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(54) Title: LEAKAGE SENSOR

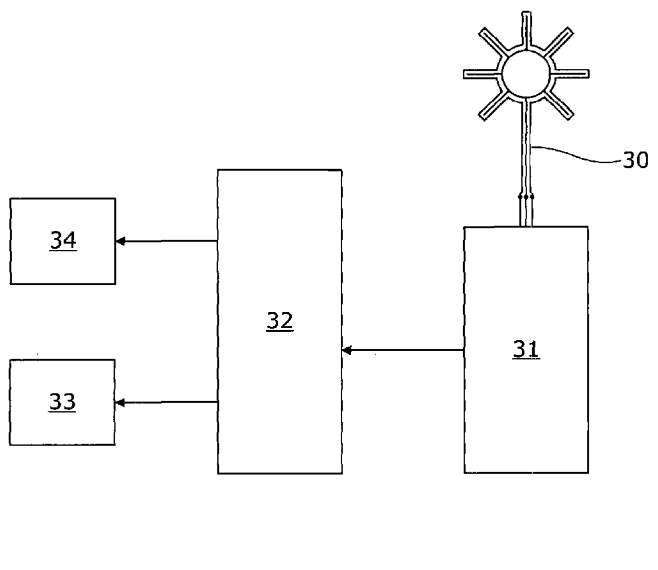

Fig. 3

(57) Abstract: The invention relates to a sensor system, especially a sensor system suitable for detecting fluids, and related sensors, methods and uses. A sensor system is provided for detecting leaks in a diaphragm, the system comprising at least one sensor element (30), said element comprising a fluid sensing component formed from an electrically conductive polymer, and a sensing circuit for measuring the electrical resistance of the electrically conductive polymer. In a preferred embodiment, the sensor system comprises sensor element (30) connected to signal conditioning unit (31). The signal conditioning unit comprises a sensing circuit for measuring the electrical resistance of the fluid sensing component and a further sensing circuit for monitoring whether or not a closed circuit condition exists between inner and outer conductive traces of the sensor element. The signal conditioning unit (31) is connected to signal processor (32), which provides an audio/visual output (33) and a serial data interface (34).

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Leakage Sensor

The invention relates generally to a sensor system, especially a sensor system suitable for detecting fluids, and more especially a sensor system for detecting fluid leakage through a diaphragm. The invention also relates to corresponding methods and uses.

Diaphragms are used as fluid barriers (or seals) in a variety of different applications. In certain applications - such as, for example, process control valves and diaphragm pumps – the diaphragm may undergo repeated flexing over long time periods, thereby leading to material fatigue and potential diaphragm failure. It is generally highly undesirable for fluids to pass through the diaphragm and accordingly, failure sensors – also known as leakage sensors - are required to provide warning of imminent or actual failure.

In the particular example of a control valve in a pharmaceutical plant, failure of a valve diaphragm can result in contamination of a pharmaceutical batch. Even after sterilization of a process line, an unknown failed diaphragm can harbour contamination that can affect subsequent product batches. Accordingly, timely identification of failure points can save significant costs by circumventing or ameliorating spoilt batches and reducing plant down time.

Several types of system for sensing diaphragm leakage are already known. For example, WO 95/27194 to Succi *et al* discloses a device for leakage detection in pumps for electrically conductive products comprising an electrically conductive layer positioned behind a diaphragm and a contact plate positioned on the product side of the diaphragm. When cracks occur in the diaphragm so that the product comes into contact with the electrically conductive layer, a closed current circuit is made. Similarly, US 6,935,180 to Weisbrodt discloses a system comprising first and second electrically conductive diaphragm layers arranged such that, when a break occurs in the diaphragm, the electrically conductive layers are wetted and the resistance between said layers drops. In both of the afore-mentioned examples, the system is suitable for sensing electrically conductive fluids.

US 6,941,853 to Hembree discloses a system which monitors the electrical continuity of a sensor element in the form of a thin conductive trace positioned behind a diaphragm. When the diaphragm is damaged the sensor element also undergoes damage, which causes either an open circuit or – if a conductive fluid comes into contact with the trace - an altered conductive circuit.

In yet another example, US 6,679,101 to Röhner discloses a device for detecting liquid leaks in membranes and so on comprising a swellable material which joins or separates electrical conductors when influenced by the liquid.

Despite previous attempts to provide a failure sensor for diaphragms, however, the process of seal inspection is often still conducted by simple visual inspection of a process plant or other facility. Moreover, because many existing leakage sensors rely on the process fluid completing a circuit between two electrodes, they cannot reliably detect the egress of fluids which are not electrically conductive. Thus, there exists a need for an improved leakage sensor which can detect electrically non-conductive fluids, and preferably detect electrically non-conductive as well as electrically conductive fluids.

According to a first aspect of the invention, there is provided a sensor system for detecting leaks in a diaphragm, the system comprising at least one sensor element, said element comprising a fluid sensing component formed from an electrically conductive polymer, and a sensing circuit for measuring the electrical resistance of the electrically conductive polymer.

It is known that an electrically conductive fluid can be detected by monitoring whether or not a circuit is completed between two electrodes upon exposure to said fluid. In theory, any electrically conductive fluid can be detected in this way including, for example, a non-conductive fluid which has been rendered conductive by an additive, although the precise electrical properties of the fluid may affect the size of the current that flows between the two electrodes. Non-conductive fluids, however, cannot be detected in this way, which includes a wide range of organic fluids. One fluid of interest in the pharmaceutical industry which cannot be detected by this method is n-hexane.

The inventors have found that the electrical resistance of an electrically conductive polymer can change upon exposure to a fluid and advantageously, the effect is generally – although not necessarily - more pronounced for non-conductive fluids. In particular, non-polar fluids tend to cause a detectable change in the resistance of a conductive polymer material. In the system of the invention, therefore, a sensor element is provided comprising a fluid sensing component formed from an electrically conductive polymer and a sensing circuit for measuring the electrical resistance of the electrically conductive polymer. Upon exposure to certain fluids, the electrically conductive polymer undergoes a change in electrical resistance and hence, by measuring the resistance change, the presence of the fluid can be detected.

The inventors have observed that expansion of the electrically conductive polymer typically accompanies the resistance change, so it is theorised that the change in resistance might result from fluid absorption causing conductive regions in the electrically conductive polymer to move apart. This means that the solubility parameters of the electrically conductive polymer and the fluid might affect the responsiveness of the sensor system to a particular fluid. However, it is not intended to limit the invention to any particular theory on how the resistance change occurs and in general, any fluid which causes the electrically conductive polymer to undergo a change in resistance upon exposure to said fluid can be detected by the system.

The fluid sensing component is formed from an electrically conductive polymer. In theory, any electrically conductive polymer that undergoes a change in resistance upon exposure to a fluid is suitable, but preferably the electrically conductive polymer comprises conductive particles in a polymer matrix. In the invention, suitable particles include conductive carbon (graphite) particles, metal particles, or composite particles of any suitable material coated with conductive carbon or metal, or any combination thereof. Suitable metal loadings include Au, Ag or Cu, or any combination thereof, and suitable composite particles include materials coated with those metals. One particularly preferred particle loading comprises Ag-coated Al particles.

Preferably, the electrically conductive polymer is an elastomer. This is because for many applications (e.g. in control valves and diaphragm pumps) the sensor element (and hence, the fluid sensing component – which is typically located in close proximity to the diaphragm) needs to withstand repeated flexing under load. For an electrically conductive polymer which comprises conductive particles in a polymer matrix, suitable polymer matrices include (but are not limited to) silicone polymers, butadiene rubbers, butyl rubber, natural rubber and nitrile rubber. Silicone rubbers have been found to have particularly suitable properties for use in the invention and hence, the electrically conductive polymer is preferably a conductive silicone polymer such as, for example, conductive polydimethyl silicone (PDMS).

For applications not according to the invention, it is often desirable that an electrically conductive polymer has an electrical conductivity which is as high as possible (typically in excess of 10^4 Sm^{-1}). Hence, the size, size distribution and loading of the conducting particles in a conductive polymer is typically selected to prevent particle agglomeration in the composite material and optimise conductivity. However, polymers having a high conductivity typically have a higher particle content and, as a result, can lose material robustness. Thus, high conductivity polymers can perform poorly in the system of the invention, which may require the sensor element to undergo repeatedly flexing.

The inventors have found that it is preferable to select a lower conductivity material which nevertheless provides suitable material properties. As a general principle, it is desirable to have the minimum acceptable conductivity for the desired polymer durability (i.e. tensile strength, fatigue, elongation to failure, hardness and so on). In the system of the invention, it is preferable that the electrically conductive polymer has a conductivity of less than about 10^4 Sm^{-1}. More preferably, the electrically conductive polymer has a conductivity in the range 1 to 1000 Sm^{-1}, even more preferably the conductivity lies in the range 10 to 1000 Sm^{-1} and most preferably the conductivity lies in the range 10 to 100 Sm^{-1}. In one example, a specific polymer material comprising conductive carbon particles in a PDMS matrix was selected having a volume resistivity of 5-10 Ωcm (corresponding to a conductivity of 20-100 Sm^{-1}).

Upon exposure to a fluid, the electrical resistance of the fluid sensing component usually increases, but the resistance may also decrease. The sense of the change in resistance is not critical to the operation of the invention, and it is merely necessary that the change in resistance is either above or below a predetermined detection threshold. In general, the detection threshold is a value which can be discerned above the baseline resistance. The resistance of the fluid sensing component can change under load, due to deformation of the conductive polymer. The inventors have found that the change in resistance during (for example) the operating cycle of a valve follows a predictable pattern, which can be used as the baseline resistance.

The sensing circuit can be any means suitable for measuring the resistance of the fluid sensing component, and the skilled person will be well aware of such circuits. The sensing circuit is conveniently located on the outside of the diaphragm housing (for example, on the outside of a valve body), optionally as part of a signal conditioning unit.

As mentioned above, electrically conductive fluids can be detected by monitoring whether or not a circuit is completed between two electrodes. In a preferred embodiment of the invention, the at least one sensor element further comprises a first electrode and a second electrode, the electrodes being electrically isolated from each other in normal use, and the system comprises a further sensing circuit for measuring any change in electrical resistance between the first electrode and second electrode. In the absence of an electrically conductive fluid (which will normally be because the diaphragm is undamaged, but may also be because a non-conductive fluid has leaked through the diaphragm) the electrodes are electrically isolated from each other and hence, no current flows between the electrodes (in other words, there is an open circuit). If an electrically conductive fluid comes into contact with the first and second electrodes, however, contact is made between the electrodes and an electrical current flows (in other words, a closed circuit is formed). Hence, the conductive fluid can be detected by measuring whether or not a current flows between the first and second electrodes.

The preferred embodiment provides a dual mode sensor system, which can detect diaphragm leakage by monitoring whether or not a circuit is completed between the first electrode and second electrode upon exposure to a fluid and/or by monitoring whether or not there is a change in the electrical resistance of the fluid sensing component upon exposure to a fluid. By providing two different types of sensing circuit, a system is provided which can detect electrically non-conductive fluids as well as electrically conductive fluids. Preferably, both modes of detection are operated simultaneously so as to provide the ability to detect a wide range of different fluids. The inventors have found that some fluids (such as, for example, water, ethanol and acetone) can produce a response in both modes.

The first electrode and second electrode may comprise any suitable conductive material, examples being a metal, a conductive polymer, a conductive fabric and/or a conductive ink. However, it is preferable that the electrodes comprise an elastomer so that the electrode can withstand repeated flexing in use (thereby reducing the likelihood of sensor damage to the at least one sensor element). Conveniently, the electrodes comprise an electrically conductive polymer, preferably an elastomeric an electrically conductive polymer. Suitable electrically conductive polymers have already been described above in relation to the fluid sensing component. The first electrode and second electrode can both be formed from different materials, but they are preferably formed from the same material for ease of construction.

The first electrode and second electrode may be separate components of the at least one sensor element, but the fluid sensing component more preferably acts as the first electrode, thereby providing a more simple and compact sensor arrangement. Most preferably, the fluid sensing component acts as the first electrode and the second electrode is formed from the same material as the fluid sensing component. This simplifies fabrication, and also provides the advantage that all of the sensor components have the same material properties.

The further sensing circuit may be any means suitable for monitoring whether or not a circuit is completed between the first and second electrodes (in other words, whether the circuit between the first electrode and second electrode is open or closed). One way of doing this is to apply a voltage between the electrodes and monitor whether or not a current flows, and another way is to monitor the resistance between the electrodes. The skilled person will be aware of other methods of monitoring the open/closed condition of a circuit. The further sensing circuit is conveniently located on the outside of the diaphragm housing (for example, on the outside of a valve body), optionally as part of a signal conditioning unit.

If desired, the continuity of the fluid sensing component and/or the first electrode and/or the second electrode can also be monitored, so as to provide sensor condition monitoring. In other words, a signal can be generated if any or all of the conductive sensor components fail.

The invention can be used in any application where a diaphragm, membrane, seal or other partition is used to provide a fluid barrier. However, the invention has particular application to a diaphragm valve comprising a diaphragm, a backing layer (usually a rubber backing layer) and a loading pin. A typical diaphragm valve is described in more detail below with regard to Figure 1. The material comprising the diaphragm is typically an inert plastic such as PTFE or Gylon™. If the diaphragm comprises a conducting material, however, the orientation of the sensor may need to be suitably adjusted.

In use, the at least one sensor element is positioned behind (that is, on the non-process side of) the diaphragm so that the sensor element remains dry in normal use, but can detect leaking fluid when the diaphragm fails and fluid comes into contact with the element. (By normal use is meant under conditions where the diaphragm has not failed.)

Preferably, the sensor element is positioned immediately behind the diaphragm so that the response time of the sensor system is as small as possible.

The at least one sensor element can take any suitable form, although a planar or near-planar configuration is preferred so that the sensor element can be positioned between the diaphragm and the backing layer. In a preferred embodiment, only one sensor element is used in the system and the sensor element covers the portion of the diaphragm which needs to be monitored. Preferably, the fluid sensing component and optional first and second electrodes are arranged to cover as much of the sensor surface as possible, so that fluid leakage at any point on the diaphragm's surface can be detected.

The fluid sensing component and optional first electrode and second electrode can take any suitable form, but are preferably conductive traces and more preferably substantially planar conductive traces. The trace may be linear, curved, looped, spiral or any other convenient shape, although the shape is preferably chosen to maximise the surface area of the diaphragm covered by the trace. Preferably, the fluid sensing component and first and/or second electrodes have complementary shapes which allow the electrodes to remain electrically isolated yet close together. This ensures that, in the preferred dual mode embodiment, the gap between the electrodes can be minimised and hence, responsiveness maximised. Examples of suitable complementary structures are an inter-digitated structure or a looped structure (preferably a looped structure having lobes, petals or similar protrusions). If the fluid sensing component acts as the first electrode, the fluid sensing component and second electrode preferably have a complementary shape.

In an application such as a control valve or diaphragm pump, the fluid sensing element and optional first electrode and second electrode ideally do not cross the part of the sensor element where the loading pin is positioned (typically at the centre of the diaphragm).

The fluid sensing component may be fabricated by any suitable technique such as, for example, by moulding a trace of the desired shape. Another simple method of forming the fluid sensing component is to cut out a conductive trace from a sheet of electrically conductive polymer and, in one example, a fluid sensing component of width 1 mm having a looped shape was cut from a sheet of electrically conductive polymer of thickness 1.5 mm. This particular example provides a thickness to width ratio for the component of 1.5:1, which has been found useful for a diaphragm valve sensor. However, this is not necessarily optimum for all fluids and more generally the thickness to width ratio is <1.5:1, so that the surface area of the sensing component in contact with the fluid is increased. In some applications, it may be desirable for the sensing component to take the form of a thin film, optionally a thin film deposited or otherwise disposed on a substrate. Methods of producing thin films are known to the skilled person, and include screen printing.

The optional first and second electrodes can be fabricated in any suitable way, including the techniques described above in relation to the fluid sensing component. Hence, for a conductive polymer, the first and second electrodes may be fabricated by moulding or by cutting a trace of the desired shape from a sheet of material. If the first and/or second electrode comprises a metal, suitable manufacturing methods include (but are not limited to) indirect or direct metal printing, or metal foil etching.

Similarly, the first and second electrodes may take any suitable shape, but preferably take the form of a trace having a thickness to width ratio ≤1.5:1.

The fluid sensing component and optional first and second electrodes are preferably formed into an integral sensor element. This can be achieved by bonding the separate components together using a non-conductive matrix, preferably a non-conductive elastomeric matrix and more preferably a non-conductive silicone matrix (such as, for example, a silicone adhesive or silicon resin). Ideally, the fluid sensing component, the optional first and second electrodes and the non-conductive matrix are all formed from the same polymeric material (clearly a conductive form in the case of the fluid sensing component and electrodes). This has the advantage that the at least one sensor element is an integral sensor element with the same material properties across its entire extent.

The inventors have found that the electrical resistance of the fluid sensing component can vary with temperature. Accordingly, the sensor element preferably comprises a thermal sensor (such as, for example, a thermocouple) so that any temperature variations can be compensated for. In a preferred arrangement, the sensor element is an integral sensor element as hereinbefore described, and the thermal sensor is embedded in the matrix material. Again, the thermal sensor preferably comprises the same material as the other components so that the sensor element has uniform material properties.

Additionally, forming all components of the sensor element from the same material makes signal processing more straightforward.

In use, the at least one sensor element may be attached to, or otherwise integrated with, the diaphragm, but this is generally undesirable because the diaphragm is a low cost consumable which needs to be easily replaced. More preferably, the sensor element is positioned between the diaphragm and the backing layer, optionally held in place by one or more inter-layers, and even more preferably the sensor element is attached to, or otherwise integrated with, the backing layer itself. An advantage of attaching the sensor element to, or integrating it with, the backing layer is that an additional interlayer is not required. One way of integrating the sensor element with the backing layer is to position the element in a recess in the backing layer.

The system of the invention provides a warning of actual diaphragm failure rather than imminent diaphragm failure. This is because the diaphragm actually has to be damaged for the fluid to leak and hence, for the sensor to be activated. In order to minimise the potential for contamination, and to provide a warning as early as possible, it is desirable that the sensor element can detect the smallest possible quantity of fluid breaking through the diaphragm. In practice, it is preferred that the sensor can detect at least 0.1 cm^3 of fluid, more preferably at least 0.05 cm^3 and even more preferably 0.01 cm^3. Once diaphragm failure is identified, the diaphragm can generally be changed without removing the valve from the pipeline.

The system of the invention can detect a wide range of fluids, provided the fluid gives rise to a change in the electrical resistance of the fluid sensing component which is above or below the baseline resistance change. Examples of fluids which have been detected by the system are n-hexane, cyclohexane, n-decane, acetone, tetrahydrofuran, diethyl ether and jet fuel. In the preferred dual sensor embodiment, the system of the invention can detect an even wider range of fluids. Examples of fluids of particular interest in the pharmaceutical industry which have been detected using the dual sensor embodiment include dimethyl sulphoxide (DMSO), water (as a liquid or a vapour), isopropyl alcohol (IPA), ethylene oxide, alcohol in saline and other balanced salt solutions and hexane. Either liquids or vapours can be detected by the invention.

The sensor system conveniently comprises an alarm. The alarm may be a local alarm positioned on or close to the diaphragm or valve housing, in which case it is preferably an audio and/or visual alarm which can readily be inspected by personnel. By audio and/or visual alarm is meant any alarm or device capable of providing an audible or visual signal, or combination thereof, which can be perceived by a human being. Examples of suitable alarm indicators are buzzers, beepers and other sounder units, and light emitting devices. Other types of audio and/or visual alarms will be known to the skilled reader. Typically, a local alarm will be hard wired to the sensing circuit and optional further sensing circuit by means of suitable connectors.

Alternatively, the alarm may be a remote alarm. The remote alarm may be an audio and/or visual alarm as described above with regard to a local alarm, or may be an alarm signal which can be input to a computer or process monitoring system. A remote alarm may be hard wired to the leakage sensor system, or may be connected to the leakage sensor system by means of wireless technology.

Typically, the alarm is configured to produce a response when the resistance of the fluid sensing component changes by more than a predetermined threshold and/or (for the preferred embodiment) when a circuit is completed between the first electrode and the second electrode.

Conveniently, the system of the invention comprises signal processing and/or control circuitry for processing the signals from the sensing circuit and/or optional further sensing circuit. The signal processing circuitry may be configured to have a basic output configuration which provides an indication of whether or not a fluid has been detected by the fluid sensor component and/or optional first and second electrodes, or may have a more sophisticated output configuration whereby the extent of the leak, the location of the leak, the fluid type and/or the number of actuation cycles is indicated.

In a typical arrangement, electrical connectors (such as, for example, electrical wires) extend from the sensor element to any system components external to the immediate environment of the diaphragm (such as, for example, the sensing circuit, optional further sensing circuit, alarm and/or signal processing circuitry). In use, any electrical connectors preferably exit from the sensor element in a plane parallel to the diaphragm.

In a pharmaceutical application, the sensor element typically needs to survive operating temperatures of about 0°C to about 80°C. Moreover, the sensor element needs to survive typical sterilisation temperatures of 121-145°C (steam), 56-80°C (formaldehyde), 45°C (H_2O_2-plasma) and ambient (radiation). Generally, therefore, the sensor element needs to survive temperatures in the range 0°C to 145°C and the materials of the sensor element are preferably chosen accordingly. It follows that, if other elements of the sensor system – such as, for example, electrical connectors - are likely to be exposed to operating and sterilisation temperatures, construction materials are preferably chosen accordingly. Suitable polymers which can withstand the above-mentioned temperatures include silicone polymers and PTFE.

According to a second aspect of the invention, there is provided a dual mode sensor system for detecting leaks in a diaphragm, the system comprising at least one sensor element comprising two fluid sensing components formed from an electrically conductive polymer, said sensing components being electrically isolated from each other in normal use; a first sensing circuit for measuring the electrical resistance of either or both of the fluid sensing components; and a second sensing circuit for measuring whether or not a circuit is formed between the fluid sensing components upon exposure to a fluid.

The dual mode sensor system according to the second aspect is capable of detecting both conductive and non-conductive fluids. In the absence of leaking fluid, the electrical resistance of the conductive polymer comprising either or both of the fluid sensing components has a baseline value, or range or values, but upon exposure to certain fluids (including certain non-conductive fluids) the electrical resistance changes. Accordingly, by measuring the resistance of either or both of the fluid sensing components, the presence of the fluid can be detected. Conductive fluids can be detected by monitoring (using the second sensing circuit) whether or not the fluid sensing components form an open or closed circuit. Under normal conditions, the components are isolated from each other and the circuit is open. If a conductive fluid comes into contact with both components, however, electrical contact is made between the conductive polymer components and a closed circuit condition arises.

According to a third aspect of the invention, there is provided a method suitable for detecting leaks in a diaphragm, said method comprising the steps of:

(i) providing at least one sensor element, said element comprising a fluid sensing component formed from an electrically conductive polymer,

(ii) positioning the at least one sensor element behind the diaphragm so that leaking fluid impinges on the electrically conductive polymer, and

(iii) providing a sensing circuit for measuring any change in electrical resistance of the electrically conductive polymer upon exposure to a fluid.

Preferably, the at least one sensor element further comprises a first electrode and a second electrode, the electrodes being electrically isolated from each other in normal use, and the system comprises a further sensing circuit for measuring any change in electrical resistance between the first and second electrodes. More specifically, the further sensing circuit measures whether there is an open or closed circuit between the first electrode and second electrodes.

Ideally, the electrical resistance of the fluid sensing element, and the resistance between the first electrode and second electrode, are measured simultaneously, thereby enabling the simultaneous detection of one or more fluids which cause either or both sensor circuits to respond.

The first electrode and second electrode may be separate components of the sensor element, but preferably the fluid sensing component acts as the first electrode. Most preferably, the fluid sensing component acts as the first electrode and the second electrode is formed from the same material as the fluid sensing component.

Preferably, the method includes the step of providing an alarm, the alarm being activated when the change in resistance of the fluid sensing element reaches a pre-determined threshold and/or a circuit is completed between the first electrode and second electrode.

According to a fourth aspect of the invention, there is provided the use of an electrically conductive polymer for the detection of a non-conductive fluid.

Any feature in one aspect of the invention may be applied to any other aspects of the invention, in any appropriate combination. In particular, system aspects may be applied to method and use aspects, and vice versa.

The invention will now be described with reference to the accompanying drawings in which;

Figure 1 is a sideways view of a diaphragm control valve incorporating a sensor system according to the invention;

Figures 2a, 2b, 2c and 2d show different sensor element configurations;

Figure 3 is a schematic representation of a preferred sensor system embodiment;

Figure 4 illustrates an integral sensor element configuration comprising a matrix material;

Figure 5 shows the integral sensor element of Figure 4 positioned on a valve seal;

Figures 6a and 6b are a cross sectional views of the integral sensor element of Figure 4, showing embedded sensor components and possible positions of leaking fluid;

Figure 7 shows an ex-situ response of the sensor system of the invention to jet fuel, n-hexane, n-decane and cyclohexane; and

Figure 8 shows an in-situ response of the sensor system to n-hexane.

Figure 1 shows a typical diaphragm valve assembly **1** incorporating the system of the invention. The valve assembly comprises a valve body **2** with two or more ports (not illustrated), a diaphragm **3**, a backing layer **4** and a valve actuator **5**. A sensor element **6** having an electrical connector **7** is positioned between the diaphragm **3** and backing layer **4**, so that any fluid breaking through the diaphragm impinges upon the sensor element. The sensor element **6** has a central hole (not visible in the illustration) so that the loading pin of the valve actuator passes through the element. A signal conditioning unit **8** is fixed to the valve body, the unit comprising a sensing circuit (not illustrated) for measuring the response of the sensor element, and an alarm **9**. Optionally, the system comprises signal processing and/or control circuitry **10**.

The sensor element comprises a fluid sensing component formed from an electrically conductive polymer, and may be a dual mode sensor element as hereinbefore described (that is, a sensor element additionally comprising a first and second electrode, preferably with the fluid sensing component acting as the first electrode). In the latter embodiment, a further sensing circuit for measuring any change in electrical resistance between the first electrode and second electrode is provided, suitably in signal conditioning unit **8**.

Figures 2a to 2d illustrate various sensor element configurations. The configurations are purely illustrative, and not intended to be limiting, and individual components of the sensor element may be formed from any of the materials hereinbefore described, and using any of the techniques hereinbefore described. Moreover, the second electrode is optional in all examples. In the illustrated examples, the sensor element comprises a central hole (for a component such as a loading pin) and has a lobed structure so that the element can be draped across a diaphragm and readily change its out of plane conformation in use.

In Figure 2a, the sensor element comprises an inner fluid sensing component **20** formed from an electrically conductive polymer, and an outer electrically conductive trace **21** capable of acting as a second electrode and electrically isolated from the fluid sensing component. The outer trace **21** is preferably formed from an electrically conductive polymer, and more preferably from the same electrically conductive polymer as the fluid sensing component **20**. Electrical connections can be made to the sensing elements at points **A** and **B**. In use, fluid impinging on fluid sensing component **20** causes a change in the resistance of the electrically conductive polymer, and fluid bridging traces **20** and **21** causes a closed circuit condition.

In Figure 2b, the inner fluid sensing component **22** has an alternative shape, which shape is complementary to that of the second electrode **21**. Again, electrical connections can be made to points **A** and **B**.

Figure 2c illustrates the arrangement of Figure 2b with an additional thermal sensor **23**. Electrical connections to the thermal sensor, can be made at points **C**. The thermal sensor preferably takes the form of an electrically conductive polymer, which is isolated from the fluid sensing component and second electrode in use. The thermal sensor is preferably not exposed to any breakthrough fluid.

Figure 2d illustrates the arrangement of Figure 2b with an additional thermal sensor **24** having an alternative, complementary shape. Electrical connections to the thermal sensor can be made at points **C**. The thermal sensor preferably takes the form of an electrically conductive polymer, which is isolated from the fluid sensing component and second electrode in use. The thermal sensor is preferably not exposed to any breakthrough fluid. This can be avoided by embedding the thermal sensor within the optional matrix material so that the surface thereof is not exposed.

The arrangements of Figures 2a to 2d may alternatively be configured so that the fluid sensing element is disposed outside the second electrode. Similarly, the thermal sensor need not be the innermost component of the arrangement.

Many other sensor element configurations can be envisaged within the general description of the invention.

Figure 3 is a schematic representation of a preferred sensor system embodiment comprising a sensor element similar to that described with reference to Figure 2a. The sensor system comprises sensor element **30** connected to signal conditioning unit **31**. The signal conditioning unit comprises a sensing circuit for measuring the electrical resistance of the fluid sensing component and a further sensing circuit for monitoring whether or not a closed circuit condition exists between the inner and outer conductive traces of the sensor element. The signal conditioning unit **31** is connected to signal processor **32**, which provides an audio/visual output **33** and a serial data interface **34**.

The sensor element shown in Figure 3 is purely exemplary and could be any sensor element configured according to the general description of the invention above.

Figure 4 illustrates a 6-lobed integral sensor element **40** comprising a fluid sensing component **41**, a second electrode **42**, a thermal sensor **43** and a matrix material **44** disposed around each element (**41, 42, 43**) to form an integral component. Preferably, the fluid sensing component, second electrode and thermal sensor are all formed from the same electrically conductive polymer, and the matrix material is formed from the polymeric matrix material of the electrically conductive polymer.

In a typical embodiment, the angle between individual lobes of the sensor element is 45°, and dimensions **a** and **b** are 72 mm and 15.5 mm respectively. One lobe extends approximately 70 mm beyond the other lobes, and is used to provide electrical contact with the signal conditioning unit.

The integral sensor element has a substantially planar form and a thickness of about 2.3 mm. Although the element is planar, the lobed structure allows the element to change its conformation when the diaphragm flexes to a concave and/or convex position.

Figure 5 shows the integral sensor element **40** of Figure 4 positioned on a valve seal **50** (top down view). The lobes of the sensor element are draped over the diaphragm **51**.

Fig 6a is a cross section taken through point **X-Y** on Figure 4. The cross section shows fluid sensing component **41**, second electrode **42**, thermal sensor **43** and matrix material **44**. It can be seen that the fluid sensing element and second electrode both have exposed outer surfaces **45** so that the elements can respond to breakthrough fluid, but the thermal sensor is preferably fully embedded in the matrix material so that it is not exposed to fluid.

Figure 6b shows the sensor element in use. When a drop of fluid **46** (which may be conductive or non-conductive) impinges on fluid sensing component **41**, there is a change in the resistance of the conductive polymer which can be measured. If a drop of conductive fluid **47** impinges on the sensor element and bridges the fluid sensing element **41** and second electrode **42**, a closed circuit condition occurs which – again – can be measured, thereby providing a dual sensing system. Fluid **46** and fluid **47** may be the same or different fluids.

Figure 7 shows the 'ex-situ' response of the system of the invention to four liquids: n-decane (shallowest gradient), cyclohexane, jet fuel and n-hexane (steepest gradient). It can be seen that in each case the electrical resistance of the sensor element increases when the liquids are applied to the sensor element.

Figure 8 shows the 'in-situ' response of the system of the invention to n-hexane (i.e. within an operational control valve) and also shows the output from the embedded temperature sensor. The cycling of the valve is apparent from the traces. It can be seen that the electrical resistance of the sensor element increases when n-hexane liquid is applied (at point P on the graph) to the element

As discussed above, it is preferable that the conductive polymer has a conductivity less than about 10^4 Sm^{-1}, more preferably in the range 1 to 1000 Sm^{-1}, even more preferably in the range 10 to 1000 Sm^{-1} and most preferably in the range 10 to 100 Sm^{-1}. Table 1 shows various electrical and mechanical properties for three different conductive polymers comprising carbon particles in a PDMS matrix, the polymers differing in the amount of conductive loading (as indicated by different conductivity parameters). It was found that polymers B and C, which both have a conductivity in excess of $1x10^4$ Sm^{-1}, performed poorly in the invention because the sensor failed during mechanical cycling tests. Polymer A, on the other hand, which has a conductivity in the range 20 to 100 Sm^{-1}, provided a good sensor response and was also mechanically durable in use.

Polymer	Volume resistivity (Ωm)	Conductivity (Sm^{-1})	Tensile strength (MPa)	Elongation to failure (%)	Hardness (IRHD)
Polymer A	0.05 to 0.1	20 to 100	3.12	427	70
Polymer B	$4x10^{-5}$	$2.5x10^{4}$	1.3	322	68
Polymer C	$8x10^{-5}$	$1.25x10^{4}$	1.98	104	85

Table 1: Properties of various conductive polymers tested for use in the invention

It will be understood that the present invention has been described above purely by way of example, and modification of detail can be made within the scope of the invention. Each feature disclosed in the description, and (where appropriate) the claims and drawings may be provided independently or in any appropriate combination. In particular, system aspects may be applied to method aspects and *vice versa*.

Moreover, the invention has been described with specific reference to detecting leaks in diaphragms or membranes, particularly diaphragms or membranes in control valves. It will be understood that this is not intended to be limiting and the invention may be used more generally in applications where a leakage detector is desirable. General fields of application include the oil and gas industry, the pulp and paper industry, the chemical processing industry and the pharmaceutical industry, and fluids that can be detected include fuels (e.g. aviation fuels) and other chemicals.

Claims

1. A sensor system for detecting leaks in a diaphragm, the system comprising at least one sensor element, said element comprising a fluid sensing component formed from an electrically conductive polymer, and a sensing circuit for measuring the electrical resistance of the electrically conductive polymer.

2. A sensor system according to claim 1, wherein the electrically conductive polymer is an elastomer.

3. A sensor system according to claim 1 or claim 2, wherein the electrically conductive polymer comprises conductive particles in a polymer matrix.

4. A sensor system according to claim 3, wherein the electrically conductive polymer has an electrical conductivity less than about 10^4 Sm^{-1}.

5. A sensor system according to claim 3 or claim 4, wherein the polymer matrix is selected from the group consisting of a silicone polymer, a butadiene rubber, butyl rubber, natural rubber and nitrile rubber.

6. A sensor system according to claim 5, wherein the polymer matrix is a silicone polymer, preferably PDMS.

7. A sensor system according to any one of claims 1 to 6, wherein the electrically conductive polymer comprises a conductive loading selected from the group consisting of graphite particles, metal particles, metal-coated particles, graphite-coated particles or any combination thereof.

8. A sensor system according to any preceding claim, wherein the at least one sensor element further comprises a first electrode and a second electrode, the electrodes being electrically isolated from each other in normal use, and the system comprises a further sensing circuit for measuring any change in electrical resistance between the first electrode and second electrode.

9. A sensor system according to claim 8, wherein the either or both of the first electrode and second electrodes comprise an electrically conductive polymer.

10. A sensor system according to claim 8 or claim 9, wherein the fluid sensing component acts as the first electrode.

11. A sensor system according to claim 10, wherein the second electrode is formed from the same material as the fluid sensing component.

12. A sensor system according to any one of claims 8 to 11, wherein the fluid sensing component and first and second electrodes form an integral sensor element.

13. A sensor system according to claim 12, wherein the fluid sensing component and first and second electrodes comprise the same polymeric material.

14. A sensor system according to any preceding claim, wherein the sensor element is substantially planar.

15. A sensor system according to any one of claims 8 to 14, wherein the fluid sensing component and first and second electrodes have a complementary shape.

16. A sensor system according to any preceding claim, further comprising an alarm.

17. A sensor system according to claim 16, wherein the alarm produces a response when the electrical resistance of the electrically conductive polymer changes by more than a predetermined threshold and/or, when dependent on claim 8, when a circuit is completed between the first electrode and the second electrode.

18. A sensor system according to any preceding claim, wherein said system is capable of detecting an electrically non-conductive fluid.

19. A dual mode sensor system for detecting leaks in a diaphragm, the system comprising at least one sensor element comprising two fluid sensing components formed from an electrically conductive polymer, said sensing components being electrically isolated from each other in normal use; a first sensing circuit for measuring the electrical resistance of either or both of the fluid sensing components; and a second sensing circuit for measuring whether or not a circuit is formed between the fluid sensing components upon exposure to a fluid.

20. A method for detecting leaks in a diaphragm, said method comprising the steps of:

(i) providing at least one sensor element, said element comprising a fluid sensing component formed from an electrically conductive polymer,
(ii) positioning the at least one sensor element behind the diaphragm so that leaking fluid impinges on the electrically conductive polymer, and

(iii) providing a sensing circuit for measuring any change in electrical resistance of the electrically conductive polymer upon exposure to a fluid.

21. A method according to claim 20, wherein the at least one sensor element further comprises a first electrode and a second electrode, the electrodes being electrically isolated from each other in normal use, and the system comprises a further sensing circuit for measuring any change in electrical resistance between the first and second electrodes.

22. A method according to claim 21, wherein the electrical resistance of the fluid sensing element and the resistance between the first electrode and second electrode are measured simultaneously.

23. A method according to claim 21 or claim 22, wherein the either or both of the first electrode and second electrode comprise an electrically conductive polymer.

24. A sensor system according to any one of claims 22 or 23, wherein the fluid sensing component acts as the first electrode.

25. A sensor system according to claim 24, wherein the second electrode is formed from the same material as the fluid sensing component.

26. A method according to any one of claims 20 to 25, wherein the method comprises the additional step of providing an alarm, the alarm being activated when the electrical resistance of the electrically conductive polymer changes by more than a predetermined threshold and/or, when dependent on claim 21, when a circuit is completed between the first electrode and the second electrode.

27. The use of an electrically conductive polymer for the detection of a non-conductive fluid.

28. The use according to claim 27, wherein the fluid is detected by measuring the electrical resistance of the electrically conductive polymer.

29. Any sensor system, method, sensor or use substantially as hereinbefore described, with reference to the accompanying drawings.

30. Any novel feature, or combination of features, hereinbefore described, with reference to the accompanying drawings.

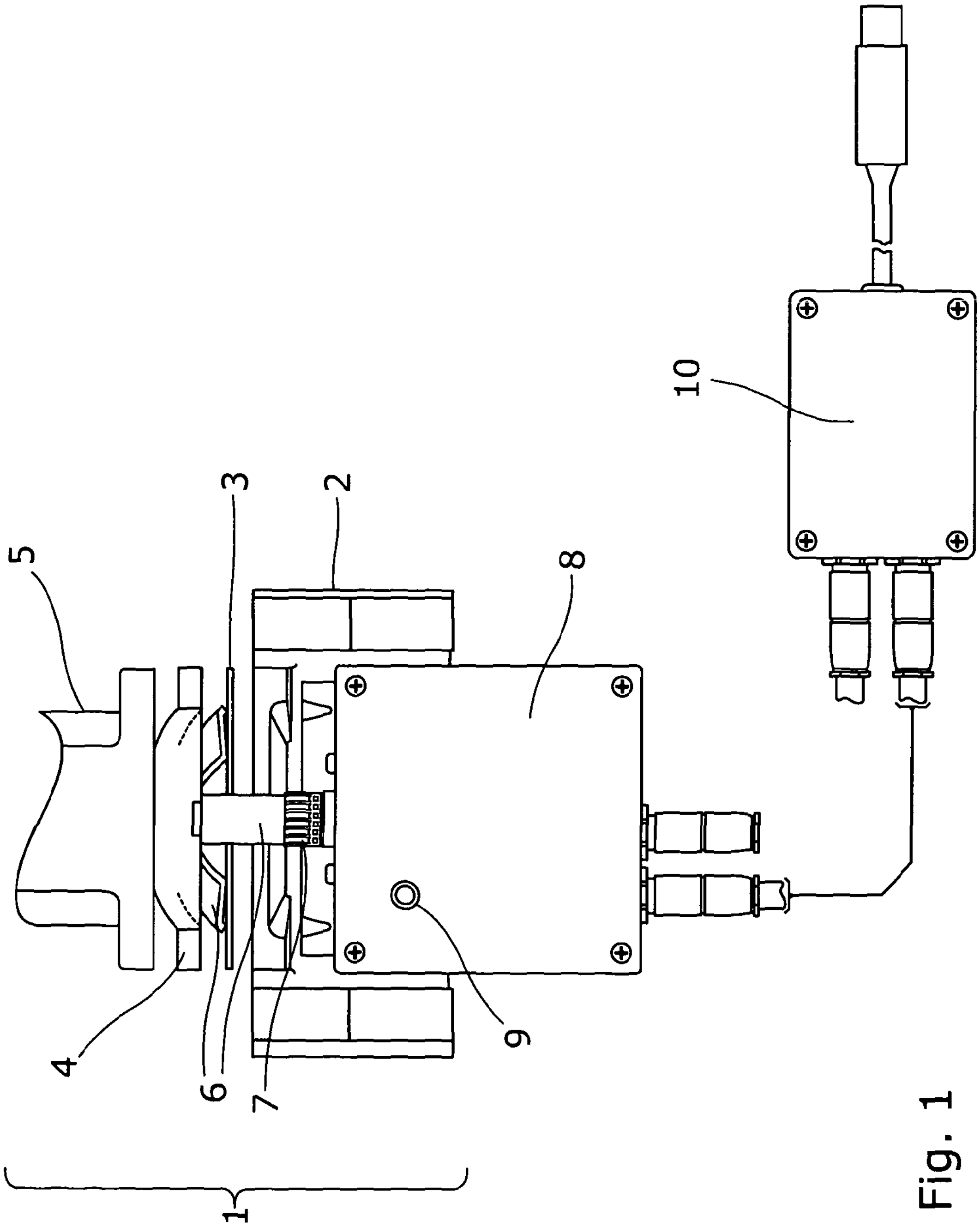


Fig. 1

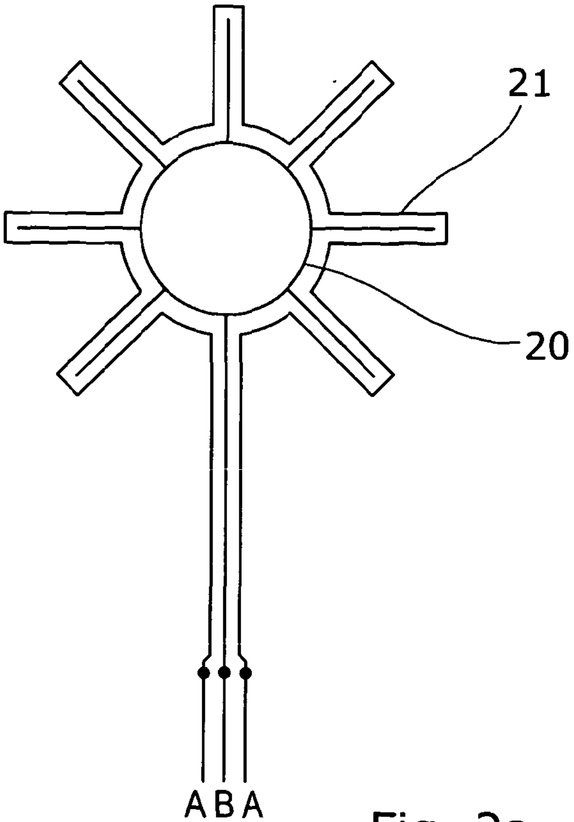


Fig. 2a

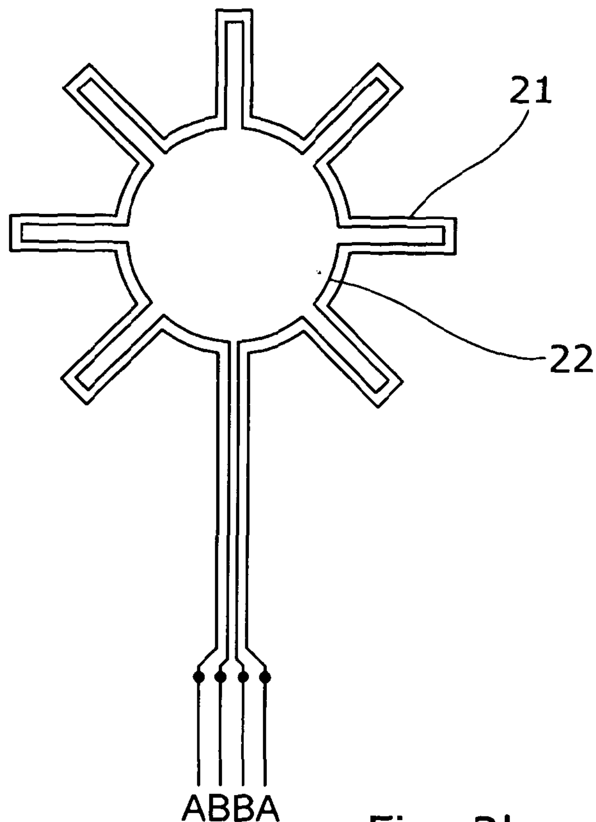


Fig. 2b

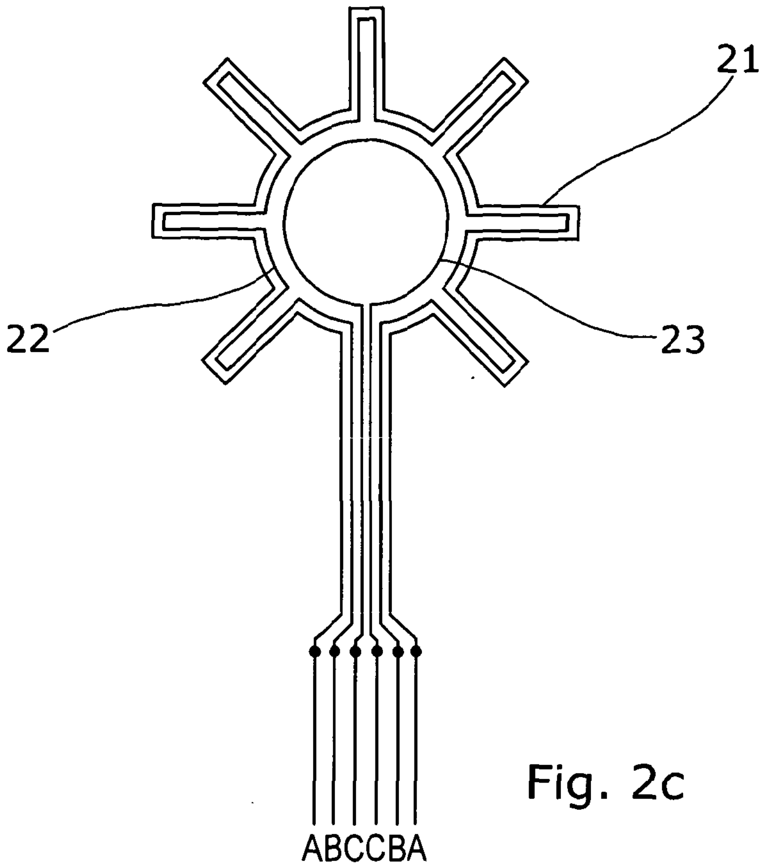


Fig. 2c

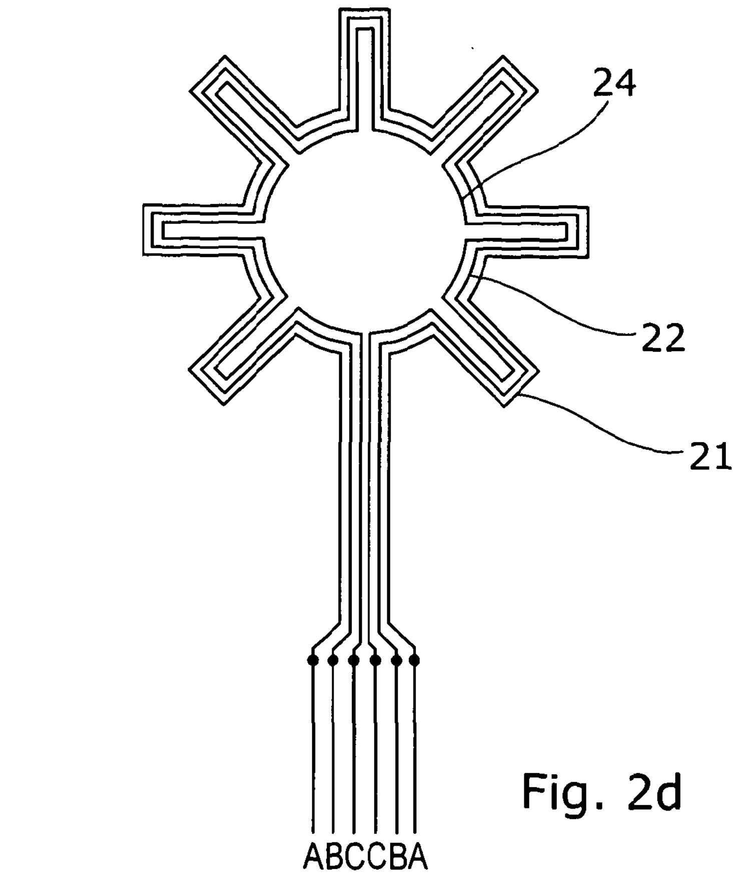


Fig. 2d

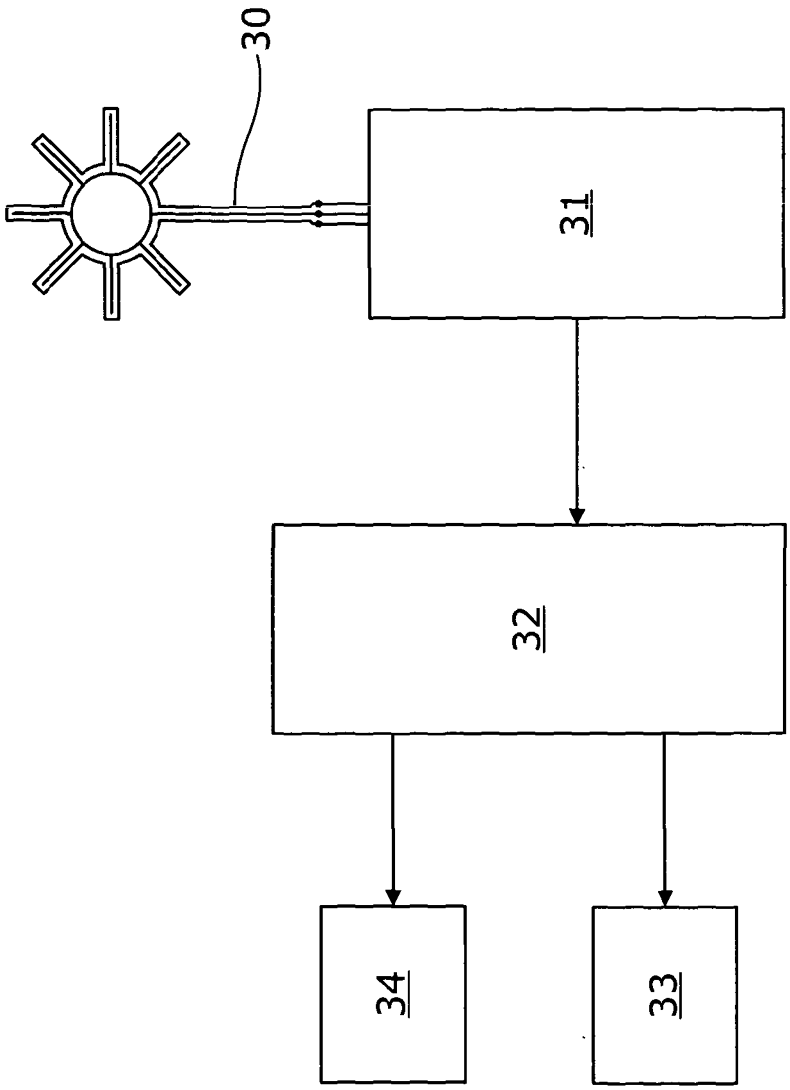


Fig. 3

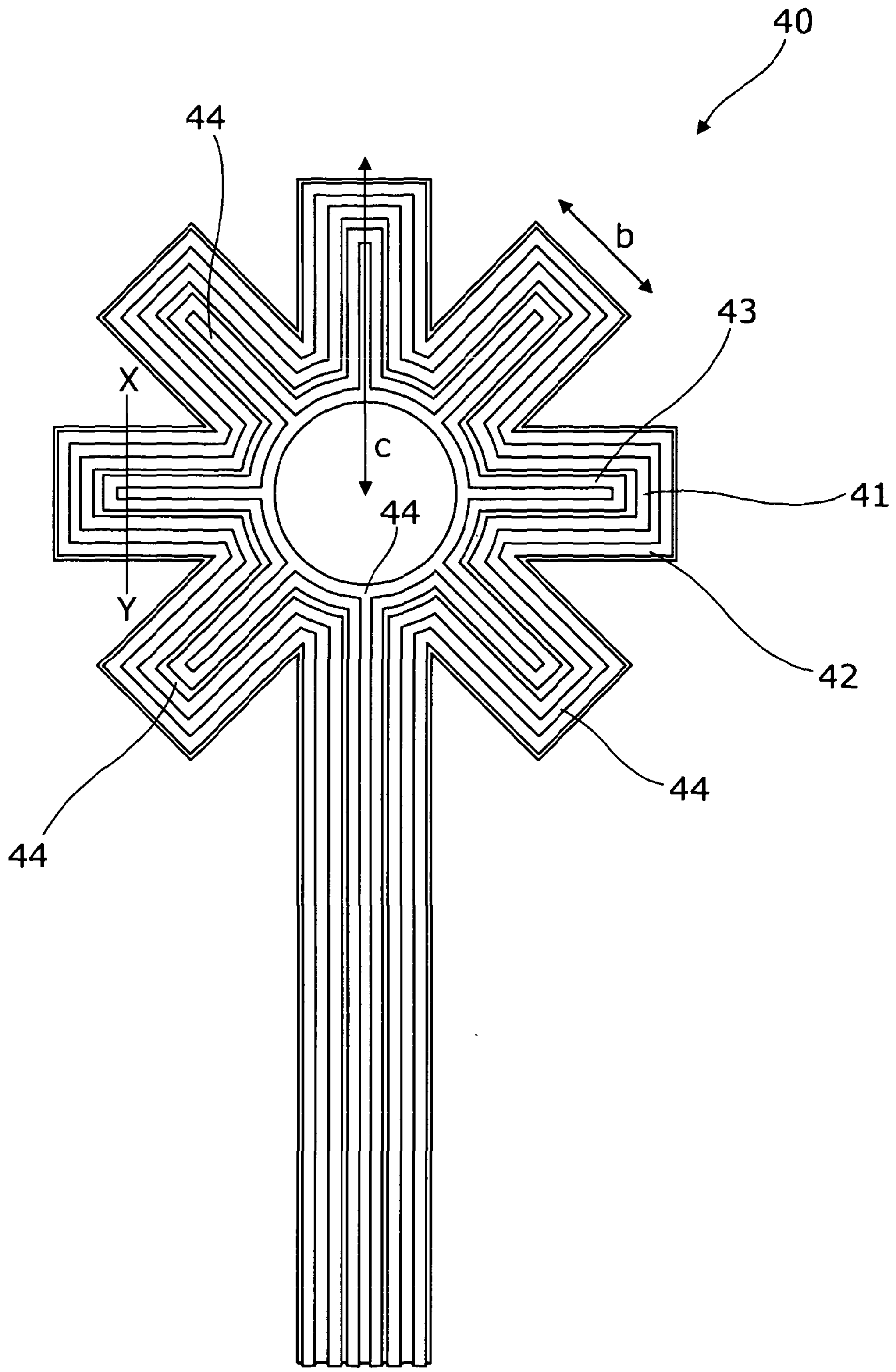


Fig. 4

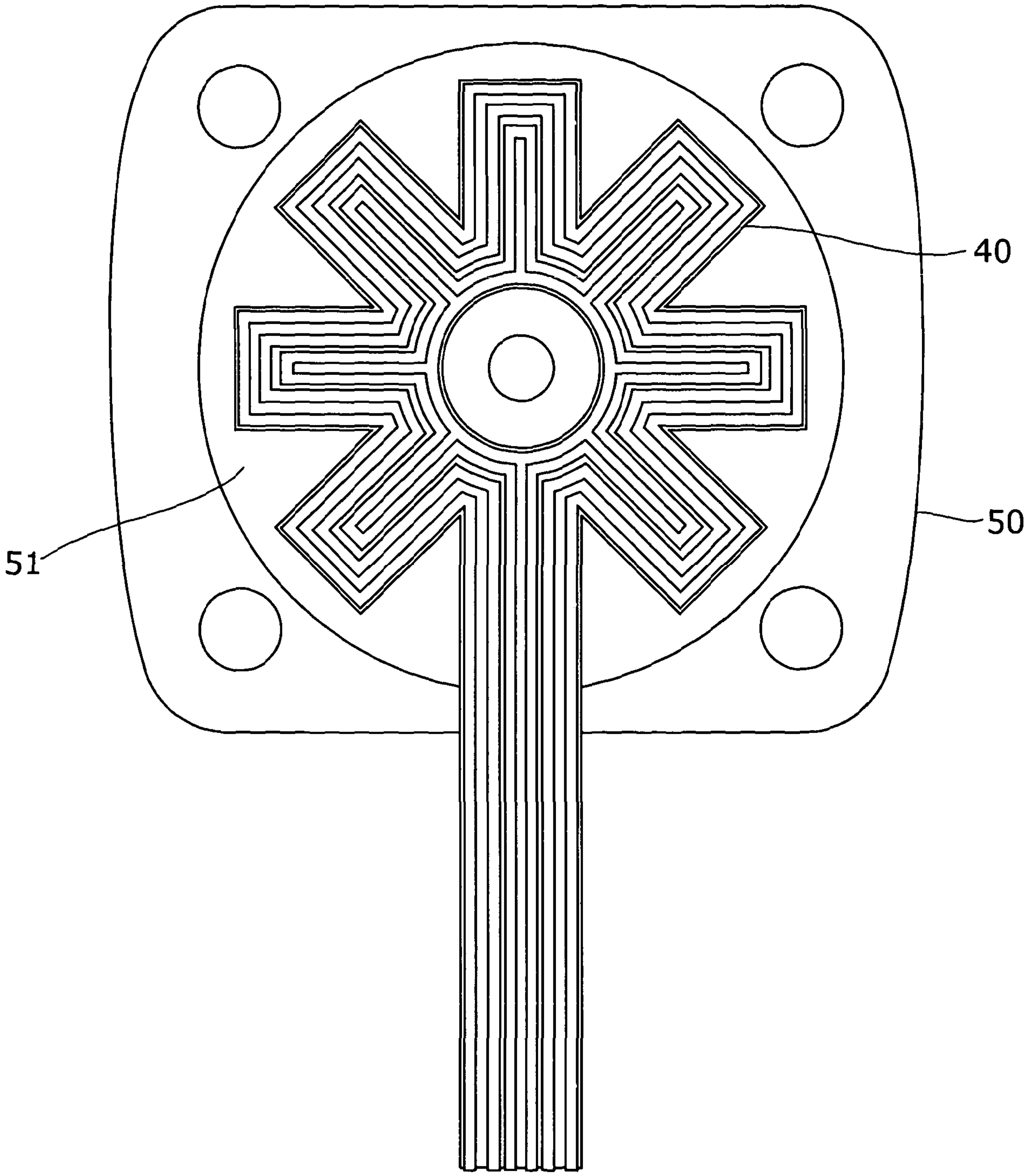


Fig. 5

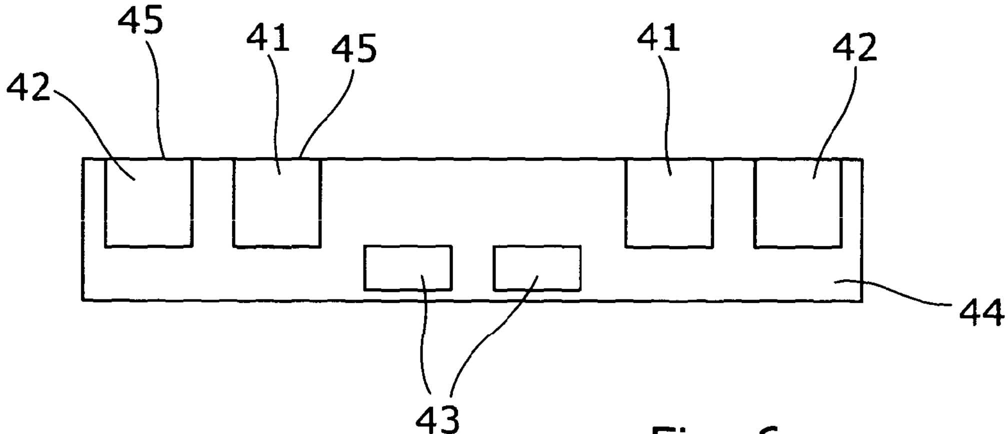


Fig. 6a

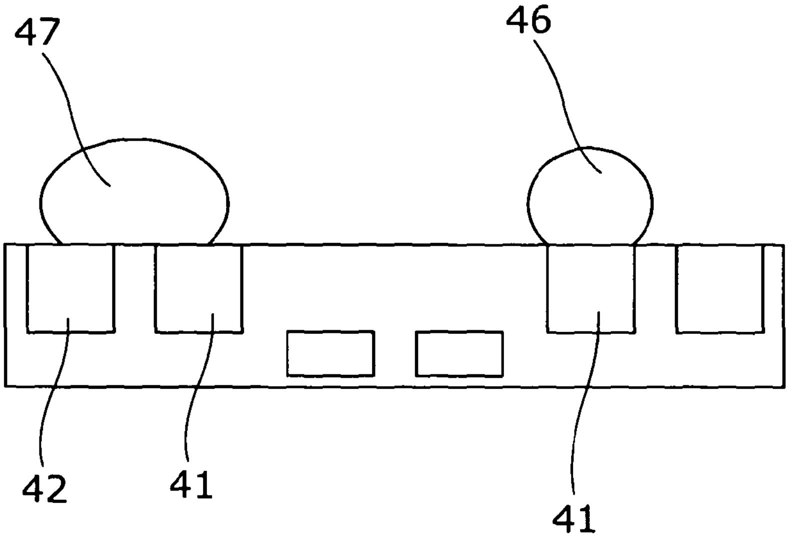


Fig. 6b

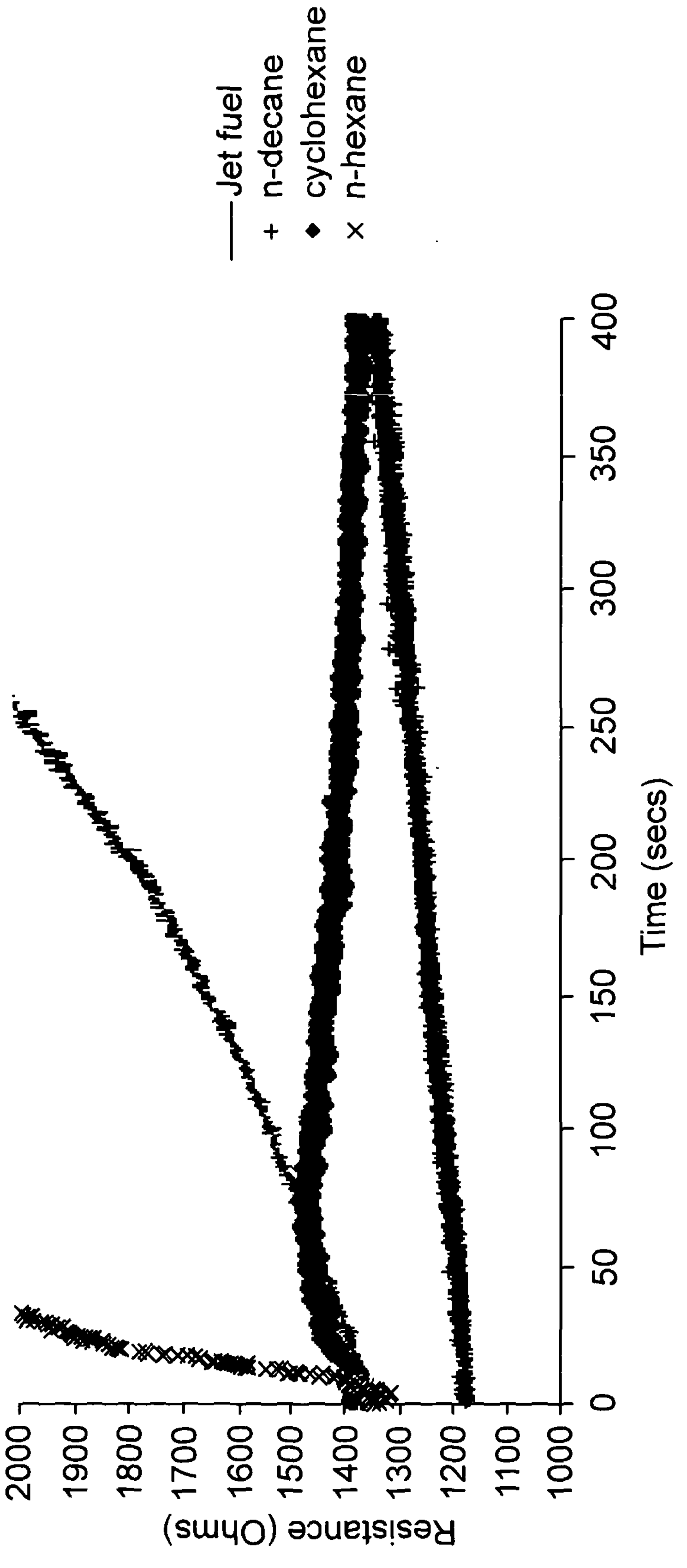
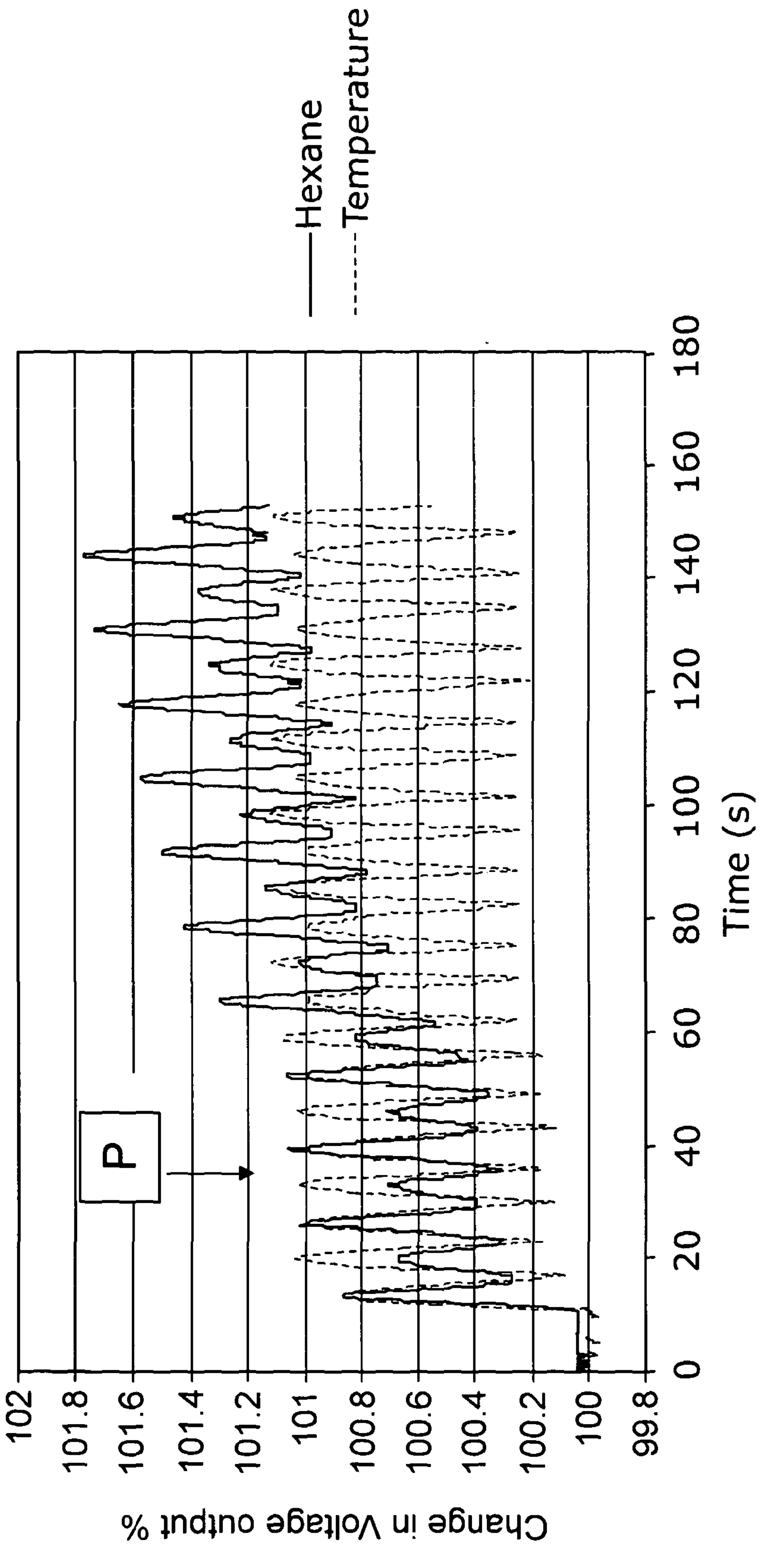

Jet fuel
n-decane
cyclohexane
n-hexane
Resistance (Ohms)
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
0
50
100
150
200
250
300
350
400
Time (secs)

Fig. 7



Hexane
Temperature
P
Change in Voltage output %
102
101.8
101.6
101.4
101.2
101
100.8
100.6
100.4
100.2
100
99.8
0
20
40
60
80
100
120
140
160
180
Time (s)

Fig. 8