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Development of a system for the metrology of irradiated fuel rods using photodiode arrays.

M T Cross (Windscale)

DEVELOPMENT OF A SYSTEM FOR THE METROLOGY OF IRRADIATED FUEL RODS USING PHOTODIODE ARRAYS

by

M T CROSS

SUMMARY

Useful experience has now been gained with a prototype non-contacting method of measuring fuel rods. The system uses an optical technique, based on a photodiode array detector, to make high-resolution measurements. By using computer-processing of the data, it is possible to calculate fuel rod diameters, the distance between cooling ribs and the rib profiles on stainless steel clad AGR fuel rods. A detailed description of the measuring system is presented, together with an evaluation of the system performance. The system is capable of a diametral accuracy of ± 3 μm and samples an area only 10 μm wide on the fuel rod. An engineered system proposed for cave use is also described.

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1. INTRODUCTION

There is a requirement at Windscale to develop an accurate non-contacting method for the metrology of fuel rods as a replacement for measuring systems using contacting LVDT (Linear Variable Displacement Transformer) - type probes. Contacting probes can provide highly accurate diametral measurements but they disturb any deposits on the pin surface and their axial resolution is limited by the size of the probe anvils. One requirement of any improved measuring system is accurately to define both the shape and the separation of the cooling ribs on stainless steel clad AGR fuel rods (0.25 mm square, centres 2 mm apart) see Fig 1; to satisfy this need an axial resolution of 0.025 mm or better is needed. The measuring system should also be capable of performing measurements on bowed fuel rods without significant loss of accuracy. Accordingly, a non-contacting optical technique was chosen to fulfill these requirements. The solution was to back illuminate the fuel rod and then view its silhouette image using a photodiode array.

2. THE MEASURING SYSTEM

2.1 PHOTODIODE DETECTORS

A photodiode array consists of a closely spaced linear assembly of light-sensitive detectors deposited on a silicon substrate (Fig 2). The individual photodiodes provide a very accurate measuring grid allowing the light intensity distribution across an optical image to be measured by using digital signal-processing techniques. The devices are robust, reliable and allow high resolution measurements to be made.

2.2 STABILITY OF PHOTODIODES EXPOSED TO $\beta\gamma$ RADIATION

Tests on the radiation stability of commercial photodiode arrays of various types (both CCD's - Charge Couple Devices and NMOS - N Channel Metal Oxide Silicon Detectors) were discouraging. In a $\beta\gamma$ radiation field of 100R/hr, an integrated dose of 10^4R gave an irreversible degradation to the performance of the photodiode arrays; ie, the radiation damage to the device causes increased signal noise and large leakage currents. It was therefore impractical to use the detectors in a cave environment (ie in $\beta\gamma$ radiation fields typically exceeding 1 kR/h) without the use of large amounts of shielding. The difficulty of adequately shielding these devices in cave, together with the general philosophy of making in-cave equipment as simple and robust as possible, led to the decision to situate the delicate photodiode arrays out of cave and use an optical system to transfer the fuel rod image through the cave wall to the photodiode array. This system then confines the radiation sensitive detectors to an area outside the high radiation field (see section 6). Using this arrangement, only the fuel rod transport mechanism, the illumination source and optics are exposed to the high $\beta\gamma$ radiation.

2.3 THE PROTOTYPE SYSTEM

In order to assess the utility of photodiode based measuring systems, a laboratory prototype rig was constructed. The aims of the prototype were:-

(a) To define the accuracy and stability of the photodiode array for fuel rod measurements. The design criteria were to achieve a diametral resolution of $\pm$ 5μm on a 15.9 mm diameter fuel rod and an axial resolution of 25 μm in order to define the cooling rib profile and spacing. The measuring system had to tolerate an off-axis shift of the fuel rod of up to ± 3 mm, caused by bow of the 1 m long fuel rod.

(b) To assess and optimise the optical components required to achieve the above design criteria.

(c) To develop electronics both to control the photodiode array and to process the signals to obtain the required fuel rod dimensions.

(d) To develop a fuel rod transport system which would be vibration free and move the fuel rod in the precise way required for the proposed system.

(e) To develop a full-automated control and data processing system using a microcomputer. This system should provide for rapid fuel rod scanning, data storage, analysis and presentation of the data as graphs and tables for direct inclusion into reports.

2.3.1 Mechanics and optics

The prototype rig (Fig 3) is mounted on a steel top bench using magnetic optical clamps. A linear fuel rod transport system based on a Unislide* assembly is used; the dummy fuel rod is moved through the field of view of the optics on two 'V' blocks using a precision 1 mm pitch lead screw driven by a stepping motor, giving 400 steps per revolution and 2.5 μm linear movement per step.

The light source for the measuring system is a 50 W quartz halogen filament lamp (Fig 4) powered by a highly stabilised DC power supply. The light is collimated using an achromatic condenser doublet and then filtered using a green colour filter. This filter blocks infra-red and has a transmission maximum at 550 nm with a 100 nm band width. The collimated light beam illuminates the fuel rod and the silhouette image is focussed onto the photodiode array using a photographic lens (50 mm, f/1.8 Oreston) giving an image magnification of 1.5X. The photodiode array is a Reticon** type 1728H containing 1728 photodiodes on a 15 μm pitch; this gives an active length of 25.92 mm and an aperture width of 15 μm.

*Manufactured by Time and Precision (Sales) Ltd, Basingstoke, Hants, UK.
**Manufactured by EG and G Reticon, Sunnyvale, CA, USA.

2.3.2 Electronics

A block diagram of the control and signal processing electronics for the photodiode array is shown in Fig 5. The array driver and sample-and-hold video processing circuits were standard Reticon circuit boards. The sample-and-hold video processor converts the current pulses from the individual photodiodes into an analogue video signal which represents the light intensity distribution on the array as a function of time. When the silhouette image of the fuel rod is viewed by the array, the video processor produces the signal as shown in Fig 6. The two shadow edges in the image caused by the interposition of the fuel rod in the light beam are clearly visible as edges in the video signal. The time elapsed for the array to scan between the two edges is then proportional to the fuel rod diameter. This can be accurately measured by a crystal controlled clock which assess the diodes sequentially. The edges of the image are detected by comparing the analogue video signal with a threshold level; when this level is exceeded it causes an electronic comparator to produce a trigger pulse, which instructs a counter to count the total number of photodiodes covered by the silhouette image. This count is proportional to the diameter of the fuel rod. The above system is capable of measuring the size of the image to an accuracy of ± 1 photodiode. On the image magnified 1.5X by the prototype system, this translates to an uncertainty of ± 10μm in diameter. This uncertainty clearly falls short of the design criteria. In order to improve the resolution of the basic system without resorting to more complex optical schemes, a hardwired interpolation system has been designed(1) which effectively divides each diode-to-diode spacing by ten and hence in principle a resolution of ± 1μm can be achieved with the system (in practice the resolution of the system may be limited by the imaging lens (see section 4.3)).

The interpolation technique allows a single photodiode array to be used with a relatively simple optical imaging system to achieve an improved performance.

3. DATA PROCESSING

The measuring system produces a high volume of data; a single scan of the photodiode array produces a 5 digit diameter reading as a BCD (Binary Coded Decimal) number every 3 to 17 ms, depending on the scan speed of the array. In addition to this data, the linear travel of the fuel rod is measured using a magnetic scale transducer* allowing the displacement of the rod to be recorded to ± 0.002 mm. This transducer provides a 6 digit displacement reading every 3 ms as a BCD number. The overall data rate from the system may therefore be as high as 1.8 Kbytes/s.

*Sony Magnescale, Stanmatic Precision Ltd, Wigmore, London W1, UK.

3.1 FUEL ROD TRANSPORT CONTROL

The measuring system is programmed to take measurements at intervals of 0.025 mm along the fuel rod; this is necessary to define accurately the shape and separation of the cooling ribs on AGR fuel rods. 4000 such readings occupy 8 Kbytes of RAM and give a fuel rod traverse of 100 mm; this length being chosen to span adequately a sub-stack of fuel pellets (a sub-stack contains 5 fuel pellets 14.5 mm diameter and 14.5 mm long).

3.2 COMPUTER HARDWARE

The prototype system uses a CBM 3032N microcomputer containing 40 Kbytes of RAM. Data-acquisition from the photodiode array electronics and magnetic displacement transducer is provided by a digital data input unit* configured to convert BCD information into IEEE-488** format. The data bytes read by the interface may be then operated on by a software program. Control functions are also provided by the computer, which drives the stepping motor and tests for the closure of limit switches on the fuel rod transport system. The software operated stepping motor control system was developed at Windscale using plug-in modules in the Harwell 6000 series format. Storage of recorded data is provided by dual magnetic floppy discs (170 Kbytes storage each). Visual displays of recorded data use 8 Kbytes of the computer's RAM to provide high resolution graphics on a matrix of 320 x 200 picture points; these displays may be printed using a dot matrix printer.

*3D Digital Design and Development, Warren Street, London W1, UK.
**Institution of Electrical and Electronic Engineers Standard 488.

3.3 COMPUTER SOFTWARE

The system software has been designed as a series of modular programs using both assembly code and a compiled form of the BASIC language. The modules are:-

(a) Data acquisition.

(b) Stepping motor drive and control functions.

(c) Data processing and storage.

(d) Display.

Programs (a) and (b) are written in assembly code in order to maximise the data acquisition speed; this makes it possible to take 20 readings per second along the fuel rod, giving a traverse time for a fuel sub-stack of 3 minutes. Program (c) converts the photodiode array data into diametral measurements, scales the data by reference to stored calibration values and then searches for cooling rib positions; statistically reduced data is then stored on disc. Program (d) generates graphical displays of the data stored on disc and allows hard copies to be made. Programs (c) and (d) are written in compiled BASIC.

4. PERFORMANCE

4.1 ACCURACY OF DIAMETRAL MEASUREMENTS

The measuring system was calibrated at 0.1 mm intervals against a standard cylindrical bar having 7 ground steps 10 mm wide, ranging from 15.0 to 15.6 mm diameter (ie covering the range of interest on AGR fuel rods). Details of this standard bar are given in Table 1.

Calibration of the measuring system was performed by imaging the largest diameter step (no 7) on the standard and adjusting the fine focus of the lens until the displayed diameter valve was equal to that measured by a contacting technique (see Table 1) ie 15.601 mm, in this instance 1560.1 of the 1728 diodes were covered by dark shadow. Using this method of calibration values of diameter could be read directly from the display. The standard bar used for the calibration had been certified at UKAEA Springfields Nuclear Laboratories to have a calibration uncertainty of $\pm$ 2μm. Diameter measurements made using the photodiode array (as the mean of 4 readings for two directions, A and B, at right angles) are shown together with the known diameters in Table 1. The maximum difference, Δd, between the mean values is $\pm$ 3μm.

4.2 STABILITY

Drift in the system was measured over an 8h period by using the computer to take 100 diameter readings (in 5 secs) on a standard bar of constant diameter at 15 minutes intervals, average them and then print the mean values. The drift was measured as 2μm in the 8h period.

4.3 OPTICAL RESOLUTION

The overall resolving power of a practical electro optical measuring system is limited both by the resolution of the imaging lens/detector combination and the frequency response of the processing electronics/display system. The theoretical resolution of a photodiode array containing photodiodes on a 15μm pitch is 33 line pairs/mm. The concept of MTF (Modulation Transfer Function[2]) is often used to characterise the performance of an electro optical system. MTF is the ratio of the amplitudes of the electrical output signal and the optical input signal of the measuring system, plotted as a function of the spatial frequency content of the input; this is analogous to the frequency response curve used in electronics. A simple way of measuring the MTF is to present a step optical input to the imaging system; this was achieved by back-illuminating a knife edge using collimated light at a wavelength of 550 mm. The response of the imaging system to this sharp shadow is shown in Fig 7; two photodiodes are required to make the light/dark transition. The MTF at the maximum spatial frequency[3] of 33 line pairs/mm is then:-

$$MTF(\%) = \frac{100}{N}$$

where N is the number of photodiodes required to make the transition and

$$MTF = \frac{100}{2} = 50\%$$

Hence the overall contrast is reduced to 50% of the maximum at a resolution of 33 line pairs/mm for the combination of the lens, detector and electronic processing system.

5. TESTING THE SYSTEM USING DUMMY FUEL RODS

Dummy unirradiated AGR fuel rods containing depleted UO_2 fuel pellets were used to test the system. The fuel rods had been thermally cycled to simulate the pellet cladding interactions which occur under irradiation. Fig 8 shows a print out of a computer graphics display of the diametral variations along a short section of fuel rod. The trace clearly shows a ridge at a pellet end and clear profiles of the cooling ribs, achieved by the narrow sampling width (10μm) of the photodiodes on the fuel rod at 25μm intervals.

The ability of the system to measure the spacings between the cooling ribs on the fuel rods (used as a measure of the axial strain the fuel rod has experienced under irradiation) was assessed as follows. A single fuel sub-stack was repetitively scanned by the measuring system and the data analysed by the micro-computer as follows, a software algorithm was devised which searches for the edges of the ribs (defined as the position where the rib rises to 50% of its final height) and then calculates the rib spacings. The standard error in the calculated rib spacings was 5μm.

6. ENGINEERING THE SYSTEM FOR CAVE USE

An engineered system for cave use is now under construction. Fig 9 shows the in cave pin handling rig. The design is based on a modification to existing optical viewing rigs now in use at Windscale. The philosophy of the design was to measure short lengths of fuel rod (ie fuel sub-stacks, $\sim$75 mm long) held between rigid chucks, in order to minimise the effects of pin bow. In order to measure the fuel rod as a sequence of sub-stacks, a fuel rod feeder was devised and operated by pneumatic chucks and a lead screw driven by a stepping motor. The fuel rod feeder pulls a section of rod into the field of view of the optics, this section of the rod is then traversed past the photodiode detector on a precision moving table controlled by a second stepping motor. When the measurement traverse is complete the next section of fuel rod is presented to the optics and the cycle repeated. The advantages of this approach are as follows:-

(a) Existing tried pin handling technology is used.

(b) The rig is compact, minimising the use of cave space.

(c) The rig is light enough to be attached to the inside face of a cave wall adjacent to a viewing port. This is important since it minimises the pick-up of vibrations along the cave floor created by other cave operations.

Fig 10 shows the layout of the measuring system. The fuel rod is back illuminated and the pin is viewed using an optical transmission tube through the cave wall. The optics exposed to $\beta\gamma$ radiation are made in stabilised glass. At the outer cave wall a periscope system, together with a lead shield block, is used to protect the operator from direct radiation. The optical image of the fuel rod is then presented to the photodiode array outside the high radiation field for measurement.

7. CONCLUSIONS

1. A prototype optical technique for measuring the diameter and rib spacing of AGR fuel rods has been successfully demonstrated in the laboratory, and could be engineered into a system for measuring irradiated fuel rods.

2. The accuracy of diameter measurements ($\pm$ 3μm) and the high axial resolutions (10μm) along the fuel rod afforded by the system allows high sensitivity diameter, rib pitch and rib shape measurements to be made.

3. The measuring system has the advantage that it is non-contacting and therefore does not damage deposits on the rod, nor lead to inaccuracies and contamination of the measuring heads.

4. Since the detector is essentially a digital device it is ideally suited to automation using computer techniques.

5. The proposed measuring system uses no radiation sensitive electronic components in the high radiation area within the cave.

8. REFERENCES

1. CROSS M T. UK Patent pending.

2. LEVI L. Applied optics - a guide to optical system design. Vol 1, 1968, Wiley, New York. p133ff.

3. HOPWOOD R K. Design considerations for a solid state image sensing system. Proceeding of the Society of Photo Optical Instrumentation engineers. Vol 230, p 72-82, 1980.

TABLE 1

Mean values of diameter obtained on standard bar

Step No.	Nominal dia./mm	Measured dia. values/mm+				Maximum difference D_w-D_s/mm
		Dia. A		Dia. B		
		D_s	D_w	D_s	D_w	
1	15.000	14.995	14.9920	14.996	14.9927	- 0.003
2	15.100	15.099	15.0972	15.097	15.0960	+ 0.002
3	15.200	15.201	15.2002	15.200	15.1995	- 0.0008
4	15.300	15.299	15.2990	15.300	15.2980	- 0.002
5	15.400	15.398	15.3980	15.398	15.4010	+ 0.003
6	15.500	15.499	15.5002	15.498	15.5012	+ 0.003
7	15.600	15.601	15.6017	15.601	15.6010	+ 0.0007

+ = Diameter A and B are taken at 0° and 90° to an orientation line marked on the standard bar.

D_s = Mean values obtained at Springfields Nuclear Laboratories (contacting technique $\pm$ 2μm).

D_w = Mean values obtained at Windscale Nuclear Laboratories.

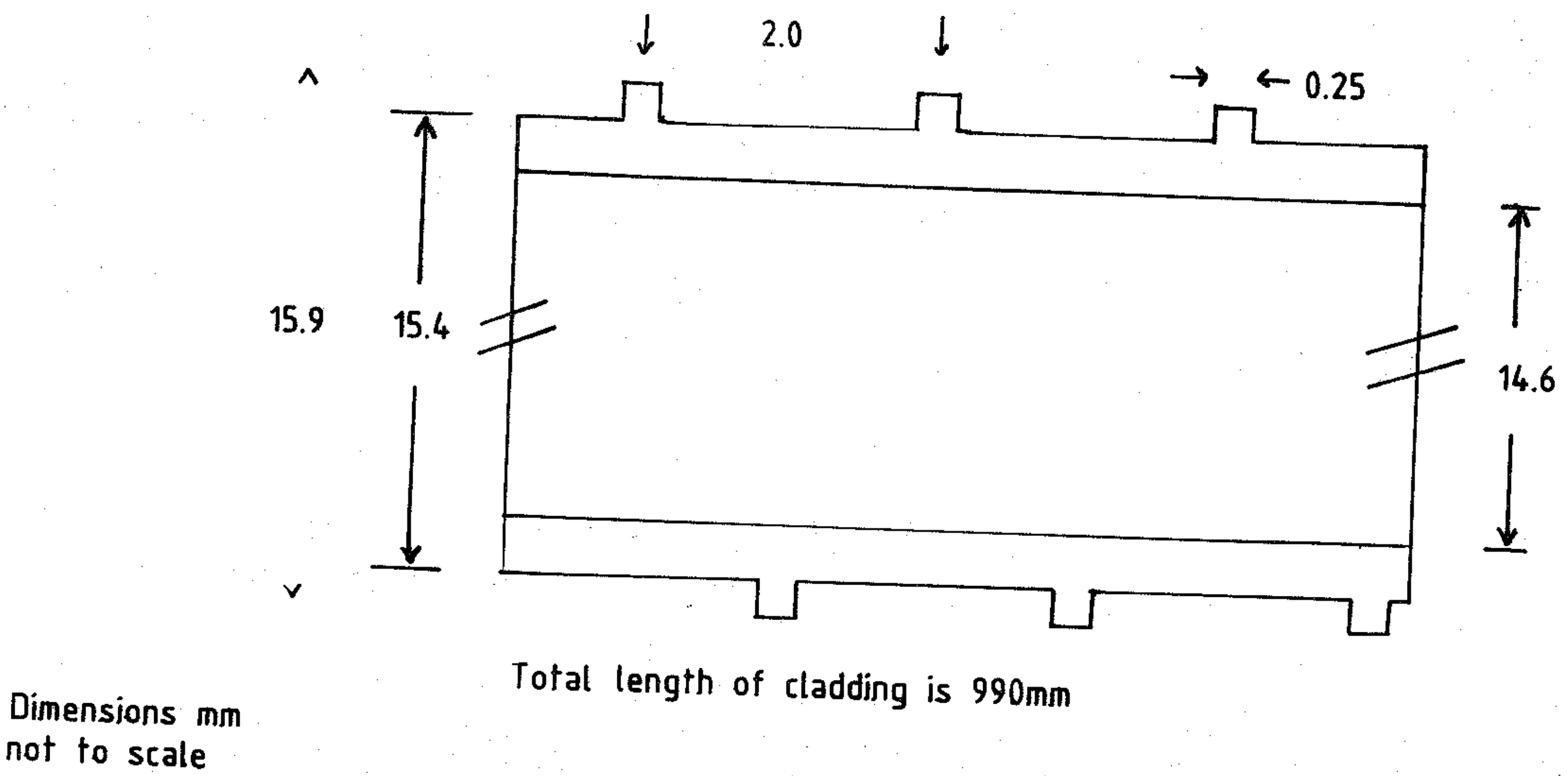


FIG 1 SECTION THROUGH HELICALLY-RIBBED AGR CLADDING

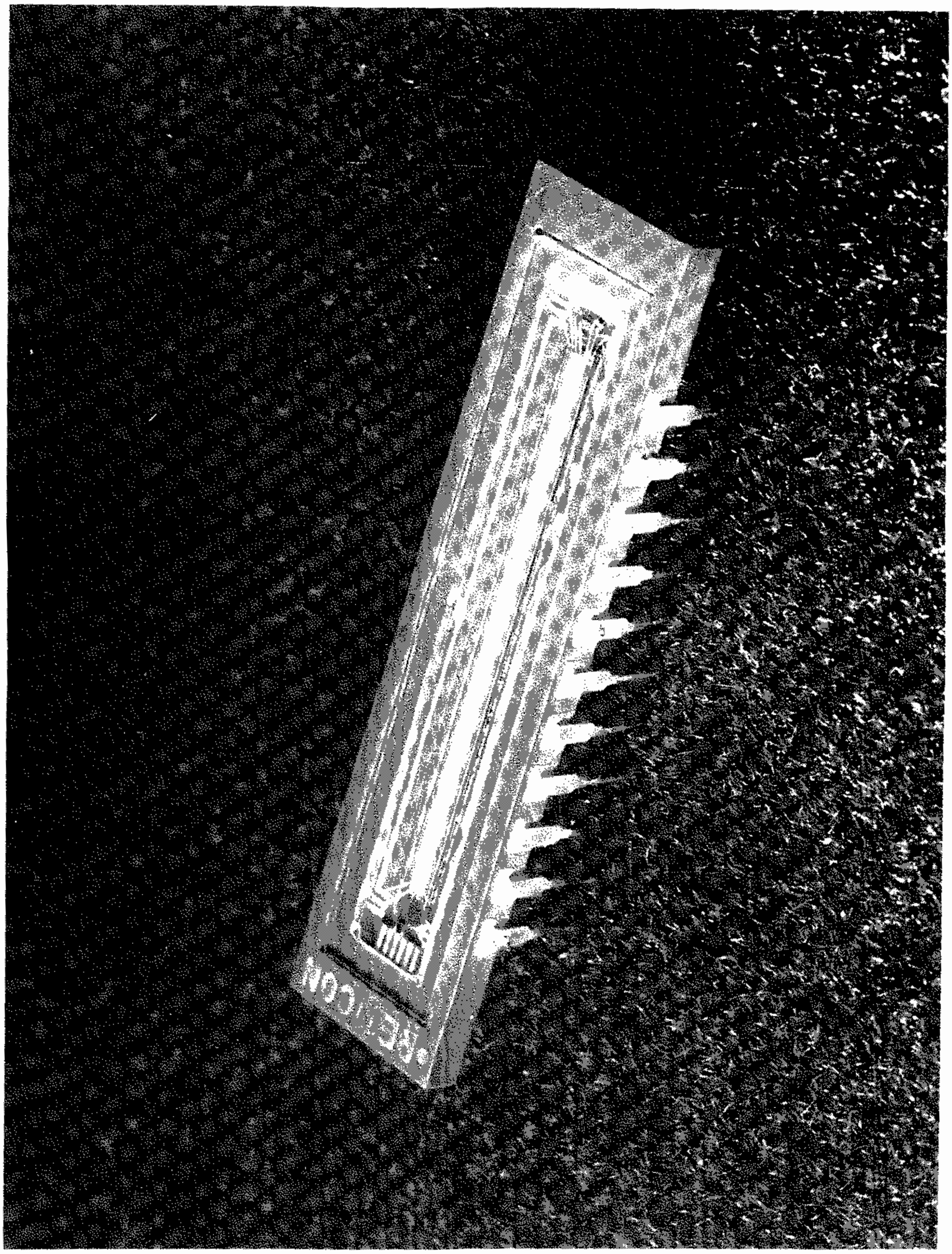


FIG 2 PHOTODIODE ARRAY DETECTOR

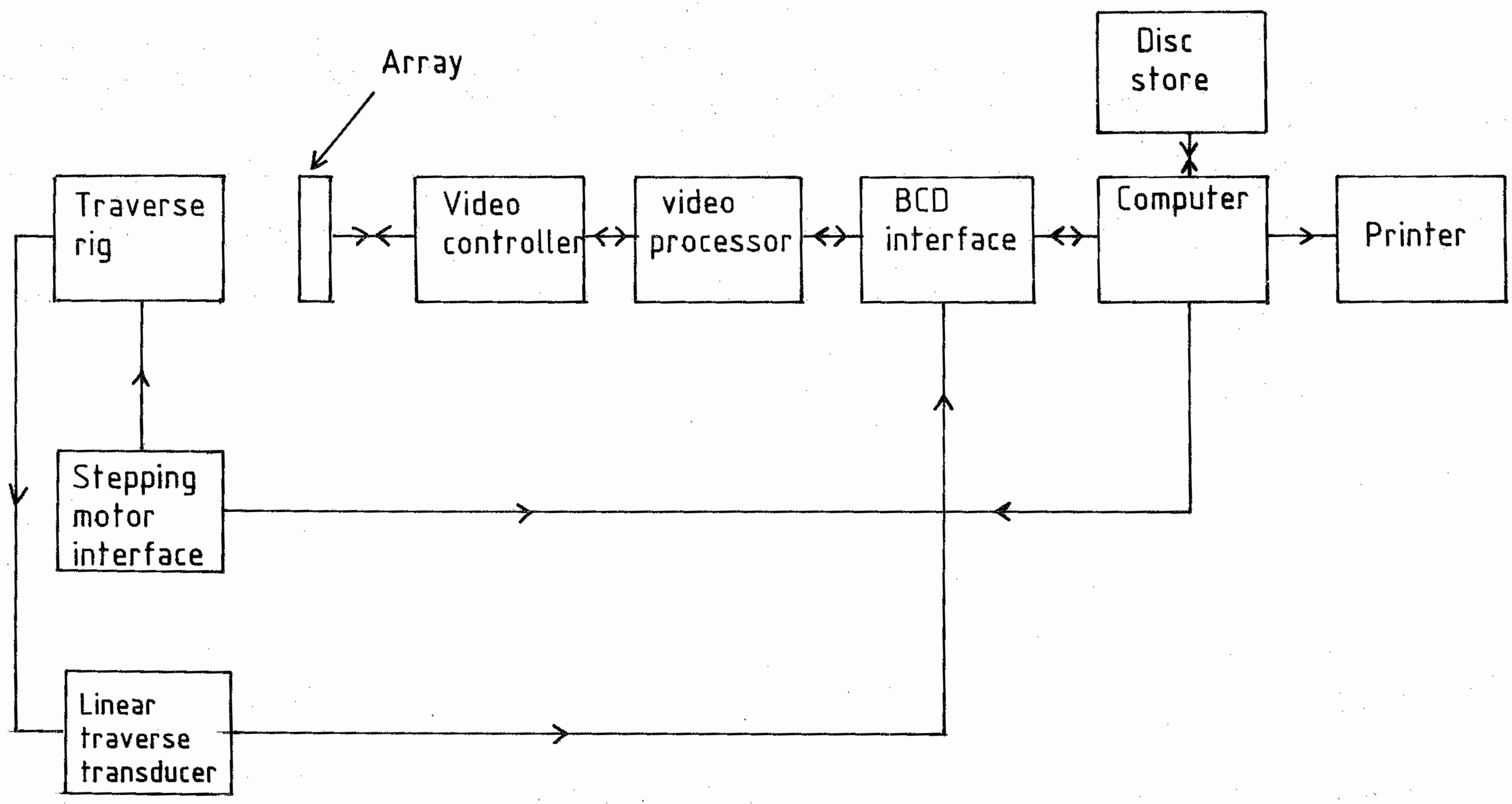
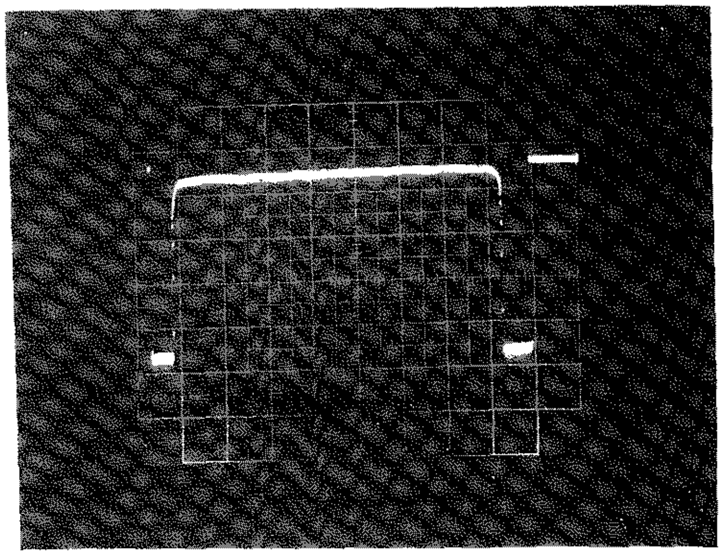


FIG. 5 ELECTRONICS (SCHEMATIC)



-100% dark

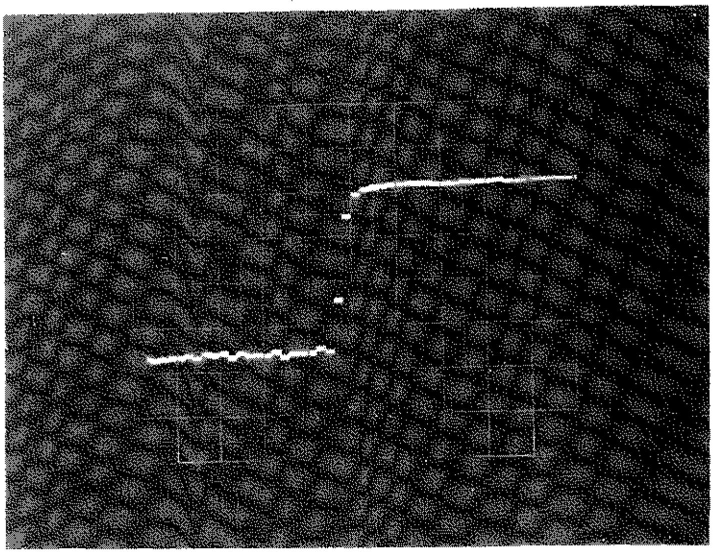
-100% light

Vertical : 0.2V/major div

Horizontal : 2 ms/major div

The dark image covers 1490 out of the 1728 photodiodes

FIG 6 VIDEO OUTPUT SIGNAL OBTAINED FROM THE SILHOUETTE IMAGE OF A FUEL ROD



100% dark

100% light

Vertical : 0.2V/major div

Horizontal : 50 us/major div

Clock frequency of photodiodes is 100kHz

FIG 7 KNIFE-EDGE RESPONSE OF THE ELECTRO-OPTICAL SYSTEM

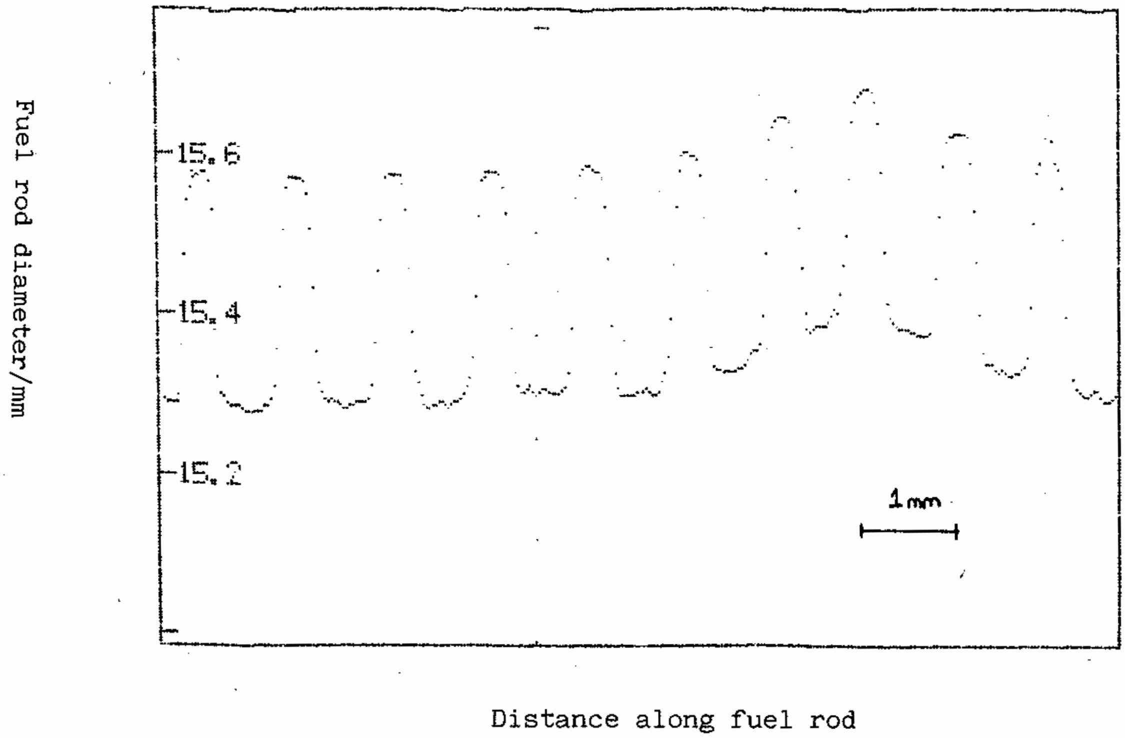


FIG 8 PRINT-OUT OF A COMPUTER GRAPHICS DISPLAY SHOWING THE DIAMETRAL VARIATIONS ALONG A SECTION OF UNIRRADIATED AGR FUEL ROD

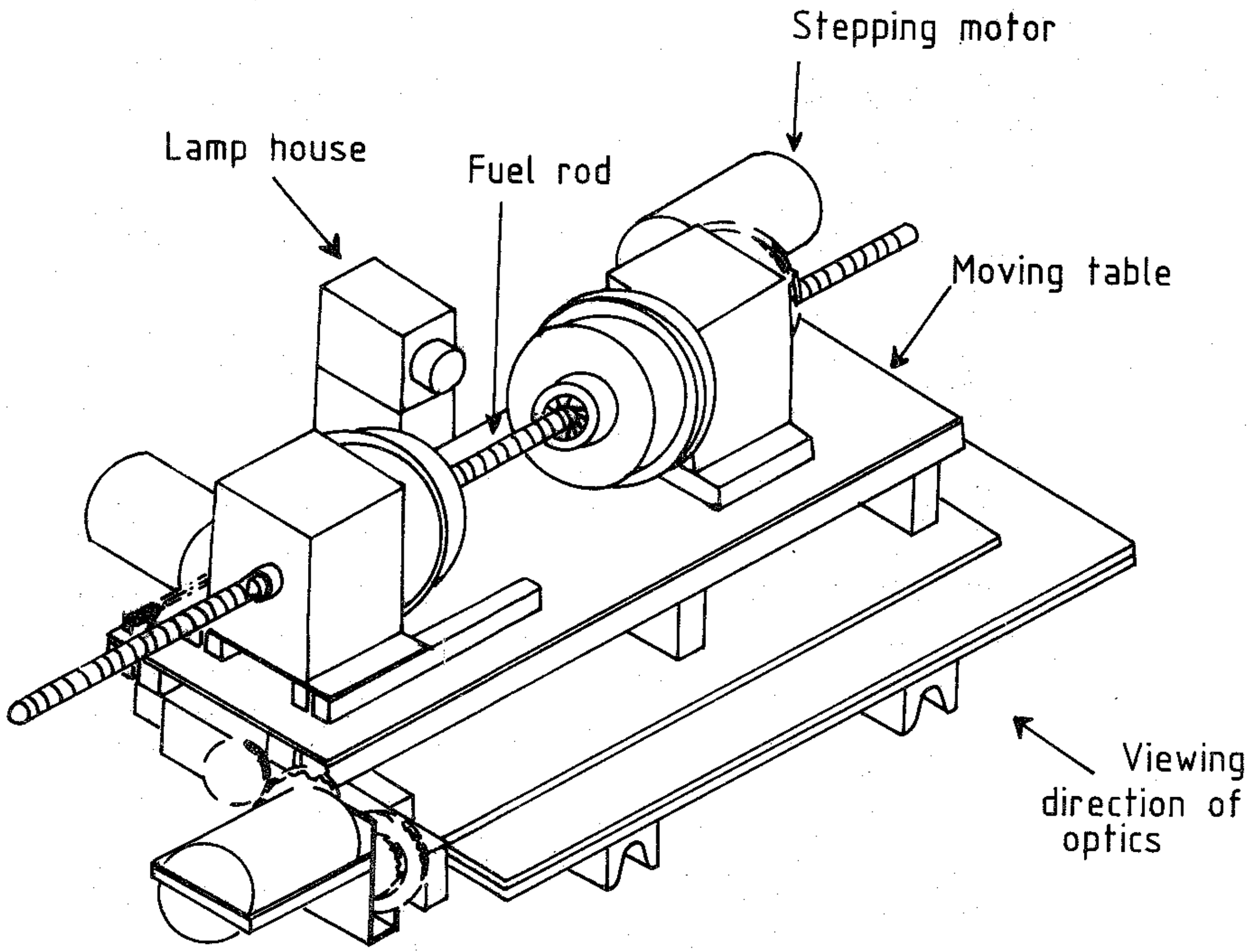


FIG. 9 IN-CAVE PIN HANDLING RIG

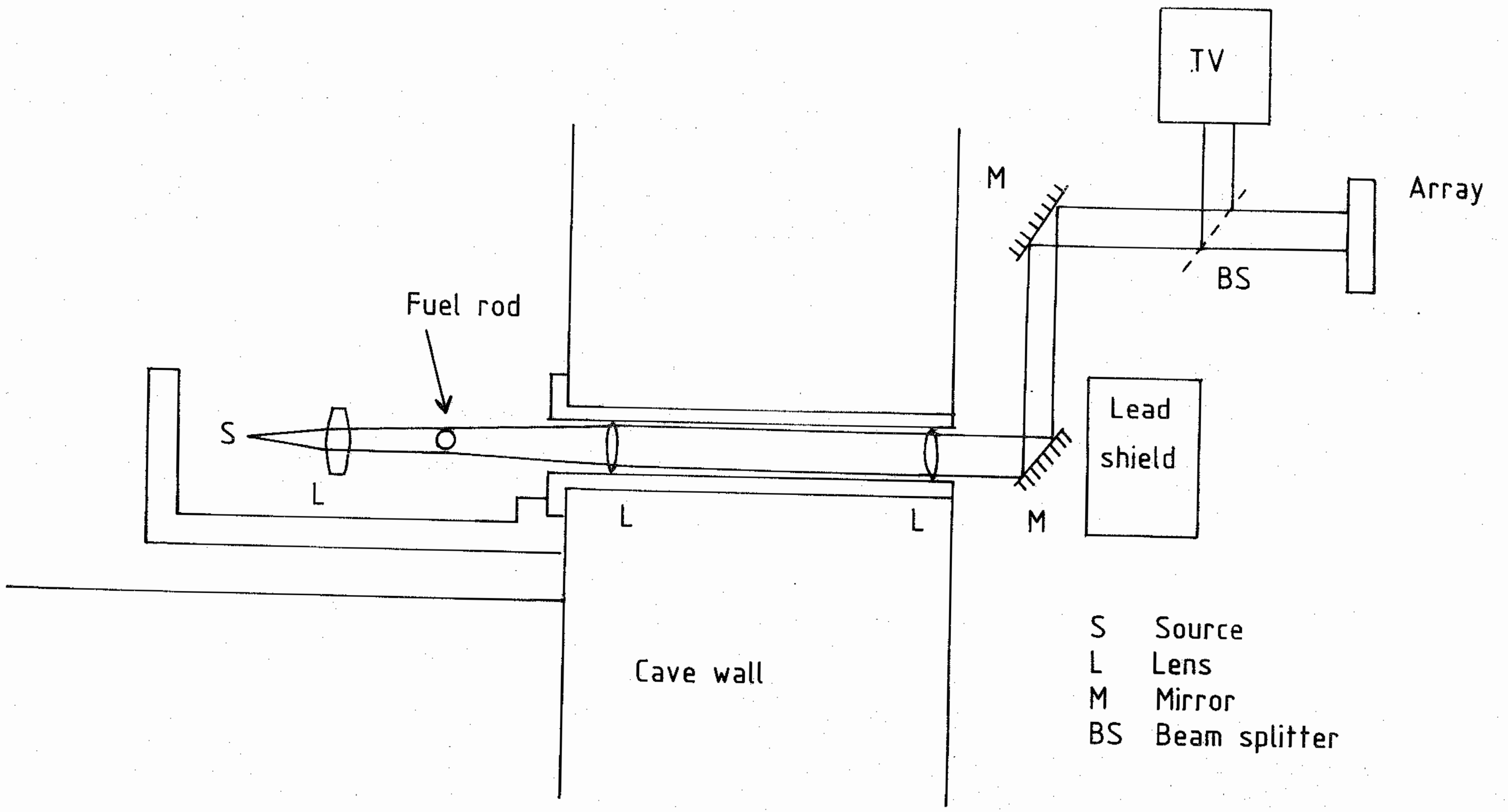


FIG. 10 PHOTODIODE MEASURING SYSTEM

DISTRIBUTION

Mr A C Demildt	SCK/CEN-LHMA, 200, Boeretang, B-2400 Mol, Belgium
Mr G Böhme	Kernforschungszentrum Karlsruhe, Abt. RBT-IT, Postfach 3640, D-7500 Karlsruhe, Federal Republic of Germany
Mr H Müller	Kernforschungsanlage, Heisse Zellen, Postfach 1913, D-517 Jülich 1
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Mr G Samsel	Europäisches Institut für Transurane, Postfach 2266, D-7500 Karlsruhe, Federal Republic of Germany