



INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification ⁴ : G02B 17/08	A1	(11) International Publication Number: WO 87/ 07392 (43) International Publication Date: 3 December 1987 (03.12.87)
(21) International Application Number: PCT/GB87/00348 (22) International Filing Date: 21 May 1987 (21.05.87) (31) Priority Application Number: 8612609 (32) Priority Date: 23 May 1986 (23.05.86) (33) Priority Country: GB (71) Applicant (for all designated States except US): NATIONAL RESEARCH DEVELOPMENT CORPORATION [GB/GB]; 101 Newington Causeway, London SE1 6BU (GB). (72) Inventor; and (75) Inventor/Applicant (for US only) : WYNNE, Charles, Gorrie [GB/GB]; Morar, Booreham Street, Hailsham, East Sussex BN27 4SH (GB). (74) Agent: CULLIS, Roger; Patent Department, National Research Development Corporation, 101 Newington Causeway, London SE1 6BU (GB).		(81) Designated States: DE (European patent), JP, US. Published <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: OPTICAL IMAGING SYSTEMS (57) Abstract A substantially unity magnification image forming system includes at least one convex mirror and at least one concave mirror supported with their centres of curvature substantially coincident and means to define a location for an object the image of which after at least three reflections including at least one reflection at each of said mirrors is a real image at a second location and a monocentric meniscus lens between the mirrors to give overall correction for Petzval sum.		

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OPTICAL IMAGING SYSTEMS

This invention relates to optical imaging systems and, in particular, to optical imaging systems for forming an image of an object at unit magnification.

US Patent 3 748,015 describes an optical imaging system for forming an image of an object at unit magnification and high resolution by means of convex and concave spherical mirrors arranged with their centres of curvature coincident. The mirrors are arranged to produce at least three reflections within the system and they are used in the system. Two off-axis conjugate areas at unit magnification are in a plane which contains the centre of curvature, the axis of the system being an axis normal to this plane and through the mirror centre.

Any unit magnification system that consists of two equal halves disposed symmetrically about a central aperture stop is intrinsically free from various types of aberration, in particular all orders of distortion and coma. The prior art system shares this characteristic, but it suffers from other aberrations and limitations which restrict its performance. In particular:-

a) It is inherent in the design that it only gives sharp imagery over a quite narrow annular area in the focal plane, so that it is necessary to use the system with a narrow arcuate slit aperture exposing only this area, and to copy the object (mask) to an image surface by scanning them both, in synchronism, across this aperture. This requires extreme mechanical precision if one micron or less is to be resolved; and the scanning process is obviously slower than direct exposure over the whole area.

b) For any aberration free optical system, there is an inherent limit of resolving power, which is proportional to the numerical aperture (N.A.). and in the prior art system there is a practical limit to the attainable N.A. In the specific embodiment of the prior art (and in practical realisations

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thereof) this maximum N.A. is about 0.18 (equivalent to $f/2.78$) which gives a theoretical limit of resolution (at which the optical transfer function falls to zero), at a wavelength of 400nm, at a spacing of $1.1\mu\text{m}$. This is certainly inadequate for
05 future requirements. A larger N.A. could only be realised by moving object and image further from the centre, and as this is done the aberrations increase, and the masking slit width decreases rather rapidly.

In order to overcome this drawback, we have devised a means
10 of improving the correction of aberrations.

In Sov.J.Opt.Technol. 50(3), March 1983 153, there are described unit magnification imaging systems with compensation meniscus lenses. However, the design parameters of the systems described therein are constrained so that the monocentric
15 meniscus is wholly on the object side of the secondary mirror so that it is not traversed a second time by light between the first and second mirror reflections. We have found that, contrary to this teaching, far greater improvement in imagery arise when the meniscus lies between the mirrors.

According to the present invention, there is provided a
20 substantially unity magnification image forming system comprising at least one convex mirror and at least one concave mirror, said mirrors being supported with their centres of curvature substantially coincident and means to define a location for an
25 object the image of which after at least three reflections including at least one reflection at each of said mirrors is a real image at a second location and further comprising a monocentric meniscus lens between said concave and said convex mirrors substantially to give overall correction for Petzval sum,
30 to produce with said meniscus lens at said second location a stigmatic image of an object at said first location.

The invention will now be described, by way of example, with reference to the accompanying drawings, in which ;

Figure 1 is a diagrammatic representation of a prior art catoptric imaging system

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Figures 2, 3, 4a and 4b are diagrams used in explaining the operation of the imaging system of Figure 1

Figures 5a - b are diagrammatic representations of a second prior art imaging system; and

05 Figures 6a - c are diagrammatic representations of imaging systems in accordance with the present invention.

Referring now to Figure 1 of the drawings, an imaging system comprises two spherical mirrors, a convex mirror 1 and a concave mirror 2, arranged to provide three reflections in the system.
10 The mirrors are arranged with their centres of curvature coincident and to have off-axis conjugate areas centred at the points O and I. The points O and I are each at a distance h from the reference axis A and at opposite sides thereof.

Although the object and image surfaces are shown as coplanar,
15 they can be separated to more convenient locations by the insertion of plane mirrors, but this does not affect the mechanical precision needed for scanning.

For such a system, we consider a ray of light, undergoing three reflections. The line joining the common centre of the mirror P, to the point where the ray meets the convex mirror obviously constitutes an axis of symmetry, and the incident and emergent rays are equidistant from the common centre on opposite sides of the axis, and their inclinations with the axis are equal and opposite (Figure 2). We take an object/image plane through P,
20 normal to this axis, containing object and image points O and I, and consider this first ray as the central ray (principal ray) of a pencil emerging from O.

An aperture ray of this pencil, shown dotted in Figure 3, makes an aperture angle u with the principal ray. Since the
25 system is monocentric, this aperture ray, after three reflections, will emerge at the same distance as the incident ray from P, on the opposite side, and equally and oppositely inclined to the line joining P to the point of incidence of this ray on the convex mirror (a subsidiary axis).

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The emergent aperture ray will not pass through the image point P (the imagery will be aberrated) unless the incident and triply reflected rays are parallel. When this condition is satisfied, the system is said to be telecentric, and the simple
05 monocentric three-reflection system is inherently incapable of meeting this condition over an extended range of object/image positions. The system is said to show spherical aberration of principal rays.

The condition is approximately satisfied for an object very
10 close to the centre of curvature, if the Petzval sum is zero (for this system, this means that the radius of the convex mirror is one half that of the concave). but in that case principal rays from objects further away from the mirror centre, that strike the centre of the convex mirror, become necessarily more divergent
15 (Figure 4a). By a suitable choice of mirror radii, principal rays at some required object distance can be made telecentric. but at larger and smaller object distances, they will be divergent or convergent respectively (Figure 4b).

There is no obvious way of securing perfect correction of
20 principal ray spherical aberration in a monocentric optical system but a high level of correction may be obtained by adding an appropriate monocentric meniscus lens to the three-reflection system of the above type, the lens and mirror dimensions being chosen to give approximate overall correction for Petzval sum.

25 The level of improvement depends on the location of the meniscus corrector. First order correction of principal ray spherical aberration can be provided by a meniscus whose concave surface is relatively close to the focal plane. in which case the meniscus will be relatively thin (Figure 5a) or by a meniscus
30 further from the focal plane (and therefore having shallower curvatures) in which case the meniscus must be thicker (Figure 5b). In each case correction of primary principal ray spherical aberration is possible. but perfect correction is not obtained due to the presence of higher orders of aberration although these
35 uncorrected residuals are successively reduced, as the meniscus corrector is moved away from the focal plane, and the overall

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level of aberration correction of the system is thereby improved. We have found that a significant improvements is obtained when the meniscus lens is positioned between the two mirrors.

The effect of this is that the limitations of performance of the prior art system discussed above. are considerably reduced. The narrow width of the annular area of sharp imagery is greatly extended, for example, a level of image quality in the prior art arrangement which restricts the slit width to 0.25mm can permit a width of a centimetre or more. And it becomes possible to secure good performance over larger numerical apertures than the simple 3-mirror system can yield, for example 0.28 in place of 0.18.

Fabrication may be simplified in the preferred embodiments where one of the mirrors is deposited as a reflecting layer on part of a surface of the meniscus.

Example 1

A 1:1 copier lens of numerical aperture 0.28 has a construction as shown in Figure 6a. It is corrected for object/image distances from the central axis 5.6cm to 5.9cm (slit width 3mm). Its parameters are as shown in Table 1.

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Table 1

	surface number	radius	axial separation 10.0 to object	refractive index 1.0 (air)	full diameter
05	1	-10.0000			15.6
			2.6220	1.5010	
	2	-12.6220			18.2
			10.4876	1.0	
	3 (M1)	-23.1096			25.6
10			-10.4876	-1.0	
	4	-12.6220			
			-2.6220	-1.5010	
	5 (M2)	-10.0			5.6
			2.6220	1.5010	
15	6	-12.6220			
			10.4876	1.0	
	7 (M3)	-23.1096			25.6
			-10.4876	-1.0	
	8	-12.6220			18.2
20			-2.6220	-1.5010	
	9	-10.0000			15.6
			-10.00 to focus	-1.0	
	10	∞ image			11.8

25 Dimensions in centimetres. A negative radius is concave to the object/image plane. A change of sign of refractive index indicates a reflection.

Example 2

30 A 1:1 copier lens of numeric aperture 0.23 has a construction as shown in Figure 6b. It is corrected for object/image distances from the central axis 5.5cm to 6.0cm (slit width 5.0mm). Its parameters are as shown in Table 2.

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Table 2

	surface number	radius	axial separation 13.0 to object	refractive index 1.0 (air)	full diameter
05	1	-13.0000			16.7
			24.9032	1.5000	
	2 (M2)	-37.9032			36.2
			-24.9032	-1.5000	
	3	-13.0			
10			-1.4344	-1.0	
	4 (M2)	-11.5656			5.2
			1.4344	1.0	
	5	-13.0			
			24.9032	-1.5000	
15	6 (M3)	-37.9032			36.2
			-24.9032	-1.5000	
	7	-13.0			16.7
			-13.0000	-1.0000	
	8	∞ image			12.0
20					

Dimensions in centimetres. A negative radius is concave to the object/image plane. A change of sign of refractive index indicates a reflection.

25 The possibility of various modifications which remain within the ambit of the invention will be apparent to those skilled in the art. For example, although single concave and convex mirrors have been illustrated, it is possible to use a plurality of mirrors of the equal or different curvatures to achieve the same
30 effect.

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CLAIMS

1. A substantially unity magnification image forming system comprising at least one convex mirror and at least one concave mirror, said mirrors being supported with their centres of curvature substantially coincident and means to define a location
05 for an object the image of which after at least three reflections including at least one reflection at each of said mirrors is a real image at a second location characterised in that it comprises a monocentric meniscus lens between said concave and said convex mirrors substantially to give overall correction for
10 Petzval sum, to produce with said meniscus lens at said second location a stigmatic image of an object at said first location.
2. A substantially unity magnification image forming system as claimed in claim 1 characterised in that at least one of said mirrors is contiguous with a surface of said meniscus lens.
- 15 3. A substantially unity magnification image forming system as claimed in claim 2 characterised in that said concave mirror is formed on a surface of said meniscus lens.
4. A substantially unity magnification image forming system as claimed in claim 2 characterised in that said convex mirror is
20 formed on a surface of said meniscus lens.
5. A substantially unit magnification image system as claimed in claim 1 characterised in that it includes a plurality of concave mirrors.

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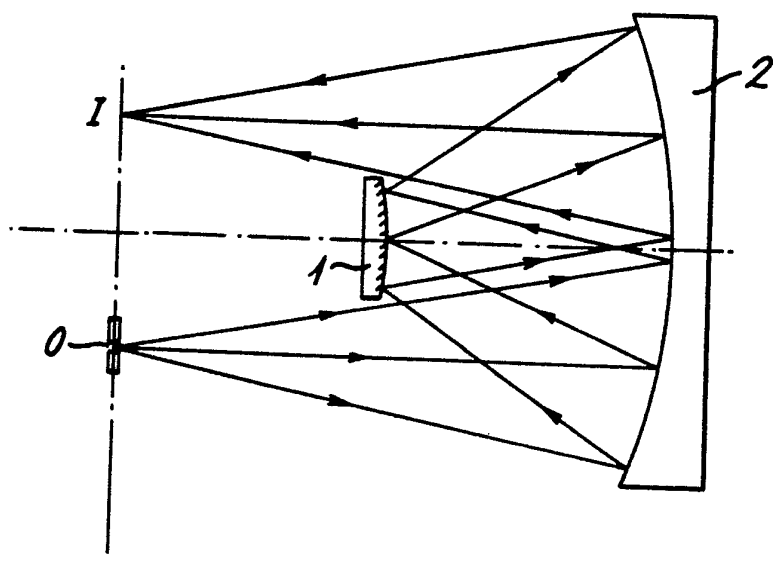


Fig. 1

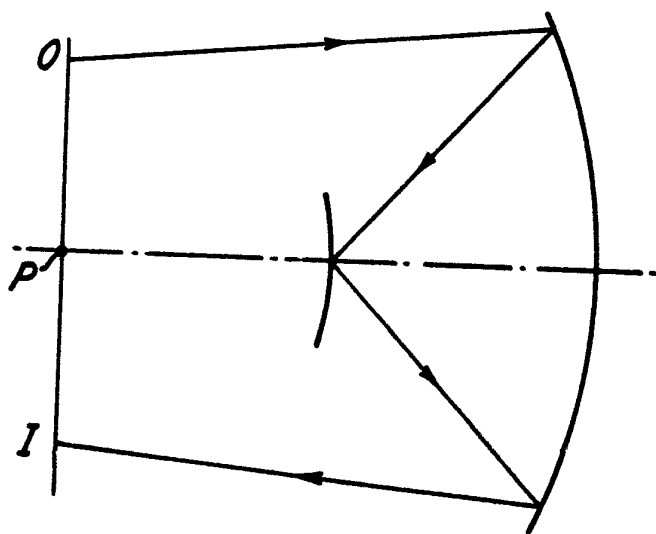


Fig. 2

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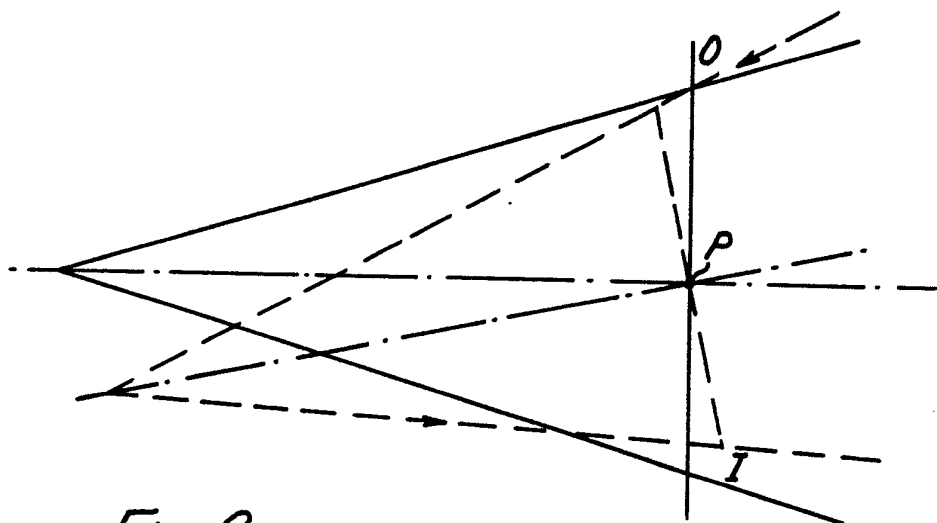


Fig. 3

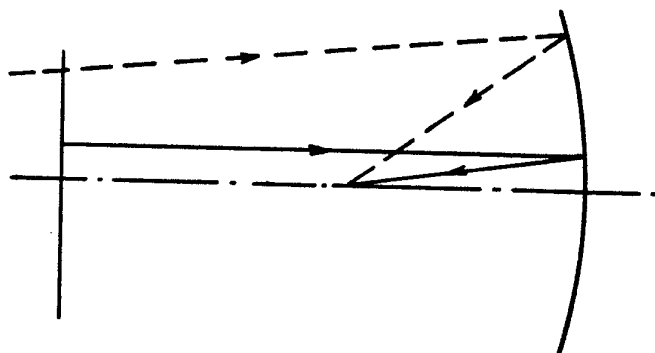


Fig. 4a

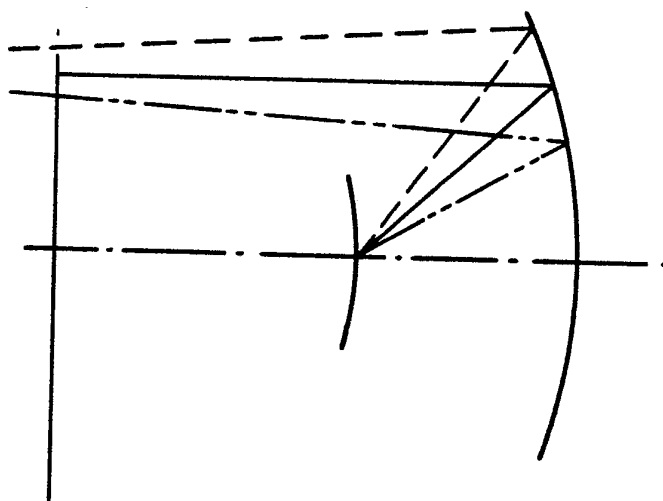


Fig. 4b

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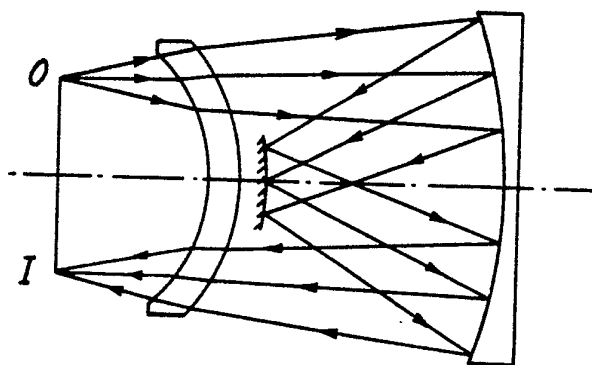


Fig. 5a

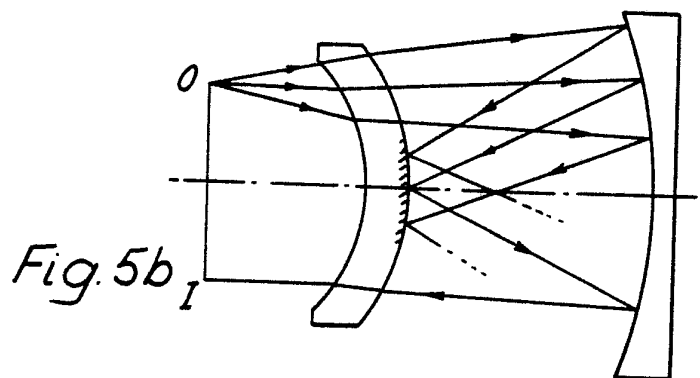


Fig. 5b

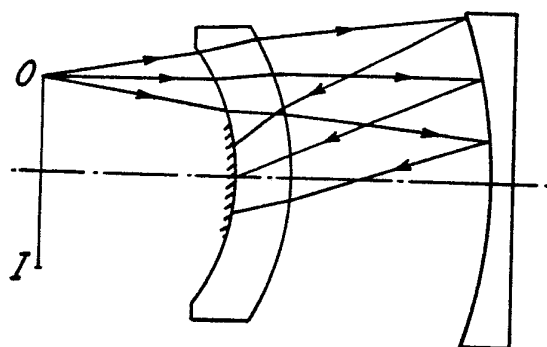


Fig. 6a

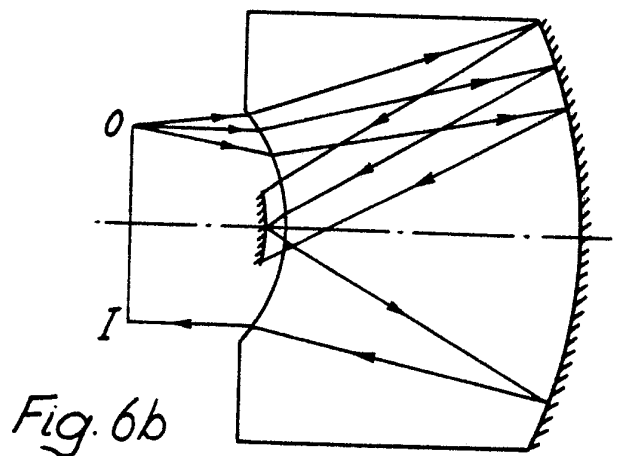


Fig. 6b

INTERNATIONAL SEARCH REPORT

International Application No

PCT/GB 87/00348

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) ⁶ According to International Patent Classification (IPC) or to both National Classification and IPC IPC ⁴ : G 02 B 17/08																	
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III. DOCUMENTS CONSIDERED TO BE RELEVANT ⁹ <table border="1" style="width: 100%; border-collapse: collapse; margin-top: 5px;"> <thead> <tr> <th style="width: 10%;">Category ⁹</th> <th style="width: 60%;">Citation of Document, ¹¹ with indication, where appropriate, of the relevant passages ¹²</th> <th style="width: 30%;">Relevant to Claim No. ¹³</th> </tr> </thead> <tbody> <tr> <td style="text-align: center; vertical-align: top;">X</td> <td>DE, A, 3033509 (PERKIN-ELMER) 23 April 1981 see page 23, line 23 - page 24, line 10; claims; figures --</td> <td style="text-align: center; vertical-align: top;">1</td> </tr> <tr> <td style="text-align: center; vertical-align: top;">A</td> <td>US, A, 4171871 (F.H. DILL) 23 October 1979 see abstract; figures --</td> <td style="text-align: center; vertical-align: top;">2,3</td> </tr> <tr> <td style="text-align: center; vertical-align: top;">A</td> <td>US, A, 3748015 (A. OFFNER) 24 July 1973 see abstract; figures (cited in the application) --</td> <td style="text-align: center; vertical-align: top;">1</td> </tr> <tr> <td style="text-align: center; vertical-align: top;">A</td> <td>US, A, 4293186 (A. OFFNER) 6 October 1981 see abstract; figures -----</td> <td style="text-align: center; vertical-align: top;">1</td> </tr> </tbody> </table>			Category ⁹	Citation of Document, ¹¹ with indication, where appropriate, of the relevant passages ¹²	Relevant to Claim No. ¹³	X	DE, A, 3033509 (PERKIN-ELMER) 23 April 1981 see page 23, line 23 - page 24, line 10; claims; figures --	1	A	US, A, 4171871 (F.H. DILL) 23 October 1979 see abstract; figures --	2,3	A	US, A, 3748015 (A. OFFNER) 24 July 1973 see abstract; figures (cited in the application) --	1	A	US, A, 4293186 (A. OFFNER) 6 October 1981 see abstract; figures -----	1
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A	US, A, 4293186 (A. OFFNER) 6 October 1981 see abstract; figures -----	1															
¹⁰ Special categories of cited documents: "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier document but 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 "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. "A" document member of the same patent family																	
IV. CERTIFICATION <table border="1" style="width: 100%; border-collapse: collapse; margin-top: 5px;"> <tr> <td style="width: 50%; padding: 5px;"> Date of the Actual Completion of the International Search 23rd August 1987 </td> <td style="width: 50%; padding: 5px;"> Date of Mailing of this International Search Report 24 SEP 1987 </td> </tr> <tr> <td style="width: 50%; padding: 5px;"> International Searching Authority EUROPEAN PATENT OFFICE </td> <td style="width: 50%; padding: 5px;"> Signature of Authorized Officer L. ROSSI </td> </tr> </table>			Date of the Actual Completion of the International Search 23rd August 1987	Date of Mailing of this International Search Report 24 SEP 1987	International Searching Authority EUROPEAN PATENT OFFICE	Signature of Authorized Officer L. ROSSI											
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ANNEX TO THE INTERNATIONAL SEARCH REPORT ON

INTERNATIONAL APPLICATION NO. PCT/GB 87/00348 (SA 17310)

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Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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		GB-A- 1605161	11/08/82

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