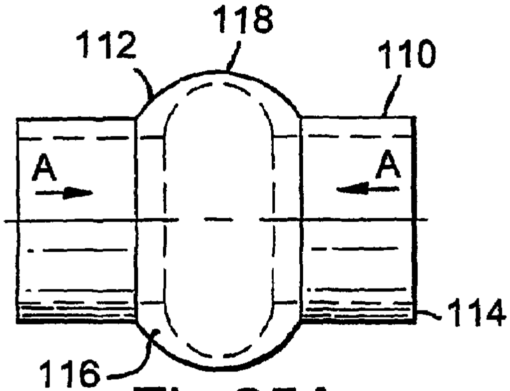


Fig.25A

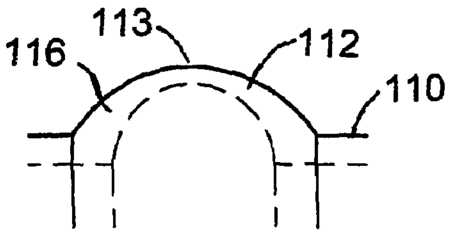


Fig.25B

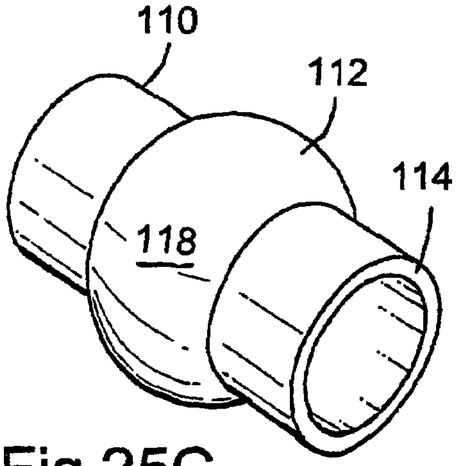


Fig.25C

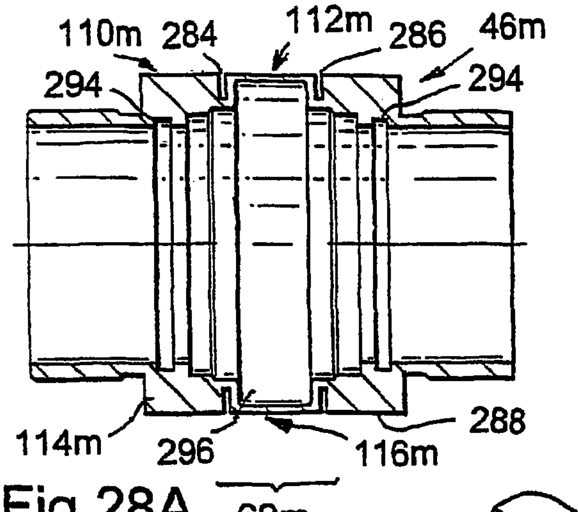


Fig.28A

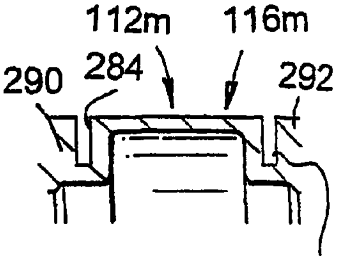


Fig.28B

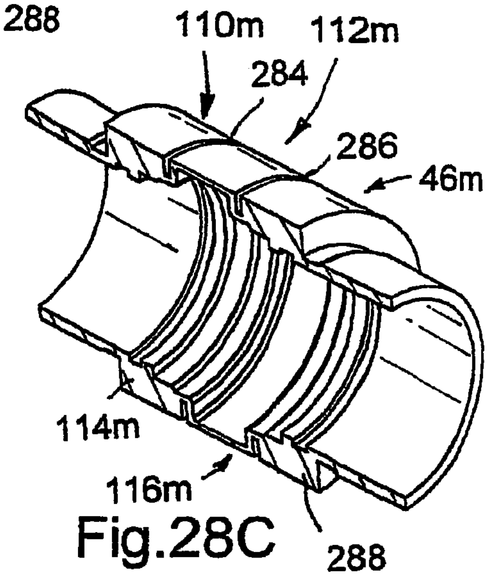
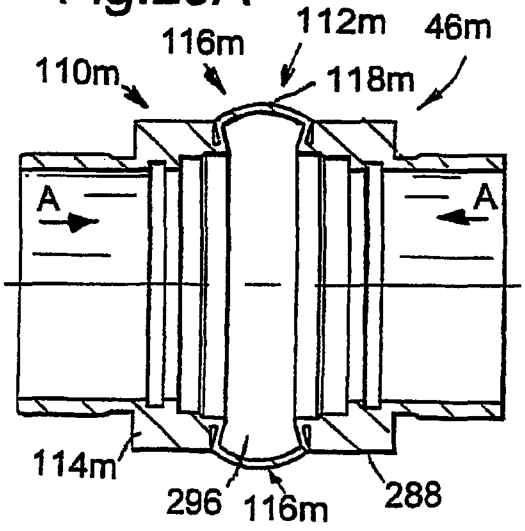


Fig.28C

Fig.29A



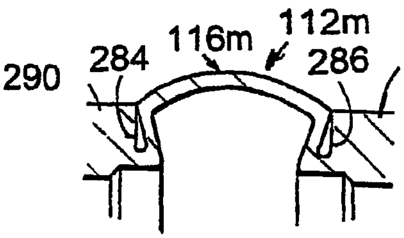


Fig.29B

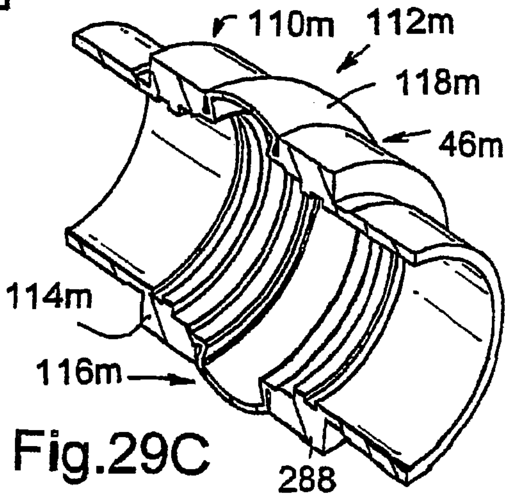
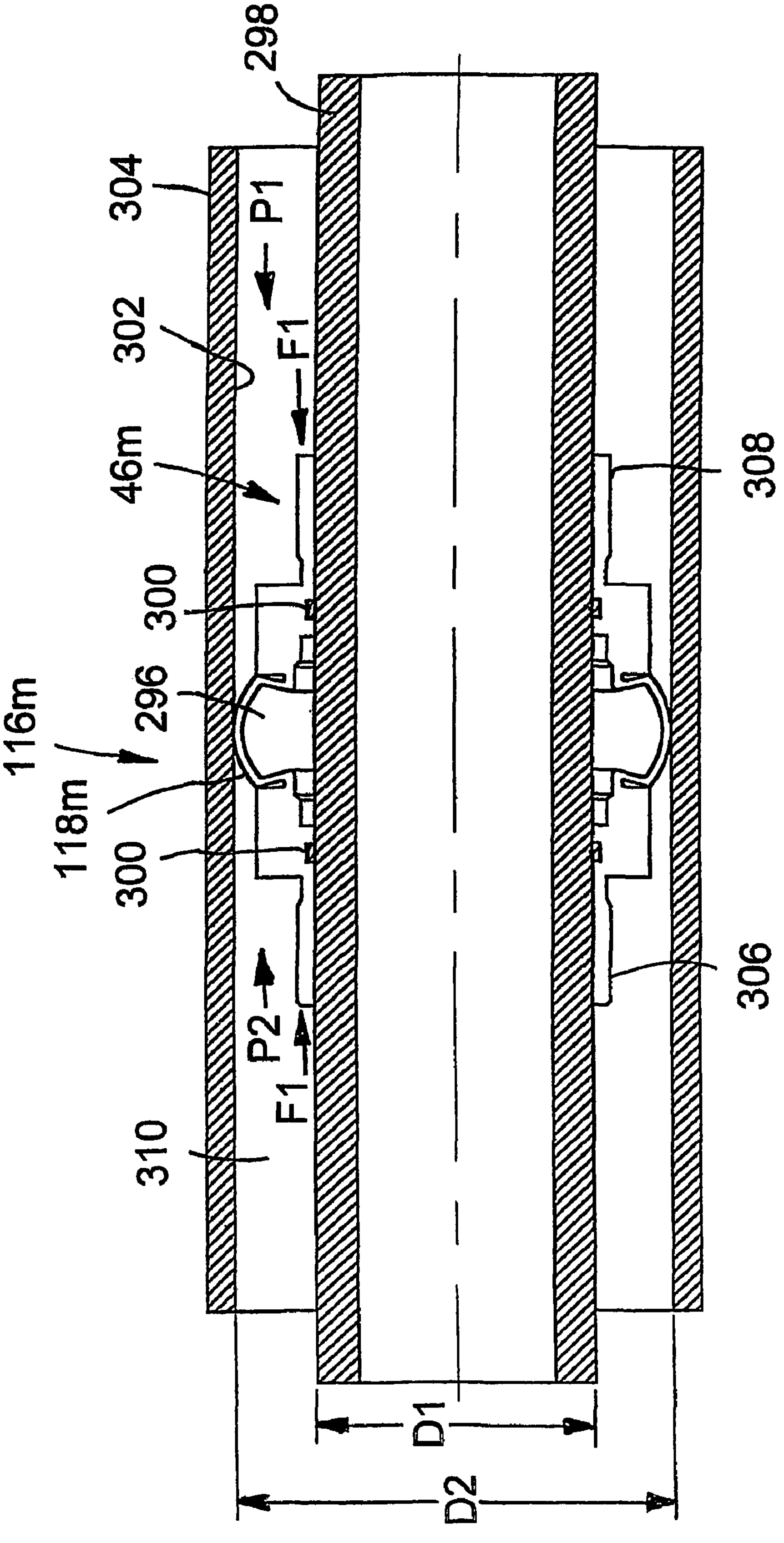


Fig.29C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D2

Fig.30

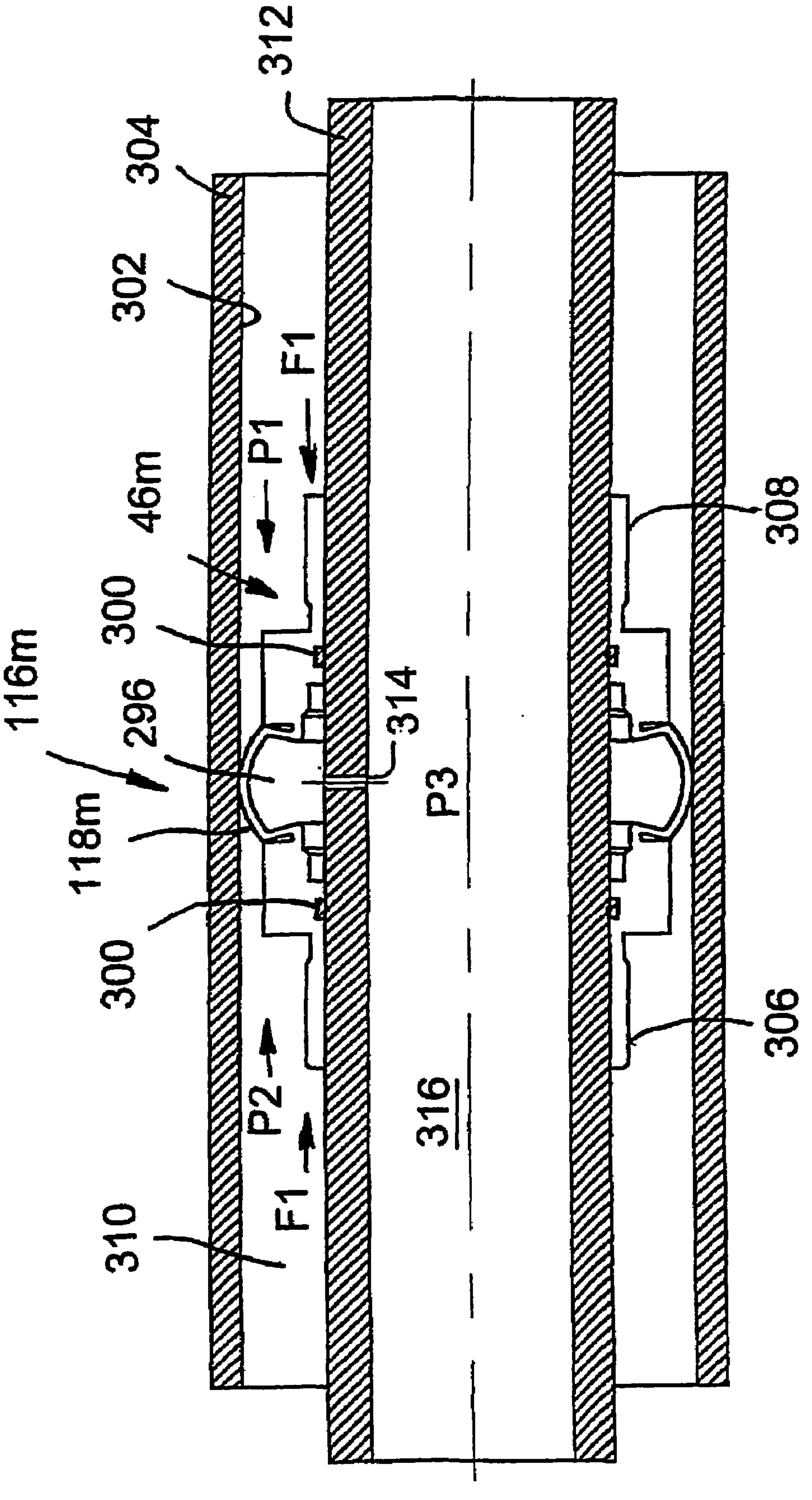
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Fig.31

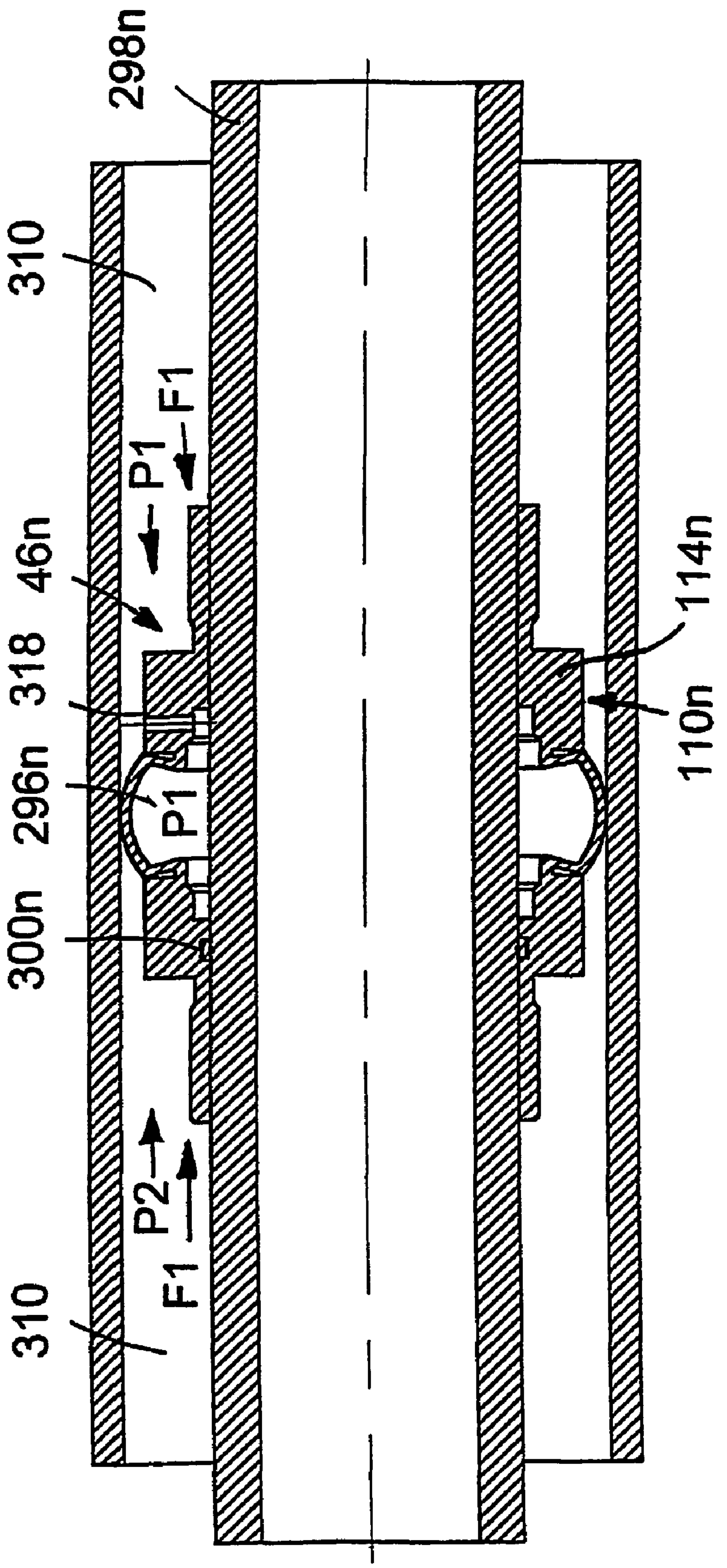
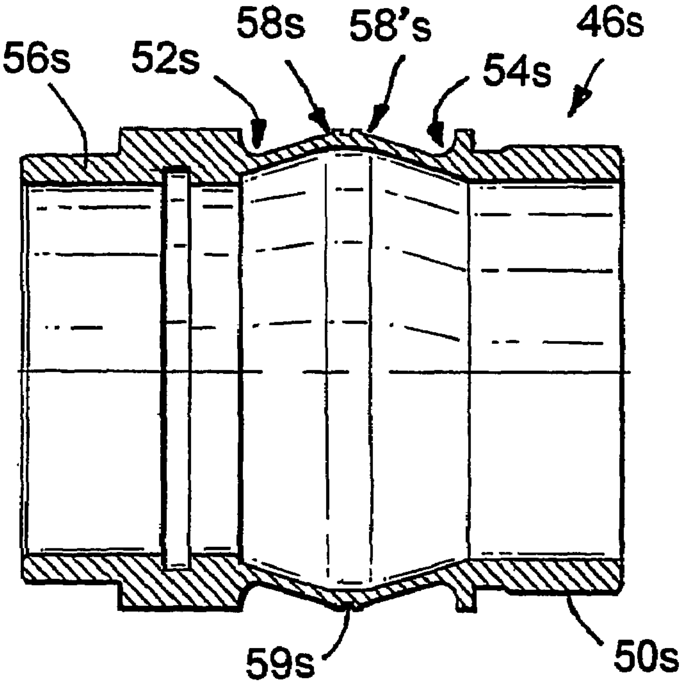


Fig.32



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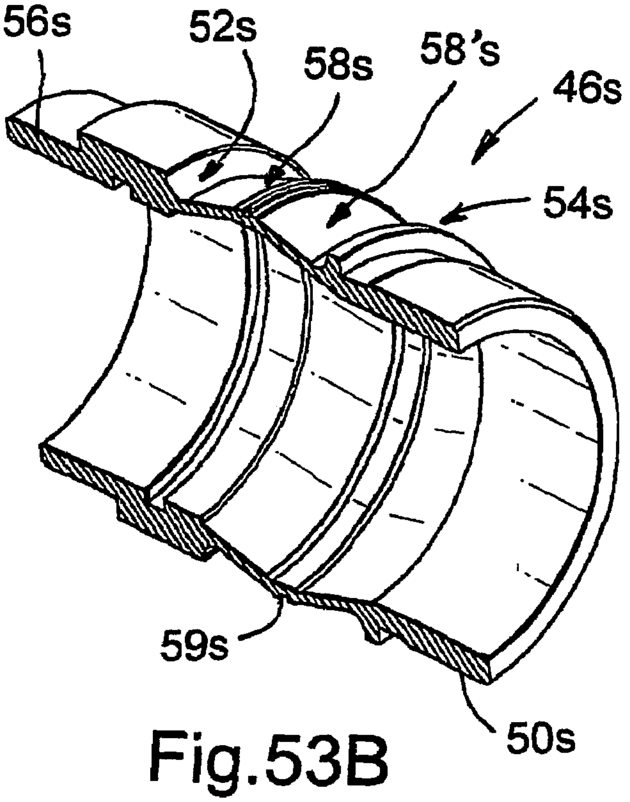

Fig.53B

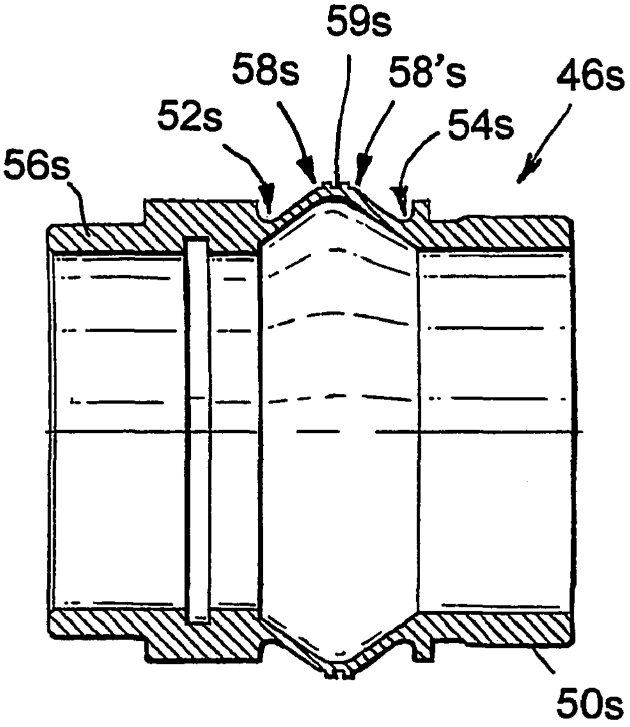

Fig.54A

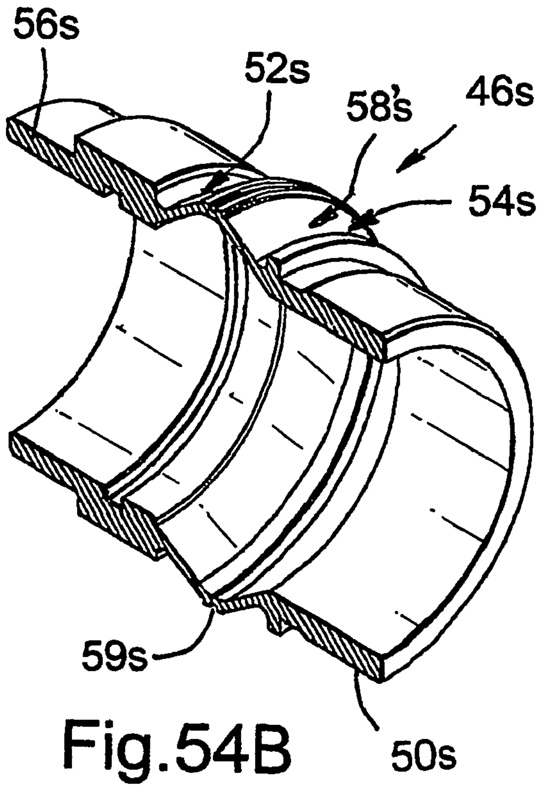

Fig.54B

a) Plastic deformation initiated about nodes
b) Seal in contact with tube/cylinder
c) Plastic secondary deformation initiated
d) Deformation zone compressed to solid
e) No further deformation

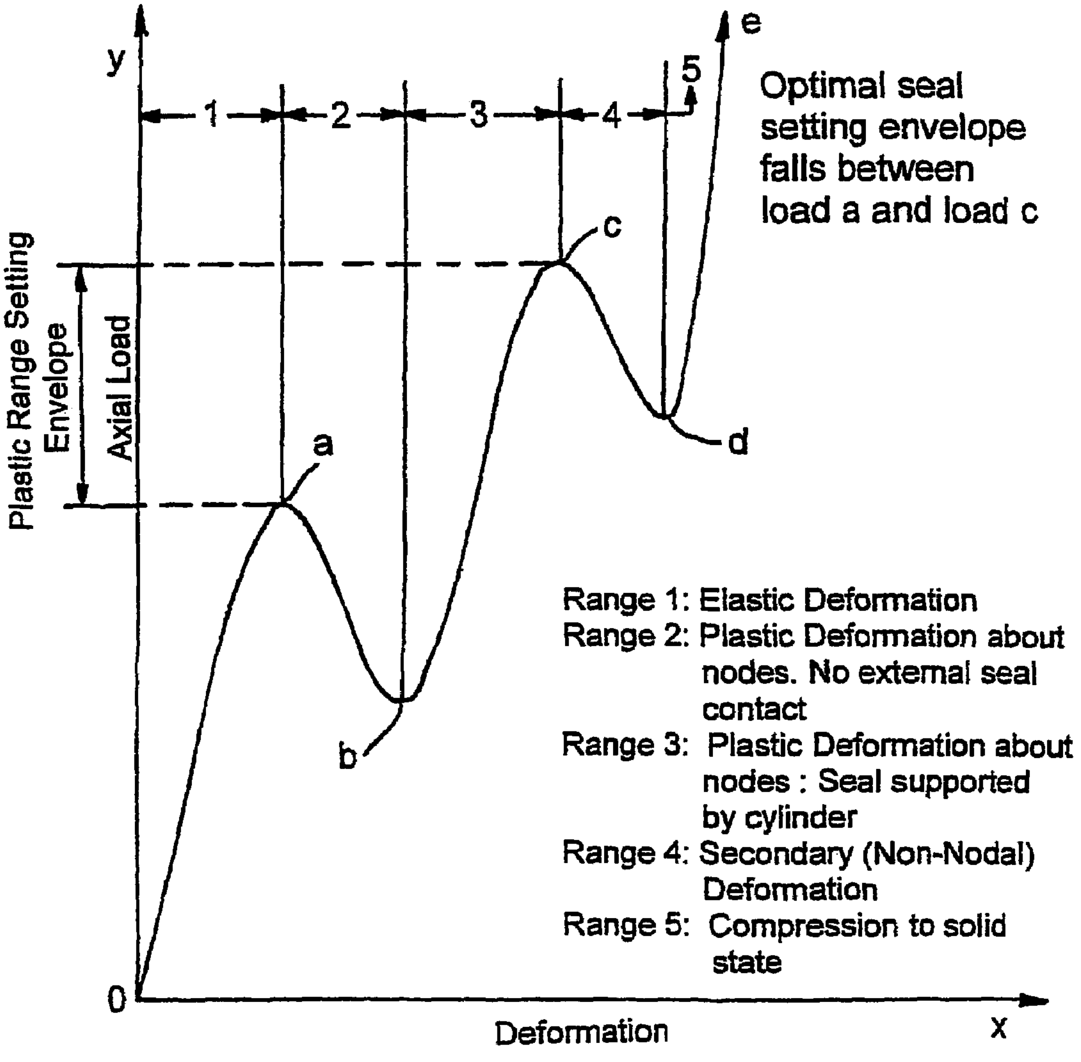

Fig.55

member in the deformation zone, when the member is in a deformed position. This may advantageously allow a force to be exerted on the member to assist in moving it to an undeformed position. Thus, a direct and controlled recovery of the deformable member to an undeformed position may be possible without requiring application of a relatively high tensile loading upon the member. Recovery may be achieved by a combination of application of an axial tensile load and a force exerted by the collapse aid. This may be particularly of use in situations where, for example, high stresses involved in deforming the member cause permanent damage, making it difficult to retract the member with a purely axial tensile load thereon.

According to a fifth aspect of the present invention, there is provided a deformable member, the member comprising a body having a first, generally hollow cylindrical body portion of a first general wall thickness, and a second, hollow bulbous deformable body portion, at least part of the second, deformable body portion being of a wall thickness less than said first wall thickness of the first body portion, the second, deformable body portion being deformable in response to an applied force, in a direction transverse to a main axis of the body, to allow the member to deform.

According to a sixth aspect of the present invention, there is provided the deformable member of the fifth aspect for use in a well tool.

Preferably, the second, hollow bulbous deformable body portion has a maximum outside diameter greater than that of the first, generally hollow cylindrical body portion. This allows the deformable member to be deformed outwardly into contact with a tube in which the deformable member is located, to provide a soft, rounded contact with the tube wall.

Advantageously, this provides a progressive, distributed load over a relatively large surface contact area with the tube wall, avoiding high stress concentration nodes. This may be particularly suited to cyclic multiple deformation applications. Alternatively, the second, hollow bulbous deformable body portion may extend inwardly to engage a tubing located within the deformable member.

According to a seventh aspect of the present invention, there is provided a deformable member, the member comprising a body having a first, generally hollow cylindrical body portion of a first general wall thickness, and a second, hollow deformable body portion, at least part of the second, deformable body portion being of a wall thickness less than said first wall thickness of the first body portion, the second, deformable body portion being deformable in response to an applied force, in a direction transverse to a main axis of the body, to allow the member to deform.

According to an eighth aspect of the present invention, there is provided the deformable member of the seventh aspect for use in a well tool.

The first, generally hollow body portion may include a first part of the wall of the member body, and may define circumferentially extending shoulders for supporting and transferring force to the second, hollow deformable body portion.

The second hollow deformable body portion may include a second part of the wall of the member body. The second part of the wall may be defined between two circumferentially extending lines of weakness formed in one of an inner and outer surface of the member wall.

According to a ninth aspect of the present invention, there is provided a bridge plug for location in well tubing of a well borehole, for selectively sealing an annulus defined between the well tubing and the bridge plug from an internal bore of the bridge plug following setting of the bridge plug in the well tubing, the bridge plug including a deformable seal having a generally hollow cylindrical body defining a seal wall, the wall having at least three circumferential lines of weakness therein, said lines of weakness being spaced along a main axis of the body, two of said lines of weakness being provided in one of an inner and outer surface of the wall and the other one of said lines of weakness being provided in the other one of said inner and outer surfaces of the wall, the axially outermost lines of weakness defining a zone of deformation of the body, wherein the seal is deformable in the deformation zone in response to an applied force applied following setting of the bridge plug, in a direction transverse to said body main axis, said direction determined by the location of the other one of said lines of weakness in the wall.

This advantageously provides a bridge plug which can be run-in to well tubing in a running position, with a deformable seal of the bridge plug in an undeformed position. The bridge plug may then be set at a desired location within the well tubing and the seal deformed into engagement with the well tubing by applying a compressive load thereon.

Also advantageously, the bridge plug is actuateable to an unset position by applying an axial tensile load to the seal member so that the deformable seal is moved to the undeformed position and the bridge plug subsequently removed from the well.

Additional and/or alternative features of the deformable seal are defined above with reference to the deformable member of the first to third aspects of the present invention.

According to a tenth aspect of the present invention, there is provided abridge plug for location in well tubing of a well borehole, for selectively sealing an annulus defined between the well tubing and the bridge plug from an internal bore of the bridge plug following setting of the bridge plug in the well tubing, the bridge plug including a deformable seal in the form of a deformable member as defined in any one of the first to sixth aspects of the present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the present invention will now be described, by way of example only, with reference to the accompanying drawings, in which:

FIG. **1** is a schematic illustration of a number of interrelated well tools, each incorporating a deformable member in accordance with the present invention;

FIGS. **2**A and **2**C are longitudinal sectional and perspective views, respectively, of a deformable member in accordance with a first embodiment of the present invention, shown in an undeformed position;

FIG. **2**B is an enlarged view of part of the deformable member shown in FIG. **2**A;

FIGS. **3**A and **3**C are longitudinal sectional and perspective views, respectively, of the deformable member of FIGS. **2**A to **2**C, shown in a deformed position;

FIG. **3**B is an enlarged view of part of the deformable member shown in FIG. **2**A;

FIGS. **4**A and **4**B are longitudinal sectional and perspective views, respectively, of a deformable member in accordance with a second embodiment of the present invention, shown in an undeformed position;

FIGS. **5**A and **5**B are longitudinal sectional views of the deformable member of FIGS. **4**A and **4**B, shown in a deformed position;

FIG. **5**C is a longitudinally sectioned perspective view of the deformable member shown in FIG. **5**B;

FIGS. **6**A and **6**C are longitudinal sectional and perspective views, respectively, of a deformable member in accordance with a third embodiment of the present invention, shown in an undeformed position;

FIG. **6**B is an enlarged view of part of the deformable member shown in FIG. **6**A;

FIGS. **7**A and **7**C are longitudinal sectional and perspective views, respectively, of the deformable member of FIGS. **6**A to **6**C, shown in a deformed position;

FIG. **7**B is an enlarged view of part of the deformable member shown in FIG. **7**A;

FIG. **7**D is a longitudinally sectioned perspective view of the deformable member shown in FIG. **7**C;

FIGS. **8**A and **8**C are longitudinal sectional and perspective views, respectively, of a deformable member in accordance with a fourth embodiment of the present invention, shown in an undeformed position;

FIG. **8**B is an enlarged view of part of the deformable member shown in FIG. **8**A;

FIGS. **9**A and **9**C are longitudinal sectional and perspective views, respectively, of the deformable member of FIGS. **8**A to **8**C, shown in a deformed position;

FIG. **9**B is an enlarged view of part of the deformable member shown in FIG. **9**A;

FIGS. **10**A and **10**C are longitudinal sectional and perspective views, respectively, of a deformable member in accordance with a fifth embodiment of the present invention, shown in an undeformed position;

FIG. **10**B is an enlarged view of part of the deformable member shown in FIG. **10**A;

FIGS. **11**A and **11**C are longitudinal sectional and perspective views, respectively, of the deformable member of FIGS. **10**A to **10**C, shown in a deformed position;

FIG. **11**B is an enlarged view of part of the deformable member shown in FIG. **11**A;

FIGS. **12**A and **12**C are longitudinal sectional and perspective views, respectively, of a deformable member in accordance with a sixth embodiment of the present invention, shown in an undeformed position;

FIG. **12**B is an enlarged view of part of the deformable member shown in FIG. **12**A;

FIGS. **13**A and **13**C are longitudinal sectional and perspective views, respectively, of the deformable member shown in FIGS. **12**A to **12**C, shown in a deformed position;

FIG. **13**B is an enlarged view of part of the deformable member shown in FIG. **13**A;

FIGS. **14**A and **14**C are longitudinal sectional and perspective views, respectively, of a deformable member in accordance with a seventh embodiment of the present invention, shown in an undeformed position;

FIG. **14**B is an enlarged view of part of the deformable member shown in FIG. **14**A;

FIGS. **15**A and **15**C are longitudinal sectional and perspective views, respectively, of the deformable member shown in FIGS. **14**A to **14**C, shown in a deformed position;

FIG. **15**B is an enlarged view of part of the deformable member shown in FIG. **15**A;

FIGS. **16**A and **16**C are longitudinal sectional and perspective views, respectively, of a deformable member in accordance with an eight embodiment of the present invention, shown in an undeformed position;

FIG. **16**B is an enlarged view of part of the deformable member shown in FIG. **16**A;

FIGS. **17**A and **17**C are longitudinal sectional and perspective views, respectively, of the deformable member of FIGS. **16**A to **16**C, shown in a deformed position;

FIG. **17**B is an enlarged view of part of the deformable member shown in FIG. **17**A;

FIGS. **18**A and **18**C are longitudinal sectional and perspective views, respectively, of a deformable member in accordance with a ninth embodiment of the present invention, shown in an undeformed position;

FIG. **18**B is an enlarged view of part of the deformable member shown in FIG. **18**A;

FIGS. **19**A and **19**C are longitudinal sectional and perspective views, respectively, of the deformable member shown in FIGS. **18**A to **18**C, shown in a deformed position;

FIG. **19**B is an enlarged view of part of the deformable member shown in FIG. **19**A;

FIGS. **20**A and **20**B are longitudinal sectional and perspective views, respectively, of a deformable member in accordance with a tenth embodiment of the present invention, shown in an undeformed position;

FIGS. **21**A and **21**C are longitudinal sectional and perspective views, respectively, of the deformable member of FIGS. **20**A and **20**B, shown in a deformed position;

FIG. **21**B is an enlarged view of part of the deformable member shown in FIG. **21**A;

FIG. **21**D is a longitudinally sectioned perspective view of the deformable member shown in FIG. **21**C;

FIGS. **22**A and **22**B are longitudinal sectional and perspective views, respectively, of a deformable member in accordance with an eleventh embodiment of the present invention, shown in an undeformed position;

FIG. **22**C is a longitudinally sectioned perspective view of the deformable member shown in FIG. **22**B;

FIGS. **23**A and **23**C are longitudinal sectional and perspective views, respectively, of the deformable member shown in FIGS. **22**A to **22**C, shown in a deformed position;

FIG. **23**B is an enlarged view of part of the deformable member shown in FIG. **23**A;

FIG. **23**D is a longitudinally sectioned perspective view of the deformable member shown in FIG. **23**C;

FIGS. **24**A and **24**C are front and perspective views, respectively, of a deformable member in accordance with a twelfth embodiment of the present invention, shown in an undeformed position;

FIG. **24**B is an enlarged view of part of the deformable member shown in FIG. **24**A;

FIGS. **25**A and **25**C are front and perspective views, respectively, of the deformable member shown in FIGS. **24**A to **24**C, shown in a deformed position;

FIG. **25**B is an enlarged view of part of the deformable member shown in FIG. **25**A;

FIGS. **26**A and **26**B are longitudinal sectional and longitudinally sectioned perspective views, respectively, of a deformable member in accordance with a thirteenth embodiment of the present invention, shown in an undeformed position;

FIGS. **27**A and **27**B are longitudinal sectional and longitudinally sectioned perspective views, respectively, of the deformable member shown in FIGS. **26**A and **26**B, shown in a deformed position;

FIG. **27**C is an enlarged view of part of the deformable member shown in FIG. **27**A;

FIGS. **28**A and **28**C are longitudinal sectional and longitudinally sectioned perspective views, respectively, of a deformable member in accordance with a fourteenth embodiment of the present invention, shown in an undeformed position;

FIG. **28**B is an enlarged view of part of the deformable member shown in FIG. **28**A;

FIGS. **29**A and **29**C are longitudinal sectional and longitudinally sectioned perspective views, respectively, of the deformable member shown in FIGS. **28**A and **28**B, shown in a deformed position;

FIG. **29**B is an enlarged view of part of the deformable member shown in FIG. **29**A;

FIG. **30** is a view of the member of FIG. **28**A, shown mounted on a mandrel and in the deformed position of FIG. **29**A, where it has been deformed into contact with a tube in which the member is located;

FIG. **31** is a view similar to that of FIG. **30**, with the mandrel shown including a pressure vent port;

FIG. **32** is a view similar to that of FIG. **30**, showing a deformable member similar to that of FIG. **28**A, except including a pressure vent port and being sealed to the mandrel by a single seal;

FIGS. **33**A and **33**B are longitudinal sectional and longitudinally sectioned perspective views, respectively, of a deformable member in accordance with a fifteenth embodiment of the present invention, shown in an undeformed position, and including a deformation aid;

FIGS. **34**A and **34**B are longitudinal sectional and longitudinally sectioned perspective views, respectively, of the deformable member shown in FIGS. **33**A and **33**B, shown in a deformed position;

FIG. **34**C is an enlarged view of part of the deformable member shown in FIG. **34**A;

FIGS. **35**A and **35**B are views of deformable members acting as anti-extrusion seals for preventing extrusion of a conventional seal, FIG. **35**A showing the members in an undeformed position, and FIG. **35**B showing the members in a deformed position in location in a tube, respectively;

FIGS. **36**A and **36**B are schematic views of the member of FIG. **2**A and a collapse aid for aiding movement of the member to an undeformed position, the member shown deformed in FIG. **36**A and undeformed in FIG. **36**B, respectively;

FIGS. **37**A and **37**B are longitudinally sectioned perspective and longitudinal sectional views, respectively, of a first embodiment of a bridge plug incorporating a deformable seal, in accordance with the present invention, the bridge plug shown in a running position where the deformable member is in an undeformed position;

FIGS. **38**A and **38**B are enlarged views of the bridge plug shown in FIG. **37**B, showing upper and lower ends respectively of the bridge plug;

FIGS. **39**A and **39**B are enlarged views of a ratchet mechanism of the bridge plug shown in FIG. **37**B, and a perspective view of segments of the ratchet mechanism, respectively;

FIG. **40** is an enlarged view of the deformable member of the bridge plug shown in FIG. **37**B;

FIGS. **41**A and **41**B are exploded perspective and perspective views, respectively, of a slip mechanism forming part of the bridge plug shown in FIG. **37**A;

FIG. **42** is an enlarged view of a connecting lower end of the bridge plug shown in FIG. **37**B;

FIGS. **43**A and **43**B are views, similar to the views of FIGS. **37**A and **37**B, of the bridge plug in a set position, where the deformable member is in a deformed position;

FIG. **44** is an enlarged view of the deformable member of the bridge plug in the deformed position shown in FIG. **43**B;

FIGS. **45**A and **45**B are exploded perspective and perspective views respectively of the slip mechanism of the bridge plug shown in a set position, when the bridge plug is in the set position shown in FIG. **43**A;

FIGS. **46**A and **47**A are views, similar to the views of FIGS. **37**A and **37**B, of the bridge plug when it has been returned to an unset position, with the deformable member in the undeformed position, after having been set as shown in FIGS. **43**A and **43**B;

FIGS. **46**B and **47**B are enlarged views of the ratchet mechanism of the bridge plug in the unset position of FIGS. **46**A and **47**A, respectively,

FIGS. **48**A and **48**B are longitudinally sectioned perspective and longitudinal sectional views, respectively, of a second embodiment of a bridge plug incorporating a deformable seal, in accordance with the present invention, the bridge plug shown in a running position, similar to that of the bridge plug shown in FIGS. **37**A and **37**B, where the deformable member is in an undeformed position;

FIGS. **48**C and **48**D are enlarged views of the bridge plug shown in FIG. **48**B, showing upper and lower ends respectively of the bridge plug;

FIGS. **49**A and **49**B are enlarged views of a locking key mechanism forming part of the bridge plug shown in FIGS. **48**A and **48**B, respectively,

FIGS. **49**C, **49**D and **49**E are enlarged views of a slip mechanism, a retractable ratchet mechanism, and a transfer key mechanism, respectively, all forming part of the bridge plug shown in FIG. **48**A;

FIG. **50**A is a view of the bridge plug shown in FIG. **48**B, with part of the bridge plug removed, for clarity;

FIGS. **50**B and **50**C are exploded perspective and an enlarged view, respectively, of the retractable ratchet mechanism shown in FIG. **48**A, with part of the bridge plug removed for clarity;

FIGS. **50**D and **50**E are exploded perspective and an enlarged view, respectively, of the transfer key mechanism shown in FIG. **48**A, with part of the bridge plug removed for clarity;

FIGS. **51**A and **51**B are longitudinal sectional and perspective views, respectively, of a deformable member in accordance with a further embodiment of the present invention, shown in an undeformed position;

FIGS. **52**A and **52**B are longitudinal sectional and perspective views, respectively, of the deformable member of FIGS. **51**A and **51**B, shown in a deformed position;

FIGS. **53**A and **53**B are longitudinal sectional and perspective views, respectively, of a deformable member in accordance with a still further embodiment of the present invention, shown in an undeformed position;

FIGS. **54**A and **54**B are longitudinal sectional and perspective views, respectively, of the deformable member of FIGS. **53**A and **53**B, shown in a deformed position; and

FIG. **55** is a graphical representation of test results for a load vs. deformation test on a typical deformable member of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring firstly to FIG. **1**, there is shown a schematic illustration of a number of interrelated well tools, each incorporating a deformable member (not shown in FIG. **1**) in accordance with the present invention.

In FIG. **1**, a well assembly indicated generally by reference numeral **10** is shown, located in a borehole **12** of an oil well. An upper portion of the borehole **12** is lined with steel casing **14** in a fashion known in the art. The well assembly **10** extends into the borehole **12** from surface, and includes a number of well tools, provided for carrying out a variety of well operations. Each of these well tools are in themselves