THERMALLY ACTIVATED WELL PERFORATING SAFETY SYSTEM

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ABSTRACT
An explosives safety system includes an explosive component, a blocking member displaceable to selectively permit and prevent detonation of the explosive component, and a thermal actuator responsive to temperature change and configured to displace the member in response to the temperature change. Another explosives safety system includes a thermal actuator with a material having a volume variable in response to the temperature change, and detonation of the explosive component being selectively permitted and prevented by the actuator when the material volume changes. A method of preventing undesired detonation of an explosive component includes the steps of: providing a material having a volume variable in response to a change in a temperature; positioning the material and the explosive component in a well, thereby increasing the material temperature; increasing the material volume in response to the increasing temperature; and permitting detonation of the explosive component in response to the increasing volume.
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BACKGROUND

[0001] The present invention relates generally to equipment used and operated in conjunction with a subterranean well and, in an embodiment described herein, more particularly provides a thermally activated explosives safety system.

[0002] In well perforating operations, it is vitally important to prevent undesired detonations of explosive components. Injury or even death of personnel can result from untimely detonations, as well as damage to the well, surface equipment and other property.

[0003] Various safety systems have been used in the past, but these have not been entirely successful. Some safety systems rely on pressure to provide an actuating force, with the pressure being present only downhole. Other systems rely on temperature downhole to melt a substance, such as a eutectic material, thereby permitting detonation of an explosive component.

[0004] Unfortunately, in some such systems the substance cannot be reformed or "un-melted" in the event that the explosive component has to be retrieved from the well, so that the substance again prevents detonation of the explosive component. Those systems which do permit reforming of the melted substance have a relatively large operating envelope. This re-arming of the safety system is important if, for example, a perforating gun or firing head mis-fires downhole and has to be retrieved to the surface with undetonated explosive components therein.

[0005] Therefore, it may be seen that improvements are needed in the art of thermally activated explosives safety systems.

SUMMARY

[0006] In carrying out the principles of the present invention, explosives safety systems and associated methods are provided which solve at least one problem in the art. One example is described below in which a thermal actuator is used to alternately permit and prevent detonation of an explosive component. Another example is described below in which a material has a volume which varies in response to a temperature change, and the variable material volume is used to alternately permit and prevent detonation of an explosive component.

[0007] In one aspect of the invention, a thermally activated explosives safety system is provided. The system includes an explosive component and a blocking member replaceable to selectively permit and prevent detonation of the explosive component. A thermal actuator of the system is responsive to temperature change. The actuator is configured to displace the blocking member in response to the temperature change.

[0008] In another aspect of the invention, a thermally activated explosives safety system includes a thermal actuator responsive to temperature change, the actuator including a material having a volume which is variable in response to a change in a temperature of the material; positioning the material and the explosive component in a subterranean well, thereby increasing the temperature of the material; increasing the volume of the material in response to the temperature increasing step; and permitting detonation of the explosive component in response to the volume increasing step.

[0009] These and other features, advantages, benefits and objects of the present invention will become apparent to one of ordinary skill in the art upon careful consideration of the detailed description of representative embodiments of the invention hereinbelow and the accompanying drawings, in which similar elements are indicated in the various figures using the same reference numbers.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] FIG. 1 is a schematic partially cross-sectional view of a well system and associated method embodying principles of the present invention;

[0012] FIG. 2 is an enlarged scale schematic cross-sectional view through a thermally activated explosives safety system in the well system of FIG. 1;

[0013] FIG. 3 is a schematic cross-sectional view of a first alternate configuration of the explosives safety system;

[0014] FIG. 4 is a schematic cross-sectional view of a first alternate configuration of the explosives safety system, taken along line 4-4 of FIG. 3, wherein detonation of an explosive component is prevented;

[0015] FIG. 5 is a schematic cross-sectional view of the first alternate construction of the explosives safety system, wherein detonation of the explosive component is permitted;

[0016] FIG. 6 is a schematic cross-sectional view of a second alternate configuration of the explosives safety system, wherein detonation of an explosive component is prevented;

[0017] FIG. 7 is a schematic cross-sectional view of the second alternate configuration of the explosives safety system, wherein detonation of the explosive component is permitted;

[0018] FIG. 8 is a schematic cross-sectional view of a third alternate configuration of the explosives safety system;

[0019] FIG. 9 is a schematic cross-sectional view of a fourth alternate configuration of the explosives safety system;

[0020] FIG. 10 is a schematic cross-sectional view of a fifth alternate configuration of the explosives safety system, wherein detonation of an explosive component is prevented;

[0021] FIG. 11 is a schematic cross-sectional view of the fifth alternate configuration of the explosives safety system, wherein detonation of the explosive component is permitted;

[0022] FIGS. 12 & 13 are schematic side elevational views of multiple thermal actuators usable in the various configurations of the explosives safety system, the actuators being depicted in a retracted condition in FIG. 12, and in an extended condition in FIG. 13;

[0023] FIG. 14 is a schematic cross-sectional view of a sixth alternate configuration of the explosives safety system;

[0024] FIG. 15 is a schematic cross-sectional view of a seventh alternate configuration of the explosives safety system;

[0025] FIG. 16 is a schematic cross-sectional view of an eighth alternate configuration of the explosives safety system, wherein detonation of an explosive component is prevented;

[0026] FIG. 17 is a schematic cross-sectional view of the eighth alternate configuration of the explosives safety system, wherein detonation of the explosive component is permitted;
FIG. 18 is a schematic cross-sectional view of a ninth alternate configuration of the explosives safety system;

FIG. 19 is a schematic cross-sectional view of a tenth alternate configuration of the explosives safety system;

FIG. 20 is a schematic cross-sectional view of an eleventh alternate configuration of the explosives safety system;

FIG. 21 is a schematic cross-sectional view of a twelfth alternate configuration of the explosives safety system;

FIG. 22 is a schematic cross-sectional view of a thirteenth alternate configuration of the explosives safety system;

FIG. 23 is a schematic cross-sectional view of a fourteenth alternate configuration of the explosives safety system; and

FIG. 24 is a schematic cross-sectional view of a fifteenth alternate configuration of the explosives safety system.

DETAILED DESCRIPTION

It is to be understood that the various embodiments of the present invention described herein may be utilized in various orientations, such as inclined, inverted, horizontal, vertical, etc., and in various configurations, without departing from the principles of the present invention. The embodiments are described merely as examples of useful applications of the principles of the invention, which is not limited to any specific details of these embodiments.

In the following description of the representative embodiments of the invention, directional terms, such as "above", "below", "upper", "lower", etc., are used for convenience in referring to the accompanying drawings. In general, "above", "upper", "upward" and similar terms refer to a direction toward the earth's surface along a wellbore, and "below", "lower", "downward" and similar terms refer to a direction away from the earth's surface along the wellbore.

Representatively illustrated in FIG. 1 is a well system 10 and associated method which embody principles of the present invention. A tubular string 12 is installed in a wellbore 14 lined with casing 16. Suspended from the tubular string 12 is a perforating assembly 18 which is used to form perforations 20 through the casing 16, through cement 22 surrounding the casing, and into one or more subterranean formations or zones 24.

Although the perforating assembly 18 is depicted in FIG. 1, as being of the type known to those skilled in the art as a "tubing conveyed" perforating assembly, other types of perforating assemblies may be used in keeping with the principles of the invention. For example, the perforating assembly 18 could be conveyed by wireline, slickline or any other form of conveyance.

Furthermore, although the perforating assembly 18 is used as an example of an assembly which utilizes explosive components, other types of assemblies may be used in keeping with the principles of the invention. For example, casing cutters, setting tools and other types of well tools and equipment are known which include explosive components, and which can benefit from the principles of the present invention to enhance the safety of their operation.

Therefore, it should be clearly understood that the invention is not limited in any manner to the specific well systems, methods, explosives safety systems, etc. described herein. Instead, the principles of the invention are applicable to a wide variety of well tools, equipment and operations which utilize explosive components.

The perforating assembly 18 depicted in FIG. 1 includes a firing head 26 for initiating detonation of explosive perforating charges (not visible in FIG. 1) of perforating guns 28. The firing head 26 may be actuated in any manner to initiate detonation of the perforating charges. For example, pressure, telemetry (such as acoustic, pressure pulse, electromagnetic or other form of telemetry), mechanical force, electrical signal, or other stimulus may be used.

Although one firing head 26 above the perforating guns 28 is illustrated in FIG. 1, there may be multiple firing heads, a firing head may be attached at a lower end of the perforating assembly 18 below the perforating guns, and different types of firing heads may be used, in keeping with the principles of the invention.

In an important feature of the well system 10, the perforating assembly 18 also includes thermally activated explosives safety systems 30, 32. The safety system 30 is depicted in FIG. 1 as being interconnected between the firing head 26 and the upper perforating gun 28, in order to prevent the firing head from undesirably initiating detonation of the perforating guns, and the safety system 32 is depicted in FIG. 1 as being interconnected between the perforating guns, in order to prevent undesirable transfer of detonation between the perforating guns.

However, it should be clearly understood that these positions of the safety systems 30, 32 are merely examples of a variety of different positions in which the safety systems can have beneficial use. For example, it is known practice to include a shearable safety joint in a perforating assembly to allow safer connection and disconnection of a firing head while the safety joint is positioned in a blowout preventer stack.

An example of such a shearable safety joint is described in U.S. Pat. No. 6,675,896, the entire disclosure of which is incorporated herein by this reference. An explosives safety system (such as one of the safety systems 30, 32) could be interconnected between the safety joint and the perforating guns, or incorporated as part of the safety joint, to thereby provide an increased measure of safety while the firing head is being connected or disconnected.

Referring additionally now to FIG. 2, a schematic cross-sectional view of a thermally activated explosives safety system 40 is representatively illustrated. The safety system 40 may be used for the safety systems 30, 32 in the well system 10 of FIG. 1. The safety system 40 may also be used in other well systems in keeping with the principles of the invention.

As depicted in FIG. 2, the safety system 40 includes an assembly 42 positioned between a firing pin 44 and an explosive component. The details of the assembly 42 are not visible in FIG. 2, but examples of the assembly will be described in detail below.

The assembly 42 selectively prevents the firing pin 44 from contacting the explosive component 46 to thereby prevent detonation of the explosive component. The assembly 42 may prevent such contact between the firing pin 44 and the explosive component 46 in various ways, for example, by blocking a passage 48 between the firing pin and the explosive component. The assembly 42 may prevent contact between the firing pin 44 and the explosive component 46 in any manner (some of which are described in detail below) in keeping with the principles of the invention.
The firing pin 44 may be a part of the firing head 26, or it may be part of another portion of the perforating assembly 18 (such as a detonation transfer sub). The firing pin 44 may be displaced in response to any type of stimulus, such as mechanical force, pressure, detonation of another explosive component adjacent the firing pin, etc.

The explosive component 46 is depicted in FIG. 2 as being of the type known to those skilled in the art as an initiator. Detonation of the initiator is transferred to another explosive component 50 of the type known to those skilled in the art as a booster, and detonation of the booster is transferred to yet another explosive component 52 of the type known to those skilled in the art as a detonating cord.

The explosive components 46, 50, 52 described above are merely examples of the wide variety of explosive components for which detonation may be selectively permitted and prevented using the safety system 40. Other types include, but are not limited to, perforating charges, cutting charges, strip charges, linear charges, setting charges, etc.

Referring additionally now to FIG. 3, an alternate configuration of the safety system 40 is representatively illustrated. In this configuration, the assembly 42 is used to selectively permit and prevent transfer of detonation between multiple boosters (explosive components 50) connected to multiple lengths of detonating cord (explosive components 52).

The assembly 42 may prevent such detonation transfer by, for example, blocking the passage 48 between the explosive components 50. However, the assembly 42 may prevent detonation transfer between the explosive components 50 in any manner (some of which are described in detail below) in keeping with the principles of the invention.

Referring additionally now to FIG. 4, a schematic cross-sectional view of the safety system 40 is representatively illustrated. In this view it may be seen that this configuration of the assembly 42 includes a blocking member 54 in the form of a plate which blocks the passage 48 to prevent detonation of an explosive component (for example, by preventing contact between the firing pin 44 and the explosive component 46, by preventing detonation transfer between the explosive components 50, etc.).

The assembly 42 further includes a thermal actuator 56 for displacing the blocking member 54 relative to the passage 48. The thermal actuator 56 is preferably of the type which includes a material having a volume which varies in response to temperature change.

Suitable thermal actuators are manufactured by Therm-Omega-Tech, Inc. (actuators include a material that changes phase at a predetermined temperature), Calterm Corporation, Rostra Vernatherm LLC, and others. Thermal actuators are available which extend or lengthen upon a temperature increase and retract upon a temperature decrease, which retract upon a temperature increase and extend or lengthen upon a temperature decrease, and others which rotate in response to a temperature change.

As depicted in FIG. 4, the thermal actuator 56 is of the type which extends upon a temperature increase, but the actuator is shown in its retracted configuration. A rod 58 of the actuator 56 is connected to the blocking member 54.

The actuator 56 may be assisted in maintaining the blocking member 54 in its position blocking the passage 48 by means of biasing devices 60 (such as springs, etc.). Alternatively, the actuator 56 may be capable of exerting sufficient force to displace the member 54 to this position, and to maintain the member in this position, without use of the biasing devices 60.

Referring additionally now to FIG. 5, the safety system 40 is representatively illustrated after a temperature increase has caused the actuator 56 to extend the rod 58 further outward and thereby displace the blocking member 54 so that it no longer blocks the passage 48. Detonation of the explosive components 46, 50, 52 in either of the configurations of FIGS. 2 & 3 is now permitted by the safety system 40.

The temperature increase is preferably due to installation of the safety system 40 in the well. Of course, the local geothermal gradient and the depth at which the safety system 40 is to be installed are factors which will influence the available temperature increase and, thus, the design of the thermal actuator 56, so that reliable operation of the assembly 42 in a particular well system is assured.

In an important feature of the safety system 40, the displacement of the blocking member 54 by the thermal actuator 56 is reversible, and may be reversible multiple times. That is, the thermal actuator 56 may displace the blocking member 54 to its positions depicted in FIGS. 4 & 5 in response to any number of respective temperature increases and decreases.

For example, when used in the well system 10 of FIG. 1, the safety system 40 may be used to prevent detonation of the explosive components 46, 50, 52 while the perforating assembly 18 is near the surface (i.e., at a relatively low temperature). When the perforating assembly 18 (including the safety system 40) is installed in the wellbore 14, the resulting temperature increase will cause the actuator 56 to displace the blocking member 54, so that detonation of the explosive components 46, 50, 52 is permitted (as depicted in FIG. 5). Upon retrieval of the perforating assembly 18 to the surface (such as due to a misfire of the firing head 26, or another circumstance resulting in undetonated explosive components possibly being brought back to the surface), the resulting temperature decrease will cause the actuator 56 to displace the blocking member 54 back to its position blocking the passage 48 and preventing detonation of the explosive components 46, 50, 52.

Referring additionally now to FIGS. 6 & 7, schematic cross-sectional views of an alternate configuration of the safety system 40 are representatively illustrated. In this configuration, the blocking member 54 is pivoted or rotated about a pivot 62 by the actuator 56, instead of being displaced laterally relative to the passage 48 as in the configuration of FIGS. 4 & 5.

In FIG. 6, the member 54 blocks the passage 48, and detonation of the explosive components 46, 50, 52 is thereby prevented at a corresponding relatively low temperature. In FIG. 7, the member 54 does not block the passage 48, and detonation of the explosive components 46, 50, 52 is thereby permitted at a corresponding relatively high temperature.

As with the configuration of FIGS. 4 & 5 (and the other alternate configurations of the safety system 40 described below), the displacement of the blocking member 54 is reversible. Thus, the safety system 40 always prevents detonation of the explosive components 46, 50, 52 at any time the safety system is at a sufficiently low temperature (such as near the surface or at a depth relatively shallow in the well).

Referring additionally now to FIG. 8, a schematic cross-sectional view of another alternate configuration of the safety system 40 is representatively illustrated. In this con-
configuration, the blocking member 54 is displaced laterally by the actuator 56 in a recess 64 which intersects the passage 48.

[0066] The blocking member 54 has an opening 66 formed therein which may be aligned with the passage 48 when it is desired to permit detonation of the explosive components 46, 50, 52. As depicted in FIG. 8, the member 54 is in a position in which the opening 66 is not aligned with the passage 48, and so detonation of the explosive components 46, 50, 52 is prevented. The actuator 56 will displace the member 54 to align the opening 66 and passage 48 in response to a sufficient increase in temperature.

[0067] In the configuration as shown in FIG. 8, the firing pin 44 is propelled through the passage 48 in response to detonation of a detonating cord (explosive component 52) and booster (explosive component 50) above the firing pin. Until such detonation occurs, the firing pin 44 is secured in place by shear pins 68 or other suitable fasteners. A vent passage 70 prevents undesirable pressure increase in the passage 48 below the firing pin 44 when the firing pin is propelled downward through the passage.

[0068] Referring additionally now to FIG. 9, a schematic cross-sectional view of another alternate configuration of the safety system 40 is representatively illustrated. This configuration is similar in many respects to the configuration of FIG. 8.

[0069] However, in this configuration the blocking member 54 does not include the opening 66. Instead, the blocking member 54 is displaced by the actuator 56 to a position in which it no longer blocks the passage 48 in response to a sufficient temperature increase.

[0070] For this purpose, the actuator 56 is of the type in which the rod 58 is retracted (to thereby laterally displace the member 54 so that it no longer blocks the passage 48) in response to a temperature increase. The actuator 56 will extend the rod 58 (to thereby laterally displace the member 54 so that it again blocks the passage 48) in response to a subsequent temperature decrease.

[0071] Thus, the actuator 56 is preferably of the type known to those skilled in the art as a "reverse" thermal actuator. Such actuators still include a material having a volume which varies in response to a temperature change, but the actuators are constructed in a manner causing the actuators to lengthen or extend in response to a temperature decrease, and causing the actuators to retract in response to a temperature increase.

[0072] As will be readily appreciated from the above descriptions of various configurations of the safety system 40, detonation of an explosive component may be prevented by blocking a passage (for example, to block displacement of a firing pin through the passage, or to prevent detonation transfer between explosive components, etc.), and detonation of the explosive component may be permitted by unblocking the passage. Referring additionally now to FIGS. 10 & 11, schematic cross-sectional views of another alternate configuration of the safety system 40 is representatively illustrated, in which another manner of blocking and unblocking the passage 48 may be accomplished.

[0073] In this configuration, the blocking member 54 is in the form of a shaft which is rotated in the recess 64 intersecting the passage 48. This rotation of the shaft is caused by the actuator 56 which extends or retracts the rod 58 in response to corresponding increases or decreases in temperature.

[0074] The rod 58 is connected to the blocking member 54 by means of a yoke 72 and arm 74. The yoke 72 and arm 74 transfer linear displacement of the rod 58 into rotational displacement of the blocking member 54.

[0075] As depicted in FIG. 10, the opening 66 is rotated so that it is not aligned with the passage 48, and the passage is thus blocked, preventing detonation of the explosive components 46, 50, 52. As depicted in FIG. 11, the opening is rotated so that it is aligned with the passage 48, and the passage is thus unblocked, permitting detonation of the explosive components 46, 50, 52.

[0076] The blocking member 54 is rotated to the position shown in FIG. 10 in response to a temperature decrease, and the blocking member is rotated to the position shown in FIG. 11 in response to a temperature increase. As with the other configurations of the safety system 40 described herein, these displacements of the blocking member 54 are reversible and repeatable.

[0077] Note that, in the configuration of FIGS. 10 & 11, the blocking member 54 is rotated about an axis (defined by the recess 64) which is orthogonal to the passage 48. In contrast, in the configuration of FIGS. 6 & 7, the blocking member 54 is rotated about an axis (defined by the pivot 62) which is parallel to the passage 48.

[0078] In some embodiments of the safety system 40, greater displacement may be desired than can conveniently be obtained from a single thermal actuator 56. In those circumstances, multiple thermal actuators 56 may be used, with the actuators being connected in series.

[0079] Similarly, in some embodiments of the safety system 40, greater force may be desired than can conveniently be obtained from a single thermal actuator 56. In those circumstances, multiple thermal actuators 56 may be used, with the actuators being connected in parallel.

[0080] In FIGS. 12 & 13, an example is representatively illustrated of multiple actuators 56 connected in series. Although only two actuators 56 are depicted, any number of actuators may be connected in series (and/or in parallel).

[0081] In FIG. 12, the actuators 56 are in their retracted configurations. In FIG. 13, the actuators 56 are in their extended configurations. It will be readily appreciated that the actuators 56 connected in series can produce greater displacement than a single one of the actuators can produce.

[0082] Referring additionally now to FIG. 14, a schematic cross-sectional view of another alternate configuration of the safety system 40 is representatively illustrated. In this configuration, multiple actuators 56 are used to produce sufficient displacement to rotate the blocking member 54 relative to the passage 48.

[0083] In addition, the displacement produced by the actuators 56 is transmitted to the arm 74 connected to the blocking member 54 via a rod 76, and the yoke 72 is integrally formed with the arm 74. The biasing device 60 biases the rod 76 downward, i.e., so that the blocking member 54 is rotated to its position blocking the passage 48 when the actuators 56 are in their retracted configurations. As discussed above, the biasing device 60 may not be used if the actuators 56 produce sufficient retracting force to rotate the blocking member 54 without assistance from the biasing device.

[0084] Referring additionally now to FIG. 15, a schematic cross-sectional view of another alternate configuration of the safety system 40 is representatively illustrated. In this configuration, the safety system 40 does not selectively block and unblock the passage 48 to thereby respectively prevent and permit detonation of the explosive components 46, 50, 52.
Instead, additional explosive components 50, 52 contained in a shuttle 80 are displaced by a material 78 having a volume which varies in response to changes in temperature. This material 78 may be the same as the material used in the actuators 56 described above.

The material 78 may be a solid, a liquid, a gas, a gel, a plastic, a combination thereof, or any other type of material. The material 78 may change phase to produce relatively large changes in volume.

For example, a material known as THERMOLOID™ is used in the thermal actuators available from Therm-Omega-Tech, Inc. This material (as well as other materials) may be suitable for use as the material 78 in the safety system 40 of FIG. 15. Indeed, the combination of the shuttle 80 and the material 78 in a chamber 82 of the assembly 42 may be considered as the thermal actuator 56 in this embodiment of the safety system 40.

The material 78 increases in volume in response to a temperature increase. When the material 78 increases in volume, the shuttle 80 is displaced laterally relative to the passage 48. Eventually, the explosive components 50, 52 contained in the shuttle 80 are aligned with the explosive components 50 in the passage 48, and detonation transfer through the passage is permitted.

The biasing device 60 biases the shuttle 80 toward the chamber 82 so that, when the temperature decreases and the volume of the material 78 correspondingly decreases, the shuttle will displace laterally and the explosive components 50, 52 in the shuttle will no longer be aligned with the explosive components in the passage 48. Detonation transfer through the passage 48 will thereby be prevented.

Other types of thermal actuators, such as the thermal actuators 56 described above and depicted in FIGS. 2-14, may be used in place of the material 78 in the chamber 82 to displace the shuttle 80, if desired.

Referring additionally now to FIGS. 16 & 17, schematic cross-sectional views of another alternate configuration of the safety system 40 are representative illustrated. In this configuration, the thermal actuator 56 includes an arm 84 made of a material which changes shape in response to changes in temperature.

The arm 84 is connected to the blocking member 54. At a relatively low temperature, the arm 84 has a shape which positions the blocking member 54 so that it blocks the passage 48, thereby preventing detonation of explosive components 50, 52 on one side of the member, as depicted in FIG. 16.

However, at a relatively high temperature, the arm 84 has another shape which positions the blocking member 54 so that it does not block the passage 48, thereby permitting detonation of the explosive components 50, 52 on either side of the recess 64, as depicted in FIG. 17.

The arm 84 could be constructed of various different materials. Examples of suitable materials include, but are not limited to, bimetallics, shape memory alloys, etc.

Referring additionally now to FIG. 18, a schematic cross-sectional view of another alternate configuration of the safety system 40 is representative illustrated. In this configuration, the assembly 42 includes the variable volume material 78 contained within an enclosure 86 positioned between a rod 88 and the firing pin 44 in the passage 48.

The rod 88 is propelled downward in response to detonation of explosive components 50, 52 above a piston 90 at an upper end of the rod. The enclosure 86 is preferably somewhat flexible, so that if the material 78 is at a relatively low temperature (and the material thus has a reduced volume), insufficient force will be transmitted from the rod 88 to the firing pin 44 to shear the shear pin 68 retaining the firing pin in the position shown in FIG. 18.

However, when the material 78 is at a relatively high temperature, the increase in volume of the material causes the combined material and enclosure 86 in the assembly 42 to become more rigid. In this condition, the material 78 and enclosure 86 in the assembly 42 can transmit sufficient force from the rod 88 to the firing pin 44 to shear the shear pins 68 and propel the firing pin into contact with the explosive component 46, thereby detonating the explosive components 46, 50, 52.

Referring additionally now to FIG. 19, a schematic cross-sectional view of another alternate configuration of the safety system 40 is representative illustrated. This configuration is similar in many respects to the configuration of FIG. 18. However, the rod 88, piston 90 and associated biasing device 60 and shear pins 68 are not used in the configuration of FIG. 19.

Instead, detonation of the explosive components 50, 52 above the assembly 42 (which includes the material 78 and the enclosure 86) applies a downwardly directed force to the assembly. If the material 78 is at a relatively high temperature (and thus has an increased volume), then the assembly 42 will have increased rigidity and sufficient force will be transmitted through the assembly to the firing pin 44 to propel the firing pin into contact with the explosive component 46. If, however, the material 78 is at a relatively low temperature (and thus has a reduced volume), then the assembly 42 will have a correspondingly reduced rigidity and sufficient force will not be transmitted through the assembly to the firing pin 44 to cause detonation of the explosive component 46.

In the configurations of FIGS. 18 & 19, the enclosure 86 may be made of any material suitable to contain the material 78 when it has increased volume, and to withstand the resulting stress caused by the expansion of the material 78, while being sufficiently flexible to reduce force transmission through the assembly 42 when the material 78 has a reduced volume. For example, the enclosure 86 could be made of high strength polymers, relatively thin metals, etc.

Referring additionally now to FIG. 20, a schematic cross-sectional view of another alternate configuration of the safety system 40 is representative illustrated. In this configuration, the actuator 56 is used to extend and retract the firing pin 44 in response to corresponding increases and decreases in temperature of the material 78 in the actuator.

In contrast to the other embodiments of the safety system 40 described above, the firing pin 44 is a part of the actuator 56 in the configuration of FIG. 20. For example, the firing pin 44 may be formed on an end of the rod 88.

When a sufficient force 92 is applied to the upper end of the actuator 56, shear pins 68 will shear and the actuator will be propelled downward through the passage 48 toward the explosive component 46. The force 92 may be applied mechanically, by pressure, such as detonation of explosive components above the actuator 56, or by other means.

If the firing pin 44 extends outwardly from the actuator 56 a sufficient distance, then the firing pin will contact the explosive component 46 and cause detonation of the explosive components 46, 50, 52. If, however, the firing pin
is retracted into the actuator 56 (as depicted in FIG. 20), then the firing pin will not contact the explosive component 46.

[0105] The firing pin 44 extends outwardly from the actuator 56 in response to a temperature increase, which causes the volume of the material 78 to increase. A piston 94 at an upper end of the rod 58 is displaced downward when the material 78 volume increases, thereby downwardly displacing and outwardly extending the firing pin.

[0106] Similarly, the firing pin 44 is retracted when the material 78 is at a relatively low temperature and has a corresponding reduced volume. The biasing device 60 may assist in upwardly displacing the piston 94, rod 58 and firing pin 44 if the decreased volume of the material 78 does not produce sufficient force to do this without the aid of the biasing device.

[0107] Referring additionally now to FIG. 21, a schematic cross-sectional view of another alternate configuration of the safety system 40 is representatively illustrated. In this configuration, the actuator 56 is used to alternately increase and decrease a gap G between the actuator and explosive components 50, 52 above the actuator.

[0108] When the gap G is sufficiently large, detonation of the explosive components 50, 52 above the actuator 56 will not generate sufficient downward force on the actuator to cause the shear pins 68 to shear and propel the firing pin 44 into contact with the explosive component 46. However, when the gap G is sufficiently small, the force applied to the actuator 56 will be great enough to cause the shear pins 68 to shear and propel the firing pin 44 into contact with the explosive component 46, thereby causing detonation of the explosive components 46, 50, 52.

[0109] The size of the gap G is determined by the volume of the material 78, which is positioned between a piston 96 connected to the firing pin 44 and an outer housing 98 of the actuator 56. When the material 78 volume increases in response to increased temperature, the housing 98 is displaced upward, thereby reducing the gap G.

[0110] When the material 78 volume decreases in response to reduced temperature, the housing 98 is displaced downward, thereby increasing the gap G. The biasing device 60 may assist in displacing the housing 98 downward, if desired.

[0111] Referring additionally now to FIG. 22, a schematic cross-sectional view of another alternate configuration of the safety system 40 is representatively illustrated. In this configuration, the thermal actuator 56 is used to rotate the blocking member 54 relative to the passage 48.

[0112] The blocking member 54 rotates about a pivot 100. The pivot 100 defines an axis of rotation of the blocking member 54 which is orthogonal to the passage 48.

[0113] As depicted in FIG. 22, the actuator 56 has rotated the blocking member 54 to a position in which the passage 48 is unblocked, and so detonation of the explosive components 46, 50, 52 below the assembly 42 is permitted. The actuator 56 rotates the blocking member 54 to this position in response to increased temperature.

[0114] However, when the temperature is sufficiently low, the actuator 56 will rotate the blocking member 54 (clockwise as viewed in FIG. 22) to a position in which the member blocks the passage 48 and detonation of the explosive components 46, 50, 52 below the assembly 42 is prevented.

[0115] Referring additionally now to FIG. 23, a schematic cross-sectional view of another alternate configuration of the safety system 40 is representatively illustrated. In this configuration, the blocking member 54 is displaced laterally by the actuator 56 in the recess 64 which intersects the passage 48.

[0116] The blocking member 54 has the opening 66 formed therein which may be aligned with the passage 48 when it is desired to permit detonation of the explosive components 46, 50, 52 below the assembly 42. As depicted in FIG. 23, the member 54 is in a position in which the opening 66 is not aligned with the passage 48, and so detonation of the explosive components 46, 50, 52 below the assembly 42 is prevented. The actuator 56 will displace the member 54 to align the opening 66 and passage 48 in response to a sufficient increase in temperature.

[0117] The member 54 is displaced laterally in response to extension and retraction of the rod 58 by the actuator 56. Specifically, a rounded end of the rod 58 engages a rounded end of the member 54 to cause lateral displacement of the member, similar to a cam and follower arrangement.

[0118] In the configuration as shown in FIG. 23, the firing pin 44 is propelled through the passage 48 in response to detonation of the detonating cord (explosive component 52) and booster (explosive component 50) above the firing pin. Until such detonation occurs, the firing pin 44 is secured in place by the shear pins 68 or other suitable fasteners.

[0119] Referring additionally now to FIG. 24, a schematic cross-sectional view of another alternate configuration of the safety system 40 is representatively illustrated. In this configuration, the actuator 56 and 58 engages a recess 102 formed in the firing pin 44 to thereby prevent detonation of the explosive components 46, 50, 52 below the assembly 42.

[0120] When the temperature is increased sufficiently, the actuator 56 will retract the rod 58 from the recess 102, thereby permitting the firing pin 44 to be propelled downward through the passage 48 in response to detonation of the explosive components 50, 52 above the firing pin. However, when the actuator 56 is at a relatively low temperature, engagement between the rod 58 and the recess 102 prevents displacement of the firing pin 44, even though detonation of the explosive components 50, 52 above the firing pin might produce sufficient force to shear the shear pins 68.

[0121] It may now be fully appreciated that the various configurations of the thermally activated explosives safety system 40 described above provide greatly improved safety in well operations utilizing explosive components.

[0122] Although some of the configurations of the safety system 40 have been described above as if the configuration is used to selectively permit and prevent detonation transfer between explosive components, and other configurations of the safety system have been described above as if the configuration is used to selectively permit and prevent contact between a firing pin and an explosive component, it should be clearly understood that any of the configurations may be used for either purpose with appropriate modifications.

[0123] For convenience and clarity of description, the various configurations of the safety system 40 have been described above with each configuration oriented as if detonation transfer occurs in a downward direction through the safety system. It will be appreciated, however, that detonation transfer can occur in an upward direction (for example, if a firing head initiates detonation from the bottom of a perforating assembly, etc.) or horizontally, or at any inclination. Accordingly, it should be understood that the various configurations of the safety system 40 may be used in any orientation in keeping with the principles of the invention.
Of course, a person skilled in the art would, upon a careful consideration of the above description of representative embodiments of the invention, readily appreciate that many modifications, additions, substitutions, deletions, and other changes may be made to these specific embodiments, and such changes are within the scope of the principles of the present invention. Accordingly, the foregoing detailed description is to be clearly understood as being given by way of illustration and example only, the spirit and scope of the present invention being limited solely by the appended claims and their equivalents.

What is claimed is:

1. A thermally activated explosives safety system, comprising:
   - an explosive component;
   - a blocking member displaceable to selectively permit and prevent detonation of the explosive component; and
   - a thermal actuator responsive to temperature change, the actuator being configured to displace the blocking member in response to the temperature change.

2. The system of claim 1, wherein the actuator includes a material, a volume of the material being variable in response to the temperature change.

3. The system of claim 2, wherein the material volume increases in response to a temperature increase, and wherein the material volume decreases in response to a temperature decrease.

4. The system of claim 2, wherein the blocking member displaces to a position preventing detonation of the explosive component in response to an increase in the material volume.

5. The system of claim 2, wherein the blocking member displaces to a position permitting detonation of the explosive component in response to an increase in the material volume.

6. The system of claim 1, wherein the actuator displaces the blocking member to a position preventing detonation of the explosive component in response to a temperature decrease.

7. The system of claim 1, wherein the actuator displaces the blocking member to a position permitting detonation of the explosive component in response to a temperature increase.

8. The system of claim 1, wherein the blocking member is positioned between a firing head and a perforating gun.

9. The system of claim 1, wherein the blocking member is positioned between a firing pin and the explosive component.

10. The system of claim 1, wherein the blocking member is positioned between a firing pin and the explosive component.

11. The system of claim 1, wherein the system includes at least two explosive components, and wherein the blocking member is positioned between the explosive components.

12. The system of claim 1, wherein the blocking member is displaced laterally relative to a passage by the actuator in response to the temperature change.

13. The system of claim 1, wherein the blocking member is rotated by the actuator about an axis parallel to a passage in response to the temperature change.

14. The system of claim 1, wherein the blocking member is rotated by the actuator about an axis orthogonal to a passage in response to the temperature change.

15. The system of claim 1, wherein the blocking member blocks a passage to prevent detonation of the explosive component.

16. The system of claim 1, wherein the blocking member has an opening which is aligned with a passage to permit detonation of the explosive component.

17. The system of claim 1, further comprising a biasing device which biases the blocking member in a direction to prevent detonation of the explosive component.

18. The system of claim 1, wherein the system includes at least two of the thermal actuators, and wherein the actuators are cooperatively operable to displace the blocking member.

19. The system of claim 1, wherein the actuator includes a bimetallic structure which changes shape in response to the temperature change.

20. The system of claim 1, wherein the actuator includes a shape memory alloy material which changes shape in response to the temperature change.

21. The system of claim 1, wherein the blocking member engages a firing pin to prevent displacement of the firing pin and thereby prevent detonation of the explosive component.

22. A thermally activated explosives safety system, comprising:
   - an explosive component;
   - a thermal actuator responsive to temperature change, the actuator including a material having a volume which is variable in response to the temperature change; and
   - wherein detonation of the explosive component is selectively permitted and prevented by the actuator when the material volume changes.

23. The system of claim 22, wherein detonation of the explosive component is prevented when the material volume decreases.

24. The system of claim 22, wherein detonation of the explosive component is prevented when the material volume increases.

25. The system of claim 22, wherein the material volume increases in response to a temperature increase, and wherein the material volume decreases in response to a temperature decrease.

26. The system of claim 22, wherein a blocking member displaces to a position preventing detonation of the explosive component in response to an increase in the material volume.

27. The system of claim 22, wherein a blocking member displaces to a position permitting detonation of the explosive component in response to an increase in the material volume.

28. The system of claim 22, wherein the actuator displaces a blocking member to a position preventing detonation of the explosive component in response to a temperature decrease.

29. The system of claim 22, wherein the actuator displaces a blocking member to a position permitting detonation of the explosive component in response to a temperature increase.

30. The system of claim 22, wherein a blocking member displaceable by the actuator blocks a passage to prevent detonation of the explosive component.

31. The system of claim 22, wherein the actuator includes a bimetallic structure which changes shape in response to the temperature change.

32. The system of claim 22, wherein the actuator includes a shape memory alloy material which changes shape in response to the temperature change.

33. The system of claim 22, wherein the actuator reduces a gap between elements of the system to thereby permit detonation of the explosive component.

34. The system of claim 22, wherein the actuator extends a firing pin outwardly to thereby permit detonation of the explosive component.

35. The system of claim 22, wherein the actuator aligns multiple elements of an explosive train to thereby permit detonation of the explosive component.
36. The system of claim 22, wherein the actuator displaces a blocking member to thereby permit detonation of the explosive component.

37. The system of claim 22, wherein the actuator aligns an opening with a passage to thereby permit detonation of the explosive component.

38. The system of claim 22, wherein the actuator rotates a blocking member to thereby permit detonation of the explosive component.

39. A method of preventing undesired detonation of an explosive component, the method comprising the steps of: providing a material having a volume which is variable in response to a change in a temperature of the material; positioning the material and the explosive component in a subterranean well, thereby increasing the temperature of the material; increasing the volume of the material in response to the temperature increasing step; and permitting detonation of the explosive component in response to the volume increasing step.

40. The method of claim 39, further comprising the steps of decreasing the volume of the material in response to decreasing the temperature of the material, and preventing detonation of the explosive component in response to the volume decreasing step.

41. The method of claim 40, wherein the volume decreasing and detonation preventing steps are performed after the volume increasing and detonation permitting steps.

42. The method of claim 39, further comprising the step of preventing detonation of the explosive component, and wherein the detonation preventing step is performed prior to the volume increasing and detonation permitting steps.

43. The method of claim 39, further comprising the step of containing the material in an enclosure, thereby forming an assembly which becomes increasingly rigid as the volume of the material increases.

44. The method of claim 43, further comprising the step of transmitting a force through the assembly when the assembly has an increased rigidity to thereby detonate the explosive component.

45. The method of claim 43, further comprising the step of preventing detonation of the explosive component by preventing effective transmission of a force through the assembly when the assembly has a reduced rigidity.

46. The method of claim 39, wherein the providing step further comprises providing the material as part of a thermal actuator.

47. The method of claim 46, wherein the detonation permitting step further comprises the actuator displacing a blocking member in response to the volume increasing step.

48. The method of claim 46, wherein the detonation permitting step further comprises the actuator rotating a blocking member in response to the volume increasing step.

49. The method of claim 46, wherein the detonation permitting step further comprises the actuator extending a firing pin outward in response to the volume increasing step.

50. The method of claim 46, wherein the detonation permitting step further comprises the actuator decreasing a gap in response to the volume increasing step.

51. The method of claim 46, wherein the detonation permitting step further comprises the actuator aligning multiple explosive components in response to the volume increasing step.

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