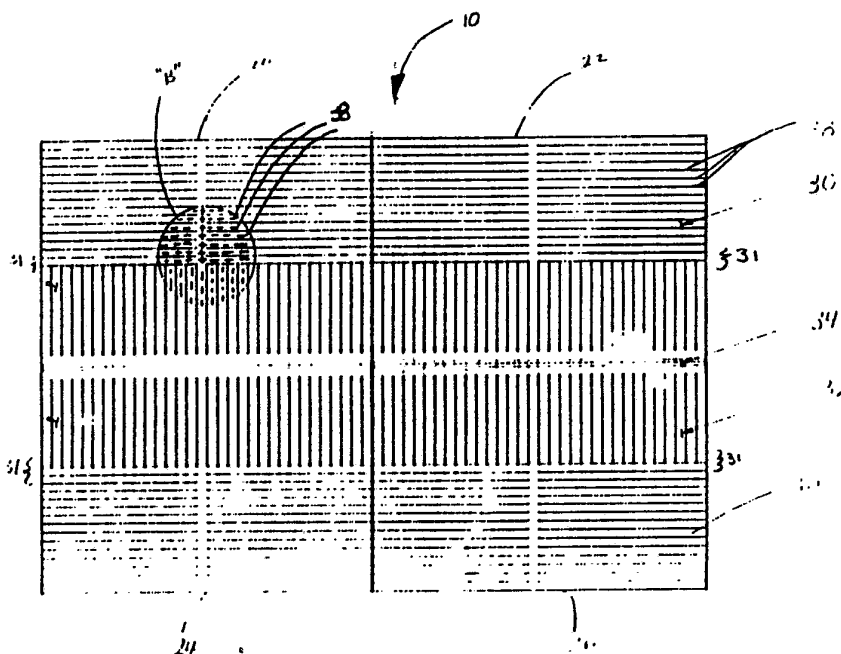




## INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

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<b>(21) International Application Number:</b> PCT/US91/03997 <b>(22) International Filing Date:</b> 6 June 1991 (06.06.91)  <b>(30) Priority data:</b> 534,142                      6 June 1990 (06.06.90)                      US 545,888                      29 June 1990 (29.06.90)                      US  <b>(71) Applicant:</b> ADVANCED NMR SYSTEMS, INC. [US/ US]; 30 Sonar Drive, Woburn, MA 01801 (US). <b>(72) Inventor:</b> RZEDZIAN, Richard ; 9 Middle Street, Lexington, MA 02173 (US). <b>(74) Agent:</b> LEE, G., Roger; Fish & Richardson, 225 Franklin Street, Boston, MA 02110 (US).		<b>(81) Designated States:</b> AT (European patent), BE (European patent), CA, CH (European patent), DE, DE (European patent), DK (European patent), ES (European patent), FR (European patent), GB, GB (European patent), GR (European patent), IT (European patent), JP, LU (European patent), NL (European patent), SE (European patent).  <b>Published</b> <i>With international search report.          Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.</i>

**(54) Title:** SHIELDED GRADIENT COIL FOR NUCLEAR MAGNETIC RESONANCE IMAGING

**(57) Abstract**

An RF shield for NMR opaque to RF energy but that permits audio frequency signals such as those of a gradient coil to penetrate an examination region. The surface of the shield is made up of an outside conductive layer (43) which is divided by etched channels (28). The etched channels (28), define circumferential strip-shaped areas (30) at the edges of the cylinder walls and longitudinal strip-shaped areas (32) at the central portion of the cylinder walls. Transition regions (31) are provided where the longitudinal and circumferential areas meet. An ancillary conductor is connected to the RF shield. The conductor acts as a high-pass coupling.

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SHIELDED GRADIENT COIL FOR NUCLEAR MAGNETIC  
RESONANCE IMAGINGBackground of the Invention

This invention pertains to shields for RF coils in nuclear magnetic resonance systems.

5 Nuclear magnetic resonance (NMR) systems may be used as medical diagnostic tools. Generally, they consist of a region that holds the patient or sample surrounded by a set of coils. The outermost coil is usually a superconducting DC coil which provides a strong, constant magnetic field  
10 that polarizes the nuclei in the molecules of the sample or the patient's body. A smaller RF coil sits concentrically within the DC coil, and generates a time-varying RF field that excites the molecules and detects their response to this excitation. A coil assembly, generally referred to as  
15 the "gradient coil", occupies the space between the above coils and generates a time-varying audio frequency gradient field that causes the response frequency of nuclei to depend on their positions within the field. This imparted spatial information allows the generation of an image of the areas  
20 excited by the RF coil.

It is known to provide a shield between the RF coil and the gradient coil for containing the RF energy but allowing audio frequency magnetic fields to pass through. This shield may be made with two overlapping conductive  
25 layers which include insulating channels dividing the layers into conductive strips. It is also known to orient these conductive strips in the direction of the current flow induced in the shield by the RF coil. RF coil shields of this type are discussed in U.S. patent number 4,642,569 of  
30 Hayes, entitled "Shield for Decoupling RF and Gradient Coils in an NMR Apparatus" (incorporated by reference).

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Summary of the Invention

The invention features, in a first aspect, providing narrower conductive strips to reduce the gradient coil power loss attributable to the shield. Narrower conductive strips  
5 reduce the eddy current losses experienced by the gradient coil (as an equivalent series resistance), thereby reducing the power required to operate the gradient coil, especially in high speed imaging where high frequencies up to 10 KHz are used. In preferred embodiments, the conductive strips  
10 are sufficiently narrow to make the power loss attributable to the shield less than that achievable with prior art shields (e.g., less than 1 kW at 1 kHz when placed in a 1 G/cm rms sinusoidal magnetic gradient field); and the strips are less than three inches in width.

15 In a second aspect, the invention features a third conductive layer placed over a transition region where there is a substantial change in the direction of the conductive strips. In such a transition region, RF current tends to travel in curved paths across the pattern of conductive  
20 strips instead of along the lengths of the strips, with resulting increase in RF leakage. The third conductive layer provides a lower impedance path for RF currents in the transition region to reduce this RF leakage and resultant power loss in various conductors outside the shield.

25 In a third aspect, the invention features connecting an ancillary conductor to the RF shield so that the conductor is insulated from the shield at the lower frequencies at which the gradient coil operates but is capacitively connected at RF frequencies.

30 This invention allows the construction of a shield that is more transparent and less lossy to the audio frequency gradient coil field, thus reducing the power required by the gradient coil. This reduction in power is

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advantageous in its own right, and is also advantageous because the gradient coils are typically driven by expensive, high-precision amplifiers. In addition, eddy currents generated by the changing magnetic fields of the gradient coil, when confined to the narrower strips of the RF shield of this invention will produce less distortion in the sensitive imaging volume and may result in better imaging performance.

The invention can be employed in MR systems using both sinusoidal and trapezoidal waveforms. With trapezoidal waveforms, it reduces power loss and eddy currents associated with the changing fields during the rise times.

Other features and advantages of the invention will become apparent from the following description of a preferred embodiment and from the claims.

#### Description of the Preferred Embodiment

FIG. 1 is a cross-sectional diagram illustrating the position of the shield with respect to the gradient and RF coils.

FIG. 2 is a view of the outer layer of the shield before assembly.

FIG. 3 is a cross-section of a portion of the circuit board that makes up the inner and outer layers of the shield in the part of the shield where the strip-shaped areas are circumferential.

FIG. 4 is a partially assembled view of the inner layer of the shield showing the third conductive layer which shields the transition layer.

FIG. 5 is a detailed view of the third conductive layer at the point of attachment of its associated capacitors.

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Referring to FIG. 1, a diagnostic NMR apparatus includes a cavity 16, for examining a patient, surrounded by a cylindrical RF coil 12. This coil 12 alternatively provides an RF field that excites the nuclei in the molecules of the patient's body and acts as a receiver to detect the response of the nuclei to their overall excitation by the NMR apparatus. The RF coil is of the type known as a birdcage resonator. Briefly, this type of coil is generally cylindrical and it provides circumferential current paths at its ends, and longitudinal paths in the center of its cylindrical walls. Birdcage resonators are discussed in U.S. patent number 4,694,255 of Hayes et al. entitled "Radio Frequency Coil for NMR".

The RF coil 12 is surrounded by a shield 10 which is in turn surrounded by a gradient coil assembly 14. The gradient coil assembly is made up of three coils: an X coil, a Y coil, and a Z coil. These coils generate audio frequency magnetic fields that allow spatial resolution of the NMR phenomenon within the cavity. The RF coil, its shield and the gradient coil assembly and main magnet are optimally concentrically arranged around the center of the NMR apparatus 18.

The shield 10 is essentially opaque to RF energy and thus contains the RF field. This shield prevents the loss of RF energy and unwanted interaction between any leaking RF energy and other parts of the system. The shield must not be, however, opaque to audio frequency signals and must permit the field from the gradient coil assembly 14 to penetrate into the cavity 16. The shield thus acts as a low-pass filter, blocking RF energy while passing the lower frequency audio energy.

The power loss attributable to the RF shield is less than that achievable with prior art shields. The preferred

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embodiment produces a power loss of about 1.0 kW at 2 kHz (0.25 kW at 1 kHz; 16.0 kW at 8 kHz), for a shield placed in a 1 G/cm rms sinusoidal magnetic gradient field. Note that these losses follow approximately a square-law dependency with frequency. Greater power loss could be accommodated in other embodiments. Preferably the power loss attributable to the shield (for a whole body MR system) is less than 4 kW at 2 kHz (1 kW at 1 kHz; 0.25 kW at 500Hz), and more preferably less than 2 kW at 2 kHz (0.5 kW at 1 kHz; 0.125 kW at 500Hz), for a shield placed in a 1 G/cm rms sinusoidal magnetic gradient field. For shields used in smaller or larger MR systems, these power loss criteria scale with the radius of the RF shield, which in the preferred embodiment is 32.2 cm. Similarly, for shields of different length from that used in the preferred embodiment (137 cm), these power loss criteria also must be scaled.

FIG. 2 shows the outside layer 43 of a shield 10 for the birdcage resonator RF coil before it is rolled into its final cylindrical configuration. This shield is made up of four individual printed circuit boards 20, 22, 24, 26. These circuit boards are assembled in the orientation shown with solder strip 34, which is shown holding printed circuit board pair 22 and 26 and printed circuit board pair 20 and 24 together at what will ultimately be the circumference of the center of the cylinder.

The surface of the shield shown in FIG. 2 is generally made up of an outside conductive layer 43 which is divided by etched channels 28. The etched channels define circumferential strip-shaped areas 30 at the edges of the cylinder walls and longitudinal strip-shaped areas 32 at the central portion of the cylinder walls. These areas are oriented to generally match the current path in the birdcage resonator, as a mirrored version of this current will be

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induced in the shield during operation of the RF coil. The circumferential strip-shaped areas 30 are typically 1 inch wide and the longitudinal strip-shaped areas are typically 1.26 inches wide. The regions 31 where the longitudinal  
5 area and the circumferential areas meet are called "transition regions".

Referring to FIG. 3, the shield 10 is made up of a two-sided flexible printed circuit board comprising an inside conducting layer 44 and an outside conducting layer  
10 43 separated by an insulating substrate 36. The circuit board is typically made of a 5 mil teflon/glass substrate (Norpflex Oak #605) with 1 ounce copper layers, and the channels are etched to 31 mils wide. The outside layer is divided into areas 30a, 30b by channels 28, as described  
15 above in connection to FIG. 2. The inside layer is similarly divided into areas 40a, 40b by inside layer channels 38 which are offset from the outside layer channels 28. Channels on one layer are always overlapped by conductive regions on the other layer, and thus inner layer  
20 channels never overlap outer layer channels. This permits the shield to be opaque to RF. The area of FIG. 2 marked "B" shows the channels from both layers superimposed (the inside layer channels are drawn in dashed lines) and illustrates the way these channels are intermingled to avoid  
25 the overlapping of channels.

The overlapping of areas of the two layers capacitively couple adjacent regions on each side of a channel. For example, channel 38 separates areas 40a and 40b and prevents any direct current flows between them  
30 across the channel, but the areas of overlap between areas 40a, 40b, and 30b form capacitors which allow currents at RF frequencies to flow from inside area 40a to outside area 30b to inside area 40b again. At RF, then, the entire shield



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looks somewhat like a continuous conductive cylindrical sheet. The channels, however, break up eddy currents at audio frequencies. The overlapping is apparent when comparing the placement of the outer layer strip-shaped areas 30, 32 (FIG. 2) and the inner layer strip-shaped areas 40, 42 (FIG. 4).

Referring to FIG. 4, further assembly of the shield 10 is shown. A second length of solder strip 46 is applied to the inside of the shield 10 at right angles from the first piece 34 to hold printed circuit board pair 20 and 22 and printed circuit board pair 24 and 26 together along the length of the cylinder.

A layer of 2 inch wide 1 mil thick insulating Kapton tape 48 is placed over each transition region, and three 1/2 inch strips of 1 ounce copper tape are placed on each piece of Kapton tape in parallel strips 50, 52, 54 & 51, 53, 55 thus forming a third conductive layer over the transition regions. This third layer improves the RF shielding at the transition regions which are found to be regions of high loss. The third layer is split into three strips to reduce induced eddy currents at audio frequencies. The resulting shield contains RF fields almost as effectively as a shield with wider conductive areas on its inner and outer layers, but is more transparent and less lossy to audio frequency fields. In the preferred embodiment, the RF operating frequency is approximately 64 MHz (1.5 Tesla).

The strips 50, 52, 54 & 51, 53, 55 are interrupted by gaps 56 which accommodate capacitors 58 that are soldered to the strips by leads 59 (See FIG. 5). These capacitors prevent low frequency eddy currents from flowing around these areas, but allows RF currents to flow. The capacitors are 3000 pF capacitors, and the gaps that they are inserted

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in are .75 inches wide. The strips are separated from each other by a distance of 32 mils.

In many embodiments of MR equipment, elements to drive and tune the RF coil are electrically attached to this shield. All such RF grounding attachments must be made capacitively so that audio eddy currents cannot be carried through these grounds. Therefore, also applied to the inside surface of the shield are pieces of Kapton tape 62 with superimposed areas 60 of 1.5 inch copper tape forming further areas of a third layer of the shield. These areas are electrically insulated from the inside conductive layer, but are capacitively coupled thereto. These areas may then be electrically connected to the ancillary conductors comprising the tuning, driving and matching equipment.

Other embodiments are within the scope of the following claims. It should be noted that the sequence of layers presented above could be different without significantly changing the electromagnetic properties of the shield. For example, the shielding of the transition regions could be applied to the outside of the shield. It also should be noted that the transition region shielding and cable mounting strips could be integral to a printed circuit board layer instead of being implemented with copper tape.

What is claimed is:

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1           1. A shield for an RF coil in a nuclear magnetic  
2 resonance system for containing the field generated by said  
3 RF coil while allowing lower frequencies to pass through  
4 said shield, said shield comprising:

5           an outer main layer composed of a plurality of  
6 conductive strips separated by a plurality of insulating  
7 channels;

8           an inner main layer composed of a plurality of  
9 conductive strips separated by a plurality of insulating  
10 channels;

11           the orientation of said conductive strips varying in  
12 different regions of said shield, there being at least three  
13 regions

14           a first region wherein said conductive strips  
15 extend in a first direction and current travels generally  
16 along the length of said strips in said first direction,

17           a second region wherein said conductive strips  
18 extend in a second direction substantially different from  
19 said first direction and current travels generally along the  
20 length of said strips in said second direction, and

21           at least one transition region located between  
22 said first and second regions wherein current changes  
23 direction from said first to said second direction and thus  
24 travels across said insulating channels;

25           a third layer composed of at least one conductive  
26 area overlapping at least some part of said transition  
27 region; and

28           insulating layers separating said inner main layer,  
29 outer main layer and third layer from each other.

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1           2. The shield of claim 1 wherein  
2           said inner main layer and said outer main layer are  
3 cylindrically shaped,  
4           said conductive strips extend longitudinally along  
5 the longitudinal axis of said cylindrically shaped layers in  
6 one of said first and second regions,  
7           wherein said conductive strips extend  
8 circumferentially in the other of said first and second  
9 regions, and  
10          wherein said transition region is located at the  
11 boundary where the longitudinally extending strips meet the  
12 circumferentially extending strips, and where current  
13 changes from a longitudinal to a circumferential direction  
14 (or vice versa).

1           3. A shield for an RF coil in a nuclear magnetic  
2 resonance system for containing the field generated by said  
3 RF coil while allowing lower frequencies to pass through  
4 said shield, said shield comprising:  
5           a generally cylindrical outer main layer composed of  
6 a plurality of conductive strips separated by a plurality of  
7 insulating channels;  
8           a generally cylindrical inner main layer composed of  
9 a plurality of conductive strips separated by a plurality of  
10 insulating channels, and being generally concentric with  
11 said outer main layer;  
12          a generally cylindrical third layer with one or more  
13 conductive regions, and being generally concentric with said  
14 inner and outer main layers; and  
15          generally cylindrical insulating layers separating  
16 said inner main layer, outer main layer, and third layer.

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1           4. The shield of claim 3 wherein said conductive  
2 strips extend longitudinally in one region and  
3 circumferentially in another region.

1           5. The shield of claim 1 or 3 wherein said  
2 insulating channels on said inner and outer main layers are  
3 placed such that they essentially never overlap each other.

1           6. The shield of claim 1 or 3 wherein said  
2 insulating channels form a pattern which essentially  
3 reflects the wiring orientation of an RF coil.

1           7. The shield of claim 6 wherein said RF coil is of  
2 the type known as a birdcage resonator.

1           8. The shield of claim 1 or 3 wherein said shield  
2 is manufactured using printed circuit board techniques.

1           9. The shield of claim 1 or 3 wherein third layers  
2 is radially inside of said inner and outer main layers.

1           10. The shield of claim 1 or 3 wherein said third  
2 layer is split into a plurality of areas.

1           11. The shield of claim 1 or 3 wherein a portion of  
2 said third layer comprises one or more gaps in said layer  
3 and said gaps are bridged by one or more capacitors.

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1           12. A structure for connecting an ancillary  
2 conductor to a shield for a coil in a nuclear magnetic  
3 resonance system comprising a dielectric strip mounted on  
4 the coil shield, said dielectric strip serving to  
5 capacitively couple the conductor to the shield at RF  
6 frequencies and to insulate the conductor from the shield at  
7 lower frequencies.

1           13. A shield for an RF coil in a nuclear magnetic  
2 resonance system, of a size to accomodate the whole adult  
3 body, for containing the field generated by said RF coil  
4 while allowing lower frequencies to pass through said  
5 shield, said shield comprising:  
6           an outer main layer composed of a plurality of  
7 conductive strips separated by a plurality of insulating  
8 channels;  
9           an inner main layer composed of a plurality of  
10 conductive strips separated by a plurality of insulating  
11 channels;  
12           an insulating layer separating said inner main layer  
13 and outer main layer,  
14           wherein, to reduce eddy current losses at said lower  
15 frequencies, substantially all of said conductive strips  
16 have widths of less than three inches.

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1           14. A gradient coil and associated RF shield for a  
2 nuclear magnetic resonance system, of a size to accomodate  
3 the whole adult body, said shield containing the field  
4 generated by an RF coil while allowing lower frequencies  
5 generated by said gradient coil to pass through, said shield  
6 comprising:

7           an outer main layer composed of a plurality of  
8 conductive strips separated by a plurality of insulating  
9 channels;

10          an inner main layer composed of a plurality of  
11 conductive strips separated by a plurality of insulating  
12 channels;

13          an insulating layer separating said inner main layer  
14 and outer main layer,

15          wherein said conductive strips are sufficiently  
16 narrow that the power loss attributable to said shield for a  
17 1 G/cm rms sinusoidal gradient field is less than 1 kW at 1  
18 kHz.

1           15. The gradient coil and associated shield of  
2 claim 14 wherein said conductive strips are sufficiently  
3 narrow that the power loss attributable to said shield for  
4 the same gradient field is less than 0.5 kW at 1 kHz.

1           16. The gradient coil and associated shield of  
2 claim 14 wherein substantially all of said conductive strips  
3 have widths of less than three inches.

1           17. The subject matter of claim 13 or 14 wherein  
2 the imaging volume of said resonance system has a  
3 longitudinal dimension (i.e., the dimension along the length

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4 of the body) that is substantially as great as the width of  
5 the adult body.

1 19. The gradient coil and associated shield of  
2 claim 18 wherein said longitudinal dimension is at least 30  
3 cm.

4 20. The subject matter of claim 14 wherein said  
5 magnetic resonance system is of a different size from that  
6 for accomodating a whole adult body, and said 1 kW figure is  
7 scaled to account for the difference in size.



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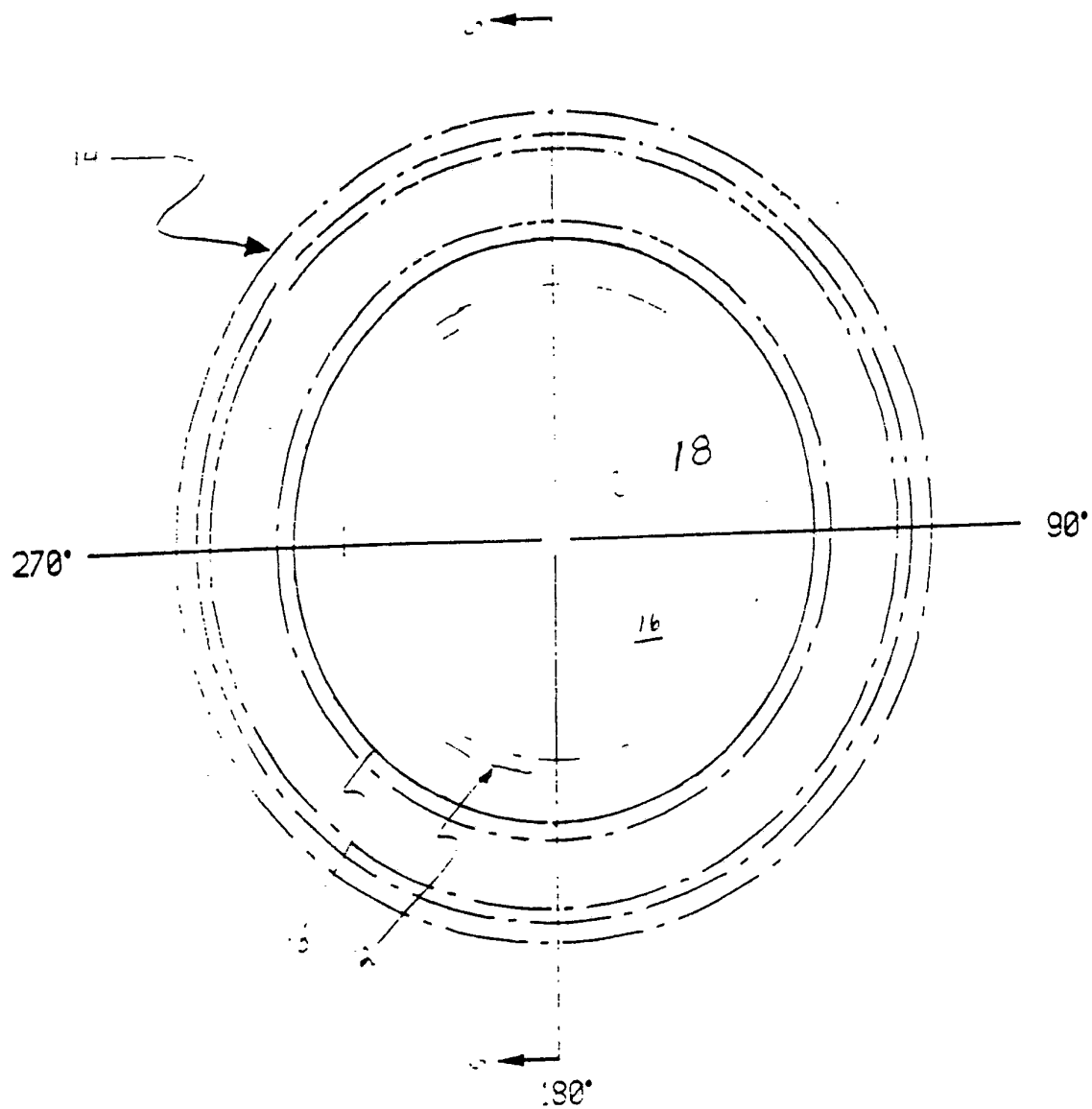


FIG. 1

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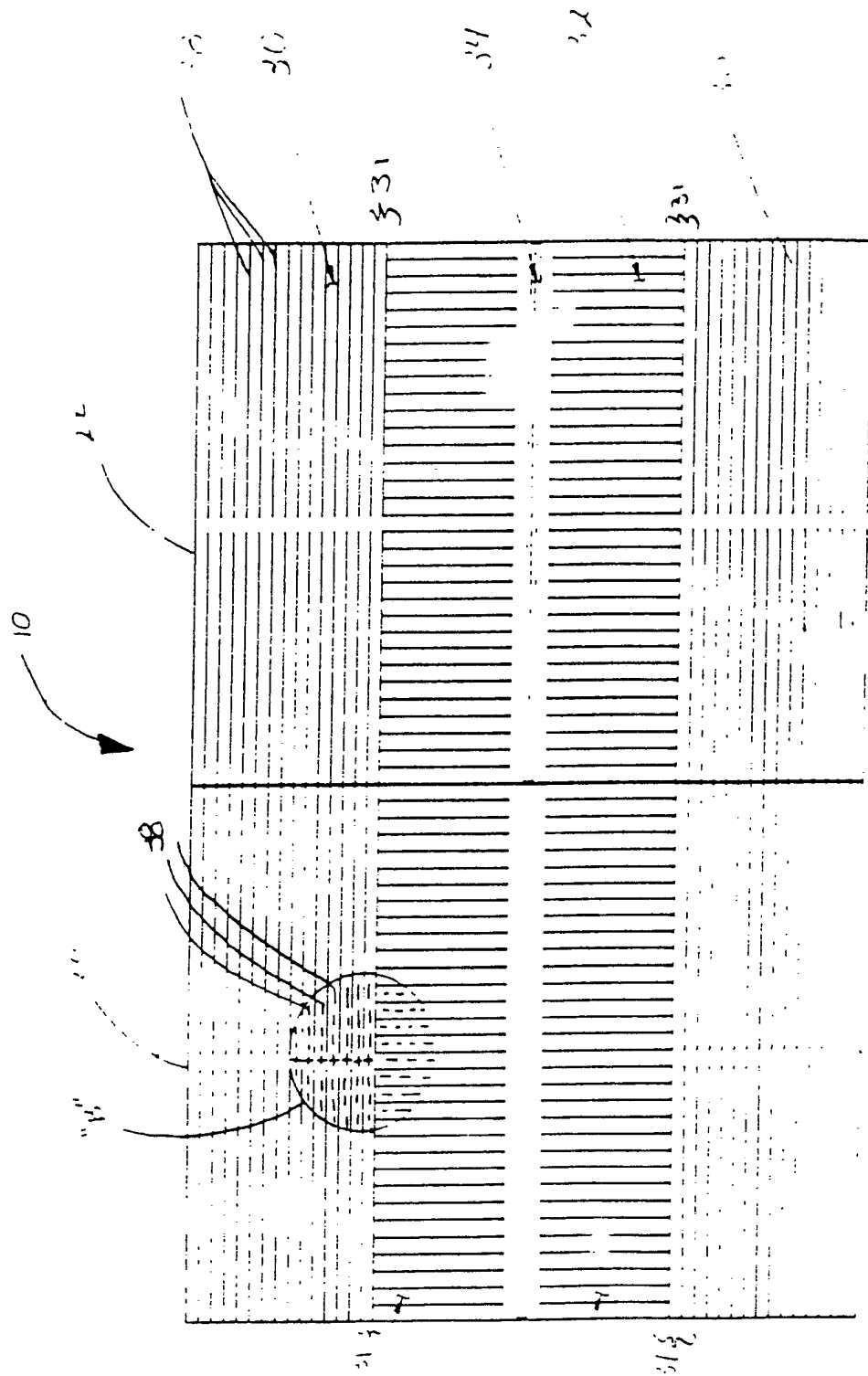


FIG. 2

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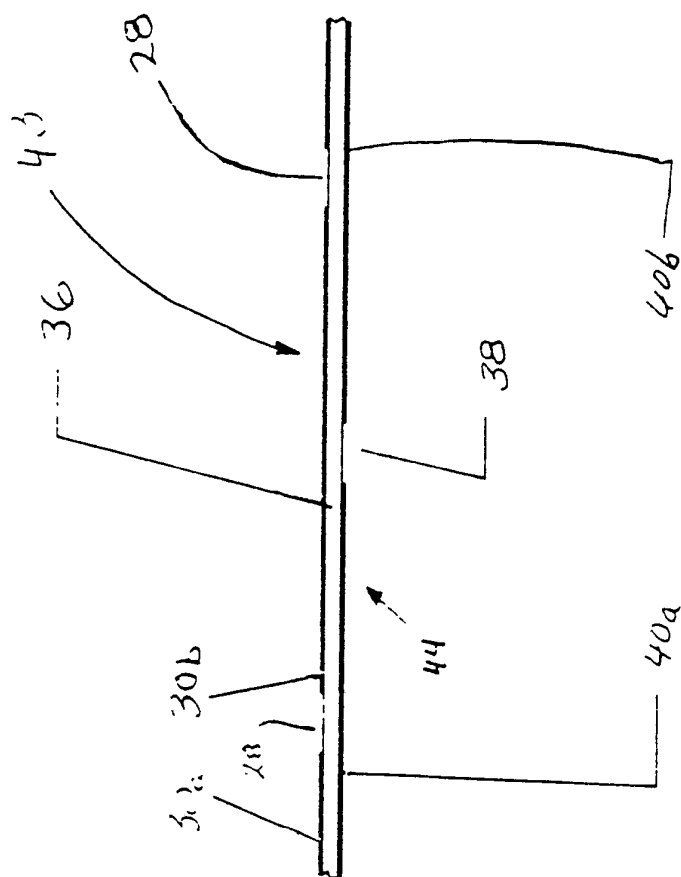
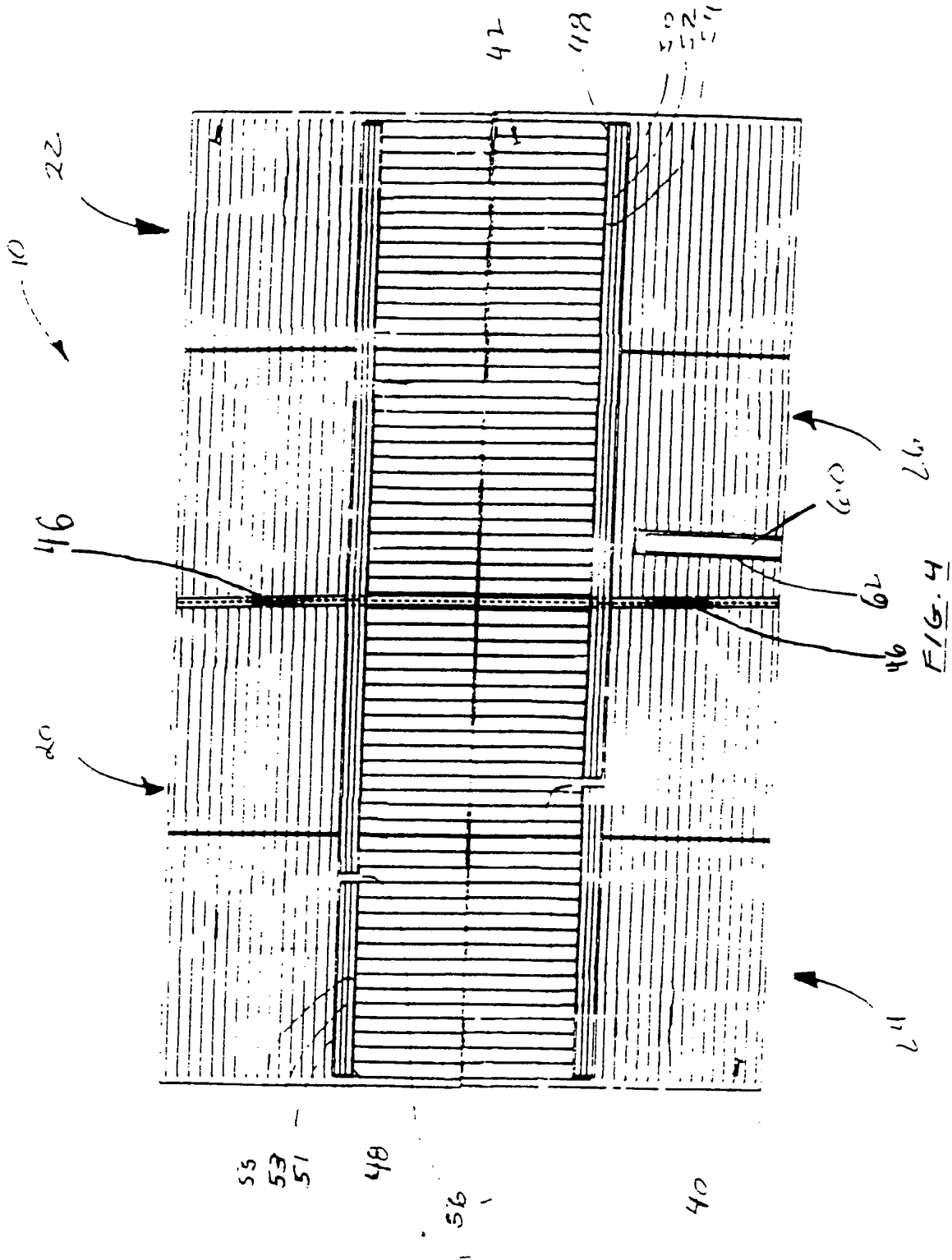


FIG. 3

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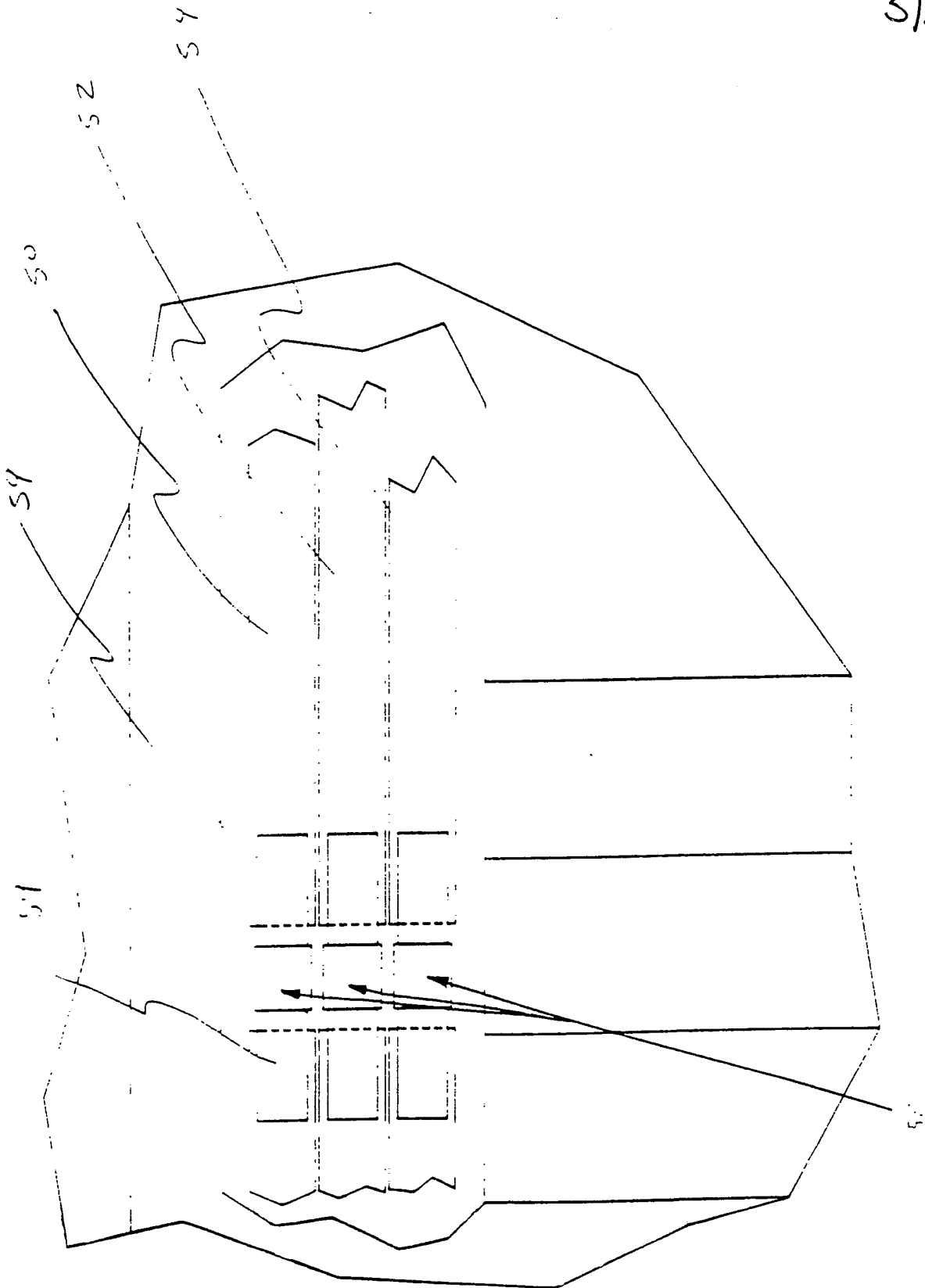



FIG. 5

# INTERNATIONAL SEARCH REPORT

International Application No.

PCT/US91/03997

<b>I. CLASSIFICATION OF SUBJECT MATTER</b> <small>Several classification symbols apply, and more than one</small> <small>According to International Patent Classification (IPC) and to both National Classification and IPC</small>		
IPC(5): G01V 3/00 US CL : 324/318		
<b>FIELDS SEARCHED</b>		
Minimum Documentation Searched <sup>1</sup>		
Classification System	Classification Symbols	
U.S.	324/318, 322, 313, 314, 307, 309	
Documentation Searched other than Minimum Documentation to the extent that such Documents are included in the Fields Searched <sup>2</sup>		
<b>II. DOCUMENTS CONSIDERED TO BE RELEVANT <sup>3</sup></b>		
Category <sup>4</sup>	Citation of Document, <sup>5</sup> with indication, where appropriate, of the relevant passages <sup>12</sup>	Relevant to Claim No. <sup>3</sup>
X	US, A, 4,879,515 (ROEMER ET AL.) 07 NOVEMBER 1989 See col. 2, lines 40-68 and col. 3, lines 1-26.	13-17,20
A	US, A, 4,638,253 (JASKOLSKI ET AL.) 20 JANUARY 1987 See the abstract of the disclosure.	12
A	US, A, 4,871,969 (ROEMER ET AL.) 03 OCTOBER 1989 See the abstract of the disclosure and col. 1, lines 5-53.	1-11,13-17,20
<div style="display: flex; justify-content: space-between;"> <div style="width: 45%;"> <p><b>* Special categories of cited documents: <sup>10</sup></b></p> <p>"A" document defining the general state of the art which is not considered to be of particular relevance</p> <p>"E" earlier document but published on or after the international filing date</p> <p>"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)</p> <p>"O" document referring to an oral disclosure, use, exhibition or other means</p> <p>"P" document published prior to the international filing date but later than the priority date claimed</p> </div> <div style="width: 45%;"> <p>"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</p> <p>"X" document of particular relevance: the claimed invention cannot be considered novel or cannot be considered to involve an inventive step</p> <p>"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.</p> <p>"A" document member of the same patent family</p> </div> </div>		
<b>IV. CERTIFICATION</b>		
Date of the Actual Completion of the International Search		Date of Mailing of this International Search Report
13 NOVEMBER 1991		<b>22 NOV 1991</b>
International Searching Authority		Signature of Authorized Officer
ISA/US		 LOUIS M. ARANA

## FURTHER INFORMATION CONTINUED FROM THE SECOND SHEET

V ☒ OBSERVATIONS WHERE CERTAIN CLAIMS WERE FOUND UNSEARCHABLE<sup>1</sup>

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

- 1 ☐ Claim numbers \_\_\_\_\_ because they relate to subject matter not required to be searched by this Authority, namely:
- 2 ☒ Claim numbers 19, 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<sup>2</sup>, specifically:

The claim is dependent on non-existing claim 18.

- 3 ☐ Claim numbers \_\_\_\_\_ because they are dependent claims not drafted in accordance with the second and third sentences of PCT Rule 6.4(a).

VI ☐ OBSERVATIONS WHERE UNITY OF INVENTION IS LACKING<sup>3</sup>

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

- 1 ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims of the international application.
- 2 ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims of the international application for which fees were paid, specifically claims:
- 3 ☐ 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 claim numbers:
- 4 ☐ As all searchable claims could be searched without effort justifying an additional fee, the International Searching Authority did not invite payment of any additional fee.

## Remark on Protest

- ☐ The additional search fees were accompanied by applicant's protest.
- ☐ No protest accompanied the payment of additional search fees.