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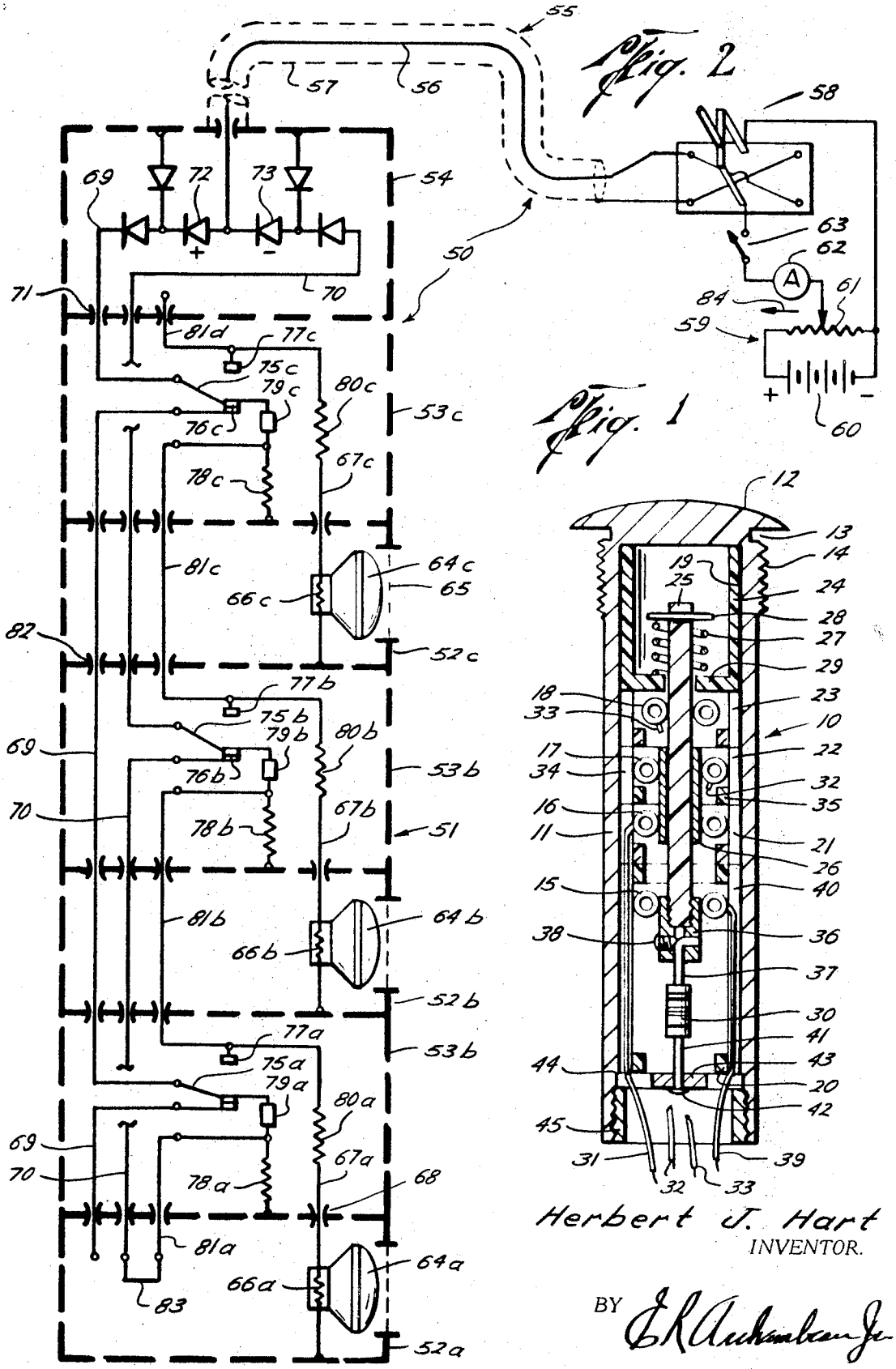

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SWITCHING APPARATUS FOR SELECTIVELY ACTUATING EXPLOSIVE WELL-COMPLETION DEVICES

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ABSTRACT OF THE DISCLOSURE

This disclosure is directed to shock-resistant switching apparatus for controlling well-completion tools having a plurality of explosive devices such as shaped charge perforators that are to be successively operated. The shock-resistant switching apparatus is normally retained in one position by an electrical resistor that is of substantial mechanical strength but is selectively adapted to fail upon passage therethrough of a predetermined electrical current. Upon passage of sufficient current through the resistor to cause its failure, the switch moves to another position to connect one or more associated explosive devices into a firing circuit for subsequent detonation.

Present day well-completion techniques often require that a plurality of electrically-actuated devices such as shaped charge perforators be selectively actuated so that only a single trip into a well is required to perforate the well at a number of different depths. Those skilled in the art will, of course, appreciate that whatever arrangement is used to selectively detonate these explosive devices must be highly reliable to, for example, avoid perforating a well casing at an incorrect depth. Accordingly, heretofore, typical control systems have employed either successively-indexed multi-contact switches or various types of normally-open switches that are closed only as a result of the detonation of a previous shaped charge. Although control switches of this nature have generally been successful, many of these switches are either fairly expensive or are unduly susceptible to damage from the extreme impact shocks typically experienced by a well perforator. Thus, there is still a need for selectively-operable control switches that are sufficiently reliable and shock-resistant for use with typical well-perforating apparatus but without being unduly elaborate or expensive.

Accordingly, it is an object of the present invention to provide new and improved impact-resistant and relatively fool-proof switching apparatus for selectively controlling the plurality of explosive perforating devices.

This and other objects of the present invention are attained by an electrical switch having a movable member that is releasably secured in a first position by an electrical resistor from moving to a second position operatively connecting a power source to one or more electrically-responsive explosive perforating devices that are to be operated together. To actuate the switch, sufficient current must first be passed through the resistor to cause its mechanical failure and allow the movable member to move to its second position for connecting the explosive devices into a firing circuit for subsequent operation.

The novel features of the present invention are set forth with particularity in the appended claims. The invention, together with further objects and advantages thereof, may be best understood by way of the following description of exemplary apparatus employing the principles of the invention as illustrated in the accompanying drawings, in which:

FIG. 1 depicts a switch arranged in accordance with the principles of the present invention; and

FIG. 2 schematically illustrates perforating apparatus adapted for control by a number of the new and improved switches shown in FIG. 1.

Turning now to FIG. 1, a preferred embodiment is shown of a control switch **10** arranged in accordance with the present invention. Although the switch **10** could, of course, be simply disposed within one of the housing sections of a typical well-completion tool, it is preferred to arrange the switch to be secured in an access port in the tool housing for purposes of convenience. In this preferred embodiment, the control switch **10** has a tubular case **11** with a suitably arranged closure member **12** on its outer end just ahead of a circumferential sealing ring groove **13** and external threads **14**. By making at least a substantial portion of the tubular case **11** of an electrically-conductive material, once the switch **10** is inserted into an access port in a tool body and the threads **14** are matingly engaged with complementary threads in this port, the tubular case **11** will be electrically connected to the tool body. A plurality of fixed electrical contacts **15–18** are spatially disposed along the internal bore **19** of the case **11** and electrically insulated from one another and the case by suitable non-conductive materials which may be conveniently formed as a stack of insulating spools or sleeves **20–24**. In the preferred manner of arranging these fixed contacts **15–18**, small garter springs of electrically-conductive materials are employed.

A shaft **25** of an electrically-nonconductive material and carrying a conductive contact member, such as a tube **26**, on its intermediate portion is suitably positioned in the case **11** for axial movement from the position shown to a more-forward position. To urge the shaft **25** forwardly with a predetermined force, means are provided such as a compression spring **27** around the forward end of the shaft that is yieldably constrained between a transverse pin **28** thereon and an inwardly-directed shoulder **29** on the insulating sleeve **24**. The shaft **25** is, however, releasably retained in the illustrated position by an electrically-destructible resistance element such as a composition or a common carbon resistor **30** of a selected power rating that is secured in tension between the trailing end of the shaft and the case **11**. The body of the resistor **30**, of course, has a normal mechanical strength greater than the spring force of the spring **27**.

It will be further appreciated, from FIG. 1 that the conductive sleeve **26** is cooperatively arranged to interconnect the contact springs **16** and **17** so long as the shaft **25** is held in its normal position. In this shaft position, the conductive sleeve **26** has radially expanded the contact springs **16** and **17** somewhat in relation to a more relaxed contracted position (such as the illustrated position of the non-contacted spring **18**) to insure satisfactory electrical contact. Forward movement of the axial shaft **25** will, however, drive the sleeve **26** into the center of the forward contact spring **18** and expand that spring as the rearward contact spring **16** relaxes onto the insulated shaft to the rear of the conductive sleeve. Conductors **31–33** are respectively connected to the contact springs **16–18** and routed out the rear of the case **11** by way of circumferentially-spaced longitudinal slots or grooves, as at **34**, formed in the walls of the insulating sleeves **20–23**. To retain the contact springs **15–18** in their respective spaced positions, the insulating sleeves **20–23** are preferably formed with inwardly-projecting shoulders as at **35**.

Since the axial shaft **25** is of a nonconductive material, a coupling **36** of an electrically-conductive material is secured (as by the illustrated threads) to the rearward or trailing end of the shaft. The forward terminal lead **37** of the resistor **30** is preferably passed through a suitable opening in the coupling **36** and clamped thereto as by a

set screw **38**. The contact spring **15** is suitably positioned to at least be initially in electrical contact with the coupling **36** and has a conductor **39** connected thereto that is routed out the rear of the case **11** by way of a longitudinal groove **40** in the insulating sleeve **20**. The rearward terminal lead **41** of the resistor **30** is passed through a suitable opening and soldered, as at **42**, to an electrically-conductive cross-shaped, transverse member **43**. To facilitate the replacement of the resistor **30**, the transverse member **43** is preferably secured against a rearwardly-directed case shoulder **44** by a suitable threaded lock ring **45**. It will also be noted that in addition to assuring satisfactory electrical contact between the case **11** and transverse member **43**, the insulating sleeves **20–24** are appropriately arranged to have a stacked height just sufficient to be snugly clamped into their respective positions by the transverse member.

Accordingly, it will be appreciated that so long as the resistor **30** remains intact, it will secure the axial shaft **25** to the case **11** and retain the shaft in its rearward position against the predetermined biasing force of the spring **27**. By selecting the resistor **30** to have a minimum wattage rating as well as a particularly-low electrical resistance, it will be quite easy to pass sufficient electrical current through the resistor to quickly disrupt or destroy the mechanical strength of the resistor body so that the spring **27** will be capable of repositioning the shaft **25** once the body of the resistor parts. For example, if the resistor **30** is a typical carbon resistor with a relatively-low resistance and a selected power rating of, for example, ¼-watt, application of only a very low voltage will be sufficient to cause a relatively-high current flow through the resistor **30**. The excessive power dissipation caused by such high current flow through the resistor **30** will, of course, quickly destroy the physical strength of the resistor. As a particular matter, therefore, it has been found that the body of such a low-resistance, low-wattage resistor will often be either completely parted or sufficiently weakened mechanically very quickly by such currents. Thus, although the resistor **30** is initially sufficiently stout to withstand severe impact shocks and the extreme environmental conditions of a well bore, the resistor body can always be reliably parted with a minimum of current flow.

Turning now to FIG. 2, a schematic representation is shown of electrical circuitry **50** employing control switches arranged in accordance with the present invention for selectively controlling perforating apparatus **51** such as, for example, that disclosed in Pat No. 3,329,218. It will be realized, of course, that the control circuitry **50** can be either distributed throughout the apparatus **51** in any convenient arrangement or else the circuitry can be concentrated into a single section thereof. However, to arrange the various elements of the circuitry **50** into fully-interchangeable integrated units as well as to allow any number of these integrated units to be assembled without special consideration, the perforating apparatus **51** includes a plurality of tandemly-connected, fluid-tight housing sections **52**, **53** and **54** that are adapted for suspension as a single body in a wel bore (not shown) from a cable **55** that is spooled in the usual manner on a winch (not shown) at the surface. As is typical, the suspension cable **55** has a single central conductor **56** that is enclosed within an electrically-conductive armored sheath **57** which serves as another electrical conductor. Both of these conductors **56** and **57** are appropriately connected to the surface by a conventional reversing switch **58** to a selectively-operable power source **59** such as provided by a battery **60** having a potentiometer **61** across it and in series with an ammeter **62** and a control switch **63**. In this manner, an operator may conveniently select both the polarity and the voltage potential that is to be applied to the conductors **56** and **57** as well as to regulate the magnitude of the current flowing through the cable conductors.

Perforating means are provided such as typical shaped charges **64** that are respectively fluidly sealed within each of the housing sections **52** and oriented along a laterally-directed perforating axis intersecting a replaceable closure **65** in the side of each section. The perforating means further include electrically-responsive detonating means, such as typical initiators **66**, that are arranged within detonating proximity of the rear of each of the shaped charges **64**. Inasmuch as the armored sheath **57** is electrically connected to all of the housing sections **52–54**, each of the initiators **66** is arranged so that one side of its filament is in electrical contact with the assembled housing sections (as schematically shown in FIG. 2) and the other side of the filament is connected to a conductor **67** that is passed through a fluid-tight seal or connector plug (as at **68**) into the adjacent housing section **53**. In this manner, well-bore fluids entering the housing sections **52** upon detonation of the shaped charges **64** will be excluded from the housing sections **53** and come into contact with the various components of the circuitry **50**.

The particular manner of connecting the circuitry **50** to the surface equipment is, of course, dependent upon the number of electrical conductors in the suspension cable employed. Where, for example, a multi-conductor cable is used, one cable conductor may be connected to the housing sections and two other cable conductors are simply connected to separate conductors, as at **69** and **70**, that begin in the upper housing section **54** and are respectively carried through appropriate fluid-tight seals or mating connector plugs, as at **71**, into the alternately-disposed housing sections **52** and **53** depending therebelow. On the other hand, since it is usually preferred to use less-bulky monoconductor suspension cables, as at **55**, for perforators, one or more oppositely-poled diodes as at **72** and **73** in the upper housing section **54** are both connected to the central cable conductor **56** and respectively connected to the conductors **69** and **70**. Thus, when the reversing switch **58** is thrown so as to connect the positive pole of the battery **60** to the central cable conductor **56**, current will readily flow through the diodes **72** and the conductor **69**, and the diodes **73** will block current flow through the conductor **70**. On the other hand, when the reversing switch **58** is in its other operating position, current will flow only through the diodes **73** and the conductor **70**, and no current will flow through the conductor **69**.

The circuitry **10** also includes a number of switches **74** arranged in accordance with the present invention as single-pole double-throw switches that are respectively mounted in each of the housing sections **53** and are selectively operable from the surface for the successive detonation of the shaped charges **64**. It will be recognized, of course, that by mounting the switches **74** in the separate housing sections **53**, the switches will be shielded from the shaped charges **64**.

In the preferred manner of connecting these switches **74**, their moving contact **75** is initially engaged with the first fixed contact **76** and is movable to the second fixed contact **77** only upon the physical failure of the resistor **78** upon passage of excessive current therethrough. An electrical insulator **79** isolates the resistor **78** from the switch contacts **75–77**. The conductors **67** from the explosive initiators **66** are respectively connected to the second fixed contact **77** of their associated control switch **74**, and preferably have a current-limiting resistor **80** serially connected between this contact and the initiator. Conductors **81** are also connected between each of the second fixed contacts **77** of one switch **74** and the resistor **78** in the next successive switch.

As is schematically depicted in FIG. 2, the conductors **69** and **70** extend the full length of the apparatus **51** and are alternately divided and successively connected in a staggered sequence to the moving and fixed contacts **75** and **76** of the several switches **74**. Thus, as illustrated, the

conductor **69**, for example, is divided and connected only to the odd-numbered switches (as at **74***a* and **74***c*) and the conductor **70** is divided and connected only to the even-numbered switches (as at **74***b*). It will be realized, of course, that to facilitate their connection and disconnection as well as to make the units fully interchangeable, the conductors **69**, **70** and **81** are all connected to fluid-tight electrical plugs, as at **82**, that are readily mated as the housing sections **52**, **53** and **54** are assembled. Thus, since only three duplicate units are shown in FIG. 2, the conductor **81***d* has no mating contact in the uppermost housing section **54** and the conductor **81***a* must be connected, as by a jumper **83** to the lowermost end of the conductor **70** to complete the circuitry **50**. It will also be appreciated, of course, that those portions of the conductors **69**, **70** and **81** passing through the housing sections **52** should be protected in some manner from the explosive forces of the shaped charges **64**.

Accordingly, once the perforating apparatus **51** is assembled and the circuitry **50** is connected as shown in FIG. 2, the apparatus is lowered on the suspension cable **55** to the first position in a well bore (not shown) where a perforation is to be made. It will be appreciated that so long as the switches **74** of the invention are in their depicted positions, not only will the initiators **66** be disconnected from the firing circuit (as represented by the conductors **69** and **70**) but the initiators will also be safely shunted by their respective resistors **78** and **80**. Thus, stray electrical currents cannot inadvertently detonate the disabled shaped charges **64** and the perforating apparatus **51** cannot be armed until the power source **59** is connected in a selected manner to the cable conductors **56** and **57** and a current of a predetermined magnitude is obtained.

Once the perforating apparatus **51** is positioned in the well bore so as to bring the lowermost shaped charge **64***a* to a selected depth, the reversing switch **58** is thrown to the left (as viewed in FIG. 2) to connect the negative pole of the battery **60** to the central cable conductor **56**. Then, after the switch **63** is closed, the potentiometer **61** is advanced (as shown by the arrow **84**) to increase the current flowing through the firing circuit conductor **70**. It will be appreciated that at this point all current flowing through the conductor **70** must pass (by way of the jumper **83**) through the resistor **78***a*. Thus, by continuing to advance the potentiometer **61**, the magnitude of current flowing through the resistor **78***a* will ultimately exceed the predetermined current level required to destroy the resistor **78***a* and release the movable switch contact **75***a* for movement to the fixed contact **77***a*. It will be appreciated that the insulator **79***a* electrically isolates the switch **74***a* itself from the resistor **78***a*.

Once passage of current through the conductor **70** fails, the resistor **78***a* and the movable switch contact **75***a* has moved into engagement with the fixed contact **77***a*, the other conductor **69** of the firing circuit is then connected through the fixed contact **77***a* to the initiator **66***a* as well as to the resistor **78***b*. At this time, however, the diodes **72** prevent any current from flowing in the firing circuit conductor **69**. Thus, the shaped charge **64***a* cannot be detonated until the reversing switch **58** is thrown (to the right as viewed in FIG. 2) to its other operating position.

It should be noted also that failure of the resistor **78***a* will open the circuit path so that upon seeing the ammeter **62** drop to zero, it will be known that the switch **74***a* has been actuated. Reversal of the reversing switch **58** connects the positive terminal of the battery **60** to the firing circuit conductor **69** and the conductors **81***b* and **67***a*. Thus, the current flowing at this time in the firing circuit will initially divide at the switch contact **77***a* and flow through both the resistor **78***b* and the initiator **66***a*. It is preferred, however, to actuate the switch **74***b* before the shaped charge **64***a* is detonated. Accordingly, by selecting the resistors **80** to have a relatively-high resistance in relation to the resistance of the resistors **78**, most of the current initially flowing in the firing circuit conductor **69** will pass through the resistor **78***b* until the body of the resistor fails. Once the resistor **78***b* has failed, however, all of the current flowing in the conductor **69** will be diverted to the initiator **66***a*. Then, if necessary, the potentiometer **61** is advanced until the shaped charge **64***a* is detonated. Here again, once the shaped charge **64***a* is detonated, the circuit will be broken and the cessation of current flow as indicated by the ammeter **62** will provide a reliable indication at the surface that the shaped charge **64***a* has been detonated.

Detonation of the next shaped charge **64***b* requires that the reversing switch **58** again be reversed. Upon reversal of the switch **58**, the initiator **66***b* and the resistor **78***c* are initially paralleled. In the same manner as already described, the resistor **78***c* is first failed to actuate the switch **74***c*. Then, once sufficient current flows through the initiator **66***b*, the shaped charge **64***b* will be detonated and the ammeter **62** will again provide a positive indication at the surface. It will be appreciated that if additional shaped charges **64** and switches **74** were positioned between the housing sections **52***c* and **53***b*, the successive actuation of these other switches **74** and detonation of these additional shaped charges **64** would, of course, be accomplished in the same fashion by alternately applying current to the first one and then the other of the firing circuit conductors **69** and **70** in successive turns.

The last control switch **74** in the perforating apparatus **51** is preferably actuated prior to the detonation of the next-to-last shaped charge **64**. Thus, referring again to FIG. 2, it will be recognized that when the reversing switch **58** is operated to direct the current flow to the fixed switch contact **77***b*, the resistor **78***c* will initially be failed to actuate the uppermost switch **74***c* before the shaped charge **64***b* is detonated. Once the next-to-last shaped charge **64***b* is detonated, only the last initiator **66***c* is now connected to the firing circuit. Thus, upon the subsequent reversal of the switch **58**, all current flowing in the conductor **69** will pass through the initiator **66***c*.

Accordingly, although there are a variety of prior-art fuse-actuated switches that presumably are functionally equivalent to those of the present invention, those skilled in the well tool art will appreciate that few—if any—of these prior-art switches woud be capable of reliably functioning in typical perforating apparatus such as at **51**. For example, in addition to the extreme pressures and temperatures typically encountered in well bores, any successful control switch of this nature must be of exceptionally rugged construction to withstand the severe physical shocks or impacts successively imposed on the switches during the course of even a routine perforating operation. It will also be appreciated that for purposes of economy, the control switches of the present invention are particularly attractive.

While a particular embodiment of the present invention has been shown and described, it is apparent that changes and modifications may be made without departing from this invention in its broader aspects; and, therefore, the aim in the appended claims is to cover all such changes and modifications as fall within the true spirit and scope of this invention.

What is claimed is:

1. In a well tool adapted for suspension in a well bore and including explosive means adapted for detonation in response to passage of electrical current therethrough, circuit means adapted for selectively operating said explosive means comprising: switching means on said well tool and having at least one fixed electrical contact and one movable electrical contact movable from a first position to a second position for making an electrical connection with said fixed contact; an electrical resistor of a selected power rating electrically isolated from and secured between said movable contact and said well tool, said resistor having a body with sufficient physical strength

for restraining said movable contact from moving from its said first position until passage of electrical current through said resistor exceeds said selected power rating sufficiently to mechanically weaken said resistor body; spring means having a predetermined spring force normally urging said movable contact toward its said second position and adapted to move said movable contact thereto only upon weakening of said resistor body; first conductor means adapted for connecting said resistor to a source of electrical power; and second conductor means connected to said electrical contacts and adapted for connecting said explosive means to a source of electrical power only when said movable contact is in its said second position.

2. The well tool of claim 1 wherein said explosive means include perforating means adapted to perforate a wall surface in a well bore; and further including means on said well tool for shielding said switching means from the detonation of said perforating means.

3. The well tool of claim 1 wherein said movable contact is adapted for movement along a selected axis from said first position to said second position axially spaced therefrom; and said resistor is generally in coincidental alignment with said selected axis so as to be tensioned by said predetermined spring force, one lead of said resistor being mechanically connected to and electrically insulated from said movable contact and the other lead of said resistor being mechanically connected to said well tool and electrically insulated from said one resistor lead and said electrical contacts.

4. The well tool of claim 3 further including an elongated body movable along said selected axis and carrying said movable contact; and a second fixed contact axially spaced from said first-mentioned fixed contact and adapted for engagement by said movable contact upon movement to its said second position to electrically interconnect said fixed contacts.

5. The well tool of claim 4 further including a tubular case around said electrical contacts and elongated body; and electrical insulating means isolating said fixed contacts from one another and from said tubular case.

6. The well tool of claim 5 wherein said tubular case is mounted to said well tool; and further including a third fixed contact secured to said tubular case to which said other resistor lead is secured.

7. A selectively-operable switch for use in a well-completion tool and comprising: a tubular case having a longitudinal bore; an elongated body movably supported in said case and adapted for axial movement therein between first and second longitudinally-spaced positions along said bore; first electrical contact means on said movable body; second electrical contact means on said case and adapted to be engaged with said first contact means in one of said positions of said movable body and to be disengaged therefrom in the other of said positions of said movable body; electrical-insulating means for isolating said electrical contact means from said case and from one another whenever said movable body is in its said other position; biasing means operatively arranged between said case and said movable body for urging said movable body toward its said second position with a predetermined force; an electrical resistor of a selected power rating connected between said case and said movable body for releasably securing said movable body in its said first position, said resistor having a body with a normal mechanical strength greater than said predetermined biasing force for retaining said movable body in its said first position until sufficient electrical current has passed through said resistor to exceed said selected power rating and reduce said mechanical strength of said resistor body below said biasing force; and conductor means connected to said resistor and adapted for connection to a source of electrical power.

8. The switch of claim 7 wherein said resistor is in generally-coincidental alignment with said movable body and adjacent to the rearward end thereof so as to be in tension for retaining said movable body against forward movement to its said second position.

9. The switch of claim 8 wherein said conductor means further include a first electrical contact on said rearward end of said movable body; means on said first electrical contact for securing the forward lead of said resistor thereto; a second electrical contact in said case and engaged with said first electrical contact at least when said movable body is in its said first position; a third electrical contact secured in said case; means on said third electrical contact for securing the rearward lead of said resistor thereto; and further including second electrical-insulator means for electrically isolating said first and second electrical contacts from one another as well as from said third electrical contact.

10. The switch of claim 9 wherein said movable body is constructed of electrically-nonconductive material; and said first electrical contact means and said first electrical contact are constructed of electrically-conductive material secured on said movable body.

11. A selectively-operable switch for use in a well-completion tool and comprising: a tubular case having a longitudinal bore; an elongated body coaxially supported in said case and adapted for axial movement in one direction therein between first and second axially-spaced positions; first and second electrical contacts spaced apart on said movable body; first, second and third fixed contacts on an electrically-conductive material mounted in said case at axially-spaced intervals therein, said first and second fixed contacts being adapted for engagement by said first electrical contact on said movable body whenever said movable body is in its said first position, said second and third fixed contacts being adapted for engagement by said first electrical contact whenever said movable body is in its said second position; first electrical-insulating means for electrically isolating said fixed contacts from one another; second electrical-insulating means on said movable body for electrically isolating said first and second electrical contacts from one another; spring means operatively arranged between said case and said movable body for urging said movable body toward its said second position with a predetermined force; an electrical resistor of a selected power rating adjacent to the trailing end of said movable body and coincidentally aligned therewith and having its forward end connected to said second electrical contact and its rearward end secured to said case so as to be in tension for releasably securing said movable body in its said first position, said resistor having a body with a normal tensile strength greater than said predetermined biasing force for retaining said movable body in its said first position until sufficient electrical current has passed through said resistor to exceed said selected power rating and reduce said mechanical strength of said resistor body below said biasing force; and conductor means connected to said resistor leads and adapted for connection to a source of electrical power.

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