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LOW COST RADON DETECTOR BASED ON SPARK DISCHARGE TECHNOLOGY

Report of Research
Prepared for CMHC
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EXECUTIVE SUMMARY

A portable radon detector has been successfully developed based on spark discharge technology . This detector was found to have a sensitivity to radon of 0.045 cpm/pCi .

Research focused on the development of a low cost ,high voltage supply, counting systems , various sensors , and a radon daughter electrostatic collector . Sensors based on conventional technology were constructed , optimised for sensitivity , simplicity of fabrication and stability . Sensors based on thin foil technology failed to function as expected and research was discontinued .

Testing was ongoing throughout the project . The first detector (prototype I) constructed during phase I and tested during phase II proved insensitive to radon at levels of 50 pCi/l . A new prototype detector (prototype II) employing a 101 radon daughter electrostatic collector and a conventional sensor as defined in phase I was therefore constructed and found to perform acceptably at the target radon level of 4 pCi/l.

The sensitivity of prototype II was found to deteriorate with time due to the buildup of some unidentified material on the anode wires . This problem is probably resolvable with more research and a fully operational low cost detector suitable for the housing market achievable.

Inductive , capacitive and direct coupling of the electronics and sensor were successfully employed . Count events were translated into a flashing LED, an audible beep or recorded on an LCD display . The electronic systems proved to be very reliable and withstood catastrophic breakdown of the sensor during early development stages .

Materials , components and labour for the prototype detector totaled $100 . In production , a commercialized version would probably cost about $50, a price that would be attractive to most concerned elements of the housing industry.

This report does not include the prototype II testing results from the CANMET ,Elliot Lake Laboratories since the detector was damaged in transit to the laboratory and no response was observed over a one day test period. The sensing and counting modules had disconnected from the sensor with the result that no response was recorded. The reference radon system used at Instruscience was however successfully calibrated in parallel at Elliot Lake to confirm work on the Prototype II detector at Instruscience and reported in this study.

The failure to test properly was considered unfortunate but not a development problem . The detector will be returned for calibration after more extensive testing at Instruscience.

1. LITERATURE REVIEW ON SPARK DISCHARGE TECHNOLOGY AND BACKGROUND TO RESEARCH STRATEGY

CONVENTIONAL TECHNOLOGY

The spark discharge detector was originally developed by Gremacher(1) ,Rosenblum(2) ,Pidd(3) , and Payne(4) . The counters consisted of small gauge 0.076mm stainless steel wire anodes stretched between insulators and maintained at high positive voltages usually in the range of 3 to 10 kv . The anode was normally separated from a grounded cathode by a narrow air gap of about 1mm . The high voltage generates an ion sheath around the narrow gauge anode . When an alpha particle from radon passes between the sheath and the ground plate , the former is shorted along the path of ionization of the alpha particle and a spark discharge occurs . By connecting a capacitor between the anode and cathode the sparks become visible and audible and can be recorded by sensing a capacitance or voltage change or even by optical or acoustic methods .

These early devices , although extremely simple , were not very sensitive ; the sensitive volume being defined by a narrow band of 1mm around the high voltage anode wire (5). Thus in an effort to improve performance a variety of multiwire detectors were built (5-19) . These devices consisted of parallel single wire anodes , a common cathode ,and operated in air or specialized gases(19). In most cases they were sensitive to alpha radiation and exhibited a plateau . Of special interest was an imaging alpha detector developed by HASL(11) where the claimed counting efficiency of 50% is better than for a conventional proportional detector(4).

Multiwire spark chambers in various forms are being increasingly used for high energy physics research because of simple inexpensive construction , the possibility of large sensitive areas and high response speed (15,16). Several new spark detectors with resistive electrodes have been developed(17,18) which are capable of detecting cosmic ray showers.

Although the spark discharge detector has been developed for over forty years , there is only minimal information available on their long term performance in open air and nothing about their suitability for radon detection . The technology is viewed as qualitative although in many cases(4,36) quantitative information was obtained about sensitivity and plateau shape.

Since the simplicity , cost and performance ,of these detectors was attractive , there appeared to be an opportunity to develop a radon detector with unique cost/performance characteristics provided that quantitative , reliable , long term operation be achieved . This report presents the results of a study to examine the feasibility of developing a low cost radon detector based on spark discharge technology.

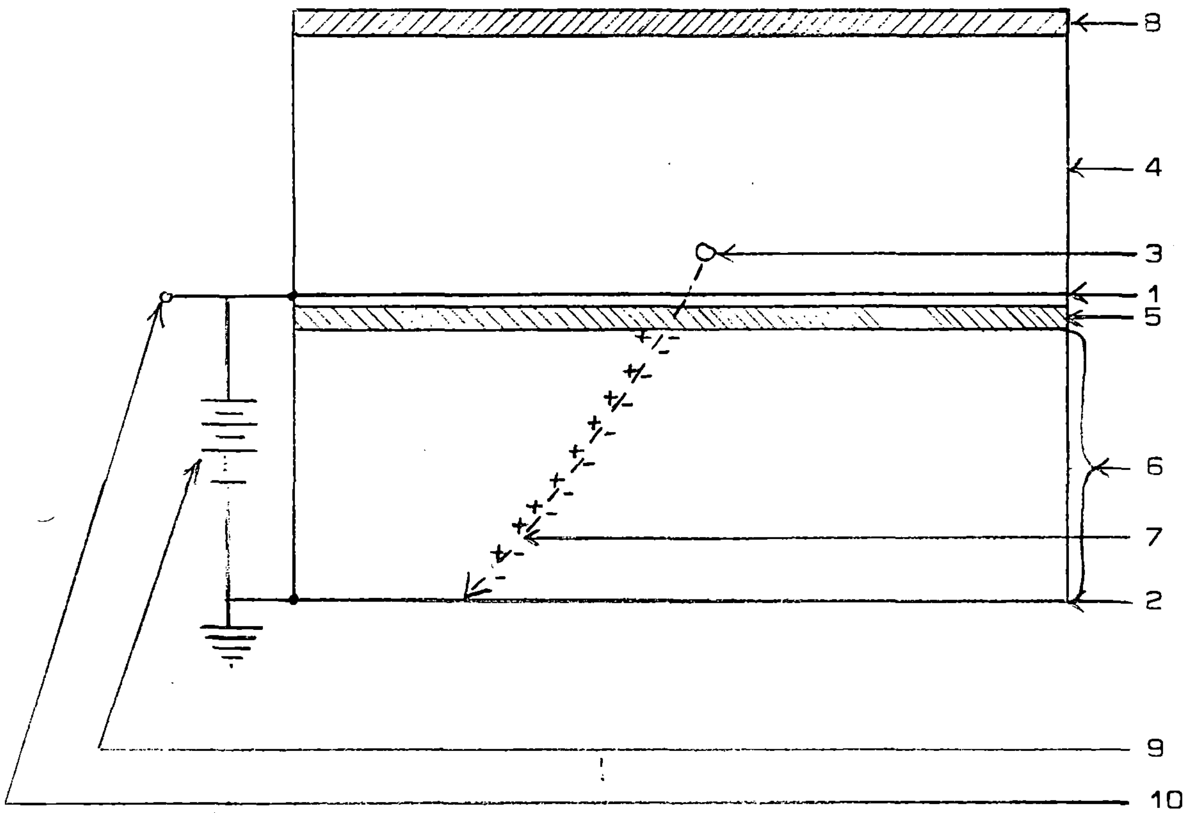
FOIL TECHNOLOGY

The spark discharge counter has been used to count alpha tracks in thin 10μm foils for a number of years (20-33), the number of tracks observed being proportional to the radon level. Physically, the foil is first etched to enlarge the alpha tracks and then placed between the high voltage electrodes of the counter. A voltage of about 500v is applied to cause a discharge in one track. The discharge proceeds until the aluminum around the hole is vaporized, increasing the resistance. At this point the discharge proceeds to the next hole and the process repeated until all the holes are counted.

Based on this concept, a second research strategy was formulated to examine the feasibility of using an ultrathin aluminized foil as an alpha particle detector. By applying a sufficiently high voltage to both sides of the foil, in the same manner as for a spark discharge detector, it should be possible to produce a breakdown discharge simultaneous with the passage of an alpha particle, the discharge being related to the characteristics of the foil and the nature of the hole melted as the particle traverses the foil. Several thin film detectors based on silicon have been successfully developed for fission fragments (34,35) but the authors have not yet successfully detected alpha particles.

The proposed radon detector based on this strategy is presented in figure (1) and a detailed description presented in appendix A.

SPARK DISCHARGE DETECTOR



1 Charged Plate
2 Charged plate
3 Alpha Particle
4 Radon Diffusion Chamber
5 Dielectric
6 Air Gap
7 Path of Ionization
8 Radon Diffuser
9 Potential Difference
10 Ouput

F I G U R E 1

2. GENERAL BACKGROUND ; NEED FOR WORK AND WHO WOULD BENEFIT

Radon gases , Rn220 or Rn222, are naturally occurring radioactive materials which originate from the trace levels of Uranium in rocks and soil . Uranium is uniformly distributed in the environment but at some locations radon is able to escape the parent material and diffuse into surface dwellings where substantial levels may build up .

Radon usually enters a building via soil or water pathways ; the level of radon in a particular dwelling being a function of building design , windspeed , pressure differential across the basement wall , soil and rock type and the effectiveness of sealing in the basement area . The level is also related to the presence of surface covers, diurnal effects , seasonal effects and the occupants living habits . In short , the level of radon in a house is extremely variable and dependent on many factors .

Radon is now recognized as the principal source of radiation exposure to the general public , and is a major indoor air pollutant and a health hazard . The hazard originates from the fact that radon and its daughters are emitters of energetic alpha radiation which can cause serious damage to living tissue .

Most countries, particularly the USA , have ongoing programs of radon monitoring to identify buildings with excessively high levels of radon , with a view to remedial action . Government agencies , measurement companies and homeowners have been actively participating in the program with either expensive direct reading monitors , or with inexpensive methods such as charcoal canisters , Eperms or track etch systems . The latter provide either short term average radon values (1 day to 1 week) or long term approximate results (1 month to 4 months) and do not provide the homeowner or inspector with intermediate period continuous or long term surveillance, or even on the spot measurements . The active sensitive direct reading monitors available are too expensive at $2000 for the homeowner and are purchased only in limited numbers by building inspectors , pesticide companies and contractors . Some lower priced direct reading radon detectors are available but these are marginally sensitive for most applications , require a minimum monitoring period of several days , and are not much of an improvement over Eperms .

There is a need for a low cost , sensitive , direct reading instrument to serve both the needs of the home inspector and homeowner . It would enable the inspector to measure more housing with better accuracy and in more detail . It would also provide the homeowner with a direct reading device for continuous surveillance like a smoke detector , warn him of radon peaks, and monitor the long term effectiveness of remedial action .

3. PROJECT OBJECTIVES

DEVELOPMENT PHASE

1. To develop a radon detector based on spark discharge technology. Conventional , and makrofoil or thin film technologies will be examined.

2. To examine methods of producing a low cost direct reading radon detector; sensors, counting methods , power supplies and methods of packaging will be examined.

3. To design a sensor with low operating voltage , high sensitivity , simple and stable construction . The work will include a literature review and analysis .

4. A suitable sensing method , low cost scaler and low cost readout method must be developed.

TESTING PHASE

5. To establish the performance of the detector at four different radon concentrations in the 0 to 500 pCi/l range.

6. To establish the performance of the detector at three levels of humidity and two aerosol levels at a fixed radon level .

7. To establish the sensor stability over a one week test period.

8. To test the device at a laboratory facility;
   - A 24 hour continuous test at fixed aerosol , temperature and humidity will be made .

   - A 48 hour continuous test at two radon levels will be made.

9. To evaluate the stability of the detector over a long term.

10. To evaluate the performance of various sensing methods (current , voltage , acoustic , optical) .

11 To calibrate the detector .

REPORTING

12. To provide a detailed report of the project to include experimental works , results and conclusions as to the utility of the detector in the housing industry .

4. SUMMARY OF PROGRESS

(i) A literature review has been completed . Conventional spark discharge technology , breakdown technology , and spark counting methods have been reviewed.

(ii) sensors

A number of sensors were developed based on conventional wire technology . Sensor 2 was selected as prototype I ,the first prototype radon detector , based on (i) low background (ii) simple low cost construction ,(iii) low power consumption (iv) excellent stability and (v) an excellent plateau . The wire based sensors were found to suffer from the following shortcomings;

(a)Need for a high voltage supply of 3 to 5 kv ; this was not considered a problem from a safety or cost perspective . The current output was in the low A range with a 40 to 80 MΩ load and inexpensive custom supplies were possible . The shock hazard with a large inline load is negligible with proper packaging.

(b) Low sensitivity ; wire sensors suffered from an angular dependence of the counting efficiency . The efficiency for alpha particle detection at right angles to the plane of the detector was 8% , a value which decreases to 2% for angles of incidence 60 from vertical .

Prototype I , based on sensor 2, responded poorly to radon levels of 50 pCi/l and a new design , prototype II was developed. This detector , which also employed sensor 2 , used an electrostatic focusing technique to enhance sensitivity and an acceptable performance at the target level of 4 pCi/l was obtained. The sensitivity of this detector was 0.04 counts/min/pCi/l , a value which although marginal , can be improved.

(c) Formation of a deposit on the anode wires and ground plate; with time a deposit formed on the sensing wires and ground plate which tended to reduce the corona current , and the sensitivity . The exact cause of this problem has not been completely solved but may arise from organic vapours , dust or other materials in the air reacting with the corona . Measurement periods were prolonged through the use of stainless components , low operating currents , and filtered air .

Sensors based on spark counting or breakdown technology were not successful . A variety of materials , thicknesses and configurations were attempted . In all cases no output signal could be detected . Even at high operating voltages , and with sensitive electrometer amplifiers no breakdown signal was observed . Detection difficulties were compounded by noise, small signals and very fast signal speeds .

(iii) Electronics

(a) Direct , capacitive, and inductive coupling between the sensor

and counting electronics was employed successfully .
(b) Output data was presented simply in the form of a flashing LED , an audible beep , and a low cost LCD counter
(c) High drive voltages for the sensor and electrostatic cage were provided by either low cost custom designed supplies or supplies from bug killing devices and electrostatic air cleaners.

(iv) Packaging

A preliminary low cost plastic package was developed .

(v) Prototype detector

The phase one detector was essentially sensor 2 . Since this detector was insensitive to radon at levels of 50pCi/l a new prototype radon detector was constructed and tested in phase II .
This detector, presented in figure(8) , consists of sensor 2, an apex focusing system with a 10l sensitive volume , a collector , a high voltage driver and readout devices which include a counter , an LED and a buzzer.The sensitivity of this detector was found to be 0.04 cpm/pCi/l with a minimum detectable level of 1pCi/l, a sensitivity value which meets USEPA compliance levels of 4pCi/l.
The prototype was insensitive to dust since air entering the sensitive volume was filtered.
The sensitivity of the prototype detector decreased slowly with time due to the slow buildup of a white powder on the wires and ground plate . This problem may be due to the decomposition of vapors from construction plastics or from the surrounding air in the corona and has not been quantified. Further research is required to solve this problem since it is the only outstanding obstacle to the development of a low cost detector for the homeowner.
The performance of the pulse detection , counting and high voltage systems was excellent over the eight month test period . The units withstood catastrophic breakdown of the detector for extended periods and proved very resilient and reliable.
The prototype detector was damaged by exposure to extreme temperatures of - 20 C due to the use of materials with dissimilar expansion coefficients . This problem was easily rectified by careful component selection .
The detector as tested was not sensitive to humidity in the range of 30% TO 70% . This result is unexpected since electrostatic fields are normally affected by humidity and hydrophobic membranes are employed to keep the sensitive volume moisture free .

5. DEVELOPMENT OF THE PROTOTYPE DETECTORS ; DESCRIPTION AND EXPERIMENTAL

Development work on the prototype detector centered on the following elements;

(i) The sensor
(ii) The electronic systems
(iii) The prototype detectors
(iv) Ongoing testing to define and optimize performance at various stages of the project.

5.1 THE SENSOR

RESEARCH ON THIN FOIL SENSORS

During the first phase of this project the suitability of thin metallized foil films as alpha particle detectors was examined . Background to this approach is found in references (12- 35) and Appendix 1.

Experimental

The basic experimental setup is presented in figure (2). Film densities of 0.1mg/cm to 1mg/cm ,voltages in the range 0 - 1000v and various plastics such as kapton , mylar , teflon and polyethylene coated with either aluminum or gold were examined . A high gain electrometer ,standard B&K oscilloscope and a 7000 dpm Am 241 alpha particle source were employed in all measurements

Results

No signal was observed for these sensors . Either the noise level interfered with detection of the weak signals or the signal was too fast for the detection electronics. In either case the probability of producing a low cost sensor via this approach was considered poor and a parallel development strategy based on conventional wire technology was initiated . No success was eventually achieved with the foil technology although the following were attempted .

(i) Increased shielding to reduce noise
(ii) Reduced output capacitance to increase electrometer gain
(iii) Pulse stretching techniques to reduce signal speed
(iv) Higher gain electrometers

Although minimal results were obtained , the concept proposed here is valuable enough to warrant additional investigation and the company intends to continue the study at a convenient time .

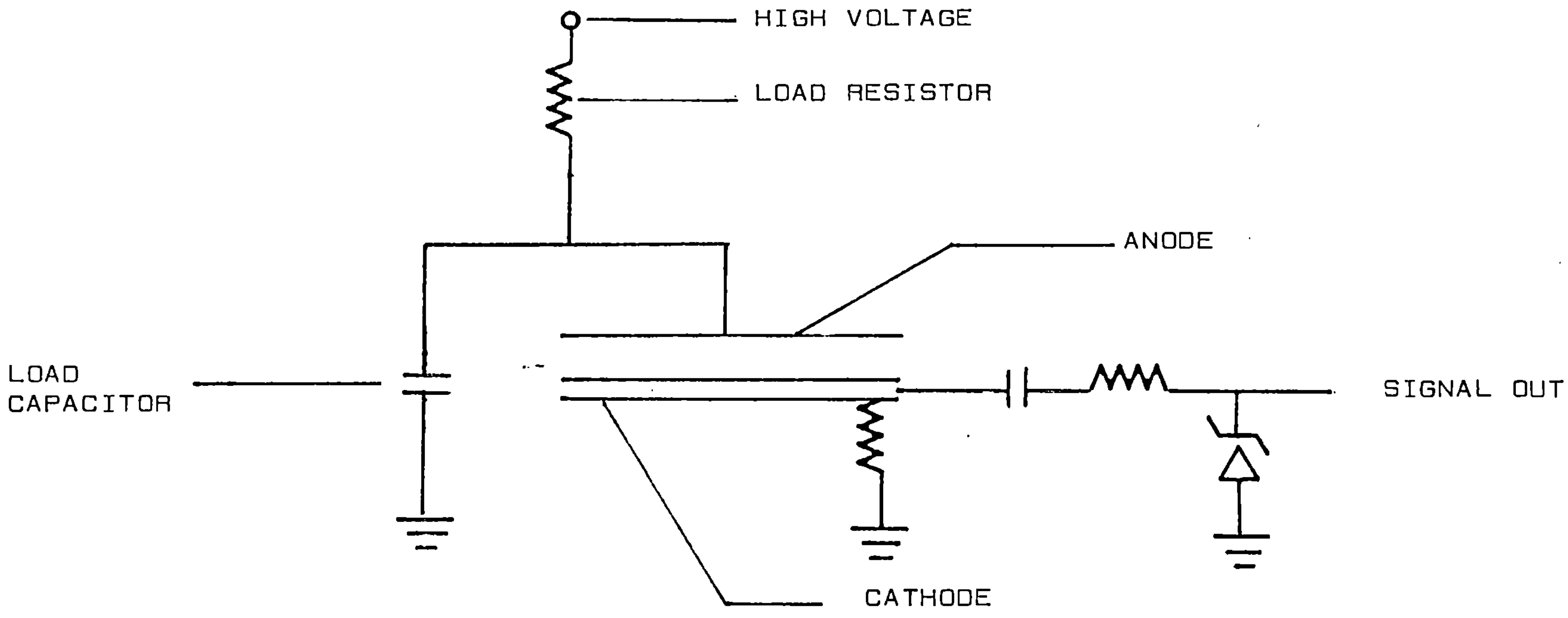


FIGURE 2 TYPICAL TEST SETUP FOR SENSORS

CONVENTIONAL TECHNOLOGY

SENSORS 1,2,3,4

Several sensors were examined. These are presented in figures (3 -6). The objective was to produce low cost , simply constructed , sensitive , reproducible , stable configurations which are safe.

Experimental

All sensors employ multiple parallel thin wire anodes of 0.05mm to 0.127mm diameter and planar cathodes of stainless plate , mesh or large diameter wire ,spaced at distances of 0.76mm to 2.28mm anode to anode, and anode to cathode. Voltages of 2400v to 5000v were applied. Load resistances varied from 1 Ω to 100 M Ω and capacitances from 10 pf to 0.002 μf. Two Am241 sources, a 7000 dpm point and 24,000 dpm (2.54 cm diameter) extended source, were employed for testing and calibration . Humidity was measured with a standard sling psychrometer ,and temperature with a standard thermometer.

Description of sensors

SENSOR 1

See figure (3) .The hv anode wires in this sensor are simply wrapped around the PVC-VERO frame in a continuous fashion and fastened to the frame with mounting screws. A uniform spacing between anodes is maintained by the VERO framework . A copper strap across all anodes maintains each anode at the same Hv potential . This sensor is the simplest to construct of the four designs attempted .

SENSOR 2

See figure (4) .The high voltage and guard wires which are parallel are wrapped successively around the PVC-VERO frame in a continuous fashion and fastened to binding posts . The anode-guard spacing is maintained at about 1.52 mm by the VERO frame and both wires are separated from the cathode plate by the same distance .The anode:guard wire diameters are maintained at less than 0.3 to minimize background.

SENSOR 3

See figure (5). The construction of this sensor is similar to 1 or 2 above but with the sensitive volume on both sides of the frame . A wire mesh screen is used for the cathode to permit alpha particle passage through both sensitive volumes in an attempt to increase sensitivity .

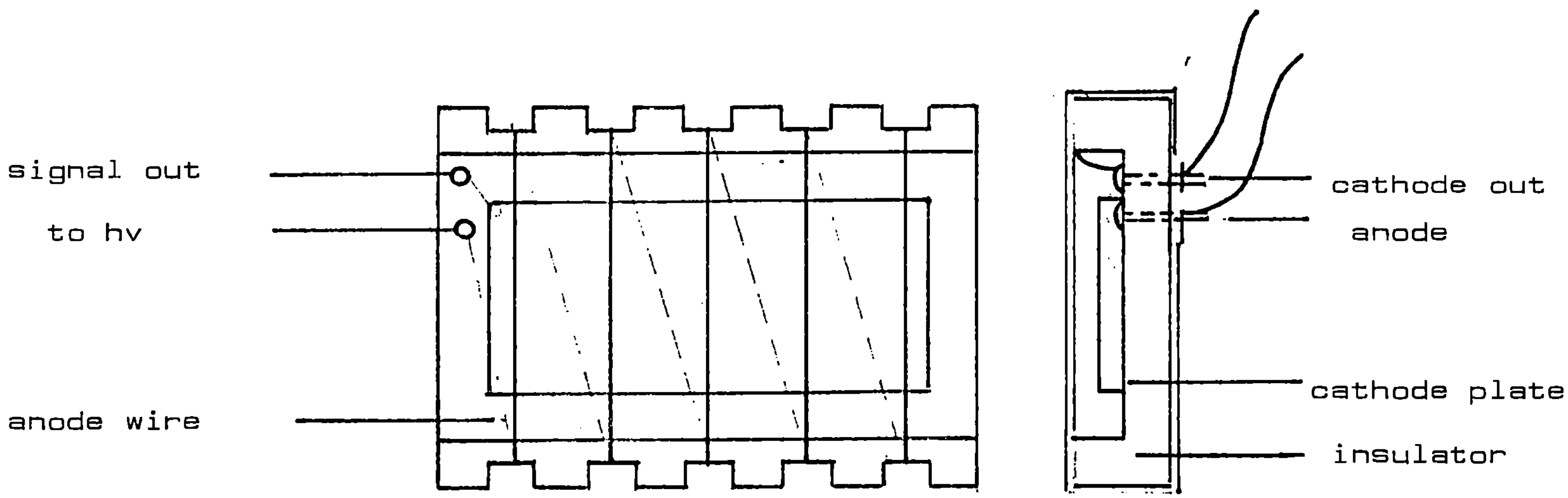


Figure 3 sensor 1

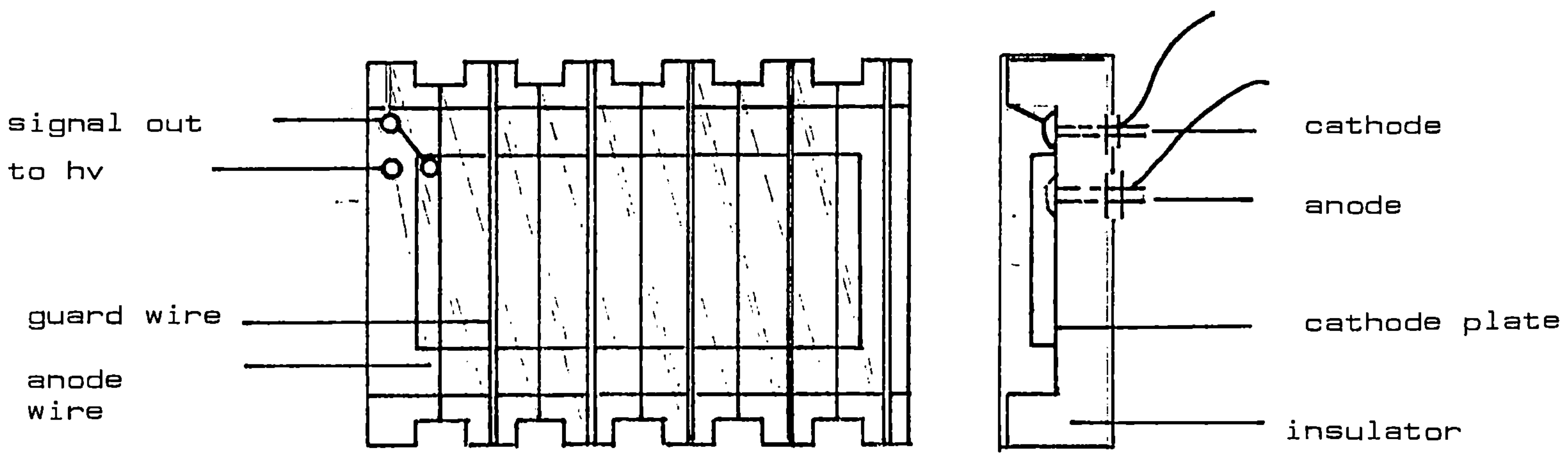


Figure 4 sensor 2

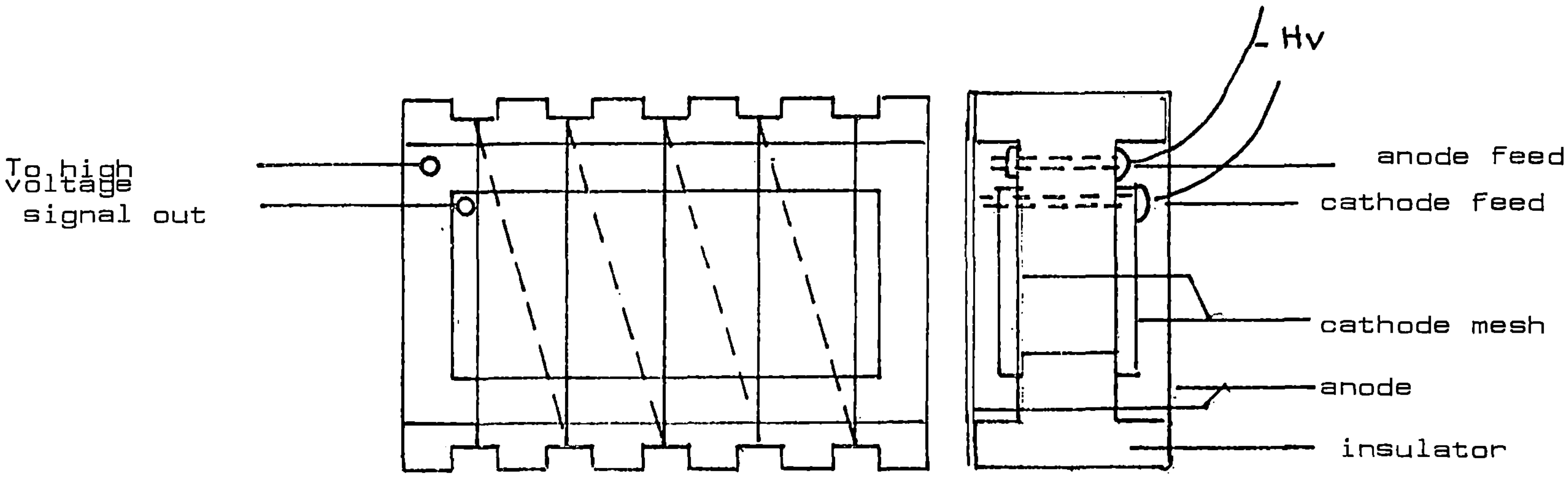


Figure 5; layered sensor

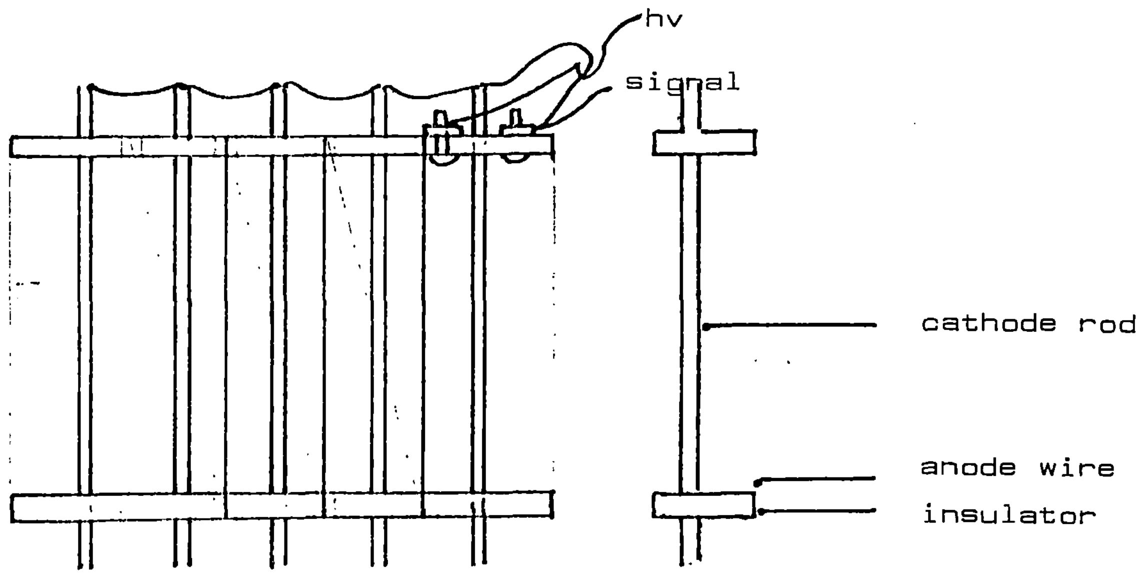


Figure 6 parallel rod sensor

SENSOR 4

See figure (6). The construction of this sensor is based on parallel 3mm rods and 1.52 mm anode wires. The anode wires are wrapped around the VERO frame in a continuous fashion and mounted to binding posts. This design is an attempt to increase sensitivity by presenting the sensitive volume of the detector broadside to the source.

SUMMARY OF EXPERIMENTS PERFORMED ON SENSORS

The following is a guide to the numerous experiments preformed on sensors 1 to 4 to study and optimize their performance.

E1 Wire spacings anode-anode ,anode-guard

E2 Anode-cathode gap

E3 Anode:guard wire ratio of diameters

E4 Materials and construction techniques

E5 Anode diameter

E6 Capacitive and resistive loading

E7 Sensitivity and response
- E7.1 plateau shape (high voltage vs count rate)
- E7.2 uniformity of detection across sensor
- E7.3 source-detector geometry and sensitivity

E8 Long term stability

E9 Background and spurious counting

E10 Humidity and temperature effects

E11 effects of dust and VOCs

The parameters E1 to E11 will be referred to in the text of subsequent sections .

SENSOR I

Results

(1) Studies on E1, E2, E5, and E7.1 are presented in figures (7 and 8).

(i) Anode wire sizes of 0.05mm , 0.0762mm, and 0.125mm diameter were examined .Although sensitivity increases with wire size , larger wires require higher drive voltages in air .

(ii) Anode-cathode gaps of 0.76mm and 1.52mm were examined . Sensitivity is higher with decreased gap but at higher voltages sensitivity is the same for both gaps studied . For smaller gaps the tendency to arc increases as does background.

(iii) Plateau shapes are well defined for most operating conditions

(iv) Corona onset is at lower voltages with smaller wires

Conclusions

(i) An optimum sensitivity is achieved with an 0.076mm anode wire size at an operating voltage of 3.5 to 4.0kv . Larger wire sizes require higher voltages for corona onset ;a 0.125mm wire requires 5 Kv in air , a voltage which may result in increased background .

(ii) Current requirements at constant sensitivity decrease with increased wire size making lower cost power supplies possible. An anode wire size of 0.076 mm in air is a practical compromise between sensitivity and cost.

(iii) Although background decreases with increased anode-cathode gap ,an 0.076 gap is an optimum compromise between background , sensitivity, and cost.

Importance for the prototype detector

An optimum tradeoff between sensitivity , high voltage, background and cost can be defined for the prototype detector.

2. The results of experiments which establish E7.3 are presented in figure (9).

Experimental

All measurements were made under the following conditions ; Hv= 3.5 kv, load= 2MΩ. capacitance = 0.002μf, T=19°C ,H= 70% , anode wire size = 0.076mm, gap =1.52mm

Results

(i) The count rate observed reached a maximum value at a 2.54mm distance from the detector .

FIGURE 7 VARIATION SENSITIVITY AND CURRENT WITH HIGH VOLTAGE AND ANODE WIRE SIZE-SENSOR 1 ANODE-CATHODE GAP= 1.5mm

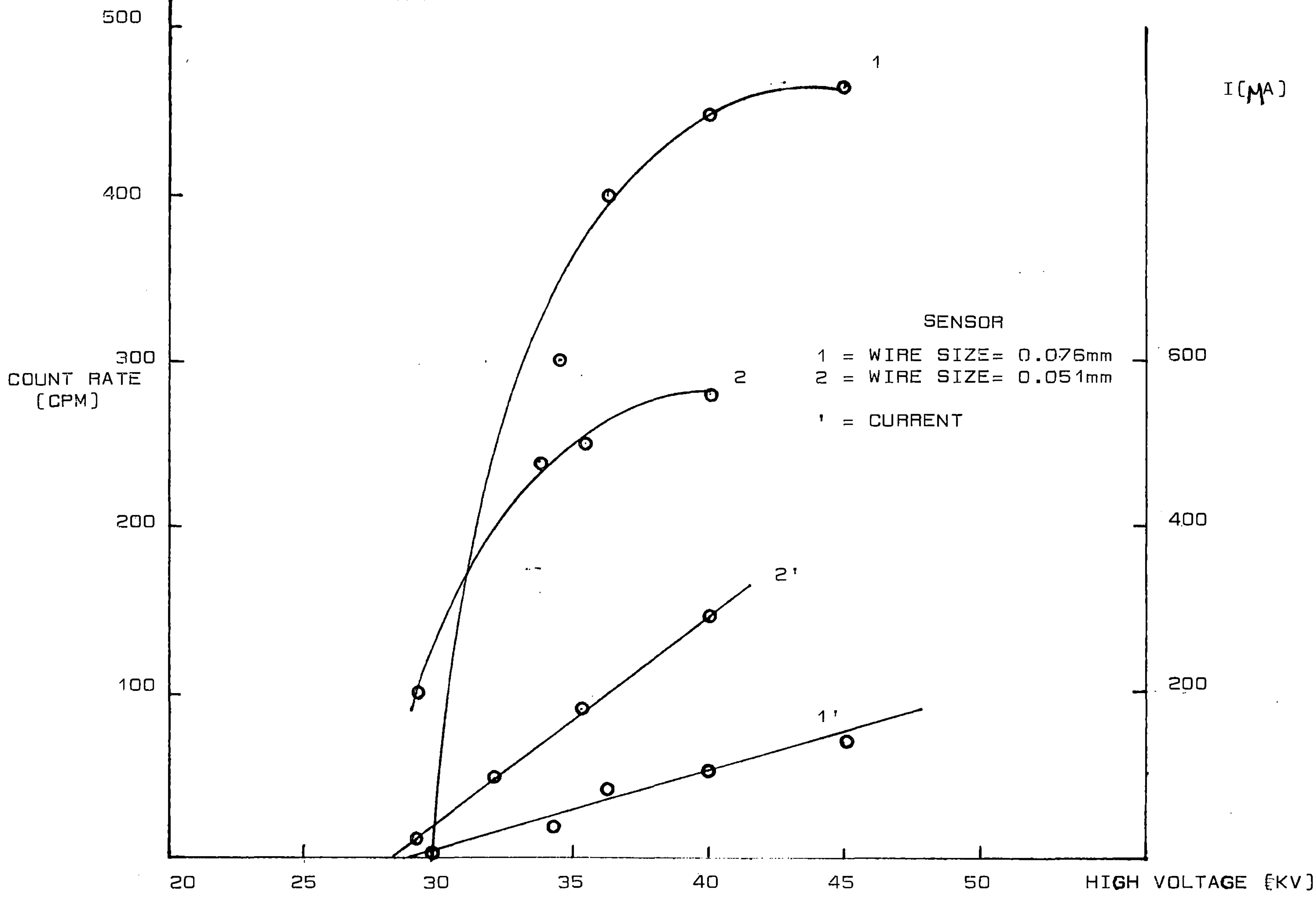


FIGURE 8 VARIATION SENSITIVITY AND CURRENT WITH HV AND ANODE WIRE SIZE-SENSOR 1 ANODE-CATHODE GAP = 0.76mm

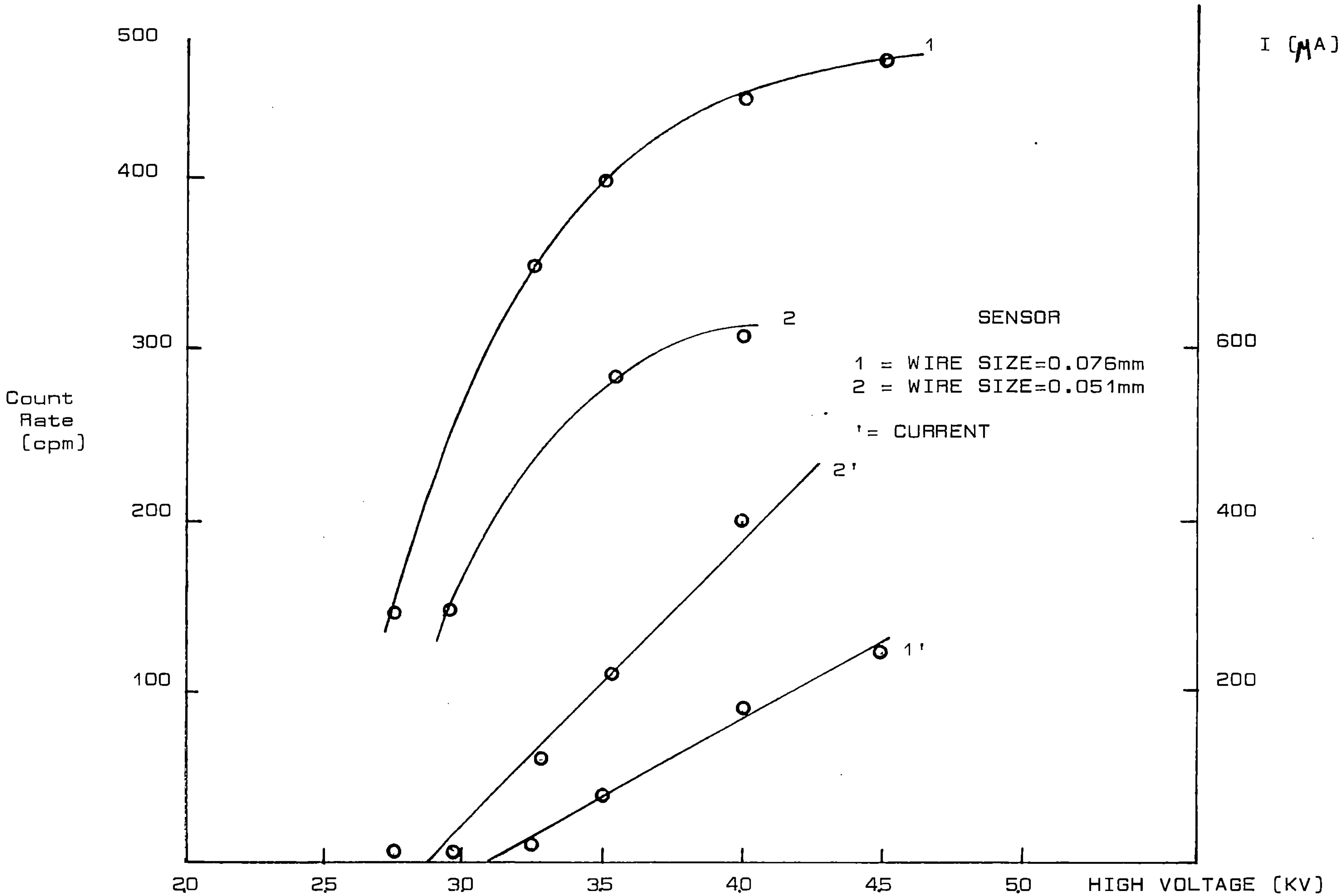
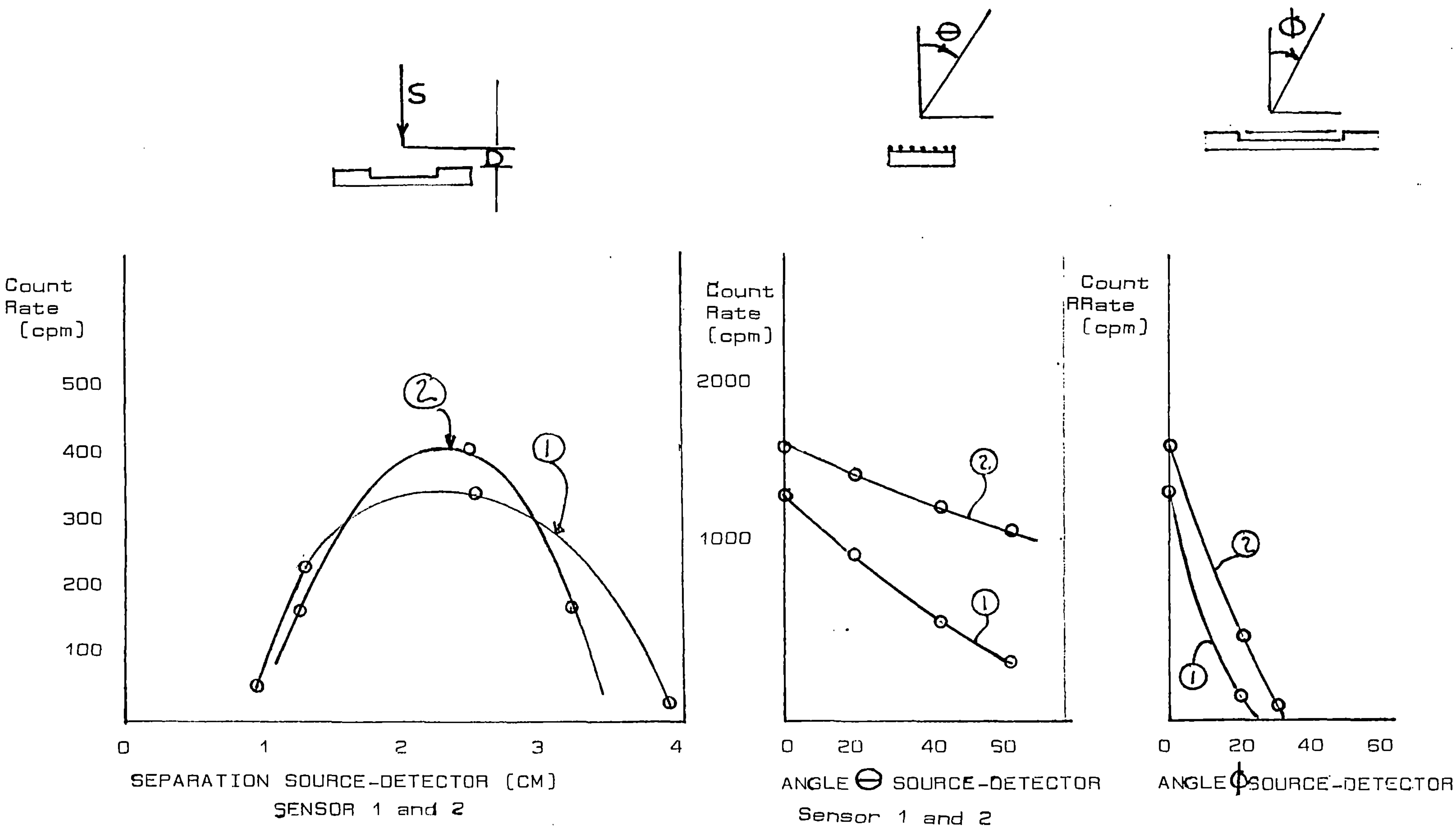


FIGURE 9 EFFECT OF SOURCE-DETECTOR GEOMETRY
ON COUNTING EFFICIENCY



(ii) The count rate fell off with increased angles and
(iii) The measured count rate reduced sharply with increased angle from the vertical.

Conclusions

The sensitivity of the detector is very dependent on the source detector geometry. An optimum distance of separation of 2.5 cm in air and an optimum angle of 0° is defined. The insensitivity of the detector to alpha radiation along angle ϕ has not been previously noted.

Discussion and importance for prototype detector

Based on these experiments an optimum distance of separation of the collector and sensor can be defined for the prototype radon detector II, where radon daughter progeny was concentrated by an electric field onto a collector located near the sensor.
The poor angular response of sensor 1 to a point source suggests that this sensor will show a low sensitivity to an extended alpha particle source (2.54 cm diameter). This was confirmed experimentally and a counting efficiency of about 2% was determined as compared with ~8% sensitivity for a point source. This result means that the prototype radon detector II will have a ~2% counting efficiency for radon progeny present on the collector (See section 5.4) , an important design criterion.

3 Studies of E6 are presented here.

Experimental

All measurements were made under the following conditions ; T= 20°C , H = 70% , anode wire = 0.076mm diameter ,

Results

See figures (10 and 11) for the effect of external resistors and capacitors on sensitivity .

(i) The sensitivity at low currents is directly a function of current . Increasing the applied voltage increases sensitivity . At low resistance the sensitivity becomes independent of the applied voltage .
(ii) For small loads sensitivity is not affected by capacitance changes in the range 200 pF to 0.002μF. At higher loads the detector sensitivity is reduced inversely with the capacitor size.

Conclusion and importance for the prototype radon detector

To achieve reasonable low cost performance the sensor was operated with a 44 MΩ load at 3.5 Kv with a 100pF capacitance(5).

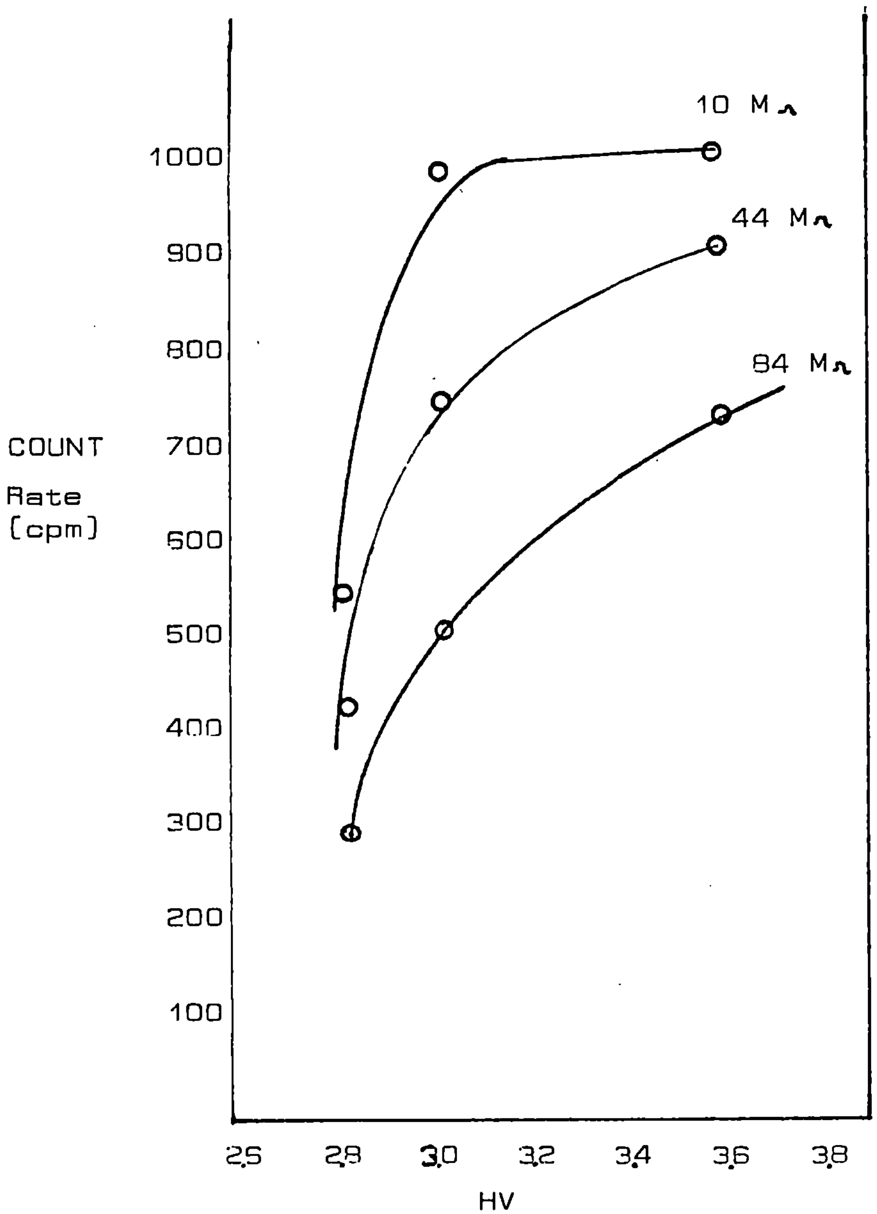


FIGURE 10 COUNT RATE vs HV AT VARIOUS RESISTIVE LOADS
SENSOR 1

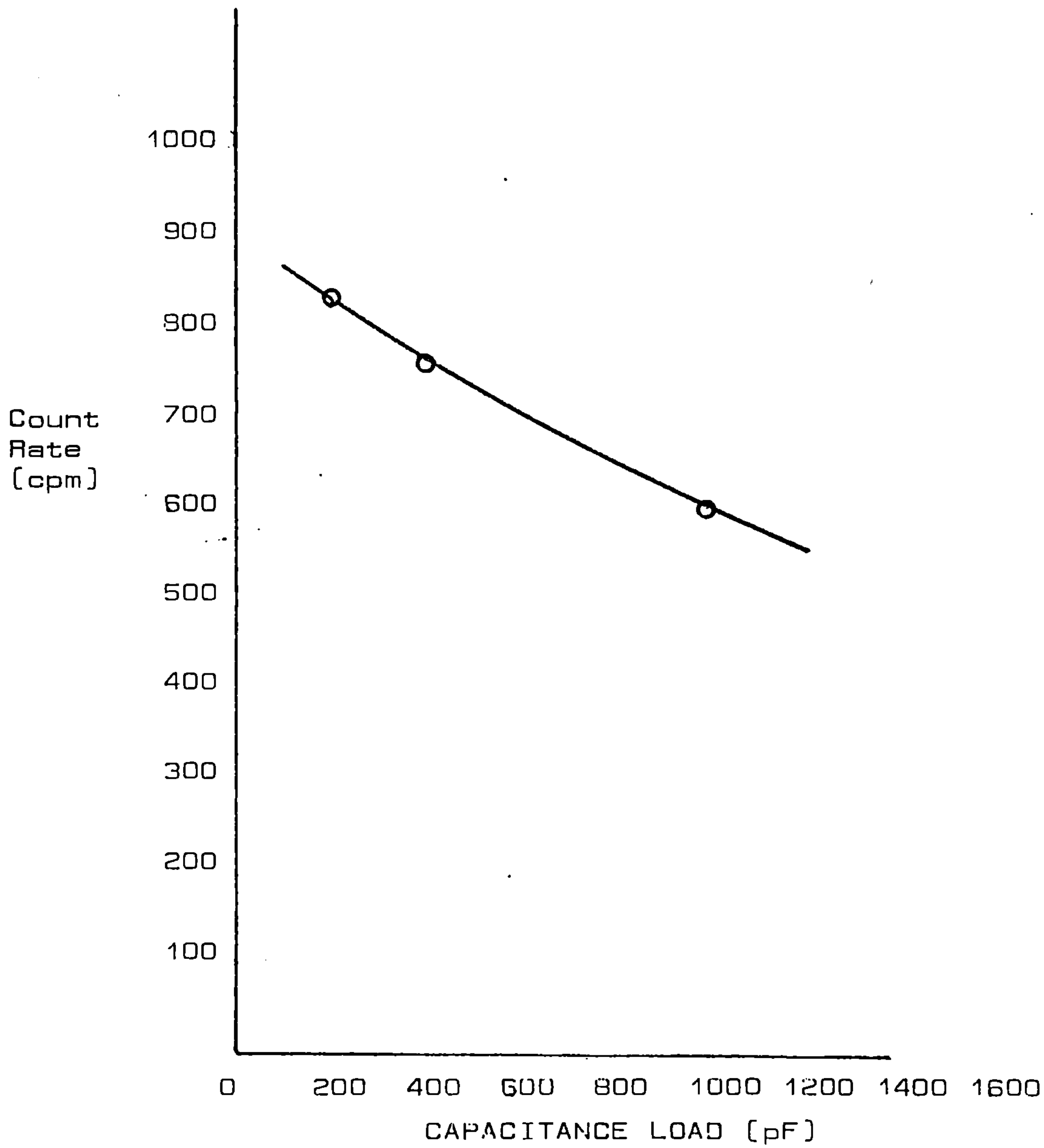


FIGURE 11 COUNT RATE vs CAPACITIVE LOAD

SENSOR 1

4 Studies of E1 are presented here

For anode wire spacings of less than 1.5mm no corona or sensitivity to alpha radiation was observed other than at the edge wires.The inner wires are insensitive to alpha radiation (5). With a gap in the range of 1.5mm to 2.54mm the sensitivity of the sensor is uniform throughout . An anode spacing of 1.5mm was chosen as optimum for the prototype radon detector.

5 Studies on construction materials E4

PVC plastics , glass and vectorboard were found to be suitable insulators in the voltage range of 0 to 5000v . Once the corona is established , shorting along the insulators to ground is negligible .The ground plane must be 3mm from the anode wires for an acceptably low background.

6 Studies on the effects of dust E11

The sensor must be protected from dust and volatile organic materials. Dust can result in spurious arcing and VOCs may decompose in the corona to generate a deposit which eventually will increase the resistance of the air gap and reduce the sensitivity. Paper filters are suitable for removing dust but a solution to corrosion from external materials has not been found.

7 Detection uniformity and sensitivity E7.1

The uniformity of detection across the sensor was established by moving a 7000 dpm Am241 point source in a plane parallel to and equidistant from the sensor. The sensitivity so measured was then compared to the value obtained with a 2.54 cm diameter extended source to establish angular effects. These results for a point source are presented in figure (12) and in table 1.
The sensitivity determined with a point source varies with position as expected from basic theory. The sensitive volume of the detector is the corona which surrounds each anode wire and has a diameter of about 1mm. The regions between each wire have a variable sensitivity depending on the strength of the corona at each point. The count rates observed along the anode wires are similar, although there may be a real difference in sensitivity between the outside and inside anode wires .
Typical sensitivity values determined with a point source are about 8% and with an extended source are about 2% , showing the effect of angular dependence on detector response.A maximum sensitivity for a point source of 10% was determined under the following conditions ; Hv=5.0Kv, load = 1 $M\Omega$, anode wire size = 0.076, anode-cathode spacing 2.54mm , gap = 2.28mm .However an unacceptably high background of 5cpm was measured.

8 Background E9

Regular spurious discharges and occasional self exiting oscillations which require manual correction occur. This behaviour was difficult

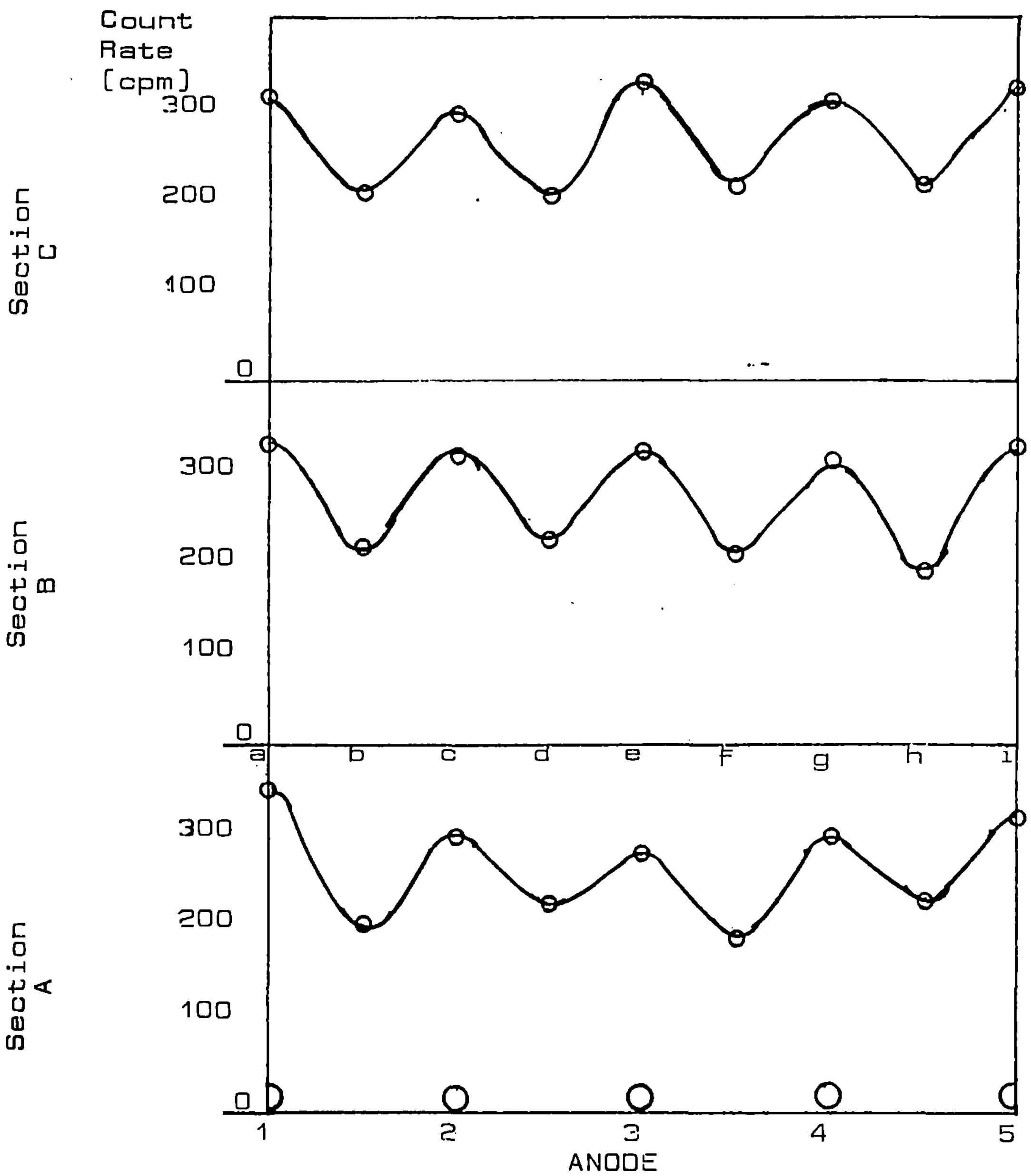


FIGURE 12a CROSS SECTIONAL RESPONSE

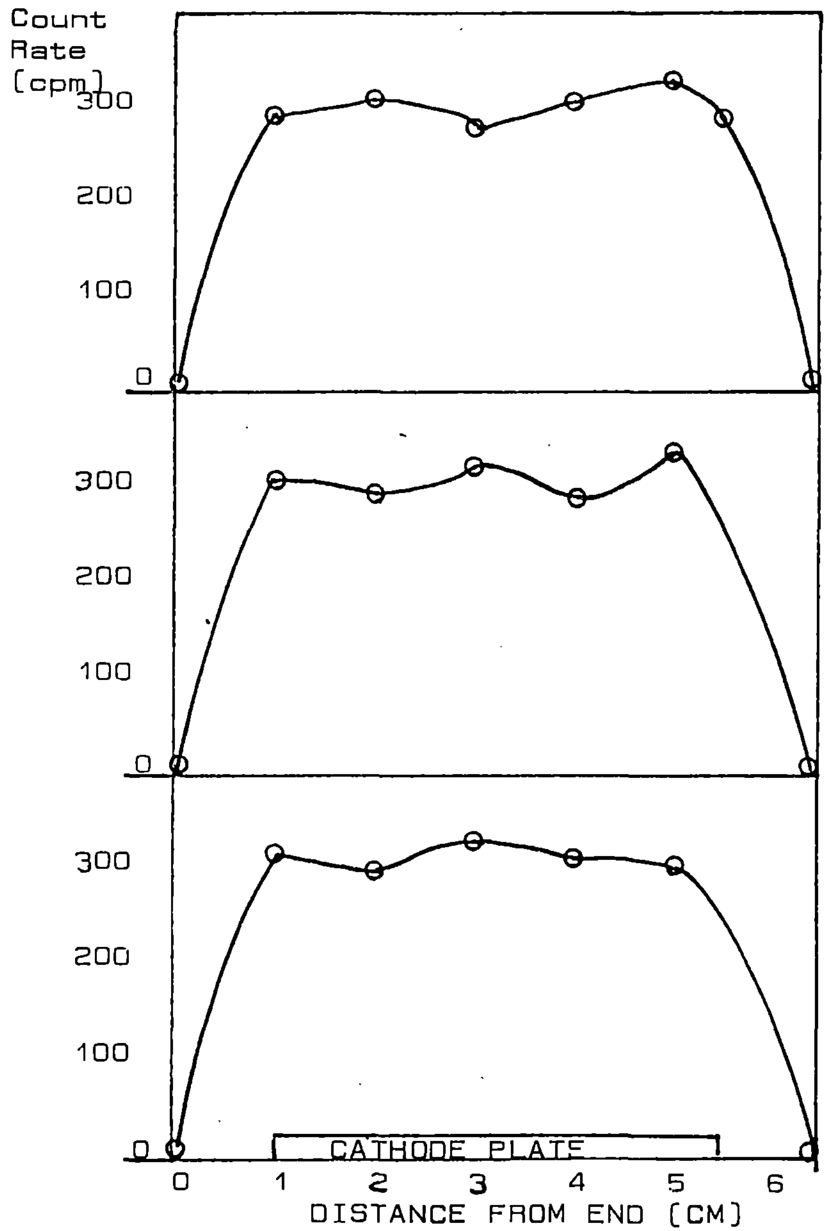


FIGURE 12b LENGTH WISE RESPONSE

TABLE 1
Cross Sectional Response
cpm

Anode	position	section A	section B	section C
1	a	350	330	315
	b	202	220	205
2	c	300	315	295
	d	225	225	205
3	e	275	325	335
	f	195	210	215
4	g	302	305	305
	h	260	190	215
5	i	320	330	327

Lengthwise Response

distance cm	anode 1 cpm	anode 2 cpm	anode 3 cpm
0	0	0	0
1	320	305	295
2	305	295	305
3	335	320	285
4	315	295	305
5	305	340	335
6	–	–	295

to correct and become more frequent with aging of the sensor . For this reason the usefulness of the sensor for low level radon detection is questionable . Typical backgrounds were about 0.1 cpm.

SENSOR 2

This sensor was constructed with guard rings and was slightly more complicated than sensor 1 . The performance of the sensor , although similar to sensor 1, demonstrated better stability , lower background, longer plateaus and looser tolerances in construction. See figure (13) .

1 Studies of load resistance E6 and plateau shape E7.1

Experimental conditions

Anode-cathode distance=1.52mm, anode-guard distance=1.52mm, load=variable resistance + 0.002 μF capacitance ,humidity=60%, T= 21°C

Results

(i) Sensor 2 exhibits a well defined long plateau
(ii) Count rate or sensitivity increases with reduced load
(iii) The counting plateau extends over a longer range and begins at a lower voltage than sensor 1
(iv) Corona onset is at a lower voltage than with sensor 2

Discussion and relevance to the prototype radon detector

This sensor displays a longer plateau shape ,lower operating voltage and current requirement than sensor 1 and is well suited for the prototype radon detector.

2 Source-detector geometry and sensitivity E7.3

Experimental

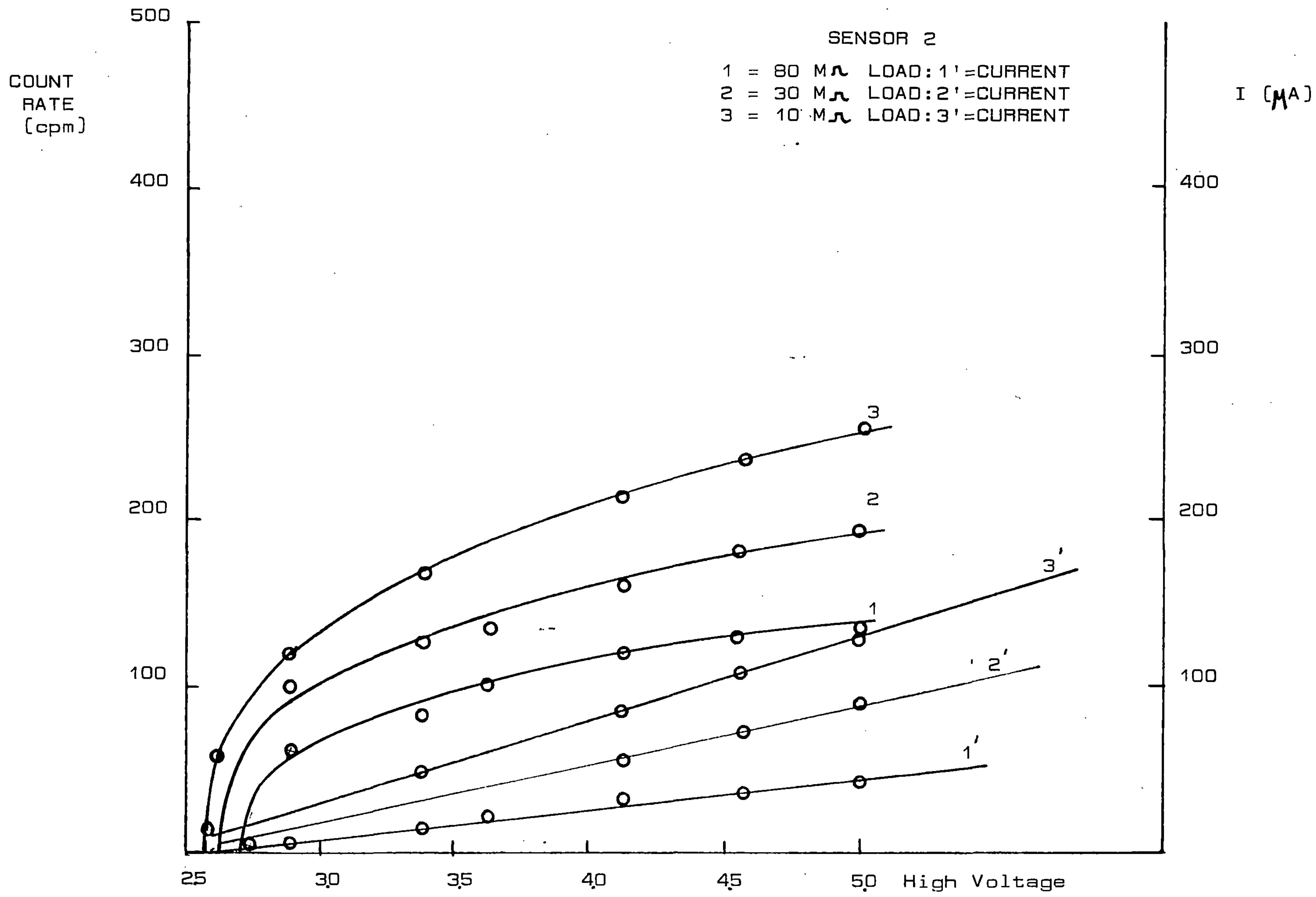
Measurements were made under the following conditions ; Hv=3.5kv, Source = 7000 dpm Am241 , load=10MΩ ,C=0.002 μf, anode wire size = 0.076mm , guard = 0.138 mm , Humidity=70% , T = 19°C

Results
See figure (9).
(1) An optimum sensitivity is achieved at a distance of separation of 19.5mm
(2) Sensitivity along angle decreases less steeply with sensor 2 than with sensor 1 . The guard wire influences the corona shape in sensor 2 ,a factor that may contribute to the better angular performance of this detector
(3) The sensitivity along angle falls off steeply with increasing angle as with sensor 1

Conclusions

(1) Sensor 2 has an improved angular performance over sensor 1 .

FIGURE 13 VARIATION SENSITIVITY AND CURRENT WITH HIGH VOLTAGE AND LOAD RESISTANCE: SENSOR 2



The result is an improved sensitivity to the extended 2.54 cm Am241 source or to the apex collector in the prototype radon detector II.

(2) Studies of anode wire vs guard wire diameter E2

Effective guard wire:anode wire diameters must be 3 for an acceptable background . Ratios less than 3 result in spurious arcing . With an anode diameter of 0.076mm , guard wire diameters of 0.25mm to 0.635mm have been studied . Larger diameter wire was difficult to use as a construction material .

(3) Studies of anode-guard gap vs anode-ground plate gap E2, and anode-guard minimal spacing E1

The following information summarizes the results of a series of qualitative measurements;

(i) The anode guard gap must be > the anode-ground plate distance . Smaller anode-guard gaps result in spurious arcing or high background

(ii) Anode-guard spacings smaller than 1.54mm resulted in reduced stability and were difficult to construct reproducibly .

(4) Studies of load capacitance E6

Results are similar to sensor 1 . Sensitivity decreases with increased capacitance .

(5) Studies of humidity and temperature E10

Background and spurious arcing were increased over sensor 1 at high humidities. This problem was eliminated by using an epoxy , or silicone sealant such as Sylguard over the insulators .Detection sensitivity was unaffected by humidity with or without the sealant in the range 30 to 70% .

(6) Studies of dust and VOC E11

Sensor 2 was less sensitive than sensor 1 to the buildup of material on the anode wires . The reason for this is unclear at this stage and requires further research.

(7) Studies of construction materials E4

The same materials were employed as for sensor 1 . This detector has exceptional tolerance to dimensional irregularities and slack tolerances can be maintained without any deterioration of performance .This result suggests that a low cost detector is easily achieved via this route.

(8) Studies of long term stability E8

The detector showed excellent stability over 5 day periods under standard operating conditions . With prolonged testing (over one week) a white residue developed on the anode and cathode which resulted in a slow deterioration of performance . This result is similar to sensor 1 and represents major research problem to be solved before the spark discharge detector can be recommended as a reliable detector for the homeowner .

(9) Background E9

This detector exhibits a very low background of about 1 to 4 cph and exceptional stability . Many versions of this detector have been constructed , with predictable performance .

SENSORS 3 AND 4

These sensors required more precise mechanical construction than sensors 1 and 2 .Although sensor 3 displayed an improved sensitivity over 1 and 2 ,this advantage was more than offset by difficulties in construction and increased background . Sensor 4 was also more sensitive but difficult to construct .
For the above reasons sensors 1 and 2 were not fully characterized .

CHOICE OF SENSOR FOR THE RADON PROTOTYPES 1 AND 2

In general sensor 2 had the following advantages over sensor 1;

(i) Easy reproducible construction . Mechanical tolerances were less critical than for the other sensors .
(ii) Background and stability were superior
(iii) Broadside and angular sensitivities were slightly better
(iv) An excellent plateau
(v) Lower operating voltages were possible

5.2 ELECTRONICS

In the development of a spark discharge radon detector a number of electronic requirements were identified and developed. They were a) a high voltage power supply

b) spark detection methods

c) counting

d) data output

and e) packaging.

a) Initially the high voltage requirements were determined to match the initial calculated transducer requirements of approximately 500 volts and 50uA with short circuit protection. An available high voltage module was selected and designed into a package to provide an adjustable supply capable of providing 1500 volts at 2mA. The circuit is shown in Figure (14). The transducer evolution required a higher voltage which was met by another module in a similar package and circuit but capable of 5000 volts at .6mA.

Once the requirements such as the nominal high voltage of 4000 volts at 15uA were established, a low cost supply could be designed supply. A number of commercial consumer products which include high voltage supplies were identified and examined for their possible use in this application. In particular a few drivers for miniature fluorescent light tubes were purchased and incorporated into a design for testing. The result of these tests were that either the load of the spark discharge circuits was too capacitive or the operating frequency of the drivers were too low to allow simple boosting of the high voltage to the required 3500 volts.

As a result transformer manufacturers were surveyed to find off the shelf transformers at reasonable cost to incorporate into our own design. In addition other high voltage components were needed and eventually diodes and capacitors capable of withstanding up to 5000 volts and a medium voltage transformer were selected. The resulting design is shown in Figure (15). It makes use of a self oscillating transformer circuit with voltage multiplication of the stepped up input voltage to obtain up to 5000 volts at 30 to 40uA. The high voltage can be adjusted by the choice of input voltage. The design of this supply required careful attention to board layout, packaging and extensive use of specialty insulators such as teflon, fish paper, ceramics and high voltage silicone.

The final prototype power supply was a compromise between prototyping costs, performance and availability of parts. Possible cost savings in the purchase of custom high voltage components for quantity orders were identified.

b) The initial spark detection was done using A.C. coupling to an oscilloscope and the use of a previously developed sensitive electrometer in the vicinity of the discharges. Beyond these methods spark detection presented various problems in the following areas;

High Voltage Power Supplies

Initial Design

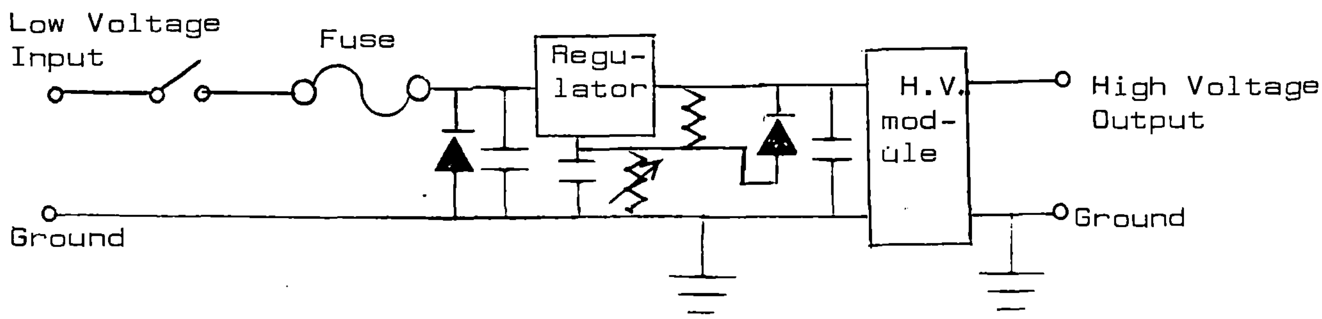


Figure 14

High Voltage Power Supplies

Final Design

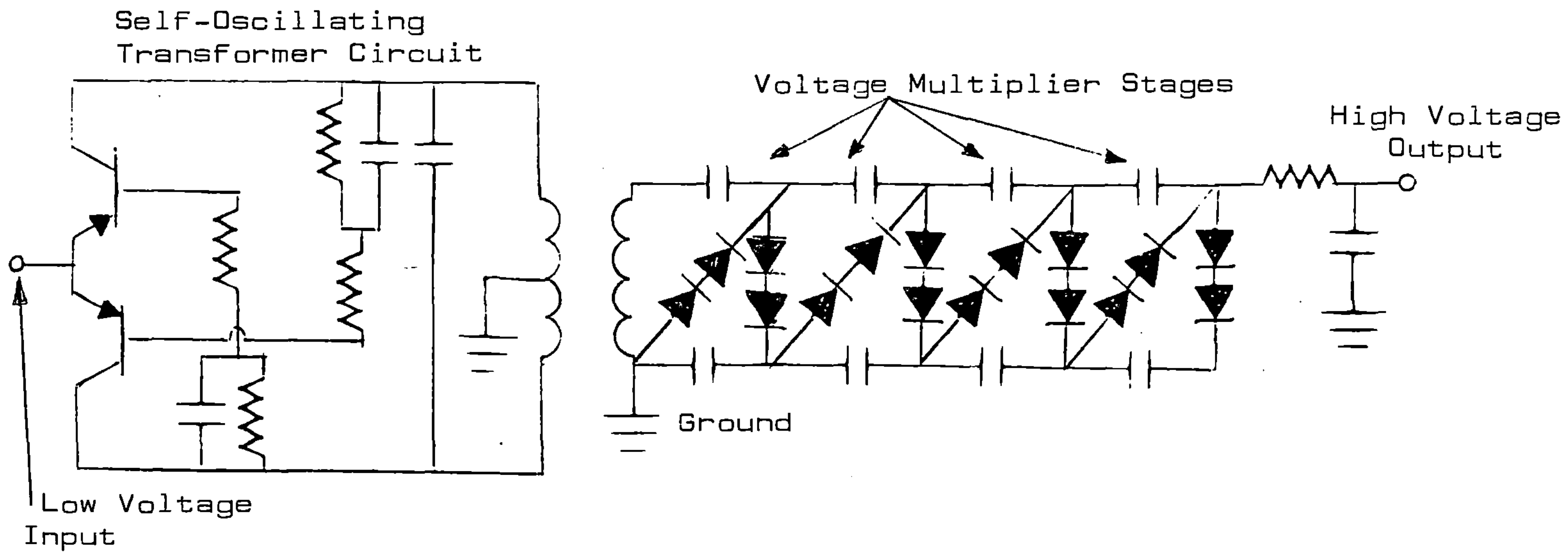


Figure 15

i) conversion of detector arcing to a low voltage pulse,

ii) conversion of spark period to a logic pulse period,

iii) elimination of oscillations,

iv) specification of high voltage components

v) power consumption,

vi) safety in layout and packaging

and vii) cost reduction.

i) The arc that occurs when an alpha particle enters the detector is of low energy but potentials equal to those of the detector (4000 volts) are possible. As a result the arc had to be attenuated to a voltage level suitable for conversion to a 5 volt logic pulse. Many methods of attenuation and attenuation factors were attempted and tested. These fell into three basic categories:attenuation on the high voltage side of the detector, attenuation on the ground side of the detector or inductive pickup of the arc. Attenuation on the high voltage side of the detector resulted in instability of the detector. This led to unpredictable and noisy results. Inductive pickup proved a useful technique but was susceptible to outside interference and was abandoned in the final prototype. Attenuation on the ground side of the detector was therefore chosen for the final prototype. An example of each of these techniques is shown in Figure (16).

ii) The period of a detector arc is short, typically less than 10mS. For the purposes of an optical output this needed to be larger than 50 mS. A value of 100 mS was chosen as optimum and a one shot was to extend the 10mS pulse to one of 100mS.

iii) In the attenuation circuitry Zener diodes were used to reduce oscillations. They also served to baseline restore the signal from the detector. They can be seen in Figure (16).

iv) As in the design of the high voltage supply, high voltage diodes, capacitors and resistors were required in the attenuation circuitry. These were designed into the final prototype.

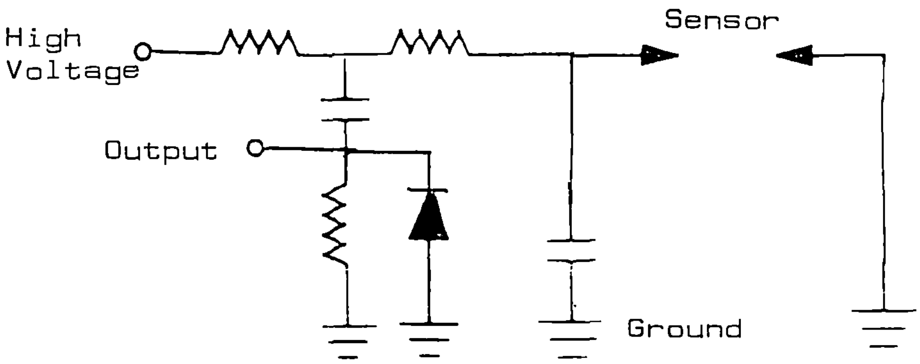
v) Certain of the detectors and their attenuation circuits required more power than others. As a result the power consumption had to be minimized. in order to make the high voltage supply as small and inexpensive as possible.

vi) Safety was greatly improved by using an opto-isolator to separate the high voltage supply and many of the associated components into a separate enclosure within the overall package. The opto-isolator can be seen in Figure (16). Use of specialty insulators and careful board layout was used as with the high voltage supply.

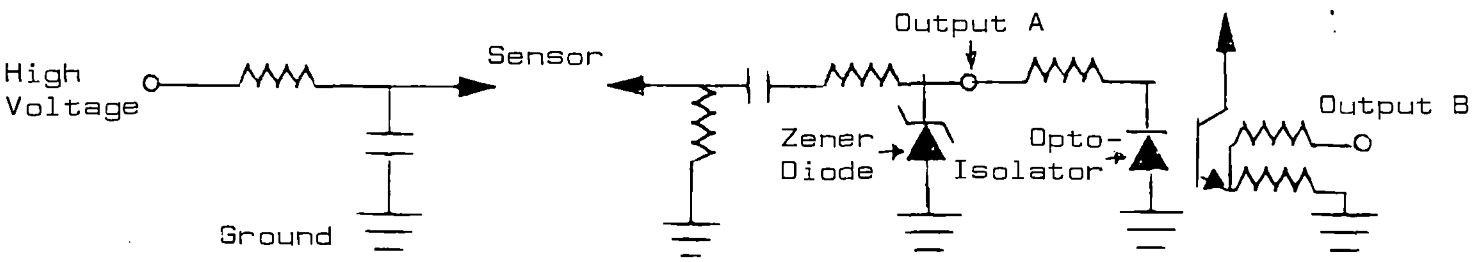
vii) Cost reduction was done through surveying various manufacturers and suppliers particularly with respect to quantity orders.

c)For counting the events occurring, a counter with a liquid crystal display and programmable time intervals was developed. This unit was necessary for the calibration and development of the unit. In terms of cost another pre-packaged counter without time intervals was obtained following a survey of available counters. It was a 6 digit LCD display capable of count rates of 100 cps. It

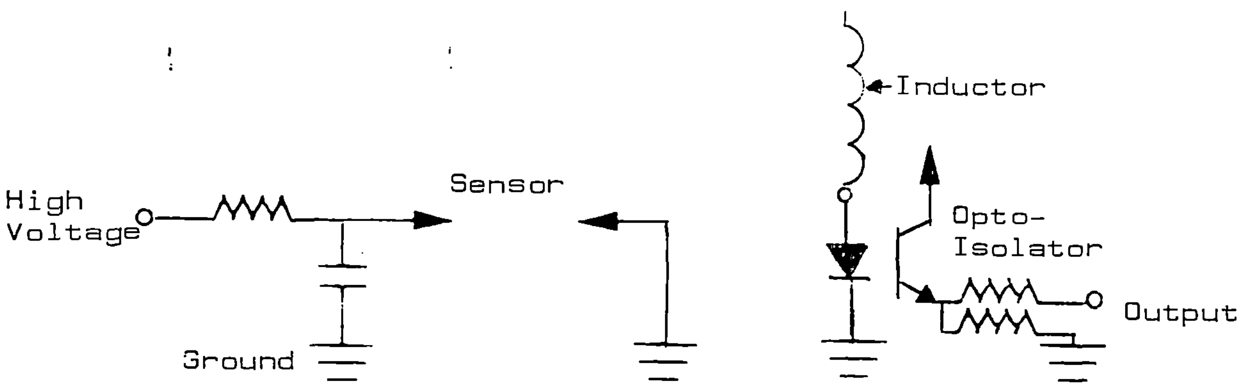
Arc Detection Circuits



High Voltage Side Detection



Low Voltage Side Detection



Inductive Pickup Detection

Figure 16

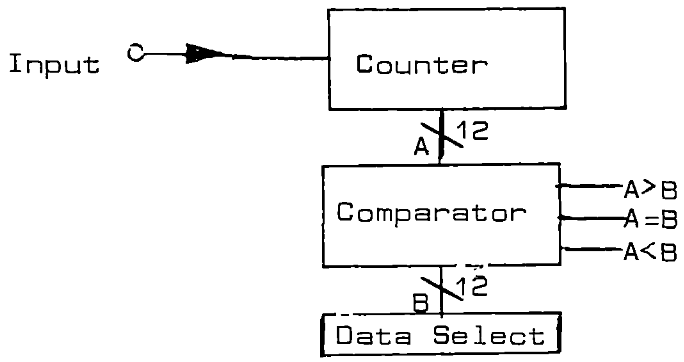
was operated from 2 N size batteries. It is available without its bezel and battery holder and for large quantities this model would bring further cost reductions if a counter is deemed necessary.

d) Data output was considered and a numeric counter described in c), an audio signal in the form of a buzzer and a visual signal, in the form of a red LED were incorporated into the final prototype. Many scenarios for alternate outputs were considered and a few were tried. Some of these are shown in Figure (17). The combination was used in the final prototype until the cost considerations and the eventual user are determined.

e)Power consumption was optimised as possible but not to the extent of a battery operated device. The counter chosen happened to also be battery operated as described in d). A standard 6 volt power adapter was used to power the other electronics.

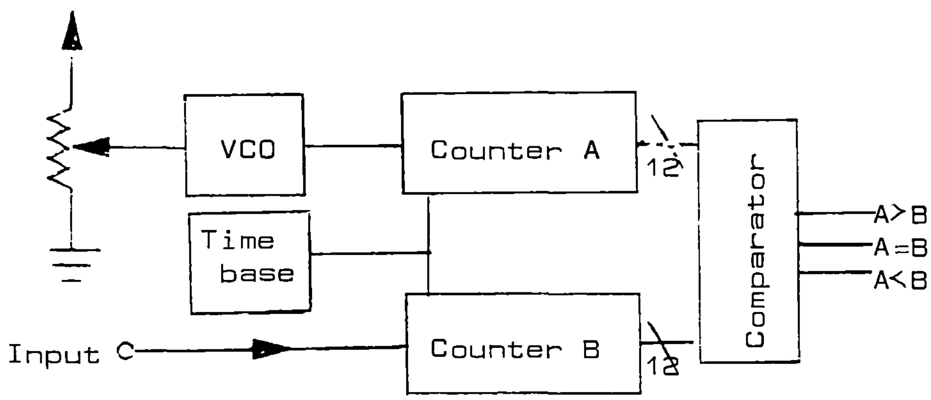
A reference system based in another technology was built in order to allow comparative measurements between a known technology for detection of radon and the new spark discharge technology. This reference system incorporated some of the electronics developed for the spark discharge technology such as high voltage and a counter as well as other electronics necessary for its operation.

Alternative Display Methodologies



No Numerical Display and No Timebase

No Numerical Display with Timebase



Numeric Display with Timebase

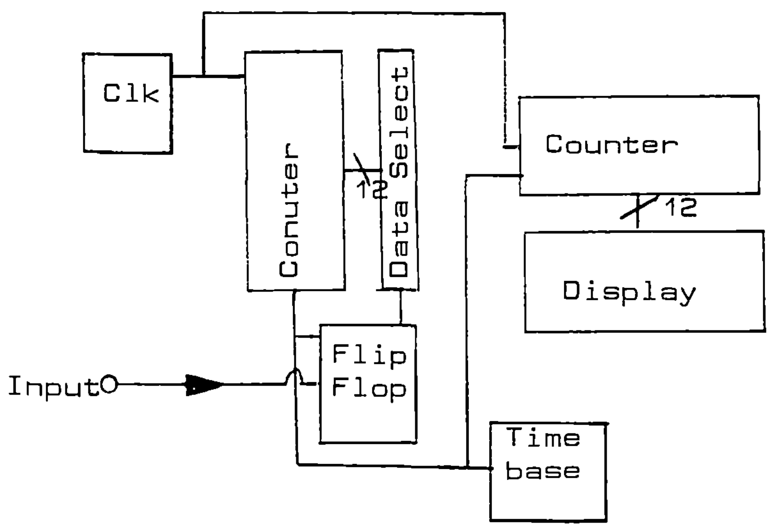


Figure 17

5.3 PHASE 2 PROTOTYPE RADON DETECTOR I;TESTING INSTRUSCIENCE

Test setup

Prototype I (sensor 2) was placed in a 300l radon chamber at 50 pCi/l , was coupled to a laboratory high voltage supply of 0 to 5000v, and a laboratory counting system . Humidity was maintained at 65% as measured by a standard sling psychrometer . Temperature was 22°C throughout the measurement period . Radon levels were measured with an Instruscience Rn2000 radon detector . Grab sampling and direct reading methods were employed.

Results

The average count rate at 50 pCi/l was only slightly above background at 4cph (bg= 2cph)

Discussion

This first detector , essentially sensor 2 , is only marginally sensitive to high radon concentrations and its response is unacceptable at the USEPA compliance level of 4 pCi/l

The poor sensitivity of this detector is probably due to the combined effects of poor angular sensitivity and a critical separation distance between the source and the detector for optimum sensitivity . The performance of the detector may also be affected by the presence of high electric fields in the vicinity of the sensitive volume . These fields may deflect radon progeny away from the sensitive volume to reduce sensitivity .

The prototype radon detector was redesigned and these results are presented in the next section as prototype detector II.

5.4 PROTOTYPE DETECTOR II;CONSTRUCTION AND TESTING AT INSTRUSCIENCE, A PHASE 2 STUDY

Background

To increase the sensitivity of prototype I , an electrostatic focusing technique was employed , see figure (18) .RaA^{+} is swept from a 101 sensitive volume and focused onto a 0.5 cm diameter aluminized mylar collector ,density 1.5mg/cm .The collector is positioned at the optimum counting distance of 6.35mm from sensor 2 (2.54 cm in air) as derived experimentally.

Prototype II detector is described by elements 1 to 6 below.

Element 1 ; the sensitive volume

The sensitive volume is a variable and was chosen large enough to ensure adequate sensitivity of the prototype at 4 pCi / 1 .Radon decomposes to RaA^{+} which is easily focused by a positive field of 3500 v onto a grounded collector (2) . About 70% of radon progeny have a positive charge and can be focused by this method although the fraction collected is related to the humidity, field strength and aerosol level. No attempt was made to optimize these factors although a simple paper filter was employed to scrub aerosols . The humidity influence can be removed by proper selection of a hydrophobic membrane which permits radon entry but rejects humidity

Element 2 ; the collector

The collector is a grounded aluminized mylar foil of 1.5 mg/ cm density . Since the sensitivity of sensor 2 reaches a maximum at a separation distance of about 6.35mm (2.54cm in air) , as derived experimentally , and a function of foil density , the collector was located at this position. The collector has an effective diameter of about 6mm and has the shape of a hemisphere.

Element 3 ; the insulated plate

The collector , high voltage cage and sensor are mounted to an insulator plate . The positioning of these elements on the plate is critical and affects the collection efficiency and counting sensitivity .The optimum positioning of these elements was derived experimentally .

Element 4 ; sensor 2

Sensor 2 was used as employed in prototype 1 studies . Extreme care was taken to construct the sensor free of vapour emitting materials such as glues and plastics . The same drive voltage was used for the sensor and the high voltage cage.

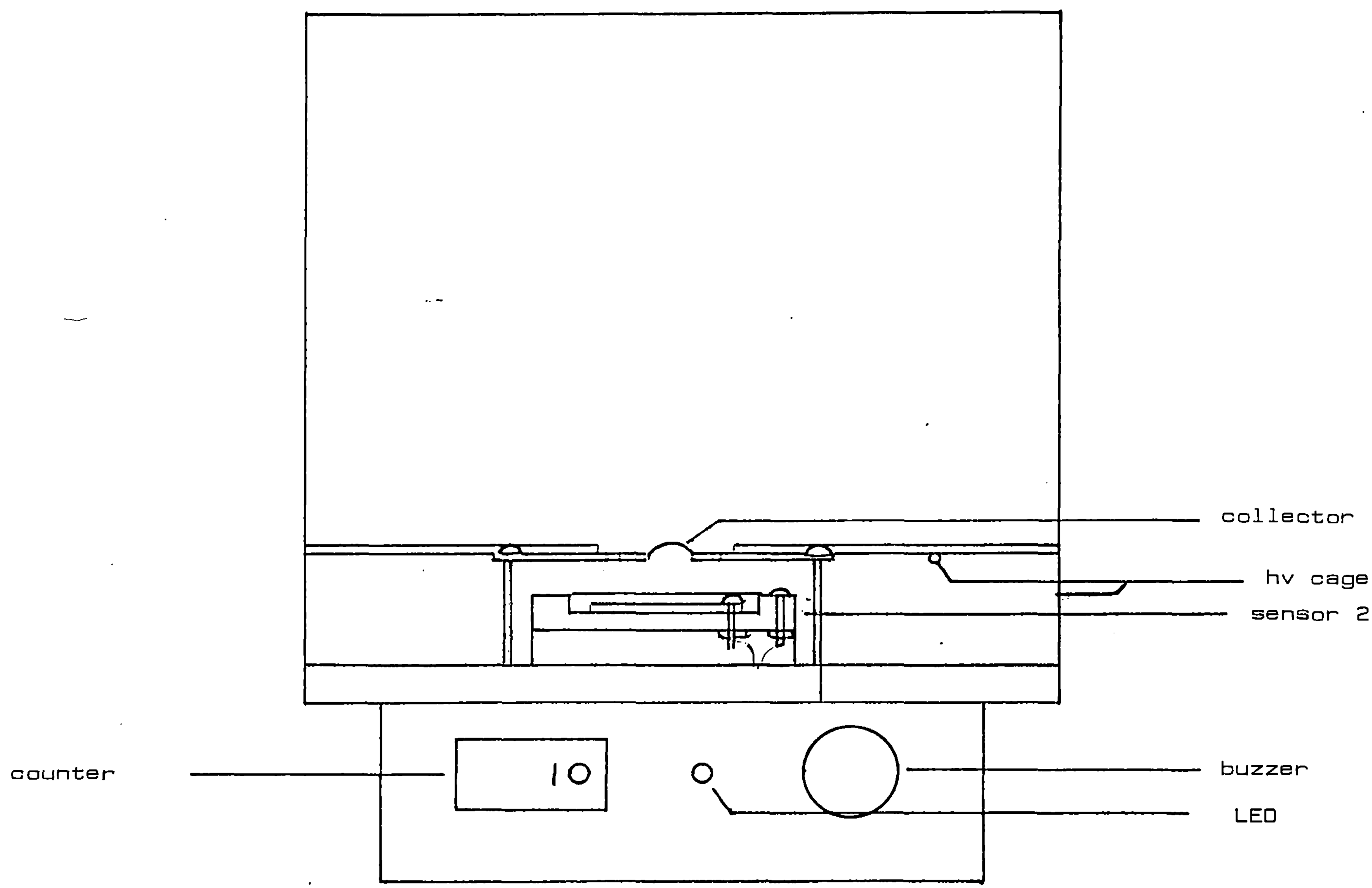


Figure 18 prototype II

Element 5 ; high voltage supply

A common high voltage transformer with an output of 500 volts was stepped up to 3500v by means of a suitable capacitor - diode voltage doubler and oscillator drive circuit . A 40 MΩload resistor and 100pf capacitor were employed to reduce the shock hazard ,optimize the sensitivity and guarantee a suitable output signal without affecting the detector speed .

Element 6 ; the counting and display electronics

A standard low cost 6 digit counter was employed . The counter was connected to the spark discharge divider circuit by means of an optoisolator or inductor .
To enable visual and acoustic monitoring of the signal , an LED, and beeper were provided . Each count event triggers the LED and beeper.

TESTING OF THE PROTOTYPE RADON DETECTOR ; PHASE 2

Experimental setup

Prototype II was placed in a 300l radon chamber equipped with an Isotope products Laboratories radon gas source . Radon levels were determined with an Instruscience Rn 2000 radon detector. either direct reading or grab sample techniques were employed . At least two samples were taken during each measurement period . Humidity was determined with a sling psychrometer . No attempt was made to measure aerosol levels ,since only filtered air was permitted to enter the detector .

Results

Experimental results are presented in table (2).

TABLE 2

date	time initial	time final	t min	count total	cpm	radon pCi/l	H %	S cpm/pCi/l
day1	6:52	10:52	224	120	0.54	11.5	70	0.047
day2	11:19	5:28	360	594	1.65	30	64	0.055
day3	6:25	11:48	303	1413	4.66	111	50	0.042
day4	7:00	3:00	480	2952	6.15	150	65	0.041
day5	8:00	12:00	240	1620	6.75	150	20	0.045

An approximate radon sensitivity of 0.046 cpm/pCi/l was determined at four different concentrations in the range 0 - 200 pCi/l . The response of the detector appears to be linear over this range.

Measurement reproducibility , precision and minimum detectable levels were only crudely established . A standard deviation in the detection sensitivity of 0.004 for a 30 minute count at a radon level of 100 pCi/l corresponds to a relative error of about 10%. A minimum detectable level of $2\sqrt{5q}$ = 3 cph or 1 pCi/l is estimated . Sensor stability over a one week test period was adequate ; no drift in sensitivities was determined.

No obvious influence of humidity on sensor performance in the range of 20 to 70 % was observed . This result is unexpected since the humidity affects the collection efficiency of the sensor and should therefore affect the sensitivity .

Although the sensor appeared to be stable over the one week test period , previous work has shown that a slow buildup of material will occur on the anode and cathode elements with a resultant decrease in detector sensitivity .

The electronic systems functioned well . There is a one to one correspondence between events as presented by the counter , LED display and audible beeper . These systems have been found to perform reproducibly over a six month test period and have not been affected by the catastrophic failures of the sensors during the developments phase of these devices.

Inductive , capacitive , and direct coupling via optoisolators functioned well as sensing methods . The possibility of acoustic or optical coupling was not studied during this research . Inductive and capacitive pickup are susceptible to outside interference from RF fields and must be shielded . Direct coupling on the other hand has proven reliable and free from the damaging effects of high voltage arcing.

PROTOTYPE DETECTOR II TESTING AT CANMET LABORATORIES, CANADIAN RADON STANDARDS LABORATORIES

Work at this laboratory was unsuccessful. The device failed completely to count over a 24 hour test period at high radon levels. Nor was any background count generated over this period.
Examination of the counter upon return to Instruscience indicated that the counting modules had become disconnected from the sensor output signal .
No attempt will be made to have the detector recalibrated until it has been tested in more detail. The prototype II detector was however compared to an Rn2000 radon detector at Instruscience and these results were reported above. The Rn2000 detector was also calibrated at the Elliot Lake laboratories in parallel with the prototype II detector to confirm work at Instruscience.

The importance of the research warrants an additional study phase and the company will continue to pursue the work until reliable operation is achieved. At that time the prototype detector will be returned to Elliot Lake for further testing.

6. AN ASSESSMENT AND INTERPRETATION OF TEST RESULTS WITH A COMMENTARY ON THE APPROPRIATENESS OF TESTING AS A MEASURE OF THE SUCCESS AND / OR FAILURES IN ACHIEVING THE PROJECT OBJECTIVES.

(a) Successful electronic counting systems and power supplies were achieved . Although the project objectives called for a low voltage system, the high voltage supply developed is safe , reliable and low cost.

(b) A variety of sensors were developed and tested

(i) Sensor2 , the most reliable sensor developed had a marginal sensitivity to radon as prototype I. To achieve the required sensitivity an electrostatic focusing method was developed and incorporated into prototype detector II. This detector was sensitive to radon at the target level of 4 pCi/l and responded in a linear manner to radon in the concentration range of 0 to 200 pCi/l over a weeklong test period .

The electrostatic cage as defined does not increase the cost of the detector but does increase the size to 10l . The field as defined may be sensitive to humidity . This is not a major problem however as suitable membranes are available to reject moisture.

The prototype detector meets most of the project objectives and its sensitivity can be easily increased by enlarging the sensitive volume . The costs of the detector on a one off basis is about $100 and in quantity probably about $50. This is well within the project objective for a homeowner based detector system.

The prototype detector is easy to construct and uses no unusual materials . The tolerances on most of the mechanical parts are large .

(ii) Thin foil detectors did not function as predicted . This research was dropped at an early stage because of anticipated high risk and cost factors . The methodology warrants additional research however and will be pursued on an ongoing basis at Instruscience.

(c) The prototype II radon detector failed in its initial testing at the Elliot lake laboratories.The count module connector came loose in transit to the laboratories and no counts were recorded . The reference system used at Instruscience was however successfully tested in parallel, confirming prior work which is reported in section 5.4. The detector will be tested in more detail before it is returned for independent calibration.

The failure to test properly is considered unfortunate but not a serious problem.

Research problems to be solved

(1) The long term deterioration of the detector due to the slow buildup of material on the anode and cathode . The nature and source of this contaminant is unclear .Postulated sources include organic vapors and fine dust but the problem would be the

principal research focus of an ongoing program.

(2) Thin foil detectors should be examined in more detail by ac high voltage methods and with high speed oscilloscopes . This approach could eventually lead to a very low cost device.

(3) A commercially available membrane must be selected to reject humidity and permit radon transfer. This work is considered straightforward.

OVERALL CONCLUSION

The detector as defined would probably meet the requirements of a low cost radon detector for the homeowner provided that improved long term performance be achieved.

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8. APPENDIX

THIN FOIL SENSORS

The proposed radon detector is presented in figure (1). A number of elements (1-10) play a significant role in the functioning of the detector and a detailed description is presented on the following pages .

When an alpha particle (3) penetrates the upper charged plate of the detector (1) capacitor and enters the air gap (6) it leaves a path of ionization (7). This path should form a conductive route and if the upper (1) and lower plates (2) have a high enough potential difference , a discharge from the upper charged plate will follow the path . This discharge takes the form of an arc or a current surge . Thus an alpha particle event can be monitored directly by sensing a very large current surge or voltage change, or indirectly by sensing a capacitance change or the light output with a photocell.

Once the potential across the plates has fallen below some critical level then the current stops and the unit should quickly come up to predischarge levels in readiness for the next alpha event .

Since the output pulses are extremely large a very simple counting system or electronics should be possible.

Detailed Description of detector elements

1,2 Charged Plates

The proposed detector will consist of parallel plates in a capacitor like arrangement . The plates may form a planar surface or a cylinder and in fact many configurations are possible , to form detectors of small (low sensitivity) or large (high sensitivity) surface area .

One of the plates (1) is thin enough for alpha penetration. The thickness must be adjusted so that maximum alpha energy is dissipated in the air gap between the plates. Maximum energy dissipation and ionization occurs at the end of the alpha particle track . Most alphas from radon are in the 6-10 Mev range of energies .

The plates are charged to a potential difference (9) when the detector is operating . The outside plate (2) would probably be held at ground potential.

(3) Alpha Particle

Radon decays into radon daughters and eventually comes into secular equilibrium with them. At equilibrium Rn222, Po218 and Po214 emit alpha particles at the same rates . The energies of the alpha due to radon is less than the daughters .

When an alpha particle event occurs the air in the particle track is ionized . About 28 ev is required for each ion pair formed in air and a considerable amount of ionization is thus formed by a 6 Mev alpha particle . The alpha particle will penetrate several mg/cm of absorber or travel up to two inches in air before its energy is dissipated .

The thicknesses of the upper charged plate (1) , the dielectric (5) and the air gap (6) will have to be adjusted to optimize the discharge along the ionization path .

(4) Radon Diffusion Chamber

The radon chamber consists of a small air space equipped with an intake filter (8) . The intake filter removes all dust and radon daughters which are present in the air around the detector . This means that the radon daughters will achieve secular equilibrium with the gas inside the detector chamber and as a result a quantitative relationship can be found between the radon gas level and the alpha emission rate.The chamber can be any practical size ; 100-300 ml volumes are typical for the levels of sènsitivity normally required.

(5) Dielectric

The detector as described mey be sensitive to humidity which tens to affect charge distributions , the nature of the ion track (3) and probably the operating voltage (9). Leakage may become a problem at elevated operating voltages .To reduce the influence of these effects a thin dielectric could be used .
The dielectric would have the property of self sealing after penetration by an alpha particle in order for the detector to regain its original operating characteristics . The dielectric would

also probably serve as a spacer to separate the two charged plates at a regular distance and would further increase the size of the output pulse since charge storage on the plates would increase considerably above the free air value .

(6) The Air Gap

The air gap (6) , dielectric (5) , upper charge plate absorber thickness (1) and potential difference (9) are all related to optimization and definition of the path of ionization (7) . The objective here iş to release maximum ionization in the air gap , to maintain the detector at the minimum operating potential and to reduce the effects of external influences such as humidity.

A small air gap is required since the sensitivity of the detector would decrease with increasing gap distance .

(7) Path of Ionization

The path of ionization(7) has been described . The path should be such that the charge from the upper plate under the influence of the applied field (9) follows the track until it arcs or discharges to the bottom plate or ground . The alpha particle may not actually penetrate to the bottom plate but with proper optimization of the operating voltage , the charge may still arc to the bottom plate to complete the circuit.

Alpha particles enter the air gap at various angles and it is part of the research to optimize the sensitivity of the detector by ensuring that most particles that enter the gap are counted.

(8) Radon Diffuser

The radon diffuser is a thin filter material readily permeable to radon . The diffuser prevents radon daughters from entering the radon diffusion chamber since they may introduce a disequilibrium with the daughters in the chamber . There would as a result be no quantitative relationship between the radon level and the alpha count rate recorded

(9) Potential Difference

The applied potential (9) is critical to the effective operation of the detector . It must be high enough to ensure breakdown and arcing between the charged plates (1 and2) when an alpha particle enters the airspace between them . The potential required should be insensitive to humidity levels in the event that the detector is exposed to environmental influences.

(10) Output

The output from the detector can take the forms of a voltage pulse , an audible sound or a light pulse.

In the case of voltage , the pulse is the result of plates discharging across the air gap . The output would appear across an external resistor . The resistor size is chosen to ensure that the plates recharge quickly before the next alpha event but not so small as to require a large power supply . Since the output pulse is large , the associated electronics would be greatly simplified .

The arc or discharge would produce an audible sound or a light pulse that can be monitored by very simple standard systems . In these cases as well , very simple electronics should be possible.