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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 5 :		(11) International Publication Number:
G01N 29/24	A1	WO 93/16381
		(43) International Publication Date: 19 August 1993 (19.08.93)

(21) International Application Number: PCT/US93/00920

(22) International Filing Date: 5 February 1993 (05.02.93)

(30) Priority data:
832,816 7 February 1992 (07.02.92) US

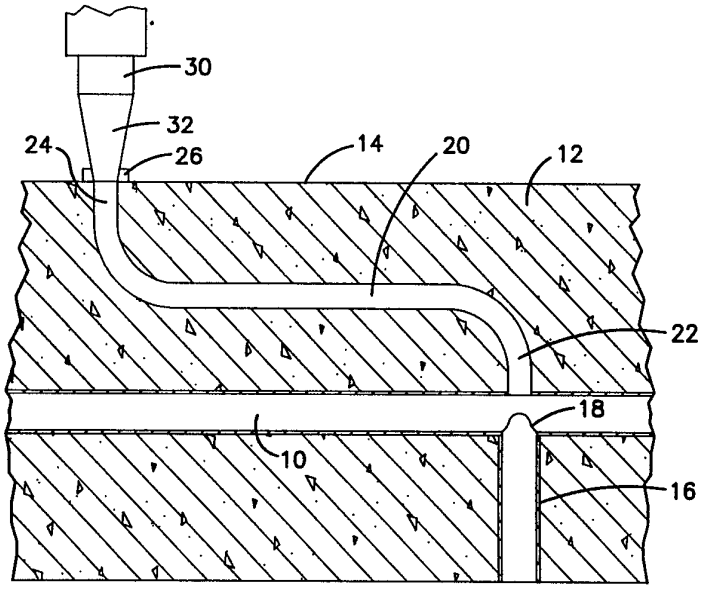
(71)(72) Applicants and Inventors: WINSTON, Thomas, R. [US/US]; 11700 Manor Drive, Leawood, KS 66211 (US). BRUNK, John, A. [US/US]; 10005 W. 101st Street, Overland Park, KS 66212 (US).

(74) Agent: CLEVELAND, Dan, Jr.; Hovey, Williams, Timmons & Collins, 1101 Walnut Street, Suite 1400, Kansas City, MO 64106 (US).

(81) Designated States: AT, AU, BB, BG, BR, CA, CH, DE, DK, ES, FI, GB, HU, JP, KP, KR, LK, LU, MG, MN, MW, NL, NO, NZ, PL, RO, RU, SD, SE, European patent (AT, BE, CH, DE, DK, ES, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, ML, MR, SN, TD, TG).

Published
With international search report.

(54) Title: METHOD AND APPARATUS FOR ULTRASONIC INSPECTION OF INACCESSIBLE AREAS



(57) Abstract

A method and apparatus which uses ultrasonic techniques to inspect critical pipe joints and other critical industrial areas that are normally inaccessible. A waveguide (20, 46) including one or more flexible fibers (72) is embedded in concrete (12) or whatever else embeds the piping which includes the critical area. One end of the waveguide (20, 46) is accessible so that an ultrasonic transducer (30) can be used to transmit ultrasonic signals along the waveguide (20, 46) and receive reflected echoes to provide an ultrasonic image of the critical area. In a case where the area to be inspected is submerged, the waveguide (20, 46) takes the form of a flexible fiber bundle which is manipulated until its end is adjacent to the critical area. Some of the fibers (72) in the bundle can be used to illuminate the critical area, and other fibers (72) can transmit optical images for display on a video monitor (78).

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METHOD AND APPARATUS FOR ULTRASONIC INSPECTION OF INACCESSIBLE AREAS

Field of the Invention

This invention relates generally to ultrasonic imaging and deals more particularly with the use of ultrasonic techniques for the inspection of areas to which access is restricted.

Background of the Invention

In a variety of industrial processes, there are areas that are inaccessible and yet at the same time critical to the process. For example, pipes which conduct the flow of process fluids are often embedded in concrete or a similar material such that inspection of critical pipe joints is impossible. If a faulty weld exists or if a critical area should otherwise fail while the pipes are in service, the lack of ability to carry out inspections creates a situation where no warning is given of a possibly dangerous condition. As an example, in a nuclear power plant or other critical facility, if piping which conducts cooling fluid should leak, disastrous consequences can follow. If the piping is capable of being inspected on a regular basis, the problem can be detected early enough to allow corrective action to be taken before there is a complete failure.

Similar situations arise as to pipes and fittings that are submerged in storage tanks for petroleum based liquids and other types of liquids. Access to submerged areas is restricted if not precluded altogether, so leaks and other problems can arise without any warning because inspections of the submerged areas are not practical and perhaps not even possible. The same problems are presented as to inspections in hostile environments such as areas exposed to the high levels of radiation or toxic chemicals.

Summary of the Invention

The present invention is directed to a method and apparatus for carrying out ultrasonic inspections and examinations of locations that are normally inaccessible and thus not subject to inspection. By way of example, through the techniques employed by the present invention, a critical pipe weld which is embedded in a concrete slab can be inspected while the piping remains in service. Accordingly, signs of problems in the weld can be detected before they become so great that the weld fails. In addition, submerged components and structures located in hostile environments can be inspected to detect problems before they have developed to the point of complete failure.

In accordance with the invention, a waveguide for transmitting ultrasonic signals takes the form of at least one and usually a number of quartz fibers arranged in a bundle. In the case of a pipe weld or other critical part which is embedded in concrete or another material, the waveguide may also be embedded with one end adjacent to the weld that is to be inspected and the other end situated at the surface of the concrete or at another accessible location. A conventional ultrasonic transducer can be permanently or detachably connected to the accessible end of the waveguide and used to transmit ultrasonic signals and receive signals that are reflected

back to the waveguide from the critical weld. In this manner, an ultrasonic image can be generated of the critical area and examined to give a warning of any problems that may exist.

In the case of a part that is submerged well below the surface of a liquid, the waveguide can be manipulated in the liquid using conventional techniques to position its end adjacent to the submerged part. Then, an ultrasonic transducer system above the liquid can be used to apply signals to the waveguide and receive reflected signals in order to provide an ultrasonic image of the part. The image that is generated can be examined for signs of damage or impending failure. The fibers can include some which transmit ultrasonic signals, others which are used for illumination of the tip end of the waveguide, and still others which transmit optical images. With the use of a video monitor, the operator of the apparatus can actually observe on the monitor how the waveguide tip is positioned relative to the part that is undergoing inspection. In many situations, this can enhance the accuracy of the procedure and the overall effectiveness of the inspection process.

It is an important feature of the invention that the ultrasonic waveguide is flexible. This allows it to be manipulated to provide access to areas that are at best difficult to reach with conventional rigid waveguides. The considerable length of the waveguide also provides it with the capability of making relatively remote areas accessible for inspection.

Description of the Drawings

In the accompanying drawings which form a part of the specification and are to be read in conjunction therewith and in which like reference numerals are used to indicate like parts in the various views:

Fig. 1 is a fragmentary sectional view illustrating how the apparatus of the present invention can be used to monitor a critical pipe joint that is embedded in concrete;

Fig. 2 is a fragmentary sectional view showing one way of coupling a quartz fiber with an ultrasonic transducer in accordance with the invention;

Fig. 3 is a fragmentary sectional view similar to Fig. 2, but showing a different way of coupling a fiber to the ultrasonic transducer;

Fig. 4 is a diagrammatic view showing how the apparatus of the present invention can be used to inspect a component that is submerged in a tank containing liquid;

Fig. 5 is a diagrammatic view depicting the use of a dual element transducer and different waveguides oriented in different directions in accordance with the invention;

Fig. 6 is an end elevational view of quartz fibers which are arranged in a bundle having the fibers closely packed together; and

Fig. 7 is an end view similar to Fig. 6, but showing the fibers in the bundle arranged in ordered rows.

Detailed Description of the Invention

Referring now to the drawings in more detail and initially to Fig. 1, numeral 10 designates a horizontal pipe which is embedded in a concrete slab 12 having only its upper surface 14 accessible. A vertical pipe 16 is connected with the horizontal pipe 10 by a weld 18. The pipes 10 and 12 may carry industrial process fluids, and the weld 18 may be at a critical area in which weld failure could lead to the leakage of the process fluid or other adverse consequences. The piping system may be a

critical one such as a system which conducts cooling fluid for a nuclear power plan or some other critical facility. Because the pipes 10 and 16 are embedded in the concrete 12, the weld 18 is not accessible for inspection. The concrete 12 is relatively impervious to ultrasonic signals so that ultrasonic signals applied from the accessible surface 14 cannot be used in a practical manner for reliable inspection of the weld 18.

In accordance with the present invention, a flexible waveguide 20 is embedded in the concrete slab 12 when it is poured or otherwise initially constructed. The waveguide 20 is arranged with its free end 22 located adjacent to and pointed at the weld 18. The waveguide 20 may have a serpentine shape or any other suitable shape, and its opposite end 24 is located adjacent to the accessible surface 14 or at some other accessible location. A collar 26 located on top of the slab surface 14 provides a port to permit detachable connection of ultrasonic equipment to the accessible end 24 of the waveguide 20 as will be explained in more detail.

A conventional ultrasonic pulser-receiver controls an ultrasonic transducer 30. A tapered transition piece 32 which is preferably of a frusto conical configuration connects with the transducer 30 and may be fitted at its lower or smaller end closely within the collar 26. This couples the small end of the transition piece 32 with the waveguide 20. The transducer 30 transmits ultrasonic signals which are applied to the transition piece 32 and from the transition piece to the end 24 of waveguide 20. The signals are transmitted along the length of the waveguide to its opposite end 22 and then to the area of the weld 18. Ultrasonic echoes are reflected from the area of the weld back to the end 22 and along the length of the waveguide 20 to end 24. The reflected signals are transmitted through the transition piece 32 to the transducer 30.

In this manner, the transducer system and waveguide act to provide an ultrasonic image of the weld 18 to permit detection of any problems in the weld that could lead to leakage of fluid or otherwise adversely affect the process. As described, the transducer 30 acts as both a transmitter of ultrasonic signals and as a receiver of the reflected signals. An alternative arrangement would be to provide one transducer acting as a transmitter and a second transducer acting as a receiver, with the transmitted signals traveling along one path defined by the waveguide 20 and the reflected signals traveling along a different path provided by the waveguide. In addition, the transducer equipment can be permanently attached to the waveguide end 24 rather than being detachable in the manner previously described.

The flexibility of the waveguide 20 is important, as it allows the waveguide to be bent, curved or formed in virtually any other desired configuration. The surface 14 immediately above the weld 18 may be inaccessible in some applications, and the ability of the waveguide to be shaped as desired thus becomes essential.

As shown in Fig. 2, the transition piece 32 may be a solid element constructed of a material that is suitable for the transmission of ultrasonic signals. Alternatively, as shown in Fig. 3, the transition piece 32 may be a hollow element having its interior filled with a liquid 34 that is suitable for the transmission of ultrasonic signals. In either case, the transition element 32 provides a tapered transition between the transducer 30 and the smaller waveguide 24 which, in the case of Figs. 2 and 3, is formed by a single fiber. The fiber may be constructed of quartz or some other material that has suitable acoustic properties for transmitting ultrasonic signals.

Fig. 4 depicts an ultrasonic system for inspecting one or more welds 36 which are used to connect a fitting 38 in

extension through one wall of a liquid storage tank 40. The tank 40 contains liquid 42 which may be a petroleum based liquid, a chemical that is potentially dangerous, or some other type of liquid. The fitting 38 is submerged well below the surface 44 of the liquid 42 where access to it is restricted. The welds 36 are critical to the liquid storage facility, and leakage or other problems that develop at the welds can lead to serious adverse consequences.

In accordance with the present invention, a flexible waveguide 46 can be manipulated such that its free end 48 is positioned adjacent to the weld 36 that is to undergo inspection. The waveguide 46 may be flexed in a serpentine shape or any other desired configuration, and its opposite end 50 connects with a transition piece 52 which may be of the type shown in either Fig. 2 or Fig. 3, or some other type if desired. The opposite or large end of the transition piece 52 connects with a conventional ultrasonic transducer 54 which operates to apply ultrasonic signals to the transition piece 52 and to receive reflected signals which are returned to the transition piece by the waveguide 46. Manipulation of the waveguide 46 as desired is carried out by a conventional manipulating device 56 which functions in a manner known to those skilled in the field of manipulation of long flexible objects such as the waveguide 46. Again, the flexibility of the waveguide is important because it allows positioning of the waveguide as necessary to reach the critical area.

The equipment may also include a conventional video monitor 58. The waveguide end 50 and the components connected with it are situated at a fixed location above the liquid level in the tank and preferably close to the tank.

In operation, the transducer 54 transmits ultrasonic signals which are applied to the transition piece 52 and

then to the waveguide which directs the signals toward the weld 36. The reflected echo signals are received by the tip 48 of the waveguide and transmitted back along the waveguide to the transition piece 52 and the transducer 54 in order to provide an ultrasonic image of the weld area. The ultrasonic image can be examined to detect any flaws or other problems in the weld 36 or at any other critical area that is inaccessible for inspection by conventional techniques.

Fig. 5 depicts a dual element system in which a pair of ultrasonic transducers 60 and 62 are used. The transducer 60 is provided with a pair of side by side fibers 64 and 66. Fiber 64 is used for the transmission of ultra sonic signals toward the area that is to be inspected, as indicated by the directional arrow 64a. The other fiber 66 is used for the transmission of reflected echo pulses as indicated by the directional arrow 66a. The tips of the fibers 64 and 66 are turned to the side such that the ultrasonic signals that are transmitted and received by them have a horizontal orientation, as the arrows 64a and 66a illustrate. This shows one version of a possible multiple element system.

The other transducer 62 has a pair of side by side fibers 68 and 70. Fiber 68 is used for the transmission of ultrasonic signals toward the area that is to be inspected, as indicated by the directional arrow 68a. The other fiber 70 is used for the receipt of reflected ultrasonic signals, as indicated by the directional arrow 70a. The tips of the fibers 68 and 70 are directed downwardly so that the ultrasonic signals they transmit and receive have a vertical orientation, as the arrows 68a and 70a illustrate.

By using the dual element transducer shown in Fig. 5, inspections can be carried out at the same time in different directions. In many applications, this can facilitate and expedite the inspection procedure and

provide ultrasonic imaging information that is complete as to the entire area that is undergoing inspection. Additional fibers can be provided and directed at different orientations if desired.

The waveguides 20 (Fig. 1) and 46 (Fig. 4) can include a single fiber or virtually any number of fibers which are arranged in a fiber bundle which may be of the type shown in Fig. 6. The individual fibers 72 are packed closely together in the bundle which is depicted in Fig. 6. In a waveguide which includes a bundle of fibers, the individual fibers are connected together in the same configuration at both ends of the waveguide but may be disconnected between the opposite ends of the waveguide. This provides the necessary flexibility of the waveguide while assuring accuracy because the locations of the ends of the different fibers are known.

An alternative arrangement of a multiple fiber bundle which comprises the waveguide is shown in Fig. 7. Here, the individual fibers 72 are arranged in ordered rows of fibers which may or may not be packed so closely as to touch one another. Fig. 7 depicts the individual fibers spaced apart from each other.

In the type of bundle shown in Fig. 6 or the type shown in Fig. 7, the individual fiber 72 may serve different functions. For example, some of the fibers 72 are used for the transmission of ultrasonic signals from the transducer and others may be used for the transmission of reflected signals back toward the transducer (or some of the fibers may perform both functions). Other fibers may be used for illuminating the tip end of the waveguide 46. These fibers 72 may be optical fibers of the type that are able to transmit light from a suitable light source such as a laser located in the above ground equipment. Other of the fibers 72 in the bundle may be optical fibers used to transmit optical images from the tip end 48 of the waveguide back to the above ground equipment

for display on the video monitor 78. This permits the operator of the equipment to view the area immediately ahead of the waveguide tip 48 in order to enhance his ability to properly manipulate the waveguide so that its tip is positioned properly for inspecting the weld 36. Thus, an actual optical image of the weld 36 may be displayed on the video monitor 58 in order to assist in the proper positioning of the waveguide, and the ultrasonic image of the weld is separately generated for the purpose of inspecting the integrity of the weld or other component that is undergoing examination.

It should be noted that the waveguide may be a probe which moves independently within a larger tube, either axially or rotationally or both. It should also be noted that various types of operations can be carried out along with the inspection. For example, a laser or cutting device can be combined with the waveguide and used to remove unwanted deposits or other material. The ultrasonic imaging equipment provides feedback for use in controlling the removal process.

In addition to the specific applications which are illustrated in the drawings, the flexible waveguide system of the present invention has use in a wide variety of industrial applications. By way of example, laser bored holes are known to be relatively irregular, and the system of this invention can be used to provide an image of the hole geometry and determine the extent of the irregularities. Chemical machining of large surfaces such as panels used in aircraft construction is a commonly used process. A flexible quartz waveguide constructed according to the present invention could be used to make ultrasonic measurements of the part without requiring the part to be removed from the chemical bath as is currently required. The quartz is inert to chemical attack and would greatly improve the process efficiency as well as reducing the errors which can lead to ruined panels. Environments which are otherwise hostile because of

chemicals, radiation or other dangerous materials can be made accessible through use of the waveguide.

The monitoring of interior surfaces of vessels or pipe networks is also made possible. Chemical processes can likewise be monitored because the waveguide is able to withstand chemical attack whereas transducers cannot be directly placed at the site of the chemical reactions because caustic chemicals would quickly destroy them. Measurement of pitting caused by corrosion or other deterioration of airframe structures or critical areas in chemical plants is also made possible by embedding the waveguide in the structure which is to be monitored. The monitoring of various other inaccessible areas such as surfaces which are subject to degradation or unwanted deposits can also be carried out.

From the foregoing, it will be seen that this invention is one well adapted to attain all the ends and objects hereinabove set forth together with other advantages which are obvious and which are inherent to the structure.

It will be understood that certain features and subcombinations are of utility and may be employed without reference to other features and subcombinations. This is contemplated by and is within the scope of the claims.

Since many possible embodiments may be made of the invention without departing from the scope thereof, it is to be understood that all matter herein set forth or shown in the accompanying drawings is to be interpreted as illustrative and not in a limiting sense.

CLAIMS

1. Apparatus for use in an industrial installation to inspect an area covered by a material which is substantially impervious to ultrasonic signals, said apparatus comprising: a waveguide including at least one elongated flexible fiber constructed of a material along which ultrasonic signals may be propagated, said waveguide being embedded in said material and extending therein from an accessible surface of said material to a location adjacent to said area; and ultrasonic transducer means adapted for coupling to said waveguide at said accessible surface and operable to transmit ultrasonic signals along the waveguide and to receive reflected ultrasonic signals traveling along the waveguide to said accessible surface, thereby providing an ultrasonic image of said area.

2. Apparatus as set forth in claim 1, wherein said waveguide includes a bundle of elongated fibers along which the ultrasonic signals are propagated.

3. Apparatus as set forth in claim 1, wherein said transducer means is constructed for detachable coupling to said waveguide.

4. Apparatus as set forth in claim 1, wherein: said transducer means comprises first and second transducer elements each operable to transmit and receive ultrasonic signals; and said waveguide includes a pair of elongated flexible fibers for each transducer element, one fiber in each pair being used to transmit ultrasonic signals from the corresponding transducer element and the other fiber in each pair being used to apply the reflected ultrasonic signals to the corresponding transducer element.

5. Apparatus as set forth in claim 4, wherein said pairs of fibers are oriented to differ directionally.

6. Apparatus for use in an industrial facility to inspect an area that is relatively inaccessible, comprising: a bundle of elongated flexible fibers having opposite first and second ends at which the fibers are bonded together, at least some of said fibers being constructed of a material along which ultrasonic signals may be transmitted; manipulating means connected to said first end of the bundle for manipulating said second end of the bundle into close proximity to the inaccessible area; and ultrasonic transducer means coupled to said first end of the bundle for transmitting ultrasonic signals along said fibers and receiving reflected signals to provide an ultrasonic image of said inaccessible area.

7. Apparatus as set forth in claim 6, wherein: some of the fibers are used to transmit light for illumination of the inaccessible area; and some of the fibers are used to transmit optical images of the inaccessible area.

8. Apparatus as set forth in claim 7, including a video monitor for visually displaying said optical images.

9. Apparatus as set forth in claim 6, wherein the fibers in said bundle are packed closely together.

10. Apparatus as set forth in claim 6, wherein the fibers in said bundle are arranged in ordered rows.

11. A method of inspecting an area that is relatively inaccessible, comprising the steps of: (a) extending to said relatively inaccessible area an ultrasonic waveguide which includes at least one elongated flexible fiber constructed of a material along which ultrasonic signals may be transmitted, leaving a first end of said waveguide at an accessible location and locating a second end of said waveguide adjacent said area; (b) applying ultrasonic signals to said first end of the waveguide for transmission therealong to said area; and (c) receiving at said second end of the waveguide reflected ultrasonic

signals for transmission along the waveguide to said first end to provide an ultrasonic image of said area.

12. A method as set forth in claim 11, wherein: said waveguide includes a plurality of flexible fibers along which ultrasonic signals may be transmitted; and said applying and receiving steps comprise applying the ultrasonic signals to some of said fibers and receiving said reflected ultrasonic signals at other of said fibers.

13. A method as set forth in claim 10, including the steps of: arranging the fibers in pairs with each pair of fibers including one fiber for transmitting ultrasonic signals and another fiber for receiving reflected ultrasonic signals; and orienting the different pairs of fibers in different directions.

14. A method as set forth in claim 11, wherein said waveguide includes multiple flexible fibers arranged in a bundle and including the steps of: transmitting light along some of the fibers to illuminate the inaccessible area; and transmitting optical images of the inaccessible area along other of the fibers to provide a visual image of the area.

15. A method as set forth in claim 14, including the step of arranging the fibers in said bundle in ordered rows.

16. A method as set forth in claim 14, including the step of packing said fibers closely together in the bundle.

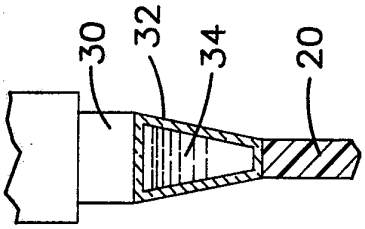

Fig. 3.

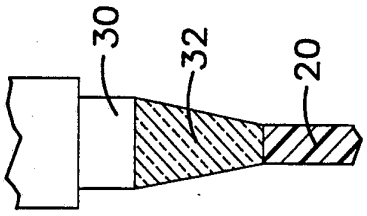

Fig. 2.

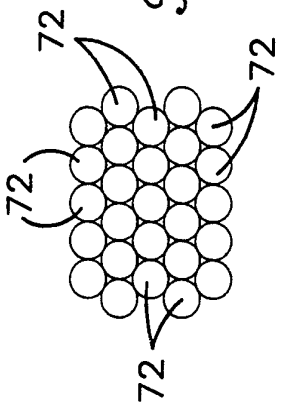

Fig. 6.

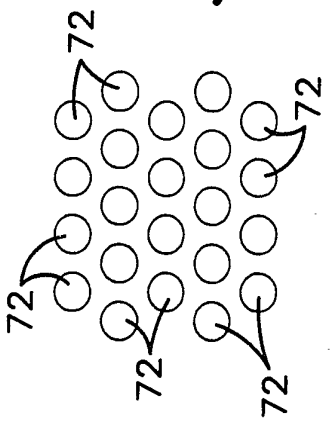

Fig. 7.

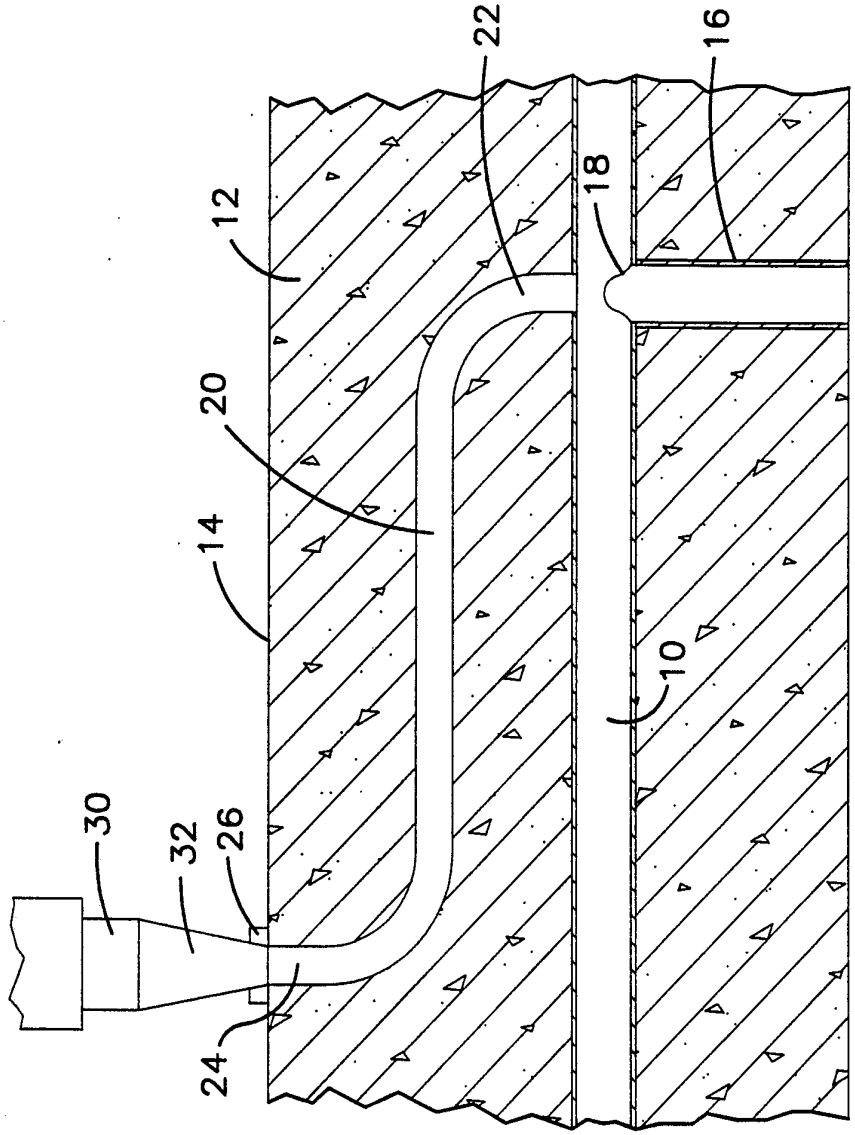

Fig. 1.

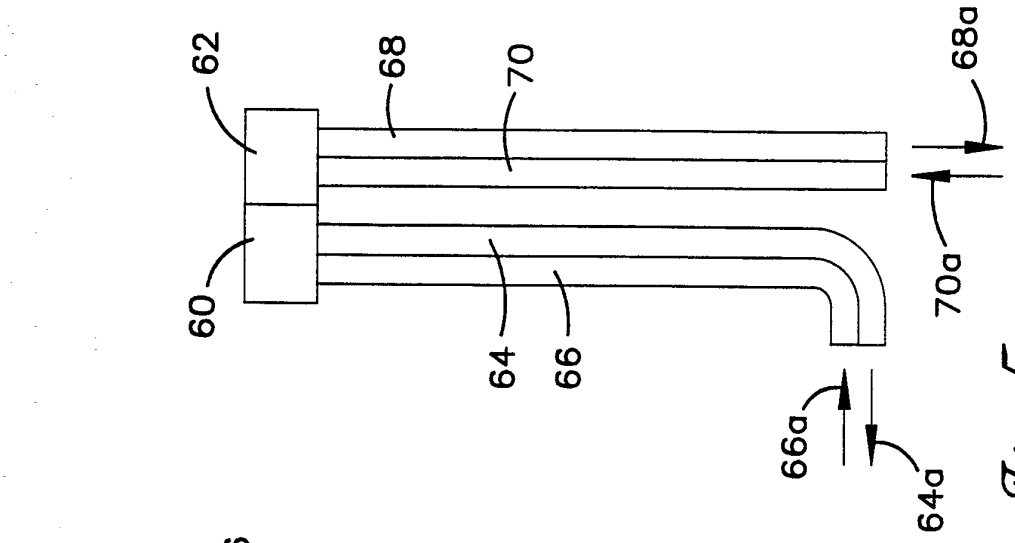
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Fig. 5.

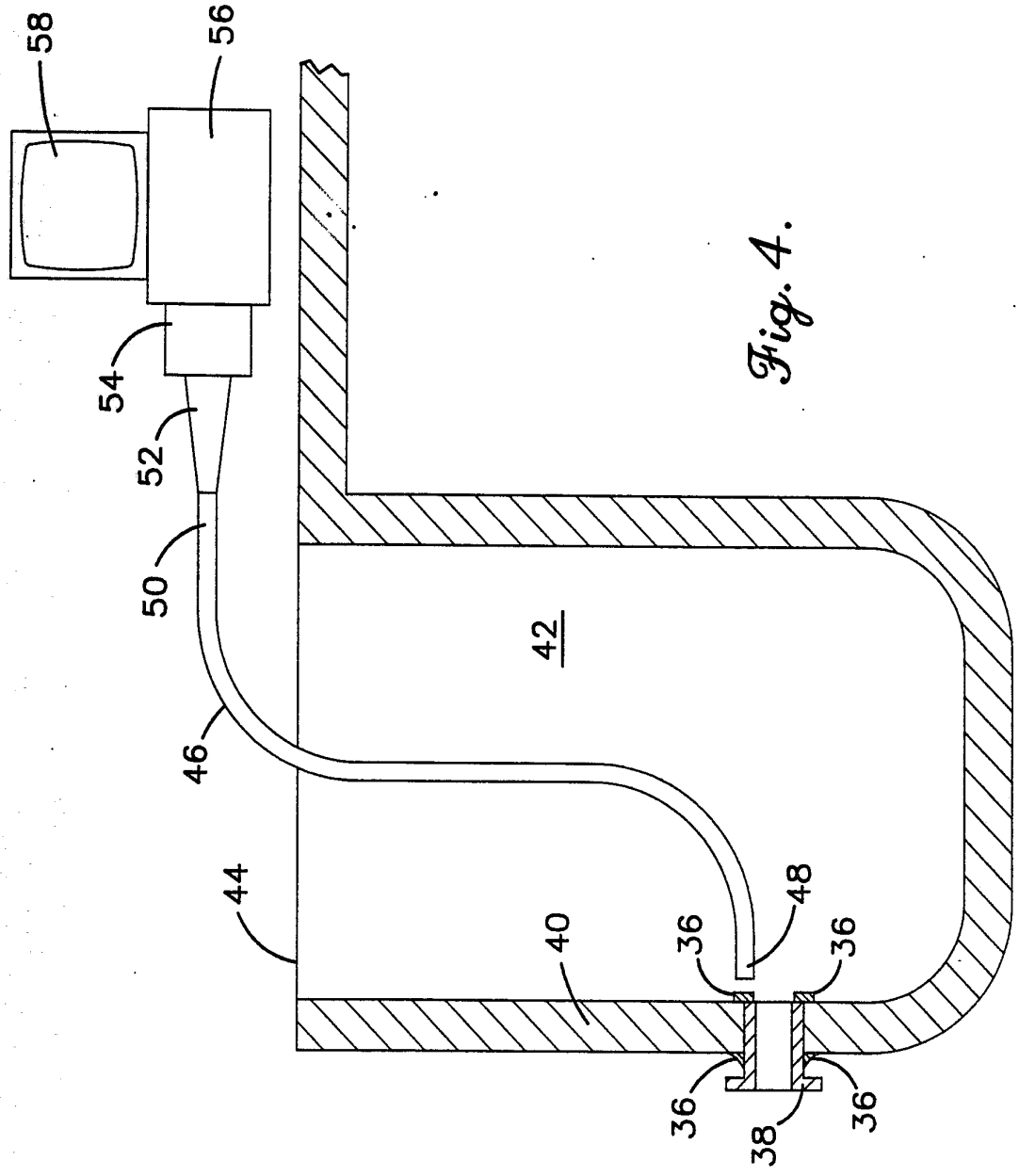
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Fig. 4.

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US93/00920

A. CLASSIFICATION OF SUBJECT MATTER

IPC(5) :G01N 29/24
US CL :073/644

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 073/644; 073/601, 592, 622, 40.5A; 376/245,248,252

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US, A, 3,915,018 (KARPLUS) 28 October 1975. See column 1, lines 53 et seq.	1-5, 11-13
Y	US, A, 3,264,893 (MAROPIS) 09 August 1966. See the entire document.	1-5, 11-13
Y	SU, A, 376,712 05 April 1973. See Abstract.	2
A	US, A, 4,208,917 (AOYAMA ET AL.) 24 June 1980. See the entire document.	1-5, 11-13

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be part of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
20 APRIL 1993	17 MAY 1993
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231	Authorized officer HEZRON E. WILLIAMS
Facsimile No. NOT APPLICABLE	Telephone No. (703) 305-4891

Form PCT/ISA/210 (second sheet)(July 1992)★

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US93/00920

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This international report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

Group I, claims 1-5 drawn to an inspection apparatus having an embedded waveguide classified in class 073/644.
Group II, claims 6-10 and 14-16, drawn to an inspection apparatus having a waveguide with manipulation means classified in class 073/644. Claims 11-13 appear to be generic.

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:
1-5, 11-13

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest.

☐ No protest accompanied the payment of additional search fees.