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To be presented at the IAEA Specialist Meeting on "Gas Cooled Reactor Core and High Temperature Instrumentation" at Bowness on Windermere. 15 to 17 June 1982.

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CONTROL AND INSTRUMENTATION DIVISION

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Abstract

The Windscale AGR concluding experiments included a comparison of theoretical and experimental power transients and required measurements of neutron flux as a function of position and time within the reactor core. These measurements were specified to cover as wide as possible working range (at least 3 decades up to a maximum neutron flux of 3×10^{13} n cm^{-2} sec^{-1}) and had to be made against the in-core gamma background of up to 4×10^{7} $R(hr)^{-1}$. The detectors were required to operate in special channels cooled by reactor inlet CO_2 and the overall system needed a response time such that it could follow transients with doubling times down to 2s with an accuracy of 2 or 3%.

These problems were solved by the use of gas ion fission chambers operating in the current fluctuation or "Campbelling" mode. Their neutron to gamma sensitivity ratio was optimised by the use of unusally low filling pressures and they were fitted with special "trilaminax" mineral insulated cables to minimise the effects of electrical interference at the 100 kHz channel centre frequency. Ten detectors were built and nine were installed in the reactor, three in each of three special stringers at different radial positions. All were processed and tested for operation at 350°C and their fissile coatings (430 μg cm^{-1} of natural uranium) were matched to give individual neutron sensitivities with a population spread better than $\pm$ 6% about the mean. The mean absolute sensitivities were determined to about $\pm$ 5% against manganese foils in the NESTOR reactor at AEE Winfrith.

The detectors were complemented by special signal processing channels which provided current fluctuation sensitivity and appropriate output signals to the experiment data acquisition system. These channels also permitted dc measurement of chamber current for more precise flux determination near reactor full power.

The paper describes the specification against which this system was built and the design process for the detectors. It gives some details of the nucleonic channels and sets out the test results from which chamber reproducibility was assessed. Commissioning experiments are described together with some of the problems which were encountered.

1 Introduction

The Windscale AGR concluding experiments were part of a collaborative programme designed to provide information on advanced gas cooled reactor parameters under relatively extreme operating conditions and one aspect of the work was to extend the validation of reactor fault study computer models by large scale transients of flow, reactivity and power in the reactor core (Ref 1). Neutron flux measurements were required as a function of time and space and for this purpose it was necessary to develop and manufacture an in-core flux measuring system based on current fluctuation (Campbell) mode ionisation chambers. This paper discusses the chambers, cables and measuring amplifiers which were used. It is written from the instrument point of view and does not consider the data loggers which were used to record the results nor the way in which these results were interpreted.

The general requirement envisaged three instrumented stringers. Each would contain three ionisation chambers installed in lieu of fuel at pre-selected heights within the reactor core. Connections would be made with mineral insulated cable through a special, neutron shield plug/stringer latch mechanism. For design purposes, it was assumed that reactor transients with a doubling time of 2 seconds would occur and the equipment was required to follow such transients so that the measured output was delayed by less than 0.1 second behind the true flux at any time, ie with an amplitude error less than 4%. It was originally hoped that this would be possible over five decades of reactor power but the requirement was later modified to the range 25 kW - 120 MW. One of the measuring points was situated at the reactor centre and neutron fluxes up to a few by 10^{13} $n.cm^{-2}.sec^{-1}$ plus gamma fluxes between 10^{7} and 10^{8} $R.hr^{-1}$ were expected at temperatures in the range 300-400°C.

A specification of this type can only be achieved with gas ionisation chambers and they can only be operated in three modes namely, pulse, dc and current fluctuation. The alternatives were considered and the pulse mode was quickly rejected because of the difficulty of manufacturing instruments small enough to operate satisfactorily at the high neutron and gamma fluxes expected. DC systems were more promising and are widely used for incore measurement (Ref 2) but they have serious disadvantages in terms of gamma to neutron sensitivity ratio. They would have provided a limited working range of 2 or 3 decades in the present application. DC fission chambers also have the disadvantage of fission product activity build up from the chamber coating and are even more restricted (Ref 3).

The so-called current fluctuation or "Campbell" method of ion chamber operation utilises the fluctuations in dc output which arise from the stochastic nature of the neutron/coating interaction process. It can be shown (eg Ref 4) that the mean square fluctuation current output from a chamber, per unit measuring bandwidth is given by

$$(1) \quad \frac{i^2}{\Delta f} = \hat{i}^2 = K_1 \; N \; (\overline{Q^2}) = K_1 \; N \; (\overline{Q})^2 \; \frac{(\overline{Q^2})}{(\overline{Q})^2}$$

where N is the neutron interaction rate (effective counting rate)

$(\overline{Q^2})$ is the mean square charge per event

$(\overline{Q})$ is the mean charge per event

Δf is the measuring band width

K_1 is a constant

This is to be compared with a dc output of

$$I = N\,(\overline{Q})$$

So that $$\hat{i}^2 = K_2\, I\, (\overline{Q})$$

where K_2 is another constant for a given chamber

The neutron to gamma ratio of the Campbell mode may be compared with that of a dc system by writing,

$$(2)\quad \frac{\hat{i}_n^{\,2}}{\hat{i}_g^{\,2}} = \frac{I_n}{I_g}\left(\frac{(\overline{Q_n})}{(\overline{Q_g})}\right)$$

where the suffixes n and g refer to neutron and gamma interactions respectively.

The factor in brackets is of order 10^3 and a Cambell channel can therefore, in principle, achieve a wide working range even under poor environmental conditions. Its disadvantage lies in the relatively low signal levels obtained from reasonable bandwidths and consequential vulnerability to electrical interference.

The Campbell based system was chosen and the problem became the provision of nine, wide range, high temperature, Campbell channels on the required timescale. This decision was made at the beginning of November 1979 and the target date for first deliveries to Windscale for stringer installation was set against a deadline date for reactor close-down in March 1981. In the event, the requirement was expanded to include mean current facilities for precise, narrow range power measurement. It also became necessary to devise and specify modifications to existing instruments so that the fast transients called for by the experiments would not lead to reactor "period" trips. The first chambers were delivered substantially as planned on 10 September 1980 and their delivery was completed by 28 November 1980. The signal processing channels were also delivered on time for commissioning by the planned experiment dates.

2 System Specification and Design

2.1 General

A chamber operating in the Campbell mode generates two pulse trains, one from the electron component of the chamber pulses and the other from the positive ion component plus, if appropriate, any negative ion contribution. The pulses within each train occur randomly in time and, at practical Campbell counting rates, the two trains may be considered independent. On its own, each produces an energy spectral density ($\hat{i}^2$ versus frequency) which is constant with frequency up to a limit set primarily by the pulse length and to a lesser extent by the pulse shape

distribution. The spectral densities of the two trains can be determined with narrow band spectrum analyers and they add together in the way illustrated by Fig 1. The operating frequency of a Campbell system can be selected in a number of ways and in the present case the measuring amplfiers were designed to operate over a relatively narrow frequency range centred at about 100 kHz. It can be seen from Fig 1 that this frequency lies on the electron plateau just above the ion transition region. One consequence is that the Campbell charge per event is generated only by the electronic component of the chamber pulse whilst dc current is produced from the total charge. This does not destroy the validity of equation (2) because conversion factors are contained within the constant but it does mean that care must be exercised in comparing different operational modes. For the rest of this paper, the two types of charge will be distinguished by the suffixes "e" and "I".

2.2 Prediction of Reactor Fluxes

The optimisation of an ionisation chamber design depends on the fluxes in which it will be used and suitable estimates were therefore required. They were not immediately available and had to be deduced.

The expected neutron flux was established from the peak irradiation rate in WAGR of 26 $W.g^{-1}$ of fuel containing 3.5% U_{235} ie 743 $W.g^{-1}$ of U_{235} (Ref 5). This related to fuel in a normal channel and corrections were necessary to allow for the fact that the chamber stringers would contain no fuel but did contain hardware to cause flux depression (Ref 6). Hence, the U_{235} fission rate in a chamber at core centre position was predicted to be 1085 ($\pm$ 15%) $W.g^{-1}$. For logistic reasons it was decided that all nine chambers should be designed identically and further corrections were therefore necessary to allow for their expected distribution through the core. It was concluded that, depending on its situation, any one chamber might see a full power rating between 443 and 1248 $W.g^{-1}$ U_{235} corresponding to hypothetical, thermal (580 barn) fluxes of 9.6×10^{12} and 2.7×10^{13} neutrons. cm^{-2} sec^{-1} respectively.

The gamma energy deposition rate in an unfuelled WAGR channel was stated to be of order 90 mW g^{-1} maximum at full power, corresponding to a gamma dose rate of 3.2×10^{7} ($\pm$ 25%) $R.hr^{-1}$ (Ref 7). Unfortunately, this figure could not be used directly since it corresponds to full power and represents an overestimate of the values to be observed during a transient from low power. It is important not to overestimate in this way since it leads to faulty optimisation between gamma effects and amplfier noise and hence detracts directly from the instrument design working range. A correction was obtained from measurements with an ionisation chamber, type DC12A, which had been installed in the neutron shield plug of WAGR stringer IE1460 (Ref 8). They suggested that a factor 20 was probably reasonable to convert gammas after prolonged periods at full power to gammas after a few hours at shutdown and it was concluded that the effective centre core gamma flux with worst case errors would not exceed 2×10^{6} $R.hr^{-1}$ at the beginning of a transient. It was further argued that this value would be proportional to local fission rate and would therefore fall to 7.1×10^{5} $R.hr^{-1}$ at the lowest neutron flux chamber position.

2.3 The Selection of Chamber Coating Weight and Filling Pressure

Current in an ionisation chamber is generated by neutrons, gammas and activation effects and the collecting electric field must be such that

the chamber is correctly saturated over the whole operational range. The parameters which control desaturation are, however, constant with chamber area whilst the total value of current increases proportionately with that area. Other limits such as those imposed by electrical leakage and by amplifier noise are constant in the absolute sense and the widest working range is therefore obtained from a chamber with the largest practicable coated area. The use of a standard design minimises production risk and a Type P7 with a 22 cm long electrode was selected for the Windscale work. This chamber has a standard electrode spacing of 1 mm and initial estimates showed that the optimum filling for the conditions under consideration would be Argon at of order 1 atmosphere pressure. The performance of such a filling can be estimated and, for moderate variations, factors such as charge per pulse can be assumed proportional to pressure. More exact optimisation then becomes possible.

From experimental data available at the time of optimisation it was known that for pressures (p) close to 1 atmosphere and for a local fission rate of F $sec^{-1}.g^{-1}$ U_{235}:-

(3) $\hat{i}^2_{ne} = 6.1 \times 10^{-28}\ p^2\ F\ W.\ A^2\ Hz^{-1}$

where $\hat{i}^2_{ne}$ is the electron component of the neutron signal and W is the chamber coating density (mg U_{235}. cm^{-1})

The corresponding electronic "Campbell parameter" for gamma irradiation was also available for this pressure range and gave:-

(4) $\hat{i}^2_{ge} = 1.1 \times 10^{-28}\ p^2\ \varphi\ A^2\ Hz^{-1}$

where φ is the gamma flux ($R\ hr^{-1}$)

Now the dynamic working range of a neutron measuring channel can conveniently be expressed in terms of 10% errors due to extraneous sources and thus, if the system were limited only by gammas, the range on this convention could be obtained from equations (3) and (4):

$(R_{0.1})_{gamma} = 0.54\ W\ (F/\varphi)$ worst operating case

(5) Hence, $(R_{0.1})_{gamma} \geq 8.7 \times 10^6\ W$

A similar calculation is possible on the assumption that range is limited by electronic noise. It depends on the lowest neutron flux to be encountered and lead to:

(6) $(R_{0.1})_{noise} \geq 3.5 \times 10^6\ p^2\ W$

The optimum coating weight and the filling pressure were governed by equations (5) and (6) and by the saturation conditions of the chamber at maximum operating current. For example, if the coating weight were too low, range would be sacrificed and if it were too high the chamber would become unsaturated and the sensitivity undetermined. The limit on maximum operating current depends on the saturation characteristics of the chamber gas and the way in which the 90% saturation voltage ($V_{0.9}$) moves with chamber current relative to the breakdown level ($V_{1.1}$). Adequate margins must exist between $V_{0.9}$, the operating potential (V_{op}) and $V_{1.1}$. The selection of these margins

is somewhat arbitrary but fortunately, the ratio of $V_{1.1}$ to $V_{0.9}$ is insensitive to pressure. In the present case, known recombination relationships at high pressures led to a maximum permitted chamber current of 2 mA at 1 atmosphere filling pressure. This current could then be estimated in terms of F, p and W and the following equation obtained:

$$(7) \quad W = \frac{4.7 \times 10^{-3}}{p}$$

Thus, from (5), (6) and (7)

$$(R_{0.1})_{\text{gamma}} = \frac{4.1 \times 10^{4}}{p} \quad \text{and}$$

$$(R_{0.1})_{\text{noise}} = 1.6 \times 10^{4}\ p$$

The system was then optimised on the assumption that:-

$$(R_{0.1})_{\text{gamma}} = (R_{0.1})_{\text{noise}}$$

Hence, p = 1.6 atmosphere and W = 2.9 micrograms U_{235} per cm^2.

The working range for 10% errors was predicted to be of order 4 decades - just within specification.

The chambers were made on the basis of these calculations but in the event one stringer was loaded in a different channel from that which had been predicted. This meant that the worst case neutron flux and the corresponding neutron to noise ratio were lower than expected whilst the neutron to gamma ratio remained unchanged. The chamber filling pressure was incorrect by about 30% and the predicted working range for the different loading position was a factor 3 shorter than might otherwise have been obtained.

2.4 Experimental Work on Low Pressure Chamber Argon Fillings

The proposed construction work represented considerable investment and relatively little information was available at that time on the Campbell operation of detectors with fillings of order 1 or 2 atmospheres pressure. Pulse and Pulse/Campbell detectors in the reactor instrumentation field are usually filled at 4 to 6 atmospheres and extrapolation was not totally justified. Experimental work was therefore undertaken with a P7 chamber at filling pressures between 0.2 and 2 atmospheres pressure in neutron fluxes between 6×10^7 and 7.5×10^9 cm^{-2} sec^{-1} and in gamma fluxes between 0.1 and 3×10^6 R hr^{-1}. Saturation voltage ($V_{0.9}$), breakdown voltage ($V_{1.1}$) and sensitivity to both types of radiation were examined using the dc and the Campbell technique. In broad terms the results confirmed the deductions made in section 2.3 and, where, discrepancies existed, they were used to correct the predictions which had been made. This work was not, of course, able to provide confirmation of high flux saturation conditions which continued to be based on extrapolation.

2.5 Mineral Insulated Cables

The current standard UK cable for high temperature neutron detectors is of triaxial copper/copper/stainless steel construction (Fig 2 (a)) suitable for all pulse and dc requirements up to 550°C (Ref 9). It is not, however, satisfactory for Campbell applications because of inadequate electrical interference rejection at the frequencies of interest. Electrical interference penetrates a detector cable by transfer from spurious current flowing

in the screen due to a variety of causes. A measure of this effect is given by the so-called surface transfer impedance (Z_T) usually expressed in ohms per metre of cable. This parameter is shown for the triaxial design as the upper curve in Fig 3. Given Z_T, methods exist by which the upper limit electrical inteference signal can be calculated for a given system at a given frequency (Ref 10) and, in the present case, it was shown that triaxial cable could have led to difficulties at a Campbell signal level of order 10^{-16} A^2 Hz^{-1}. This would correspond to a reactor power of order 10 - 100 MW and was clearly unacceptable. An improved cable was therefore necessary. A number of designs were already under consideration at the time for just these reasons and a choice was made partly on the need for improved interference rejection and also because of a requirement for bending on radii of order 10 cm to facilitate installation in the stringer. Bending is a serious problem in mineral insulated systems but can be achieved, provided it is done only once so that fatigue effects are not encountered (Ref 11). The so-called "Trilaminax" mineral insulated cable was selected. It comprises a coaxial copper sheath surrounding a copper centre conductor in contact with a mild steel sheath which is insulated from and further surrounded by, a stainless steel outer jacket (Fig 2(b)). The magnetic effect of the mild steel changes the transfer impedance to that shown as the middle line of Fig 3 and gives an improvement of approximately $(9)^2 = 81$ over the triaxial type at 100 kHz. This was only marginally acceptable but the trilaminax cable was the best in existence at the time and we were fortunate that it had been developed as a stage towards yet better "superscreened" mineral insulated cables such as the "Colaminax" design (bottom line in Fig 3). Something which was immediately available had to be used if the timescales were to be met with any degree of certainty.

A cold end termination appropriate to the stringer latch mechanism and which took advantage of the electrical interference rejection properties of Trilaminax cable was designed.

2.6 The Final Detector Design

Summarising, the final chamber design comprised a standard P7 detector filled with Argon at 1.6 atmospheres and coated to 2.9 μg U_{235} cm^{-2}. This coating was applied as natural uranium for practical reasons. The predicted dc sensitivity was 6.2×10^{-17} A (unit thermal flux)$^{-1}$ and the predicted Campbell sensitivity was 6.9×10^{-30} A^2 Hz^{-1} (unit thermal flux)$^{-1}$. On the final chambers these figures were measured as 6.56×10^{-17} and 9.75×10^{-30} respectively (Table 1). $(\overline{Q^2})$ was estimated to be 6×10^{-27} (coulombs)^2 and the operating potential was assessed at 300 V. These values were, of course, important to the design of the electronic equipment. A dimensioned sketch of the detector is shown in Fig 4.

2.7 Signal Processing Channels

Each channel comprised a head amplifier, a logarithmic Campbell amplifier and a power supply unit which also generated the +300 volt chamber polarising potential. This configuration (Figure 7) was adopted partly to facilitate rapid channel repair by replacement of individual units but also to enable the mean current in any of the nine chambers to be measured independently. This was achieved by a circuit arrangement that provided an outgoing signal proportional to the total current drawn from the polarising supply. The method was considered feasible since the shunt resistance of the chamber connecting cable at full operating temperature was expected to draw negligible current, due to the quality of the mi cables

employed. The design of the polarising supply and filtering system was also arranged to compensate for variations in chamber mean current, so ensuring a constant voltage at the chamber.

The low noise head amplifiers presented an input impedance of 33 ohms to match the trilaminax chamber cables. Each incorporated a facility for injecting a test current into the chamber input connection, a feature that was used to check overall channel electronic sensitivity and to make channel gain intercomparisions.

The Campbell amplfier contained filters to define the operating bandwidth centred on 100 kHz, a controlled gain amplfier, a fixed gain amplifier and a squarer. The smoothed average squared signal was compared with a reference and the difference acted upon the controlled gain amplifier via a conventional gain-control loop. The latter had a logarithmic relationship between control signal and gain and was arranged to provide an output signal of -1 volt per decade increase in neutron flux.

A preset gain control was provided to accommodate manufacturing tolerances in gain and noise bandwidth. Initial adjustments of sensitivity were achieved for each complete channel by means of a pseudorandom waveform generator connected in place of the chamber or to the test input. This provided a power spectral density of 1.2×10^{-19} A^2 Hz^{-1} in the Campbell frequency band, equivalent to about half way up the logarithmic range.

The more significant aspects of channel performance are listed below.

Head Amplifier

Input impedance	33 ohms
Head amplifier insertion (voltage) gain at 100 kHz	61 dB

Campbell Section

Output scale factor	-1.1 V/decade
Output working range	-4.3 V to -10 V
Nominal sensitivity at -8 V	1.2×10^{-19} A^2 Hz^{-1}
Noise bandwidth	10^4 Hz
Typical measured electronic noise in a complete channel with chamber connected	5.6×10^{-22} A^2 Hz^{-1}
Integration time constant	40 mS
Typical departure from log law as percentage of indicated neutron flux	$\pm$ 2.5%
Temperature coefficient of channel sensitivity	+0.67% $^{o}C^{-1}$
Reproducibility at constant temperature	$\pm$ 0.5%

Mean Current Section

Measurement range	0 to 2×10^{-3} A
Output scale factor	10 V = 2×10^{-3} A
Measurement accuracy	$\pm$ 0.5%

3 Manufacturing Procedures and Test Results

3.1 Manufacture of Cables and Detectors

Eleven trilaminax cables were ordered from Smiths Industries Ltd on 10 January 1980. They were manufactured to a layout generated by the company in discussion with AEE Winfrith and were completed in late June. The test specification included certification of chemical compositions, visual inspection, examination of conductor concentricity, examination of surface cleanliness, dimensional checks and measurements of continuity, capacitance and insulation resistance at room temperature. Additional measurements of insulation resistance were made at 550°C and outer sheath integrity was checked by water immersion.

At this stage the major problem was that of small pulse breakdown in the cable. This effect manifests itself as a charge limited breakdown phenomenon which generates pulses of order 10^{-13} coulombs at a pulse length of order 20 nS - a close simulation of chamber output. The onset voltage varies with temperature but in trilaminax cable tended to be of order 500 volts at the expected operating temperature. Time did not permit a proper solution of this difficulty but it was shown that the effect could be reduced by finishing the cable in a half hard, non-annealed condition. This increased the difficulty of stringer manufacture but additional tests showed that appropriate bending was both possible and permissible. The cables after delivery were sent under contract to Centronics Limited who fitted the cold end terminations.

The manufacture of 10 detectors was put in hand at AEE Winfrith. Piece parts were completed and outgassed without undue difficulty and assembly of the chamber units took place at the rate of 2 units every 1½ weeks. Each chamber was processed by heating to 450°C (operating temperature plus 100°C) and was then filled to the operating pressure with Argon using standard techniques. Normal pulse testing procedures were not applicable because of the low filling pressure and quality was from assessed from Campbell frequency spectrum measurements. This is a very sensitive test and on several units it was found that the ratio of the electron to the total current plateau varied with applied volts - interpreted as being due to electron capturing impurities in the filling. These chambers were reprocessed with great care to the extent that even the temporary chamber valves were changed to high temperature versions and processed with the chambers themselves. Tests were then found to be satisfactory but, to guard against subsequent outgassing during final testing, an extra 100 hour test bake at 200°C under Nitrogen was introduced. Campbell tests were carried out before and after this bake and no changes were seen. The chambers were then assembled into their outer, triaxial cases and fitted with cables. The assemblies were processed to remove hydrocarbons and backfilled to suppress breakdown in the terminal compartment. This processing took place in 10 foot long ovens to ensure that the cables would not subsequently outgas onto the chamber seals. The completed units were leak tested with a helium spectrometer before and after hydraulic testing to an external pressure of 124 Bar.

3.2 Detector Test Procedures

The chamber and cable assembly was tested generally to the procedures given in Ref 12 modified to take account of the unusual nature of the Campbelling unit. In addition to the obvious resistance and pulse breakdown tests, a Campbell frequency characteristic was measured at room temperature in the NESTOR reactor at AEE Winfrith. Each assembly was then placed in a 20 foot long furnace and heated to 400°C. Insulation and electrical breakdown performance were again measured before and after a 100 hour test bake and this was followed by a further Campbell check. Fig 5 shows a typical result. Chambers were accepted on the criterion that no parameter changed by more than 10% during the bake and no failures were observed.

3.3 Total Channel Tests at AEEW

The flux measurement performance of the system was specified in terms of relative accuracy, channel to channel and absolute accuracy for any one channel. The former parameter was required to be between $\pm$ 5% and $\pm$ 10% population standard deviation for any chamber used with any measuring amplifier and an additional $\pm$ 5% was added to allow for absolute calibration.

In order to establish the chamber contribution to this requirement, the final irradiation test of section 3.2 was carried out in the NESTOR reactor by means of a jig which ensured flux reproducibility and each chamber output was measured with one of the channel measuring amplifiers which had been carefully calibrated against the pseudo random pulse generator (Ref 13). This instrument was used essentially as a standard. Table 1 gives the chamber relative campbell sensitivities obtained in this work, a population spread of $\pm$ 6% being derived. The reproducibility of individual readings was checked and is considered to be $\pm$ 1 or 2% so that the observed differences chamber to chamber are real. They are probably due to variations in coating weight.

Absolute sensitivity is given at the foot of Table 1 and was derived from neutron flux measurements using manganese foils. It may be trusted to an accuracy of about $\pm$ 3% in flux, plus observational errors, plus errors associated with calibrating the standard - about $\pm$ 15% in all. The measured sensitivity was in reasonable agreement with prediction (Section 2.6), the difference being due probably to extrapolation errors in estimating $\bar{Q}_e$ and the doubling produced by the fact that the Campbell signal depends on $(\bar{Q})^2_e$.

DC sensitivities were measured at the same time with results which are also given in Table 1. In this case, correction for gamma effects was necessary so that, whilst individual relative values are still reproducible to $\pm$ 1 or $\pm$ 2%, the absolute accuracy was somewhat worse than in the Campbell case. The measured values were, however, in good agreement with prediction.

One unit was tested for dc gamma sensitivity in the AERE fuel element facility and gave a value of 7.6 ($\pm$ 1.0) x 10^{-12} A R^{-1} hr.

4 Stringer Assembly

The above results were considered satisfactory and the chambers were despatched to Windscale Nuclear Laboratories for stringer assembly. The design and the

manufacture of the stringers were specialist operations and were carried out at WNL. A sketch is shown in Figure 6 and it will be appreciated that the work involved considerable complexity which was not eased by the constraint imposed on cable bending radii. Detailed discussion of this phase is outside the scope of the present paper, but it is worth noting that an accident, occured whilst one of the many welds was being made. It caused local melting of the sheath of the cable of chamber serial 019 and is reported here because a repair in situ proved possible. It was fortunate that the damage did not penetrate the inner sheath of the cable and the repair was carried out by direct electrical heating using current through the outer sheath from a heavy current transformer. The magnesia near the hole was dried out by heating to about 350°C for tens of minutes and the temperature was then raised to melt and flow silver solder into the damaged area. A very adequate patch was obtained and no degradation of chamber characteristics could be observed.

The insulation resistances of all nine installed chambers were checked at various stages during the stringer assembly process and one chamber (serial number 024) was changed for the spare because of dissatisfaction with some of the results.

5 Commissioning Experience

The three stringers with nine chambers were loaded into the reactor during March and April 1981. Figure 7 shows a sketch of the overall system and indicates that only one chamber from each stringer was used to supply dc signals in addition to cambell output. Every chamber was, however, tested in situ both for campbell and dc performance with external equipment and with its related measuring amplifier. This was done partly because it was the first time that nine, high temperature and ostensibly identical campbell chambers have been compared one with another in the same reactor. Much of the information obtained was, therefore, of relevance to the future and, for the present, it is sufficient to note that the physics performance of the system was in good agreement with prediction.

Fig 5 shows a typical frequency spectrum from WAGR and permits comparison with analogous results obtained at AEEW before the chamber was despatched. Fig 8 shows measurements made on an installed channel and demonstrates that reasonable campbell saturation characteristics could be obtained. Fig 9 gives equivalent dc results and permits the inference that, at the start of the experiments at least, good electrical insulation peformance was available.

The effective campbelling and dc working ranges were also estimated. Details varied from chamber to chamber because of the different fluxes but, for example, the output from chamber 020 changed from 1.6×10^{-16} A^2 Hz^{-1} at full power to about 7×10^{-22} A^2 Hz^{-1} due to gammas plus noise at shutdown (Fig 8). This gives a value for $(R_{0.1})_{gamma} < 2.6 \times 10^4$ - very close to that predicted (section 2.3). The amplifier noise level was about 5.6×10^{-22} A^2 Hz^{-1} so that $(R_{0.1})_{noise}$ was also close to prediction. The dc working range for 10% errors can be seen from Fig 9 to have been of order 10^2 so that the decision to use the campbell technique was completely justified. The current at shutdown given in Fig 9 also leads to an estimate of reactor gamma flux equal to 1.1×10^5 R/Hr. The chamber in question was installed at a relatively low neutron flux position but even so it appears that the predictions of gamma flux were a little high.

It was clear by the early part of May that the chamber system was operating correctly in accordance with specification. The concluding experiments went ahead as planned but difficulties then began to be encountered. In general, experience with high temperature radiation detectors is good and problems would not be expected after installation in times measured in weeks at temperatures as low as 350° and irradiations less than a few by 10^{17} n.cm^{-2}., ie, at epochs comparable with test times. Indeed, good experience with P7 counters and similar chambers extends over years (Ref 14). In the event, however, of the nine chambers involved, two eventually failed because of broken cables (Serial numbers 019 and 027) and three others developed dc electrical leakage at levels much higher than those of Fig 9. Other chambers showed a tendency to pulse breakdown which led to head amplifier and measurement difficulties. Remedial action was taken by reducing operating voltages and, apart from the two cable failures, the channels continued to function in their campbell role although some of the dc measurements were lost because of the way in which instruments had been assigned to the data logger. Channel outputs could not be changed from defective units within the time available.

The cause of the various failures is of considerable interest and has yet to be fully investigated. Nevertheless, comment is possible:

a The positions of the failures on chambers 019 and 027 have been determined with some accuracy by electrical pulse reflectometry. Figure 10 (centre) shows a reflectometer trace from a normal channel and, top and bottom, those given by Channels 019 and 027 respectively. As can be seen, the open circuit is at the same position on both faulty cables viz at 190 $\pm$ 10 nS, corresponding to a distance of 10.6 ($\pm$ 0.5) m from the cold end termination. The chambers concerned are fitted in the centre positions of two stringers and, while this is not statistically significant (probability due to chance = 0.25), the fact that the breaks are at the same height cannot be a coincidence. Examination of drawings shows that the position in question is possibly on a cable coil immediately above a straight run near the stringer gag but it is far from clear how breaks could have happened. There seems to be no mechanism for inducing stress and in any case the tensile failure strength of the cable is greater than 1 Te. Furthermore, it has not been possible to induce sample failure by laboratory temperature cycling nor by fatique tests within reasonable limits. The point of failure on 019 does not coincide with the position of the brazed repair referred to in section 4.

b The low leakage resistances developed after a short period of service and deteriorated rapidly. Values tended to an asymtote which was very similar for the three chambers in question (15, 19 and 18 K ohms for chambers 022, 023 and 025 respectively). These values did not change significantly with reactor power although most leakage processes in devices of this type are strongly temperature dependent. It may be concluded either that the problem occurred in a low temperature region at the top of the stringer (very unlikely) or was due to certain conduction processes, foremost among which is that due to carbon deposition. The obvious suspicion is that these failures are an incipient version of the open circuits of chambers 019 and 027 and that the low resistances are due to the ingress of reactor gas followed by reduction to carbon in the cable magnesia insulant. Laboratory experiments with a trilaminax cable in a CO_2 atmosphere at 400°C have given results of the type illustrated in Figure 11 and it is very tempting to compare the final resistance of this experiment (28 kΩ) with those quoted above. The final resistance does not vary with temperature.

Resistances of the magnitude concerned cannot be detected by pulse reflectometry but it is hoped to obtain further data during post irradiation examination.

c It is conceivable that the breakdown problems also have their roots in cable damage but from the results obtained during stringer build and the fact that a chamber was rejected before loading, they seem more likely to be due to inadequate processing of the original chamber units. This is considered surprising in view of the care which was exercised but there is no doubt that serial 021 which broke down early at 300 V in the reactor also tended to mis-behave at 400 V on test during stringer assembly. This, too, is an area which is under investigation.

6 Summary and Conclusions

Nine ionisation chambers were designed, made, fitted with a new cable and supplied to the reactor for rig assembly in the very short time of 12 months. Complementary electronic channels were also supplied on a similar timescale and together they provided the experimental data required for some of the WAGR concluding experiments. The system met its specification in physics terms but operational problems were encountered and some of these were very surprising in view of the comprehensive preinstallation tests which were carried out. However, the campbelling mode proved robust enough to override a number of faults and permitted operation in circumstances under which the dc mode was made inoperable. The choice of campbelling was also justified by the working range achieved ie of order 4 decades under incore conditions. Such a range could not have been provided in any other way.

This is probably the first occasion on which a substantial number of high temperature ionisation chambers have been made under essentially laboratory conditions and compared with each other in terms of sensitivity and other operational parameters. It was gratifying to find that their physics performance matched prediction very well and that they could be built with a sensitivity spread of less than $\pm$ 10%. A great deal of useful instrumentation design experience has been obtained which will undoubtedly be of great value in the future.

7 Acknowledgements

The work which has been described was a team effort. A large number of people were involved and became committed to achieving the programme dates. The authors would particularly like to thank the staff of Special Techniques Workshop, Engineering Services Branch and of Experimental Physics Section, Control & Instrumentation Division, AEEW, all whom made significant contributions to the chamber work.

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Table 1 The Chamber Neutron Sensitivities

Detector Serial Number	Relative Campbell Sensitivity	Relative dc Sensitivity
018	1.07	1.12
019	0.94	0.95
020	1.08	1.12
021	1.06	1.08
022	0.90	0.86
023	1.01	1.00
024	1.00	0.96
025	0.95	0.95
026	1.01	1.02
027	0.97	0.98

Notes

1 All measurements made at 300V.

2 The relative measurements on any one chamber were reproducible to $\pm$ 1½% and are probably accurate in the longer term to $\pm$ 3%.

3 The population standard deviations of the Campbell and dc results are $\pm$ 6% and $\pm$ 8% respectively.

4 The mean absolute sensitivity of the Campbell group was 9.75×10^{-30} $A^2 . Hz^{-1} .$ $(\text{unit flux})^{-1}$ to an accuracy of $\pm$ 5%.

5 The mean absolute dc sensitivity was 6.56×10^{-17} A. $(\text{unit flux})^{-1}$ to about $\pm$ 10%.

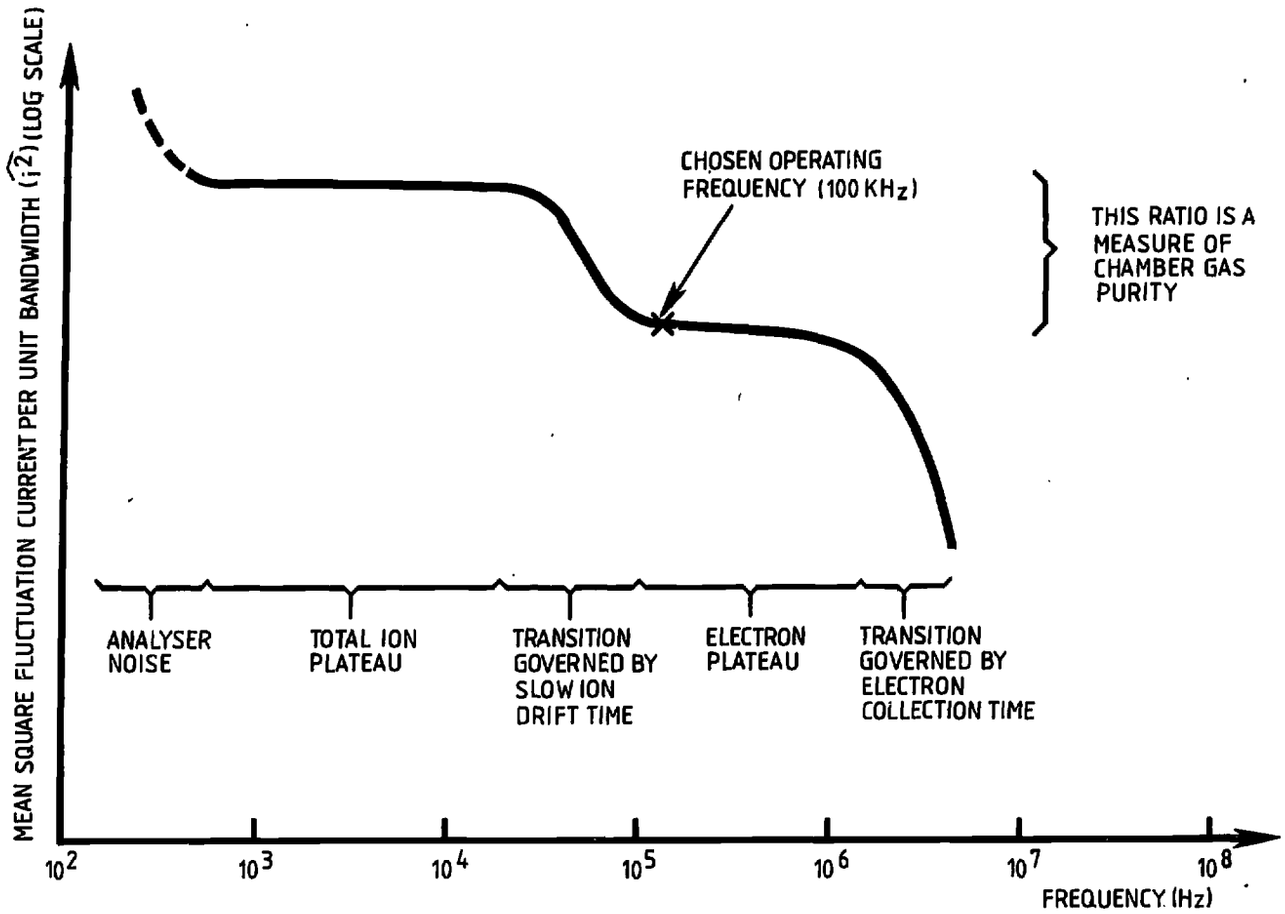
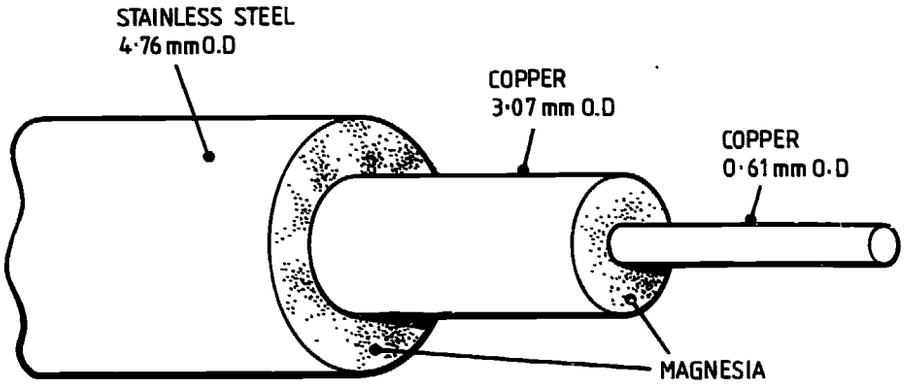
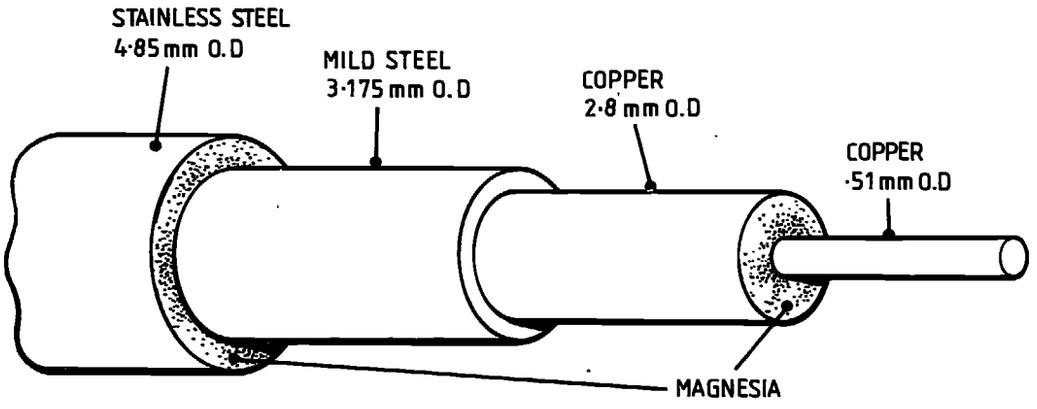


FIG.1. SKETCH OF A CURRENT FLUCTUATION SPECTRUM



(a) TRI-AXIAL CABLE



(b) TRI-LAMINAX CABLE

FIG. 2. CABLE CROSS SECTIONS

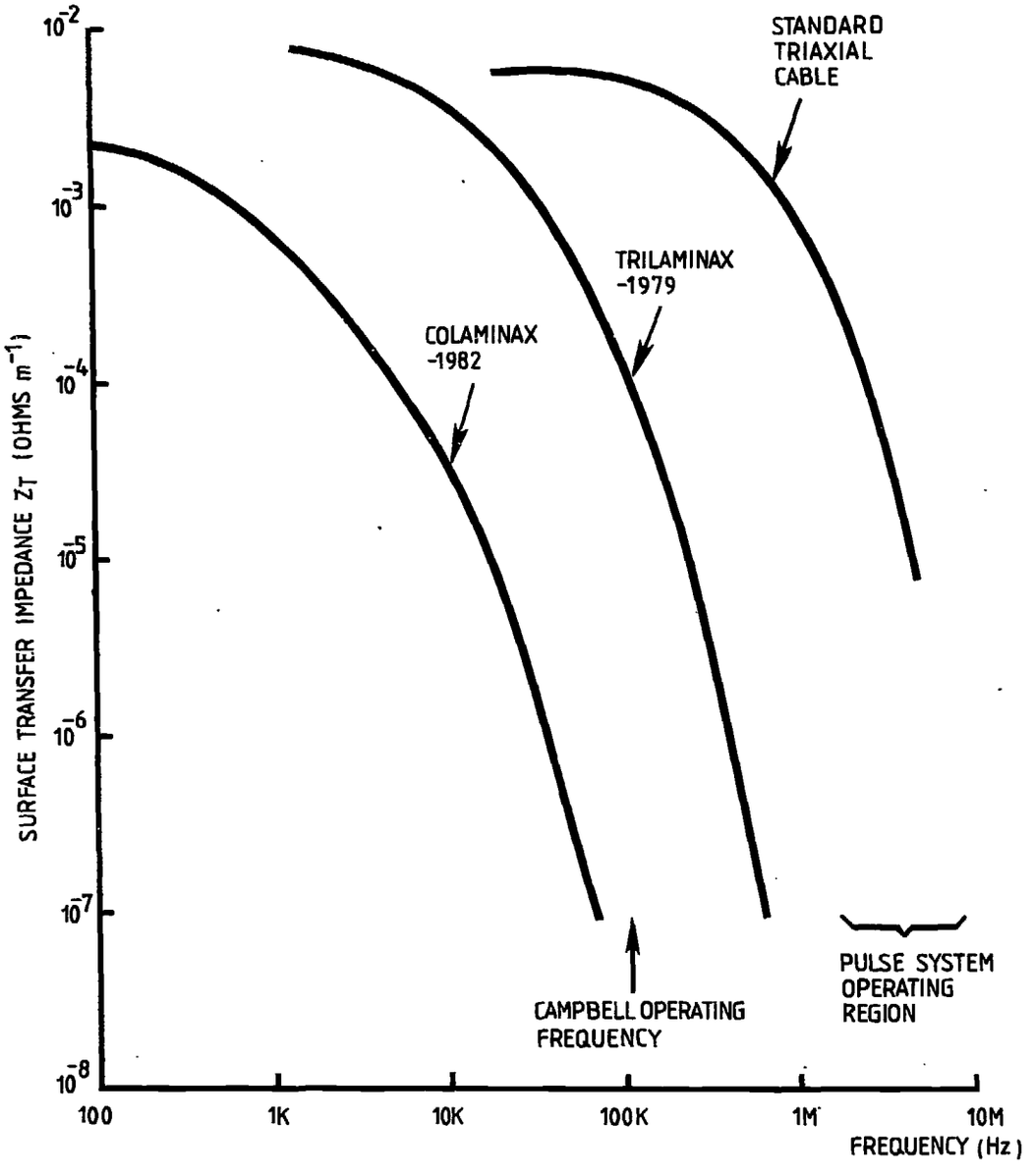


FIG.3. CABLE SURFACE TRANSFER IMPEDANCES

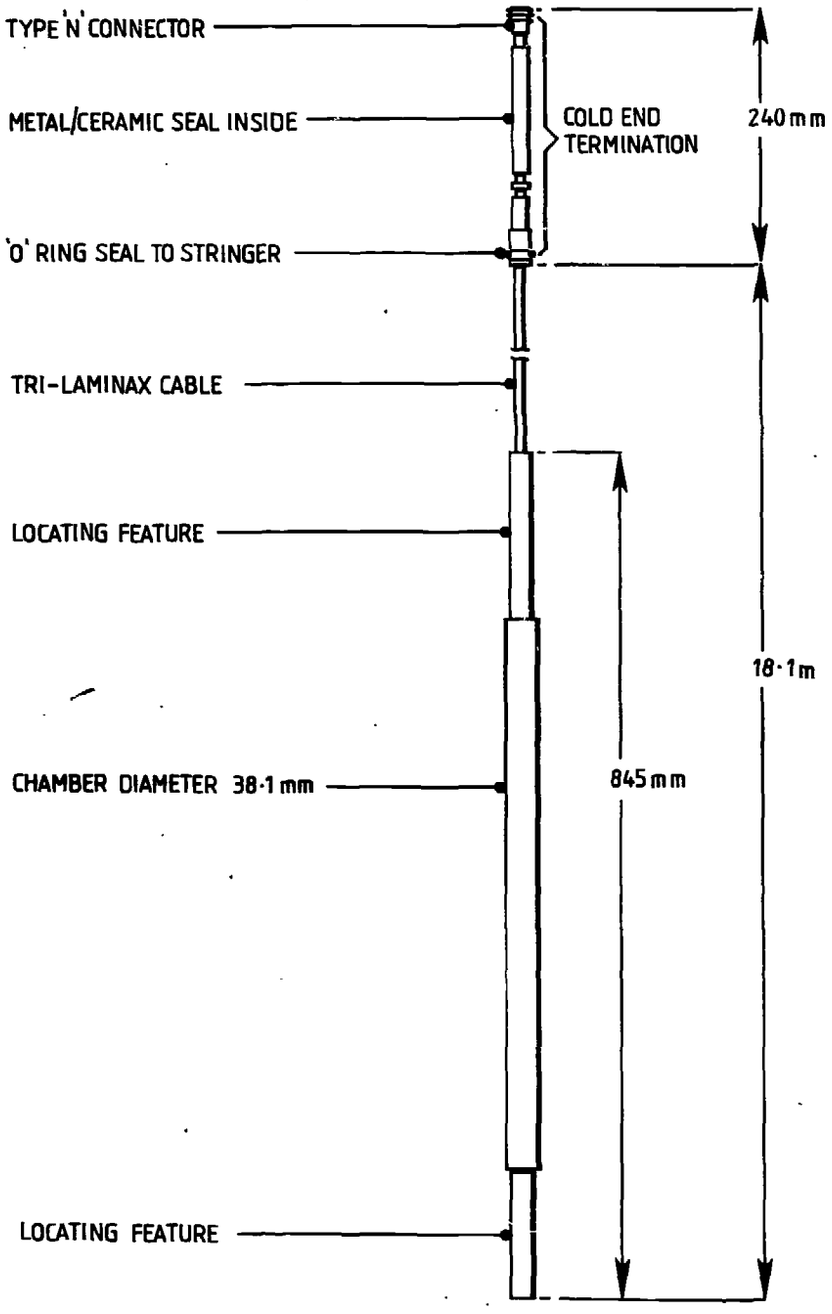


FIG.4. OUTLINE SKETCH OF CHAMBER AND COLD END TERMINATION ASSEMBLY

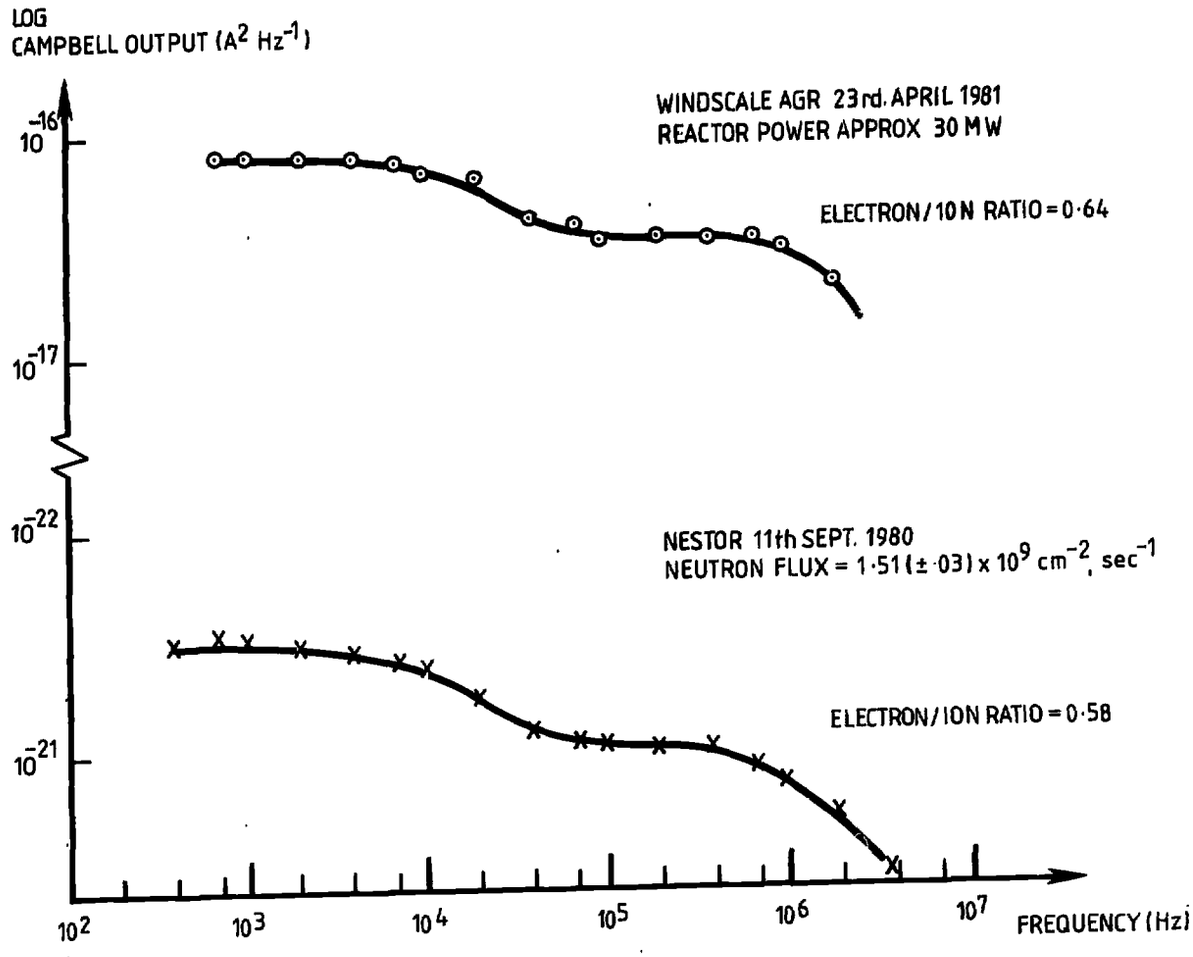


FIG. 5. TYPICAL MEASURED FLUCTUATION SPECTRA – CHAMBER 020

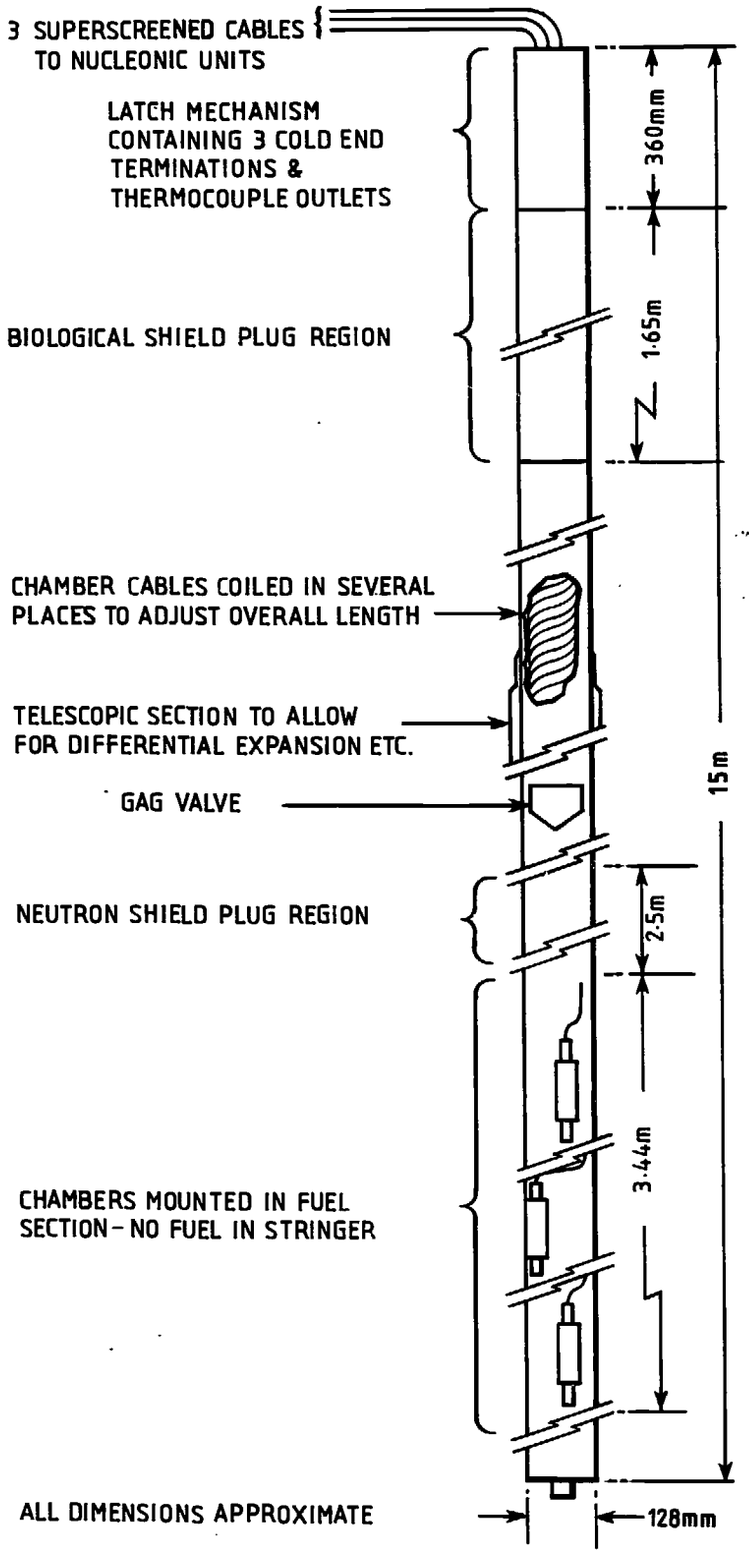


FIG.6. OUTLINE SKETCH OF STRINGER.

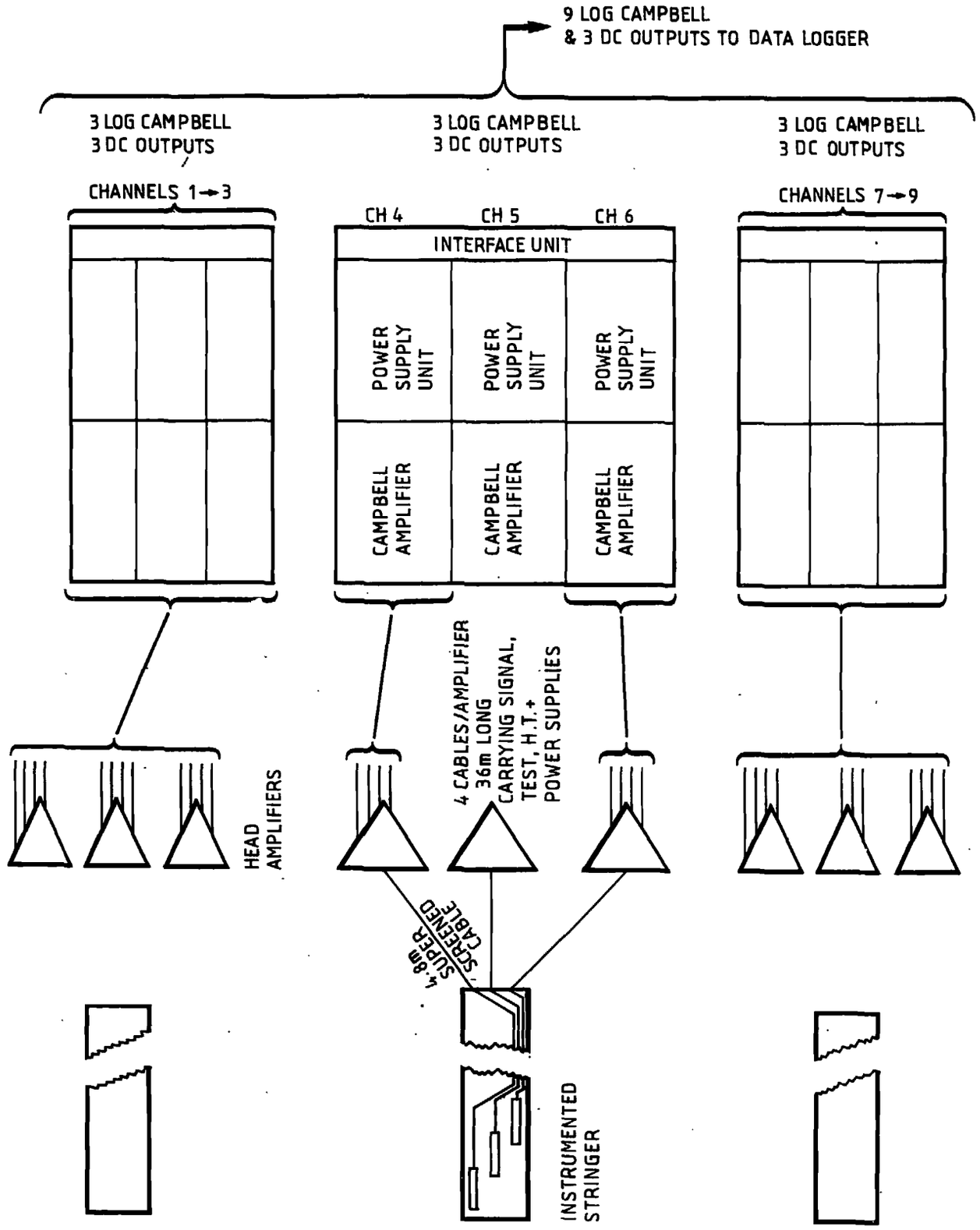


FIG.7. SKETCH OF THE EQUIPMENT CONFIGURATION

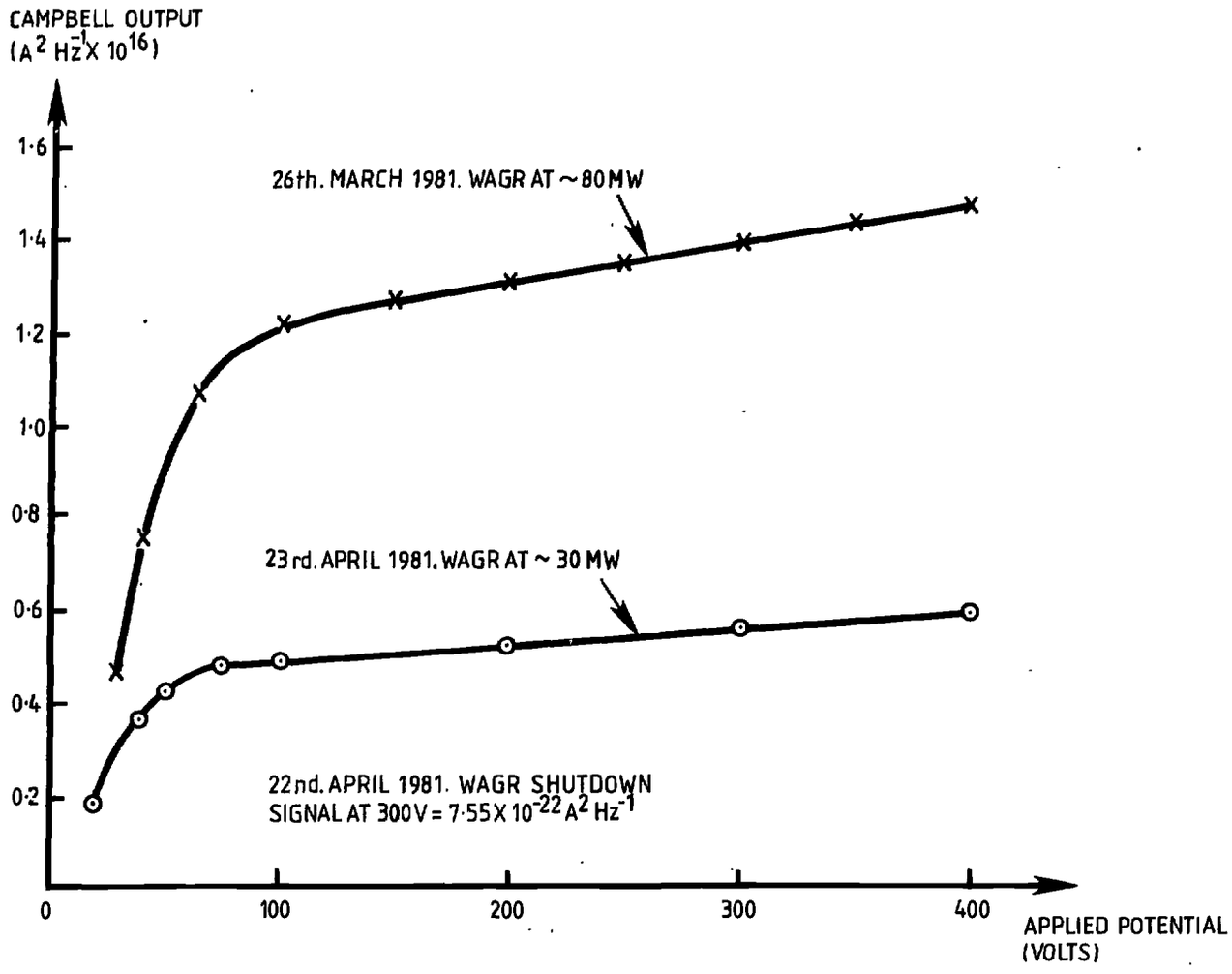


FIG. 8. TYPICAL CURRENT FLUCTUATION SATURATION CHARACTERISTICS – CHAMBER 020

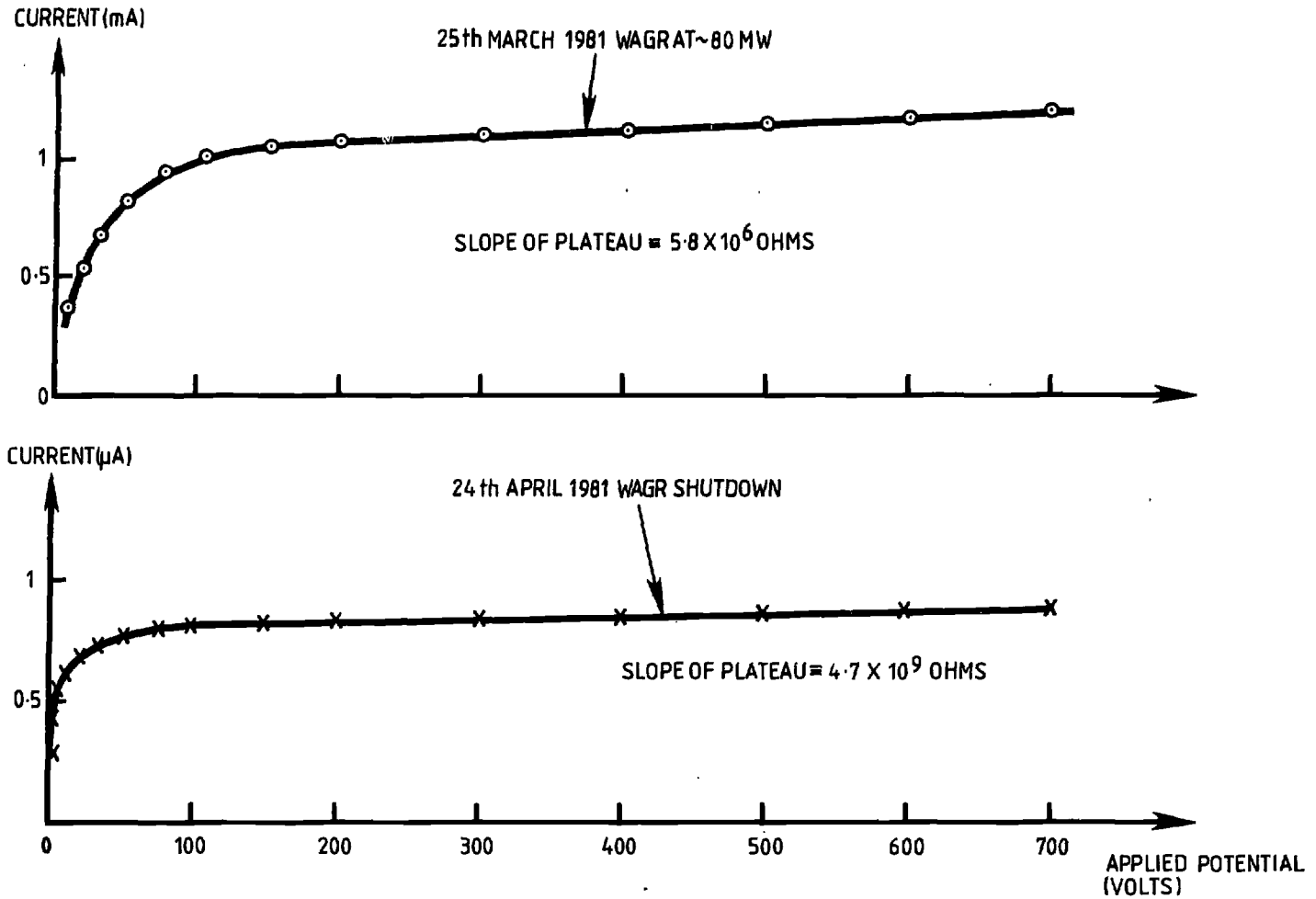
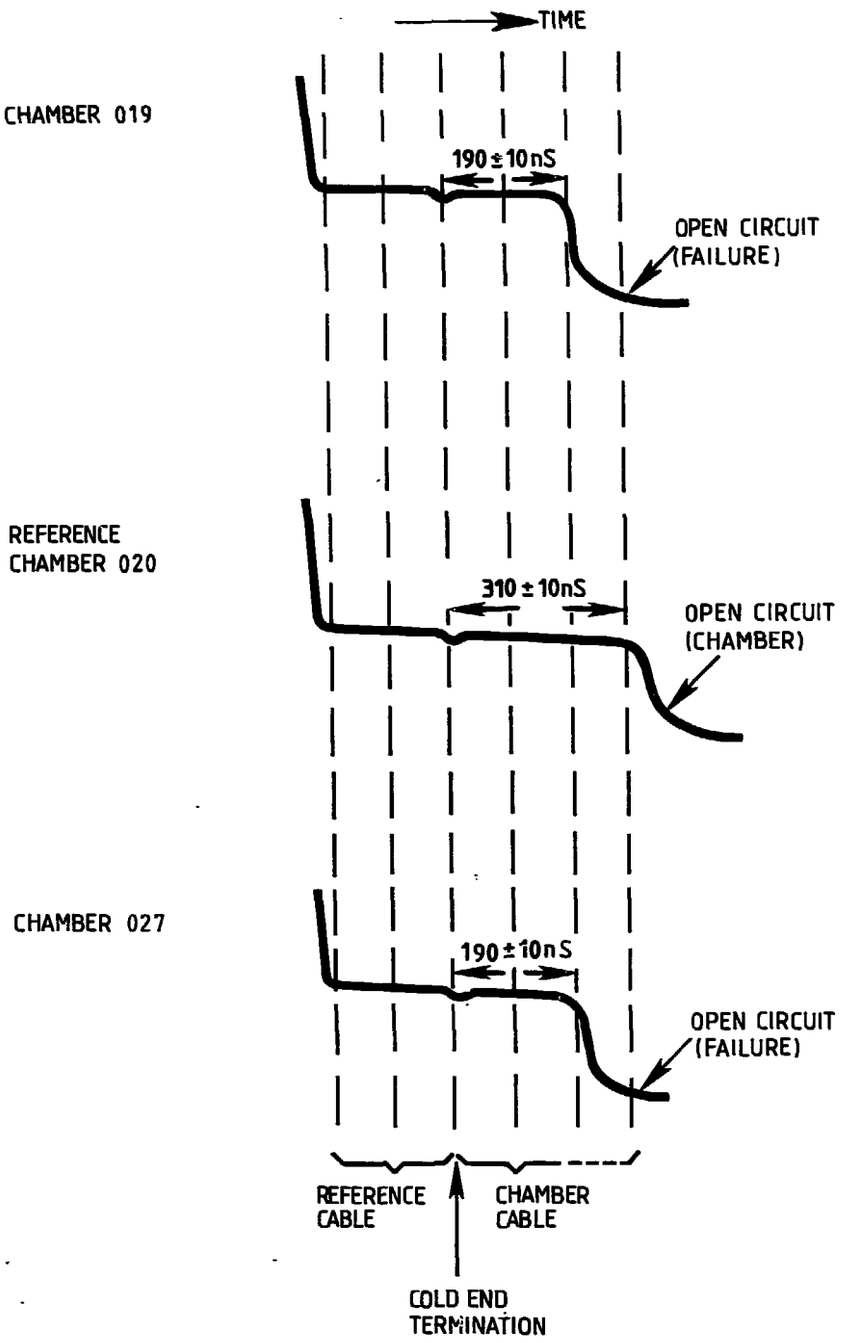


FIG.9. TYPICAL d.c. SATURATION CHARACTERISTICS – CHAMBER 020



TIME SCALE = 100 ns / DIV. EQUIVALENT TO 5·6 ± 0·2 m / DIV.

FIG. 10. PULSE REFLECTOMETER TRACES FROM BROKEN CABLES

RESISTANCE (OHMS)

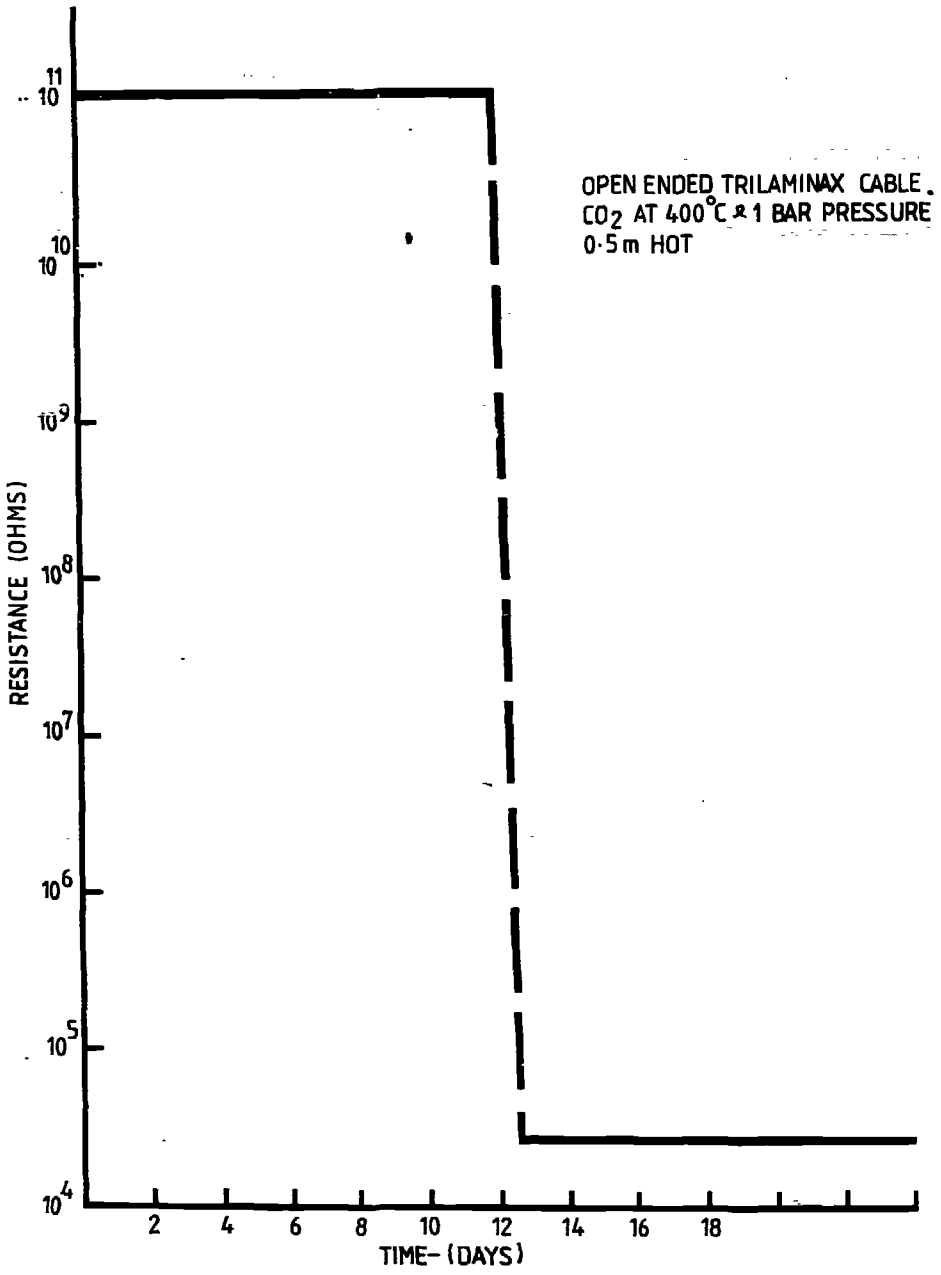


FIG. 11. INSULATION PERFORMANCE OF BROKEN CABLE HEATED IN CO_2