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SALIM ABID TABASSUM

SOLAR REFRIGERATION
Evaluation Of Technical Options and
Design Of A Solar-Generator-Adsorber For
A Novel Adsorption Refrigerator

(Volume II)

SUPERVISOR

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CHAPTER SEVEN

Characterization of Adsorption Pairs

7.1 Determination of isosteres

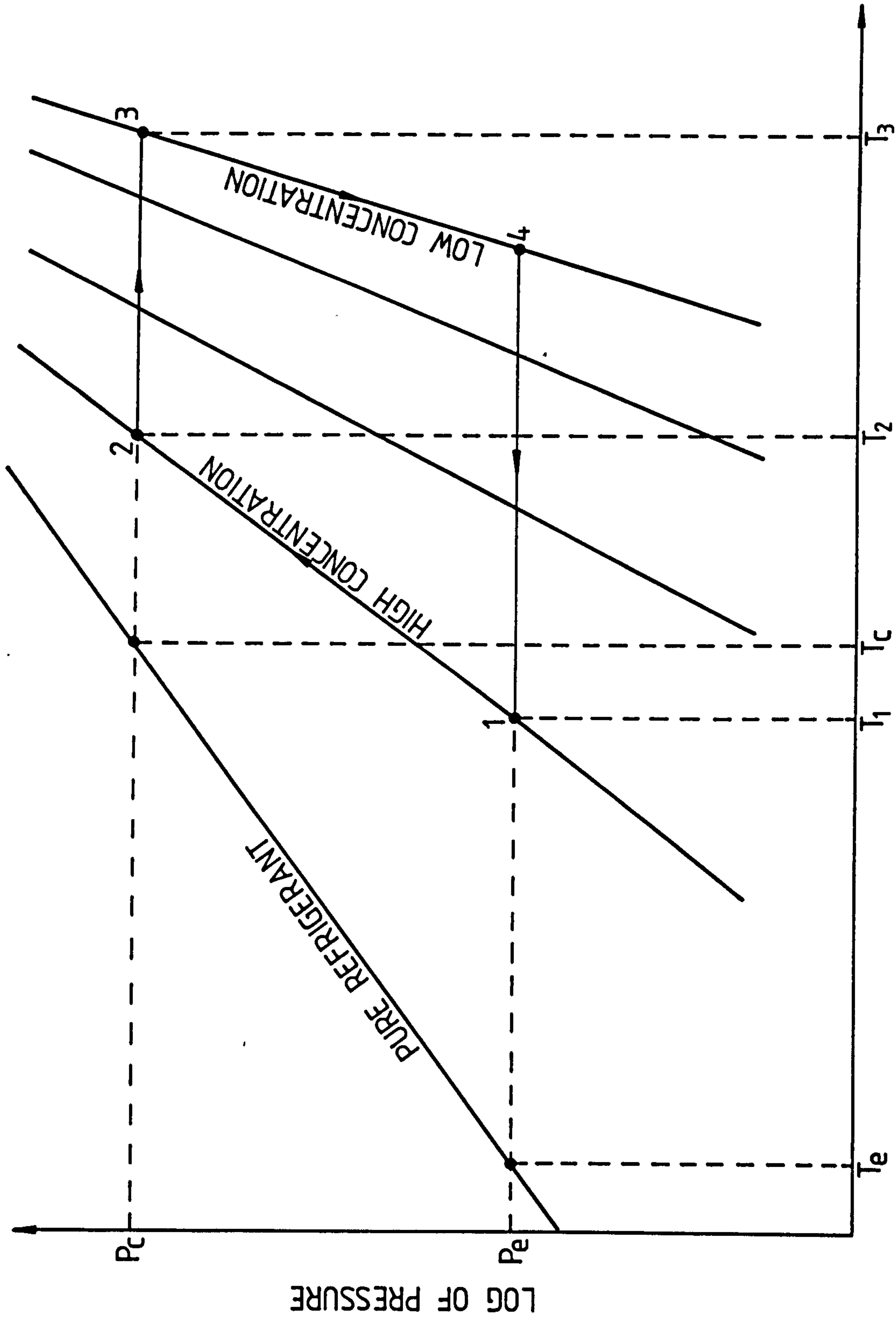
An isostere graphically represents the variation with respect to temperature of vapour pressure of the adsorbate at the interface boundary with the adsorbent, while the concentration of the adsorbate in the adsorbent remains constant. Mathematically an isostere is represented by

$$m = F(p, T)$$

7.1

where m is the ratio of the adsorbate mass to the adsorbent mass, p is the vapour pressure of the adsorbate at the interface, and T is the absolute temperature of the mixture.

Isosteres play a very vital role to determine the suitability of a particular adsorbent-adsorbate pair for its application in a refrigeration cycle. Figure 7.1 shows a complete refrigeration cycle represented on a $\ln(p)-1/T$ plane (sometimes also referred to as Clapeyron diagram). The generation process starts at point 1 and follows the constant concentration line (i.e. the isostere) to point 2, followed by desorption of the adsorbate(refrigerant) at constant pressure to point 3. Point 1 is fixed by the evaporation temperature T_e and the adsorption temperature T_1 . Point 2, at which desorption of the adsorbate(i.e. refrigerant) vapours commences, is determined by the condensation pressure of the refrigerant. Point 3 represents the maximum temperature of the cycle and the completion of the desorption process. The maximum concentration in the generator, represented by point 1, may be read readily from the



NEGATIVE RECIPROCAL OF TEMPERATURE (K⁻¹)

Fig 7.1 Adsorption refrigeration cycle on a Clapeyron diagram

figure. The slope of the isosteres represents the heat of adsorption (or desorption). Thus the amount of adsorbate(refrigerant) desorbed and the heat required to desorb it, between the points 2 and 3, may also be determined from figure 7.1. This information facilitates assessment of the thermodynamic performance of the chosen adsorbate-adsorbent pair in a refrigeration cycle.

7.2 The experimental rig

The functions of pressure and temperature representing the isosteres have already been discussed in chapter 4, e.g. the Dubinin-Astakhov (D-A) equation. However to employ these relations for analysis purposes, required the characteristic constants which were unique to a particular adsorbate-adsorbent pair. These can at present only be determined experimentally. An experiment was thus designed which may be used to establish these characteristic constants for a range of different possible pairs. Activated carbon and zeolite were the adsorbents selected(see chapter 6) for investigation with either methanol or ammonia in each case as the adsorbate.

The general principle employed to establish each isostere was to place a mixture of adsorbate-adsorbent of known concentration in a sealed vessel, and heat it to different temperatures within the range of interest. When the whole mixture was at a uniform temperature, the corresponding pressure was noted. The chosen adsorbents, being poor thermal conductors, were expected to take a long time to reach a uniform temperature while being heated or

LEGEND FIG 7.2

- 1 'BBC Master' micro-computer
- 2 Disc drive unit
- 3 Visual display unit
- 4 IEEE-488 interface unit
- 5 MAPS.data acquisition system
- 6 SOLARTRON 7055 microprocessor voltmeter with serial interface
- 7 Cold junction card (CJC)
- 8 Stabilized dc supply for pressure/vacuum transducer
- 9 Stabilized dc supply for CJC unit
- 10 Mains remote control unit
- 11 Oil bath
- 12 Stirrer
- 13 Pressure vessel
- 14 Cooling coil
- 15 Ammonia cylinder

OVERLAY BOUND IN ORIGINAL

INCORRECTLY

FIG 1.5 General layout of experimental rig for characterization of absorption bands

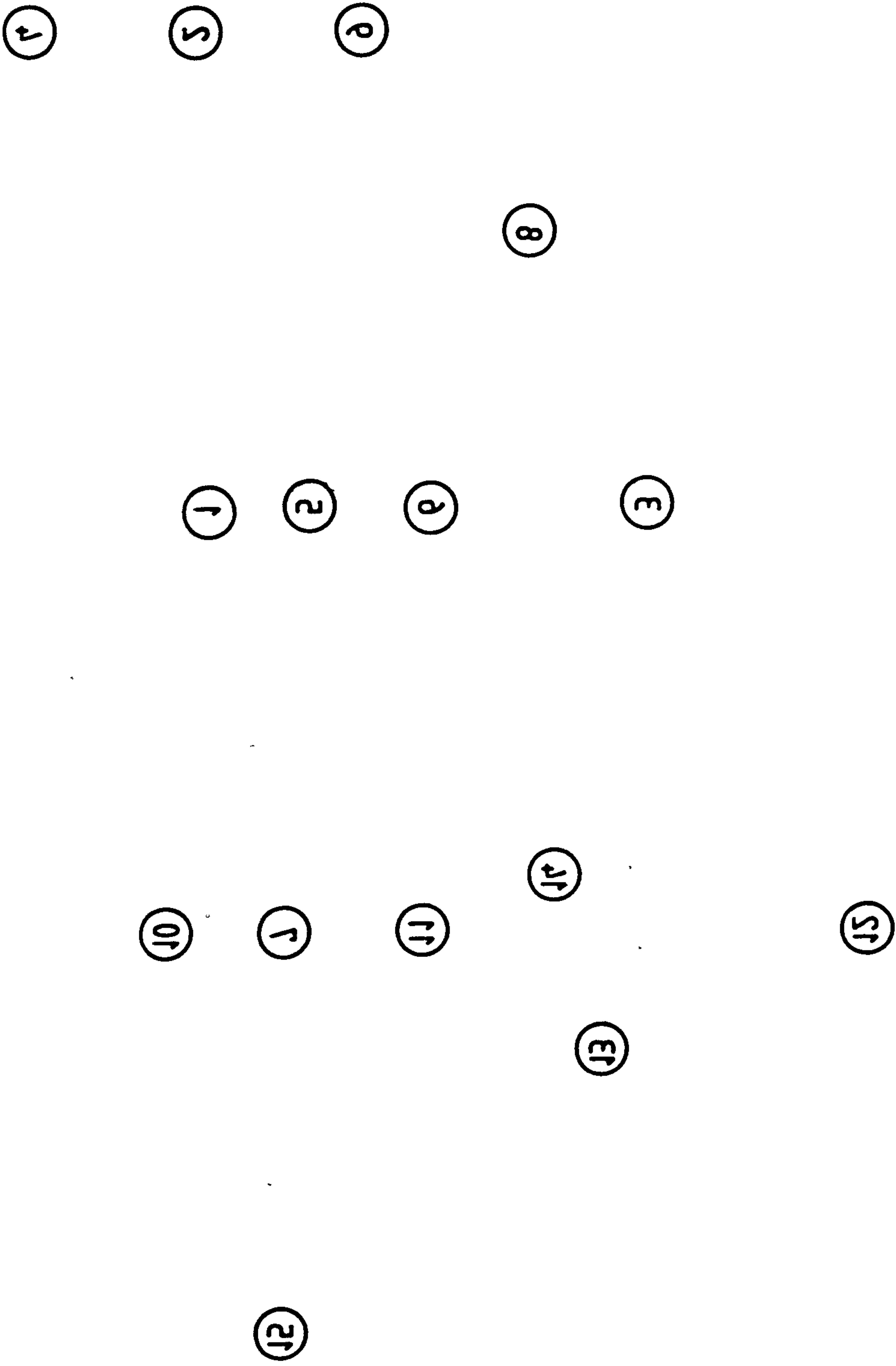
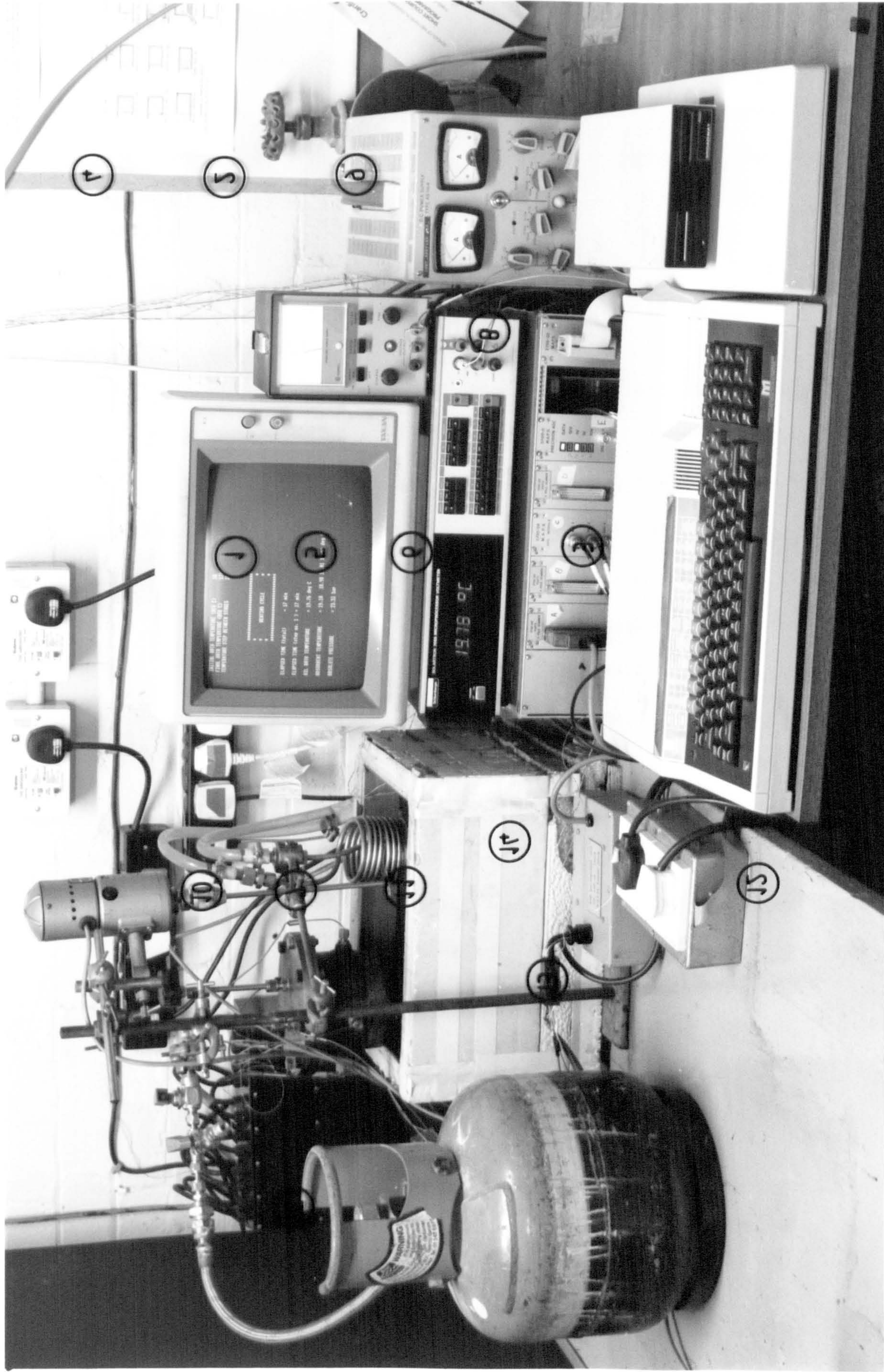




Fig 1.5 General layout of experimental rig for characterization of adsorption isotherms



cooled. Therefore it was necessary that the whole operation was automatic. This was ensured by the use of a micro-computer-based data acquisition and control system. A general view of the experimental set-up is shown in fig 7.2

7.2.1 The pressure vessel

A small cylinder, shown in figure 7.3, of 104 mm diameter and 80 mm deep was fabricated by welding 10 mm thick mild steel plate at one end of a mild steel pipe. A flange was welded to its top to take on a circular plate for its sealing. The flange was machined and a groove cut in it to accommodate an 'O'ring seal. The top plate was also cut from a mild steel plate of 10 mm thickness and its surface, which was in contact with the O'ring, machined. The plate had two holes at the top, through which a pressure transducer was connected and the refrigerant vapours introduced. Midway between the base and top of cylinder were four holes of 2 mm diameter which were spaced equally on the perimeter. Four mild steel bosses with tapped holes were welded at these locations through which were fixed thermocouples. Stress calculations for the pressure vessel are shown in appendix C.

7.2.2 The 'O'ring seals

In view of the maximum applied temperature of 120°C during heating of the pressure vessel a viton 'O'ring seal was selected whose safe application temperature was 250°C. The manufacturers recommended the material for use with aqueous ammonia as well. Thus it was

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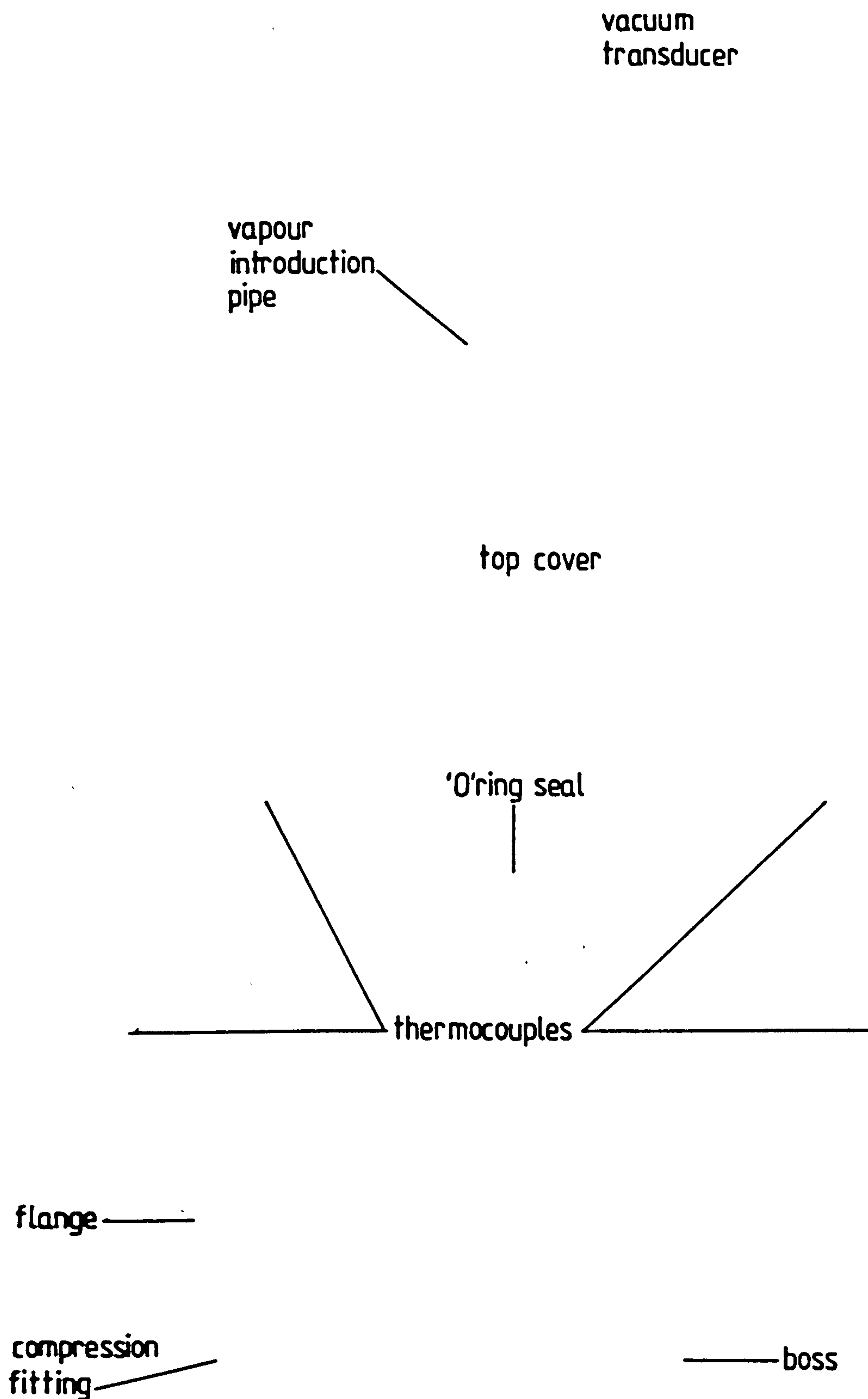
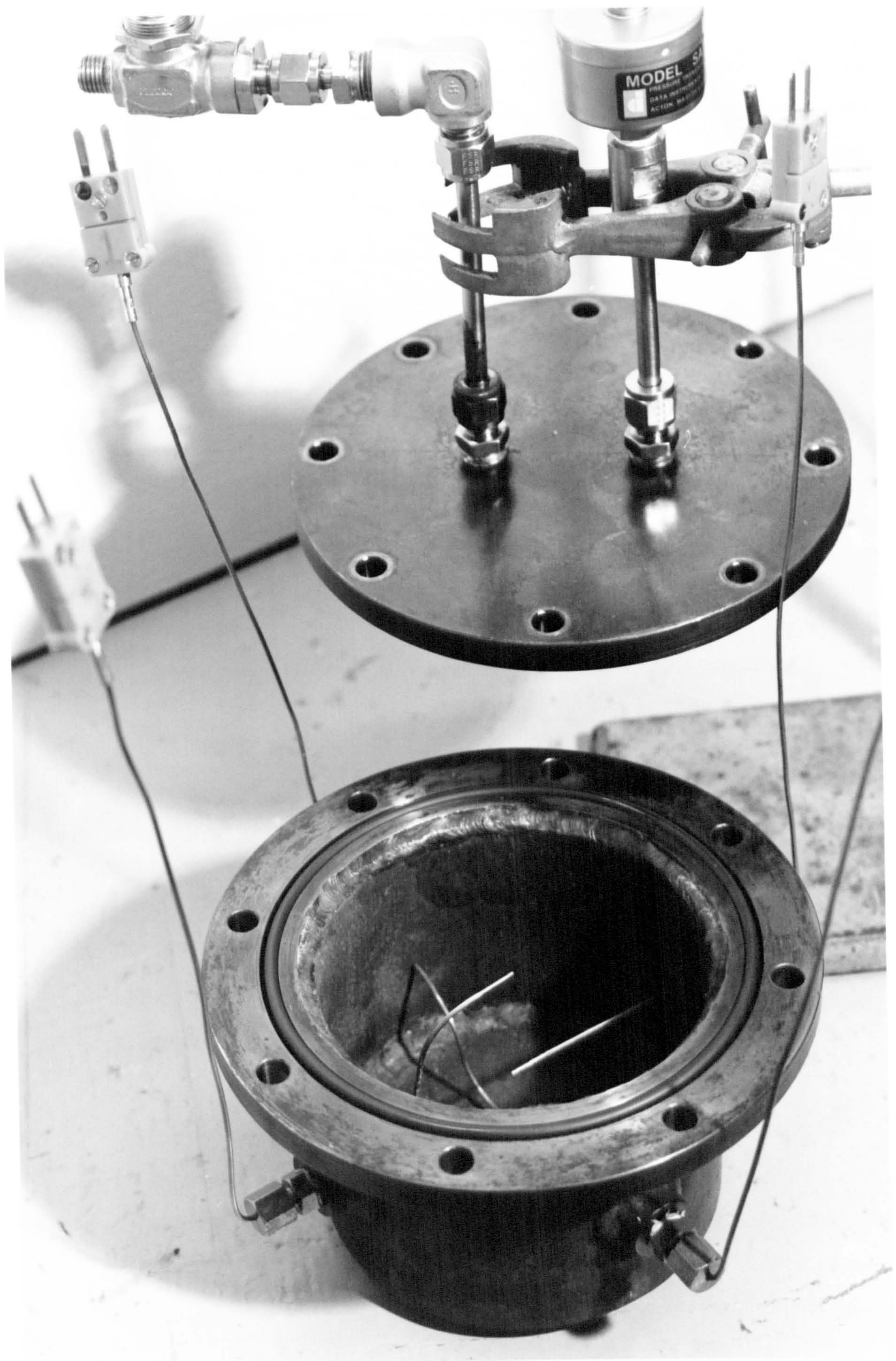


Fig 7.3 The pressure vessel assembly



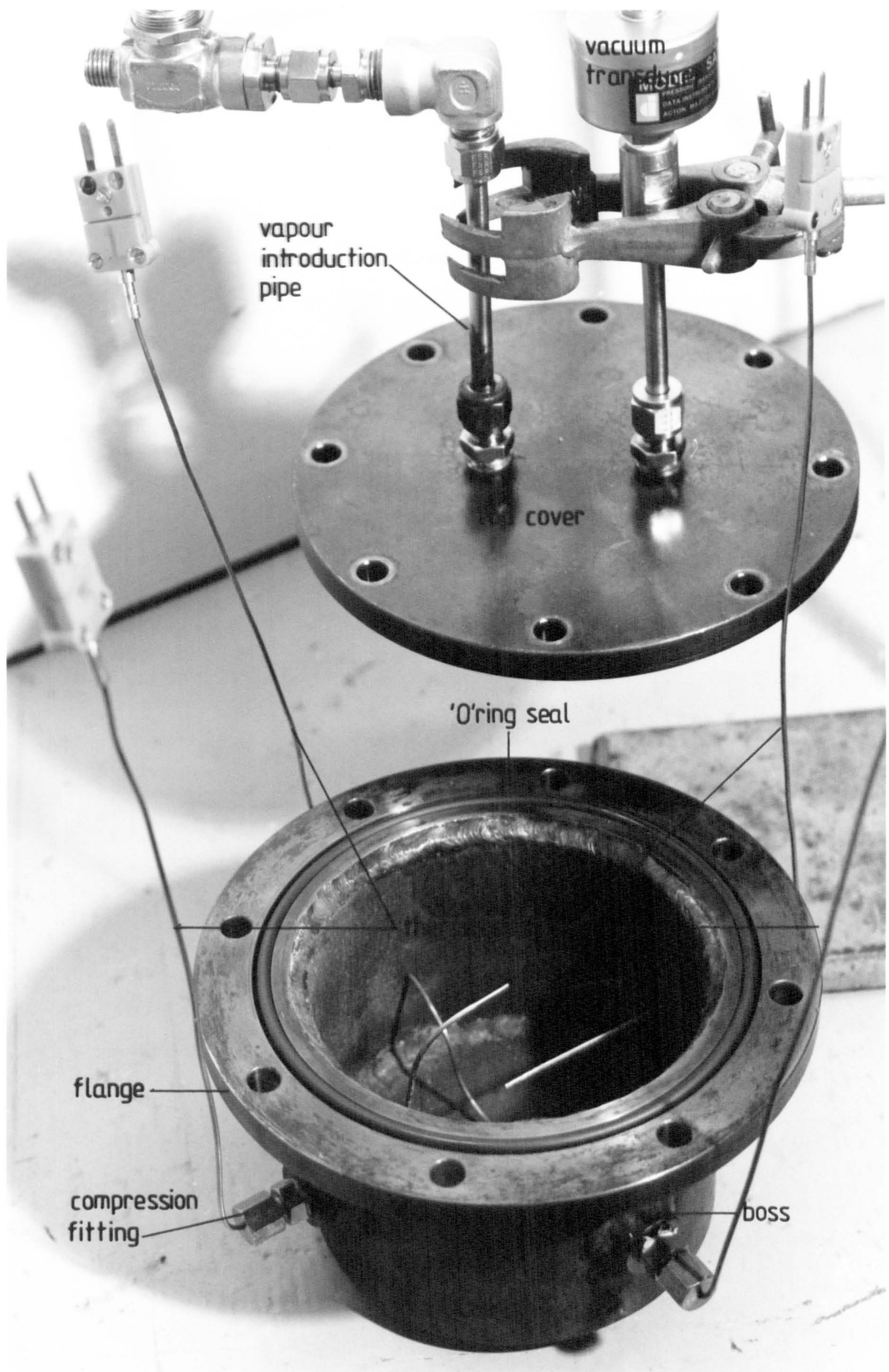


Fig 7.3 The pressure vessel assembly

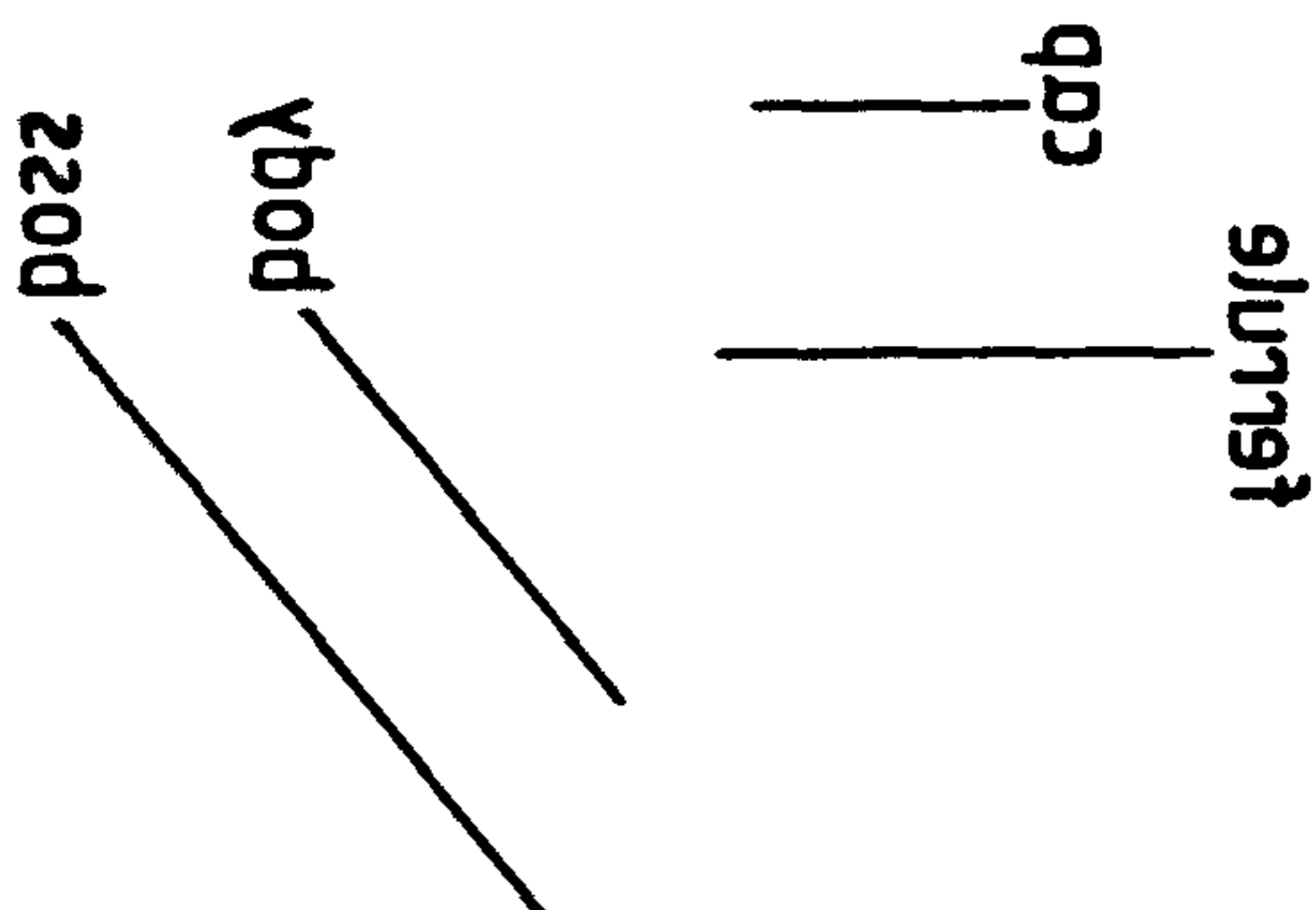
considered safe when ammonia was used as the adsorbate. But subsequent tests with ammonia proved that viton was not a suitable material when warm anhydrous ammonia vapours are to be contained. Then in further tests with ammonia 'O'ring seals made from teflon were used which proved successful. Though the repeated use of teflon 'O'rings was not safe as it became squashed after assembly and could not regain the original round cross-section. During the tests with methanol viton 'O'rings gave satisfactory performance.

7.2.3 The thermocouples

The temperature range of interest in these experiments was between -20°C and 120°C . Copper-constantan (i.e type T) was the only type of thermocouple which could be used for sub-zero temperature measurement[1,2]. It generates an emf which is exactly represented by an eighth-degree polynomial in temperature in the range 0°C to 400°C [1,2]. The inverse relation is represented by a fourth-degree polynomial with an accuracy of $\pm 0.2^{\circ}\text{C}$. Thus type T thermocouples were considered suitable for the application. The temperature of the sealed and sometimes hostile (e.g. ammonia) environment inside the pressure vessel was to be sensed avoiding any leakage. Therefore stainless steel sheathed thermocouples with compression fitting were selected. The accuracy of these thermocouples was $\pm 1.5^{\circ}\text{C}$ [2].

Figure 7.4 shows a thermocouple with the compression fitting. The fitting, made of stainless steel, consisted of three parts namely, the body, the ferrule, and the cap. The body had $1/8"$ BSP taper

Fig 1.4 Details of the compression lifting on the attached thermocouple



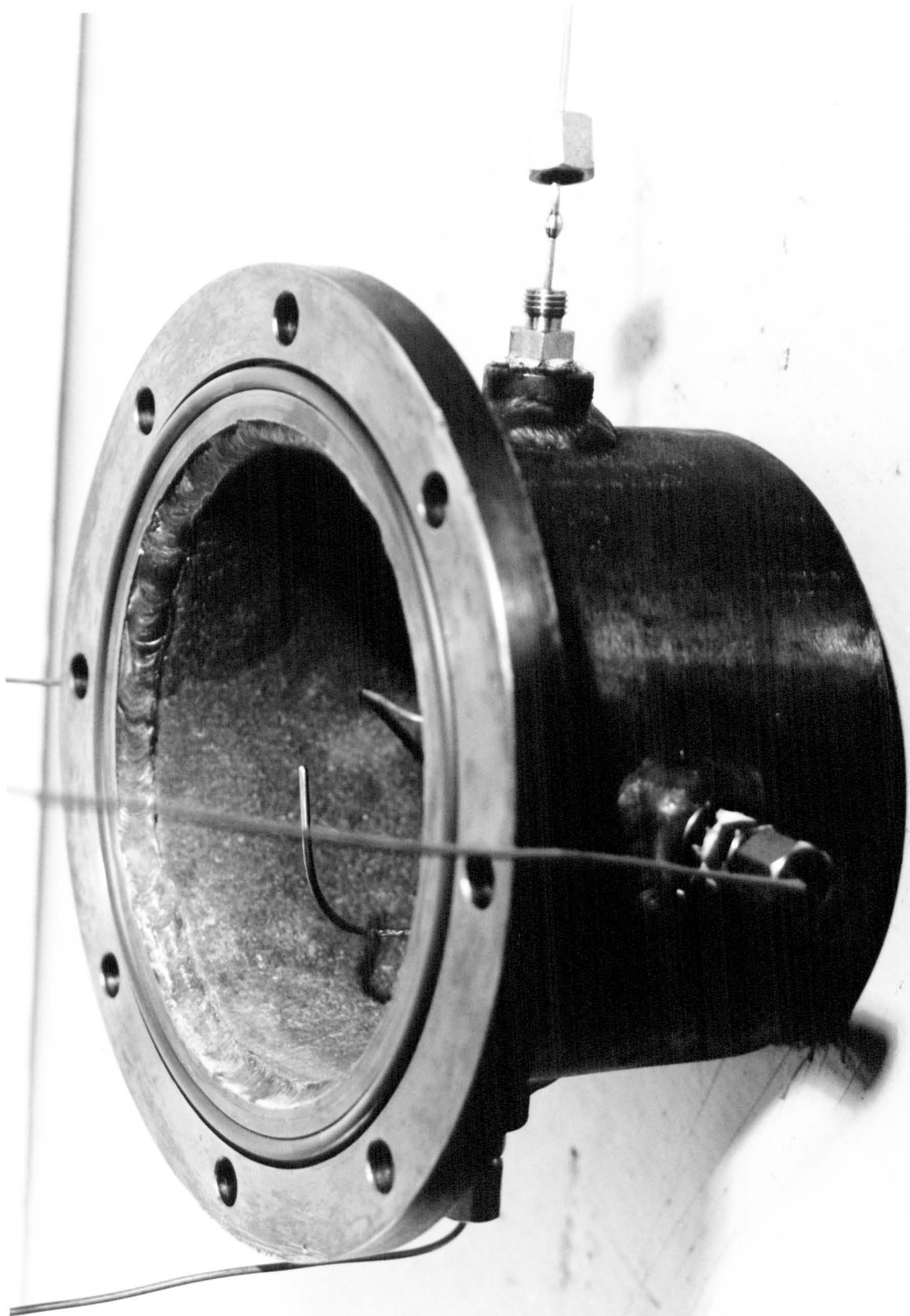
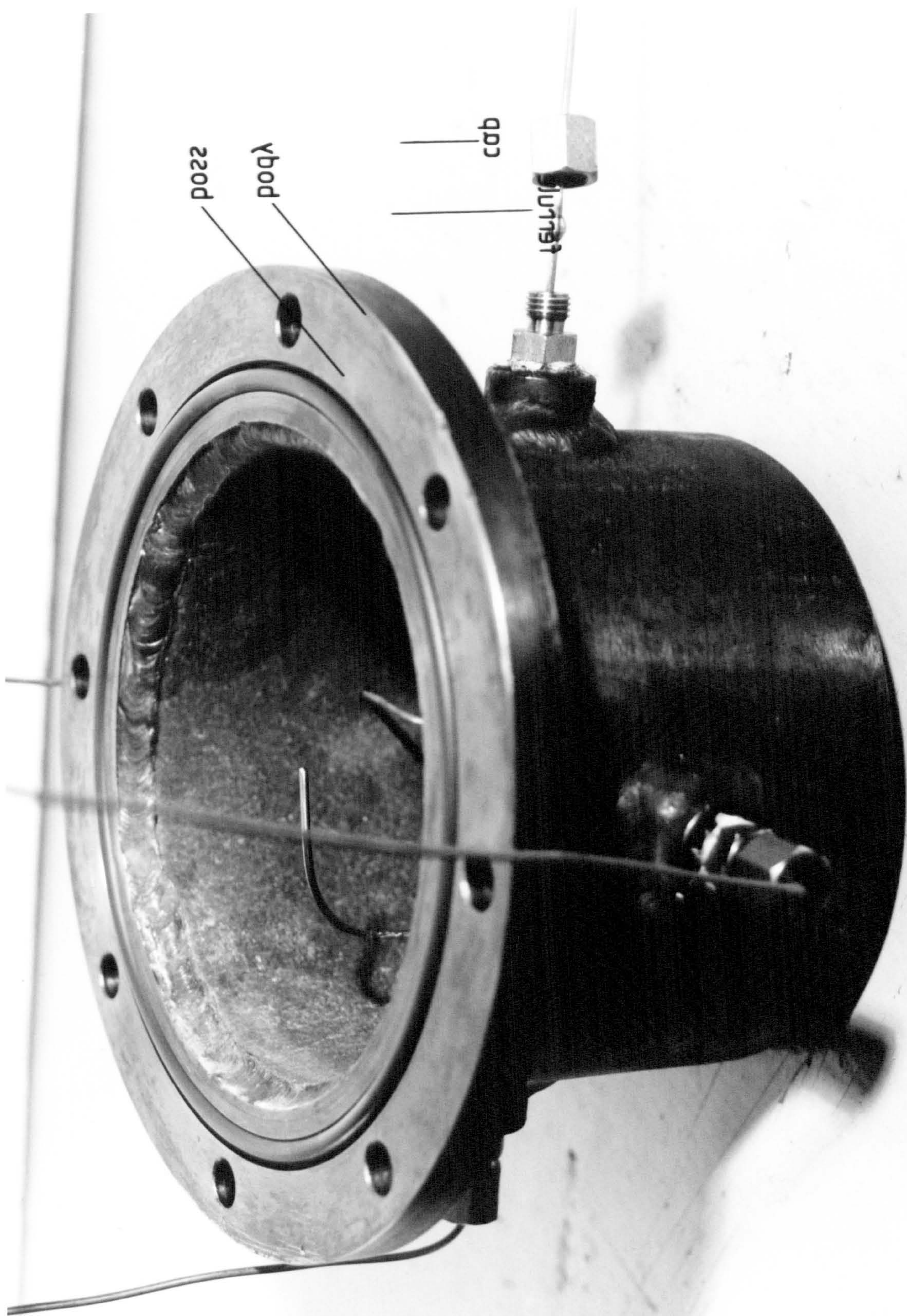


Fig 1.4 Details of the compression fitting on the sheathed thermocouple



threads which ensured a leakproof assembly to the bosses on the pressure vessel. The ferrule was a double-cone shaped thin metal shell through which the sheathed thermocouple was threaded. The ferrule could be slipped along the length of the sheath to position it at a desired location. On firmly securing the cap on the body, the ferrule was squashed making a seal against any leakage through the thermocouple insertion hole. This arrangement secured the thermocouples to the pressure vessel ensuring there was no undesirable leakage from this joint. The tips of the four thermocouples were placed to measure the temperatures at four different locations; bottom, centre, top, and middle of the side wall.

7.2.4 The pressure/vacuum transducers

The isosteric data for ammonia systems was to be obtained within the range of 0-20 bars absolute pressure. Ammonia being very corrosive to many metals it was important that the parts of the transducer in touch with vapours were made of steel. Thus a transducer model EA300 from Data Instruments (USA) was selected which covered this range. It had a 300 series stainless steel diaphragm. It had a built-in voltage stabilizer and an output signal amplifier. Thus excitation signal in the range of 9-20 Vdc could have been applied which gave a flexibility of operation.

The output signal over the complete range of 0-20 bar varied from 1-6 volts giving a sensitivity of 2.5 mV/kPa. The response of the

transducer was claimed to be linear with maximum shift of $\pm 1\%$ of full scale deflection (FSD) from the best-fit straight line. The transducer was calibrated on a dead weight tester and the output signal was measured with a precision of 1 micro volt. The calibration curve is shown in fig 7.5. Uncertainty in calibration data was negligible due to the high precision of calibration equipment. The best-fit straight line did not pass through each measured-data point. The standard error of estimate (SEE) was 0.164 indicating that maximum uncertainty in best estimated value could be ± 0.328 bar or $\pm 1.64\%$ of the full scale deflection (FSD). This was more than the manufacturer's claim of 1% but was very reasonable.

As the non-linear response of the transducer would have introduced the largest error in readings below one bar, it was decided to connect a vacuum transducer in parallel with the pressure transducer. It was connected to the main circuit through a manual valve to isolate it when the system pressure reached one bar. This arrangement ensured that the accuracy of the acquired data was not compromised. The vacuum transducer acquired for methanol system was used for this purpose.

Methanol system being sub-atmospheric required a vacuum transducer. A model SA15 from the above mentioned company was selected which had all the built-in features which the above mentioned pressure transducer had. It covered a range of absolute pressure of 0-1 bar which was suitable for our application. The accuracy of the device was $\pm 1\%$ span. The calibration curve for the transducer is shown in

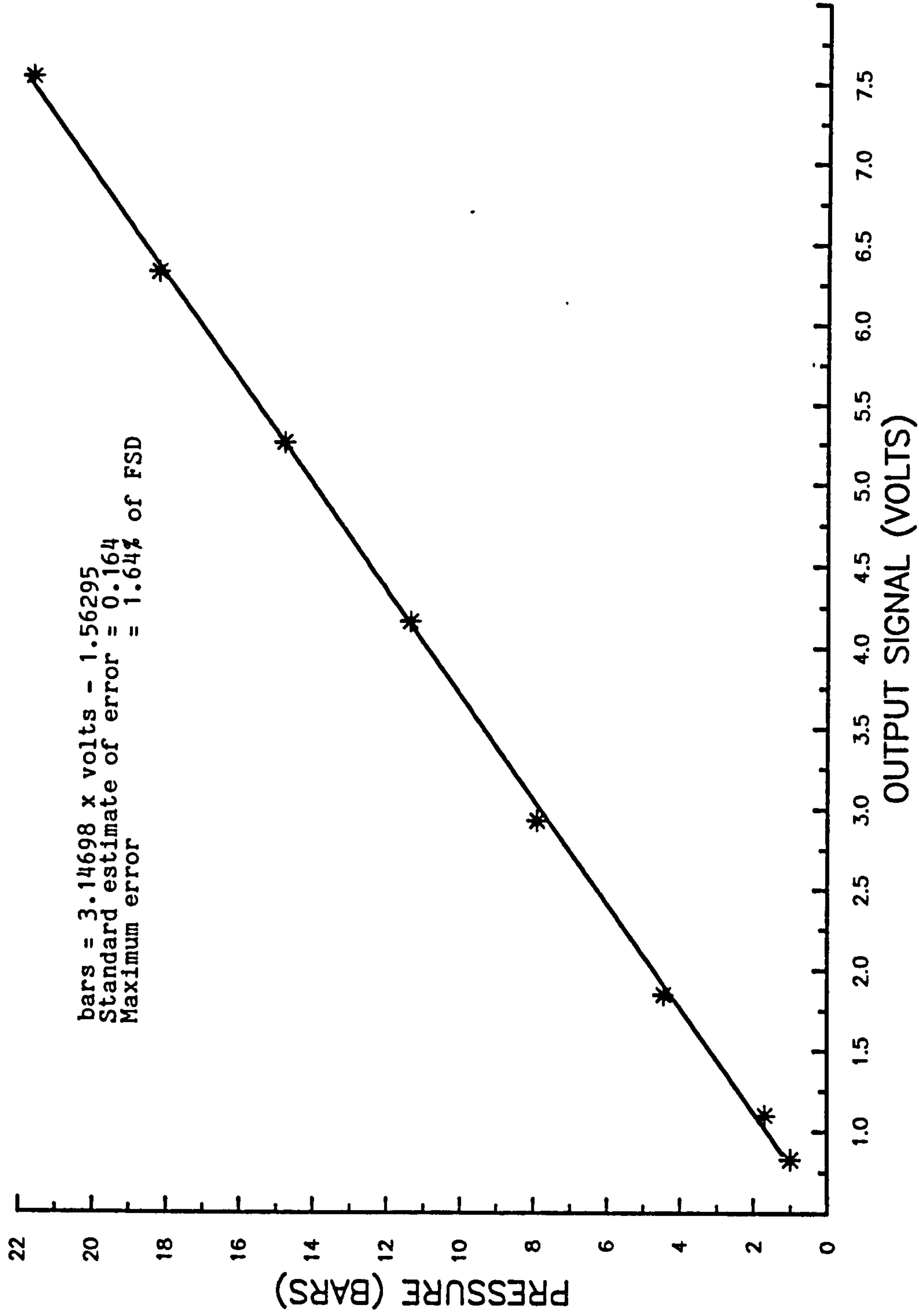


Fig 7.5 Calibration curve for the pressure transducer

fig 7.6. The SEE for the best-fit straight line was 3.1 which gave an accuracy of $\pm 0.93\%$ which is within the manufacturer's claimed limits.

The temperature compensation in both the devices was upto 85°C but the maximum operating temperature to be encountered was 120°C . It was estimated that if the vapour pipe connecting the transducer to the pressure-vessel was about 120 mm long then the vapours reaching the transducer would always be below the 85°C (i.e. the limit of compensation). Thus the transducers were connected to the pressure vessel through a 120 mm long vapour-pipe.

7.2.5 The oil-bath

A convenient way to heat up, in a controlled manner, the mixture of adsorbent and refrigerant in the pressure vessel was by immersing the vessel in an oil-bath. To maintain the oil-bath at the required temperature facilities for both heating and cooling the oil were necessary. A stainless steel tub, 300 mm long by 200 mm wide and 170 mm deep was made out of 1.5 mm thick sheet metal. It was fitted with a 1kW immersion heater to heat up the oil. A coil wound out of 10 mm diameter copper pipe was immersed in the oil-bath. Propylene-glycol solution from a refrigerating cooling unit was circulated and in the coil to cool the oil when required. Santotherm-66, a heat transfer oil, was used as the heat transfer medium in the bath.

Two thermocouples, also of type T, were fixed at two locations in the oil-bath to measure the oil temperature. A motorized stirrer

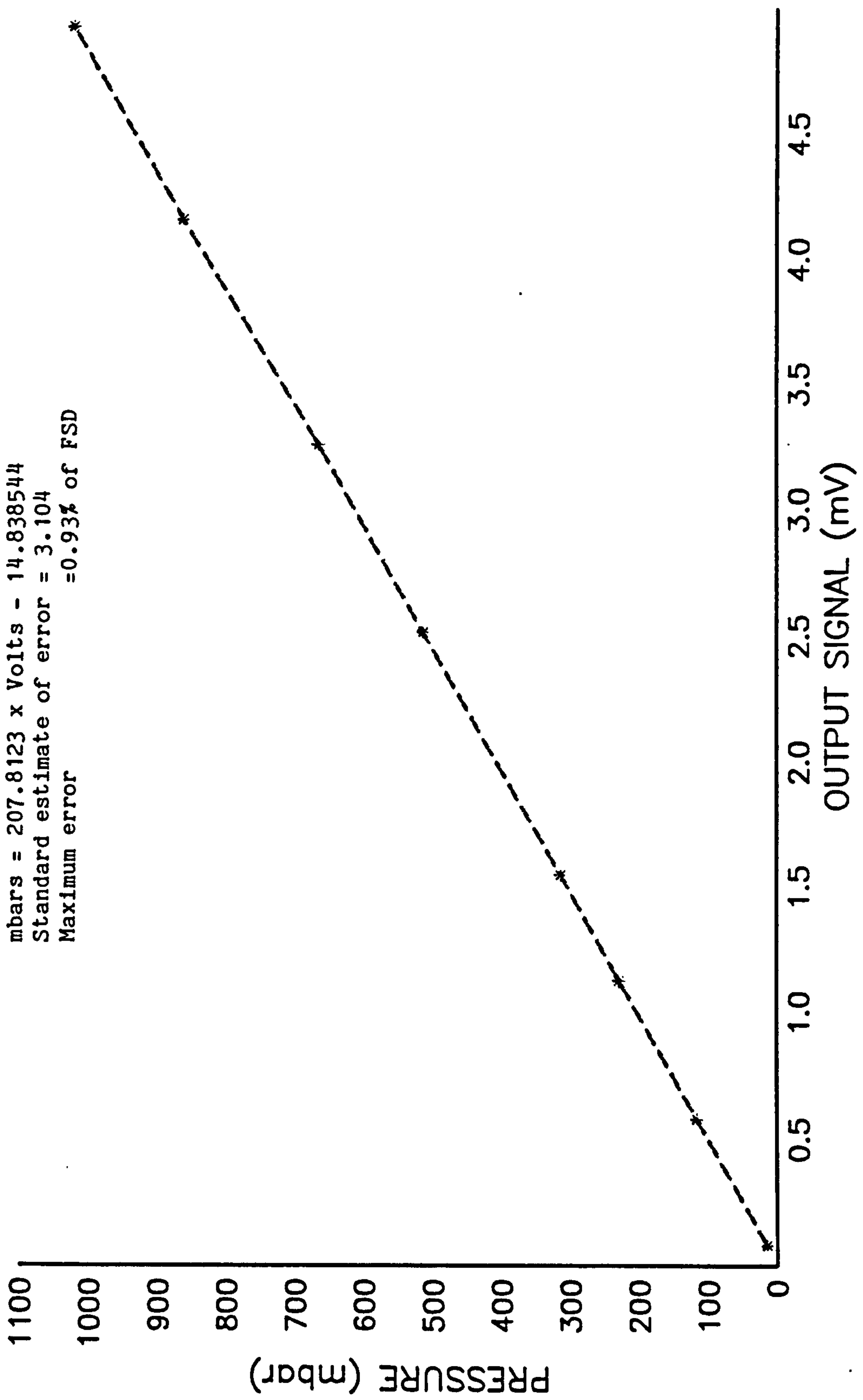


Fig 7.6 Calibration curve for the vacuum transducer

ensured the uniformity of temperature in the oil-bath. The expected time to acquired sufficient data for the construction of one isostere was 36-48 hours. The oil-bath temperature had to be controlled automatically according to a predetermined sequence. This required the switching of the heater

(i) on, if the temperature of the oil-bath was lower than the desired

(ii) off, when the desired temperature was reached and

(iii) to operate the cooling unit when the oil-bath was warmer than required.

To achieve this object a Acorn "BBC master" micro-computer was used which had built-in interface, the 'user port', for operating the external devices. The micro-computer controlled both the heater and cooling unit by operating the mains control unit (described below) under the instructions from specifically written software (see appendix D).

7.2.6 The overheat controller

The mains supply to the immersion heater was connected through a temperature controller. This device was capable of isolating the power supply to the heater if the oil temperature exceeds a preset maximum temperature. This was done in a view to safeguard the experimental set-up against any accidental failures. The controller had as its own integral, and custom-built, temperature sensor a type K (i.e. chromel-alumel) thermocouple.

7.2.7 The mains control unit

The Acorn "BBC master" micro-computer employed had a user port with eight lines which could be used for either input or output (for details see [3]). When used for the purpose of output these can be set to low or high transistor-transistor logic (TTL) signals; when set low (i.e. logic 0) no voltage was present on the lines and when set high (i.e. logic 1) they were energized to 5 volts. These TTL signals (see ref [4] for further details) could be used to drive some solid-state relays and other semiconductor devices. The whole operation may be clearly understood with reference to fig 7.7.

A solid-state relay, SSR, which consisted of a driver circuit optically coupled to a light emitting diode, LED, was employed. The optical coupling ensured complete electrical isolation between input and output circuit of the relay up to 800 volts. Since the input circuit of the relay consisted of a diode, it could be driven easily from the user port of the micro-computer. The user port lines were set to logic 1 when micro-computer was switched on.

If the relay was directly connected to those lines that could switch it on, when the micro-computer was just switched on or was reset after pressing 'break' in case of an emergency. That was not safe! Thus the relay was indirectly operated through a transistor which would provide the relay a logic 1 signal when the user port line is at logic 0. The transistor's collector, through a current limiting resistor, is connected to a 5 volts line and so is the solid state relay. The emitter of the transistor and the other terminal of the

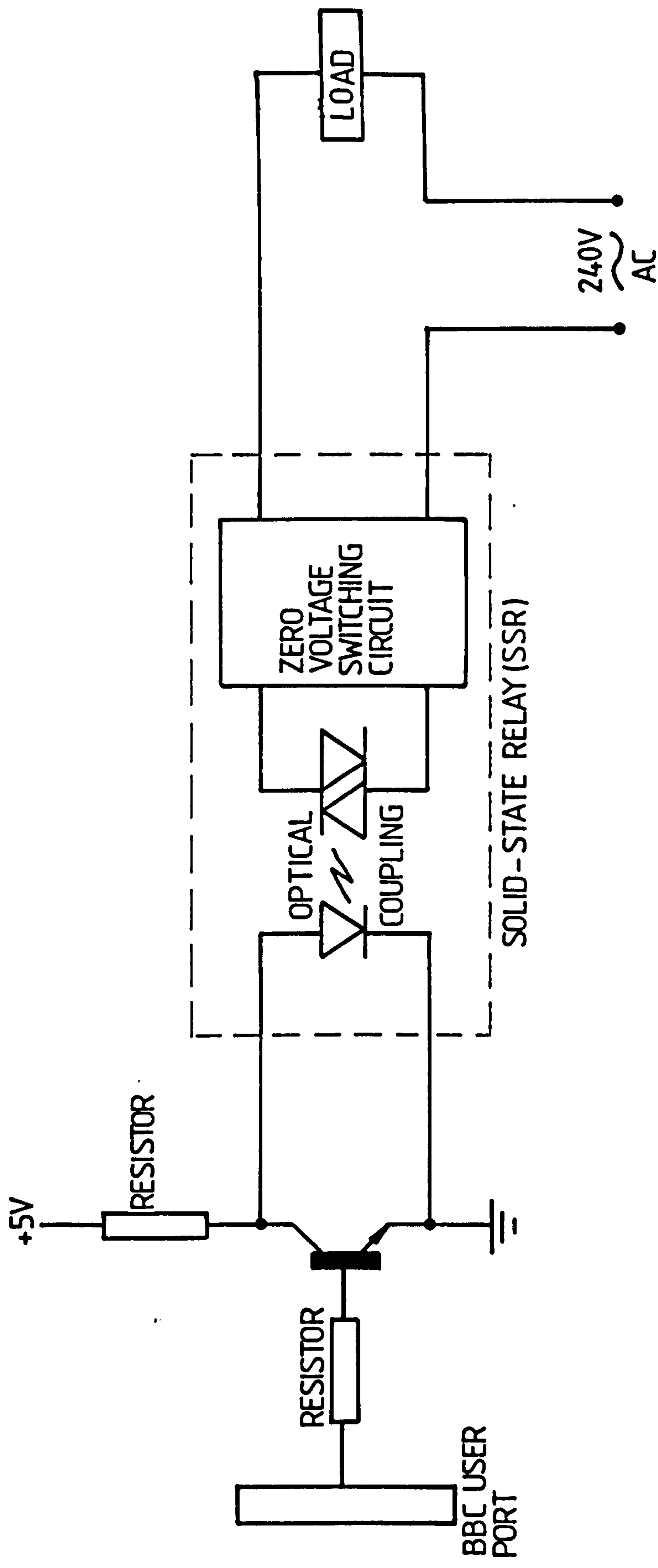


Fig 7.7 Illustration of working principle of mains remote control unit

relay are connected to a 0 volt line. When a low TTL signal is present at the base of the transistor 5 volts are present across the LED of the relay and it switches on the power to the device. When a high TTL signal from the user port line is fed to the base of the transistor 0 volt is present at the collector and the net potential across the relay becomes zero and it switches off the power to the device.

Two of such circuits operated by two lines from the micro-computer's user port were built as a single interface unit. The power supply to the immersion heater and the refrigerating cooling unit was connected through this control box. The temperature of the oil bath was sensed by two thermocouples and communicated to the computer through a data-acquisition system described in the next paragraph. The specially-written controlling program (listed in appendix D) then enabled the computer to make decision about operating the heating and cooling devices.

7.2.8 Data acquisition system

The automatic operation of the experimental rig over 36-48 hour period necessitated the automatic acquisition and recording of both data for temperature and pressure. A multi-application peripheral system, MAPS, data acquisition system had been employed to do this task. This system, built on a modular approach, consisted of a multi-purpose 19" main rack which could accommodate and connect different modules to the mother board. The mainframe was fitted with a power supply and a fully comprehensive implementation of the

IEEE-488 standard interface [5]. Another IEEE-488 interface, connected to the micro-computer, enabled the two devices to communicate with each other. Signals from the six thermocouples and the transducer were connected to a 10 channel 4-pole scanner module. The scanner, on receiving a command signal from the computer, selected the desired channel. The analogue signal present on the selected channel was then fed to the mother board.

An analogue-to-digital converter (ADC) module, connected to the mother board in the main rack, was then commanded to take the measurement of the signal. The measured analogue signal was output to the IEEE-488 main data bus as a twelve bit digital signal. The so converted digital signal was then available at the input buffer of the computer. The computer then interpreted the signal, analyzed it and recorded the relevant data on to the floppy disc. On the basis of the analysis performed on these signals the computer was then able to control the heating and cooling devices.

Preliminary tests indicated that the ADC was not capable of dealing with the 'floating' analogue signals generated by the transducers; the ADC was modified accordingly. The thermocouples were then required to be earthed at the junctions. This was too much cumbersome and additionally the 'thermal emf' introduced by the ADC itself introduced temperature errors of up to 2°C. This approach was thus abandoned.

The subsequent use of a Solartron microprocessor voltmeter with a serial interface eliminated these problems and reduced the margin

of instrument error (from 2°C) to only 0.5°C in the temperature readings. The serial interface board, in addition to the communication facilities, had nine built-in programs which could be used to convert the input analogue signal into a digital signal in engineering units. This feature allowed the programming of calibration curve for the transducer into the voltmeter and the output was in the pressure units. One program allowed the selection of the thermocouple type to output the measured signal in temperature units. This program required the temperature of the reference junction. This information was acquired through the cold junction card (CJC) which was used to connect the thermocouples to the scanner module.

A CJC was a small interface with on-board electronic circuit and terminals to connect 10 analogue signals to it. The signals from the board were then fed to the 10-channel scanners for further processing. The electronic circuit was energized by 12.5 volt supply from the main rack. It was designed to produce a voltage which was 1/10 times the temperature of the card. This voltage could be measured at channel zero which was permanently connected to the electronic circuit. The CJC was calibrated before connecting it to the main circuit.

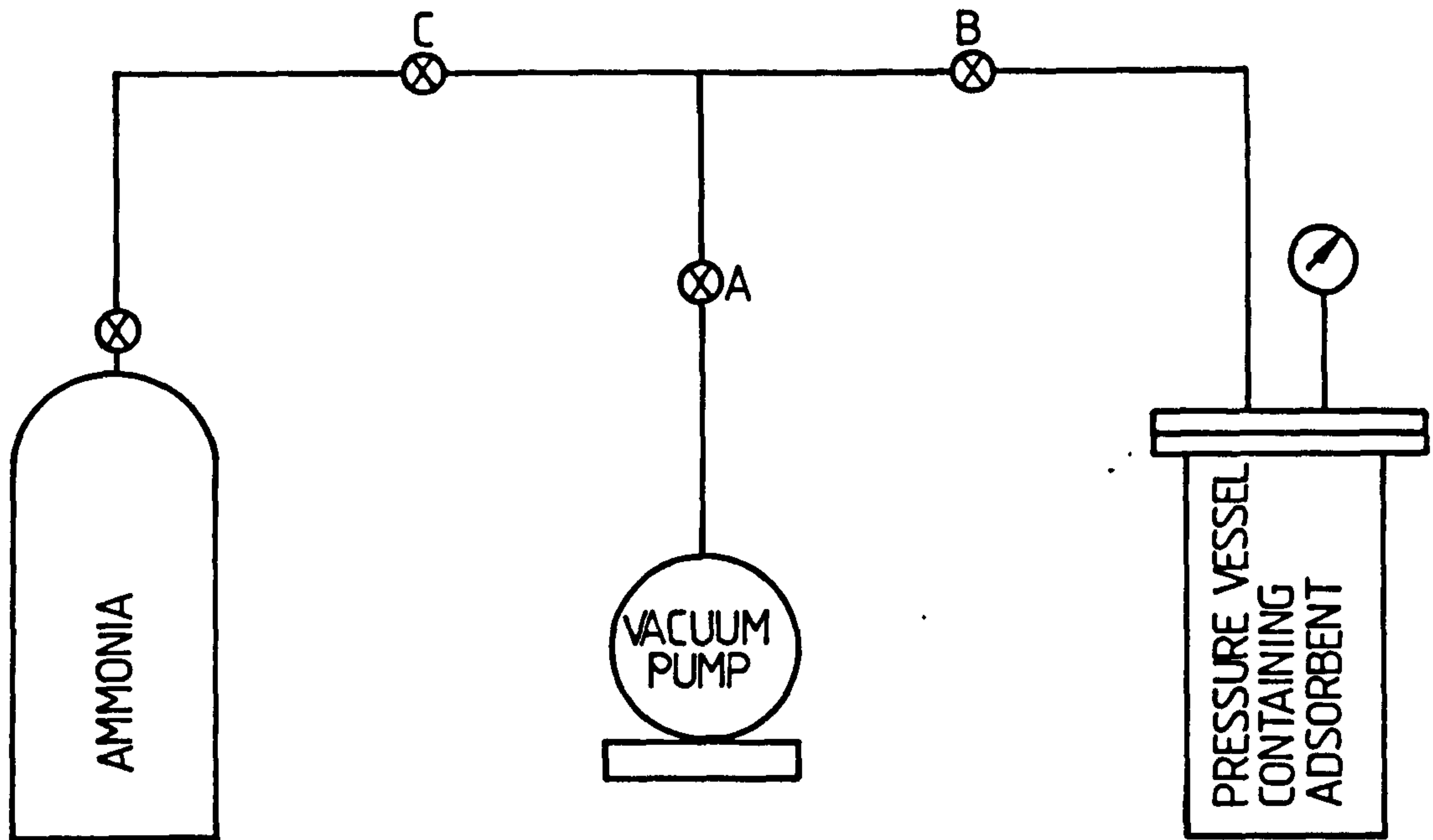
On receiving instruction from the micro-computer, through its serial interface link, the voltmeter measured the signals and made the information available at the computer's serial-input-buffer in the form of ASCII characters. Computer then transferred the information to its main memory, where the data was assessed and decisions were

made concerning the operation of the external devices. Double density single sided floppy discs of 200 kbytes capacity were used to store the data acquired during these tests. The temperature and pressure in the pressure vessel was continuously measured and the information displayed on a visual display unit attached to the micro-computer. All of this was happening under the control of a specially-written software (mentioned earlier, see also appendix D) which recorded the information onto the floppy discs at the fixed intervals.

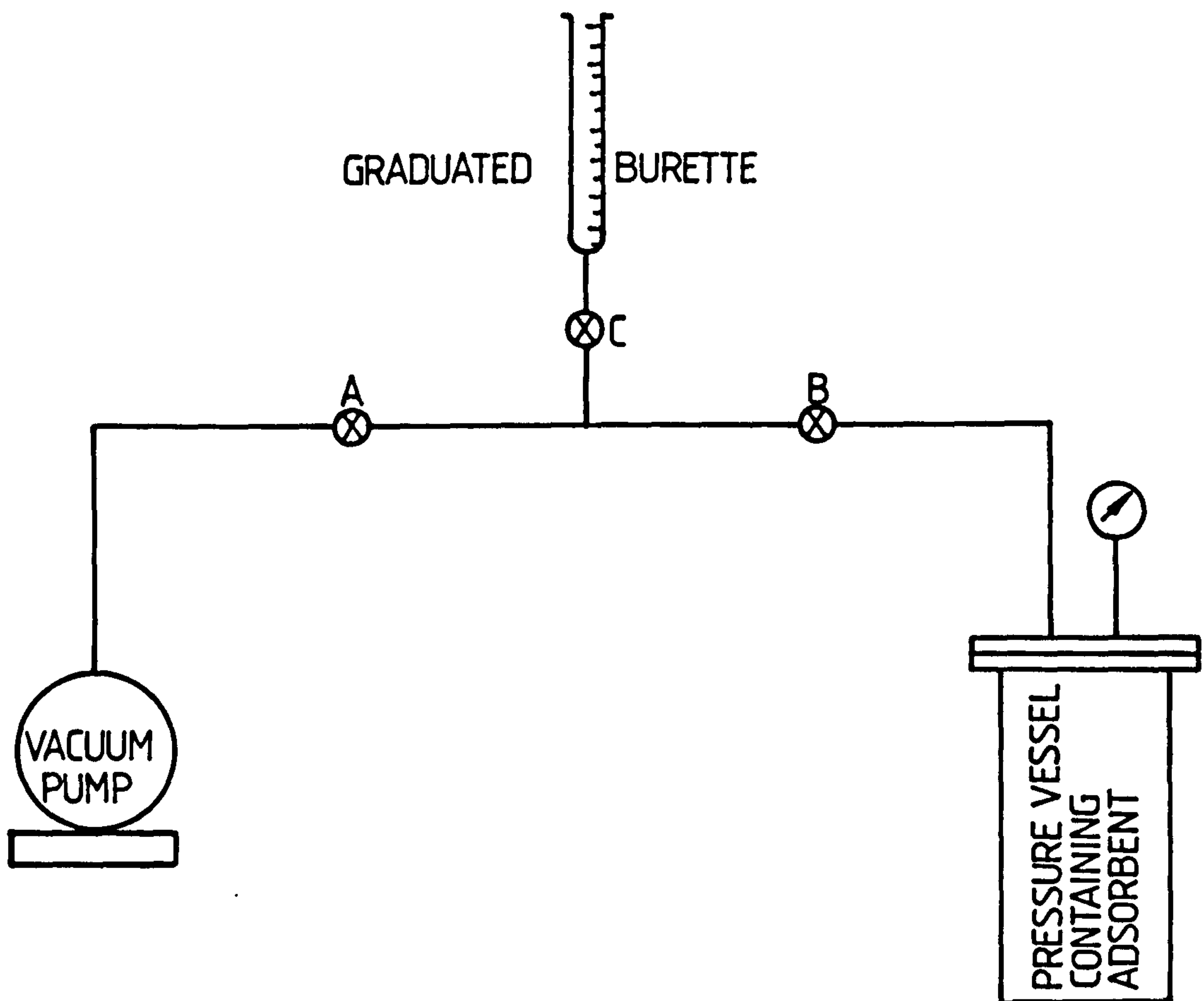
7.3 Experimental procedure

A quantity of the adsorbent sufficient to fill the pressure vessel was heated in an oven under a vacuum of about 0.5 mbar for a period of 24-36 hours. This was necessary to outgas the material from the atmospheric gases and moisture which it would have adsorbed during the storage. This outgassed sample was then weighed and transferred to the pressure vessel. To minimize the error in the concentration of the adsorbate the vessel was filled to the top. This reduced the dead volume of the vapours to a minimum. The vessel was then closed by securing the top plate. The adsorbate container and vacuum pump were then connected to the vessel.

The arrangement for ammonia is shown in fig 7.8a. The connecting pipe work was evacuated and sealed off with the valve 'A'. Then the adsorbate vapours were introduced into the vessel by opening the valves 'B' and 'C'. In case of ammonia the vessel was disconnected and weighed after the introduction of vapours to measure the amount



(a)



(b)

Fig 7.8 Arrangement for introduction into the pressure vessel
(a) of ammonia vapours (b) of methanol vapours

adsorbed. Methanol is liquid at normal room temperature. It was, therefore, possible to introduce measured doses of it in the system. This was done by connecting a burette to the pipe work as shown in fig 7.8b.

The vessel containing a known quantity of adsorbent-adsorbate mixture was then placed in the oil-bath. The mixture was heated in a controlled manner in temperature steps of 10°C within the range of $10\text{--}120^{\circ}\text{C}$ and then cooled back to the starting temperature. During each temperature step the oil in the bath was maintained within $\pm 2^{\circ}\text{C}$ of the anticipated temperature. The temperature at the four locations and the pressure in the vessel were continuously monitored and readings were recorded on to a floppy disc. Variation in temperature at all four locations in the vessel was evaluated after each fresh scan and when the maximum variation was less than 1°C the mixture was heated to the next temperature stage. To maintain the temperature of the bath both the immersion heater and cooling coil were operated automatically when required. The same procedure was adopted during the cooling operation as well. At the end of the test data stored on the disc was analyzed and processed and the isosteres were constructed from the equilibrium readings of temperature and corresponding pressure during each time step.

7.4 Determination of porosity

Porosity has been defined, and uncertainty in its determination has also been discussed, in the previous chapter. The method adopted here is based on gravimetrically establishing the constant

representing the pore-volume in the D-A equation. A sample of outgassed adsorbent was placed in the pressure vessel and the vessel was sealed, evacuated, and weighed. Then the container holding the refrigerant (ammonia or methanol) was connected to the vessel and the refrigerant allowed to be adsorbed. The process continued until the pressure and temperature inside the vessel reached equilibrium with that of the container. The pressure vessel with its contents was re-weighed carefully and the mass of the refrigerant adsorbed was derived. The volume of the adsorbed refrigerant represent the volume of pores or porosity of the adsorbent.

7.5 Determination of characteristic constants E and n

The D-A equation in gravimetric form can be written as

$$m = m_0 \exp[-(D/E)^n] \quad 7.2$$

where m is the mass of adsorbate and m_0 the maximum adsorbable amount. D is the change in Gibbs free energy, on adsorption, of adsorbate molecules, defined by the expression

$$D = -\Delta G = RT \ln(p_s/p) \quad 7.3$$

and E is specific to the adsorbent-adsorbate pair and is defined as the characteristic energy of adsorption of the vapour on the adsorbent.

When $n = 2$, equation 7.2 and the D-R equation are identical and the quantities B (the so called structural constant) and E are related by

$$E = 0.008314(1/B)^{1/2} \quad (\text{in kJ/mole}) \quad 7.4$$

Equation 7.2 can be linearized by twice taking its logarithm on both sides.

$$\ln(\ln(m_0/m)) = n \ln(D) - n \ln(E) \quad 7.5$$

This is a linear equation in coordinates $\ln(\ln(m_0/m))$ and $\ln(D)$; n represents the slope of it whereas the intercept is given by $n \ln(E)$. The graphs in these coordinates were plotted and the values of E and n were calculated by linear regression.

7.6 Discussion of experimental results

Zeolite-13X (manufactured by Laporte Chemicals, U.K.) and activated carbon 207C and 208C (produced by Sutcliffe Speakman Carbons, U.K.) were characterized when ammonia and methanol were used as the adsorbates.

7.6.1 Zeolite-13X-ammonia

Zeolite-13X specimen used in these experiments was acquired from the manufacturer about four months prior to the use. It was kept stored in an airtight jar to avoid adsorption of moisture and other atmospheric gases.

A quantity of 500 g was heated at a temperature of 350°C under a vacuum of 0.5 mbar for 24 hours, after which a 10% loss of weight was recorded. This confirmed that the moisture adsorbed during the storage period had been removed. Due to the very low thermal conductivity of zeolite (i.e. 0.1 - 0.15 Wm⁻¹K⁻¹ [6]) data for the construction of one isostere over the range of 20 to 120°C took about 31 hours (i.e. both for heating and cooling).

The results were plotted in the Clapeyron coordinates (i.e. $\log p$ & $-1/T$). The points along each isostere fitted nicely on a straight line (see fig 7.9). These results were compared with the only other known results by Critoph [7]. The maximum adsorbable amount of ammonia was found to be 21.5% which was very close to Critoph's 21.8%. For the functional relationship between pressure,

ISOSTERES FOR THE PAIR ZEOLITE/AMMONIA

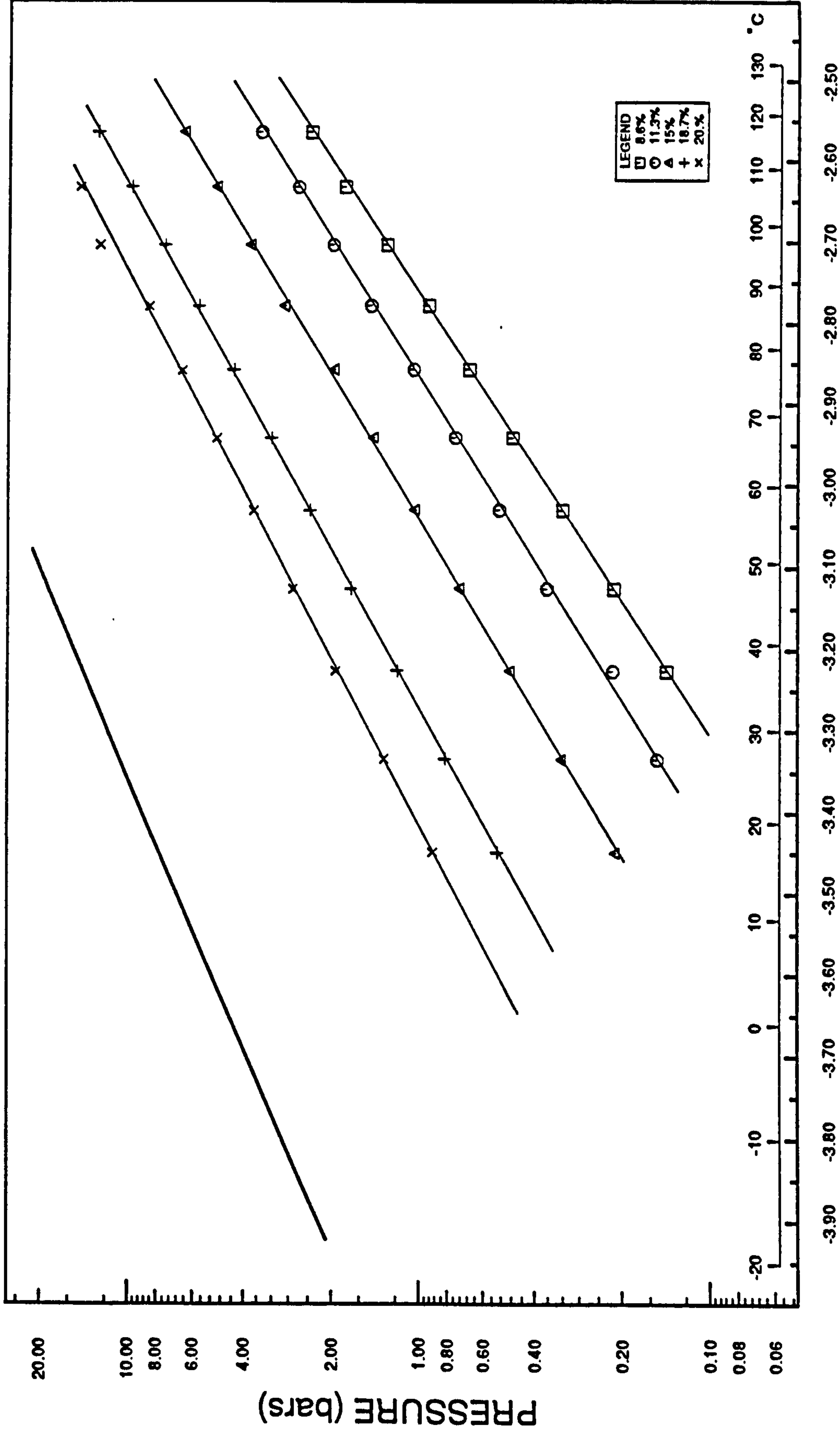


Fig 7.9 Isosteres for the pair zeolite-13X/ammonia

temperature and concentration, in the form of D-A equation, the procedure described in section 7.5 was followed. The graph shown in fig 7.10 was plotted. Linear regression fitted a straight line through the data. The slope of the line gave a value of $n=3.06$. The value for the parameters $E=12.11$ kJ/mole was obtained from the intercept. The isosteric heat of adsorption, determined from the slope of the isosteres, ranged from 1617 kJ/kg for 20% concentration to 2007 kJ/kg for 8.6% concentration.

The values determined by Critoph [7] are much different (e.g. $E=7.047$ and $n=1.75$) from the present results, predicting a different adsorption equilibrium for the pair. The isosteres determined by Critoph are shallower and closer to the saturation line. Therefore his result predicted a higher equilibrium pressure and a low heat of adsorption. Zeolite has a definite crystal structure and thus the equilibrium established should apply universally. The difference in the two sets of experimental results indicated some error in either of them. Apart from the instrument error the other major source of error in these experiments could be the preadsorbed moisture in the zeolite specimen.

Zeolite-13X has a regular crystal structure with a window of 10 Å. Sodium cations are present in their micropores which act as centres for the adsorption of molecules with a nonuniform distribution of electron energy (e.g. water, ammonia, methanol, etc) and polarizable molecules. This effect contribute towards higher heat of adsorption exhibited by zeolites (in comparison with, for example, activated carbon). Dubinin and Astakhov [8] have done extensive studies in

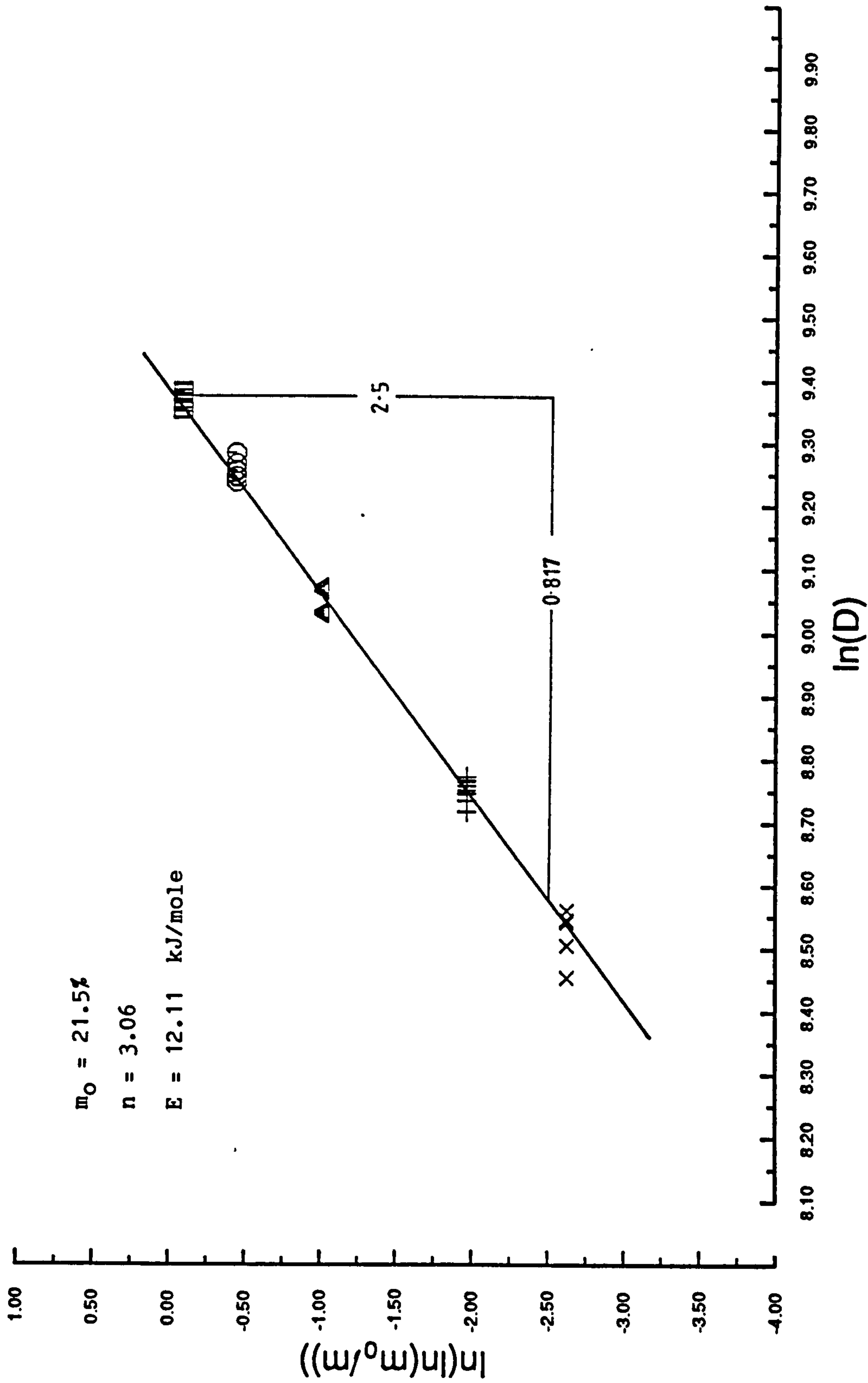


Fig 7.10 Characterization curve for the pair Zeolite-13X/ammonia

representing the adsorption equilibrium of vapours on zeolites. They showed in their study that zeolites, due to their smaller micropores and cationic adsorption centres, are best represented by values of n which lie between 3 and 6.

Ammonia has a kinetic diameter of 2.6×10^{-8} cm which is smaller than to the size of micropores in zeolite-13X. Thus when all the adsorption centres are covered with small adsorbate molecules (like ammonia) there is adsorption space available for more molecules. After the initial strong adsorption at the cationic centres, the process continues under the influence of adsorbent-adsorbate (i.e. dispersion) and adsorbate-adsorbate forces until the saturation is reached. Thus the overall equilibrium in case of smaller adsorbate molecules is represented by a value of n at the lower end of the range (i.e. $n=3$).

Dubinin and Astakhov [8] observed during their experiments with blocking of adsorption centres (i.e. cations in zeolite) that preadsorption of 5.1% water practically blocked the adsorption centres in zeolite. They explained further that with the cations blocked adsorption equilibrium on zeolites was represented by a value of $n=2$. As the equilibrium pressure of preadsorbed water at 20°C is of the order of 0.001 mbar it does not affect significantly the measurement of equilibrium pressure of the subsequently adsorbed vapours.

The evidence from [8] suggests that the value of $n=3.06$ determined in the current work is in line with the general behaviour of

zeolites witnessed by the most researchers. The lower value of n in case of Critoph's results could be due to the presence of preadsorbed water which would slightly increase the equilibrium pressure of ammonia as well (depending on the amount of preadsorbed water).

7.6.2 Activated carbon-ammonia

Two types of activated carbons with the largest surface area, from the range produced by Sutcliff Speakman Carbons, were selected for the current research. These coconut shell based carbons were, 207C (surface area $1100-1200 \text{ m}^2\text{g}^{-1}$) and 208C (surface area $1200-1300 \text{ m}^2\text{g}^{-1}$). These samples were obtained out of a fresh batch.

Both the carbon samples (350 g each) were outgassed by heating at 250°C under a vacuum of 0.5 mbar for 24 hours. In both cases a loss in weight of about 6% was recorded; which substantiates the importance of a thorough outgassing of the sample (even if it is freshly manufactured). Activated carbon is a very poor thermal conductor (thermal conductivity is less than $0.6 \text{ Wm}^{-1}\text{K}^{-1}$) and thus a complete heating and cooling cycle took about 28 hours.

The results for 207C and 208C were plotted in a Clapeyron diagram and are shown in fig 7.11 and 7.12 respectively. The data for each of the isosteres, in both cases, produced a straight line in the plane of $\log p - 1/T$. Which proved that the outgassing was complete, as the presence of moisture or air in the system would have introduced some curvature in the isostere plot.

ISOSTERES FOR THE PAIR ACTIVATED CARBON 207C/AMMONIA

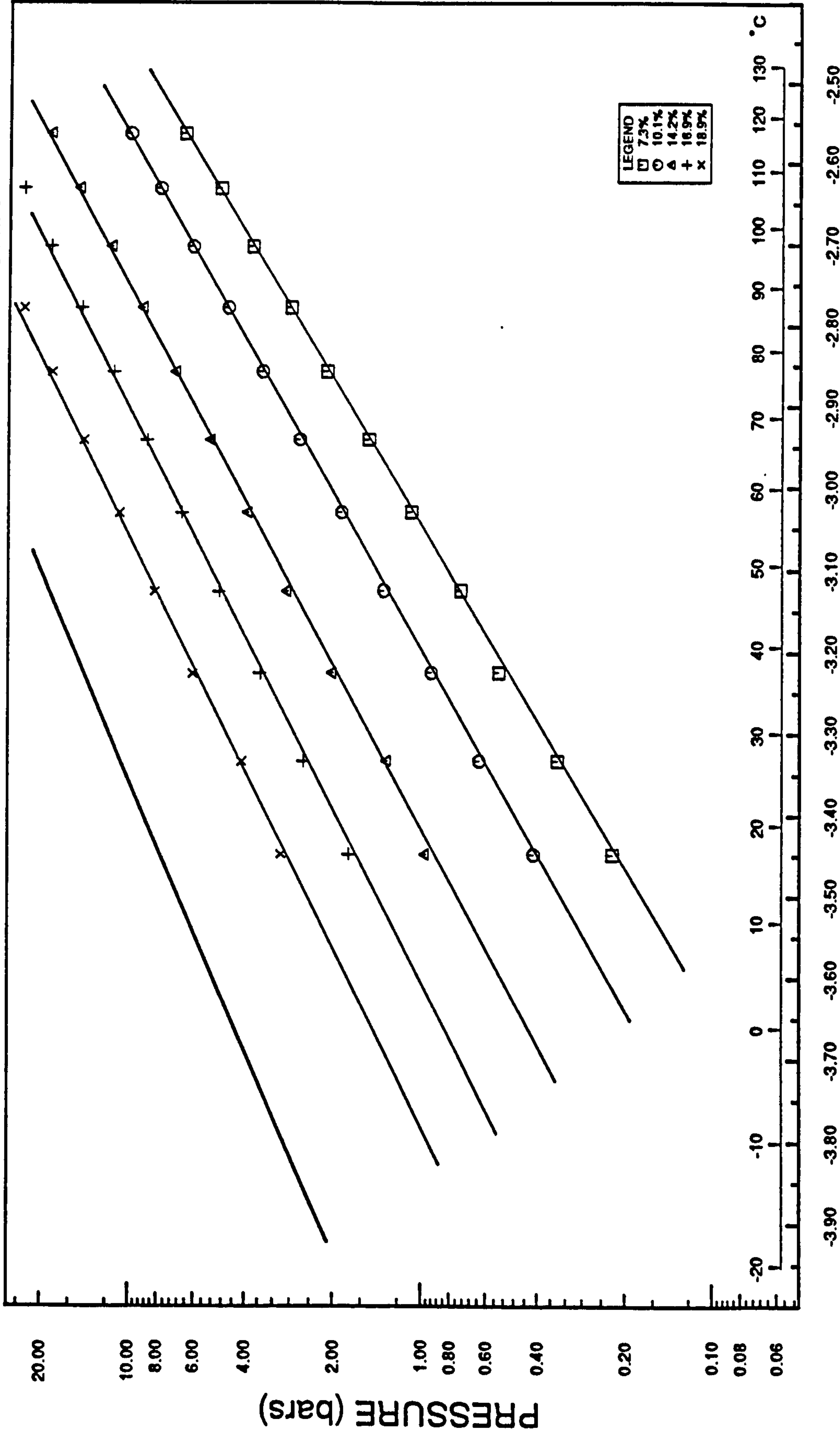


Fig 7.11 Isosteres for the pair activated carbon 207C/ammonia

ISOSTERES FOR THE PAIR ACTIVATED CARBON 208C/AMMONIA

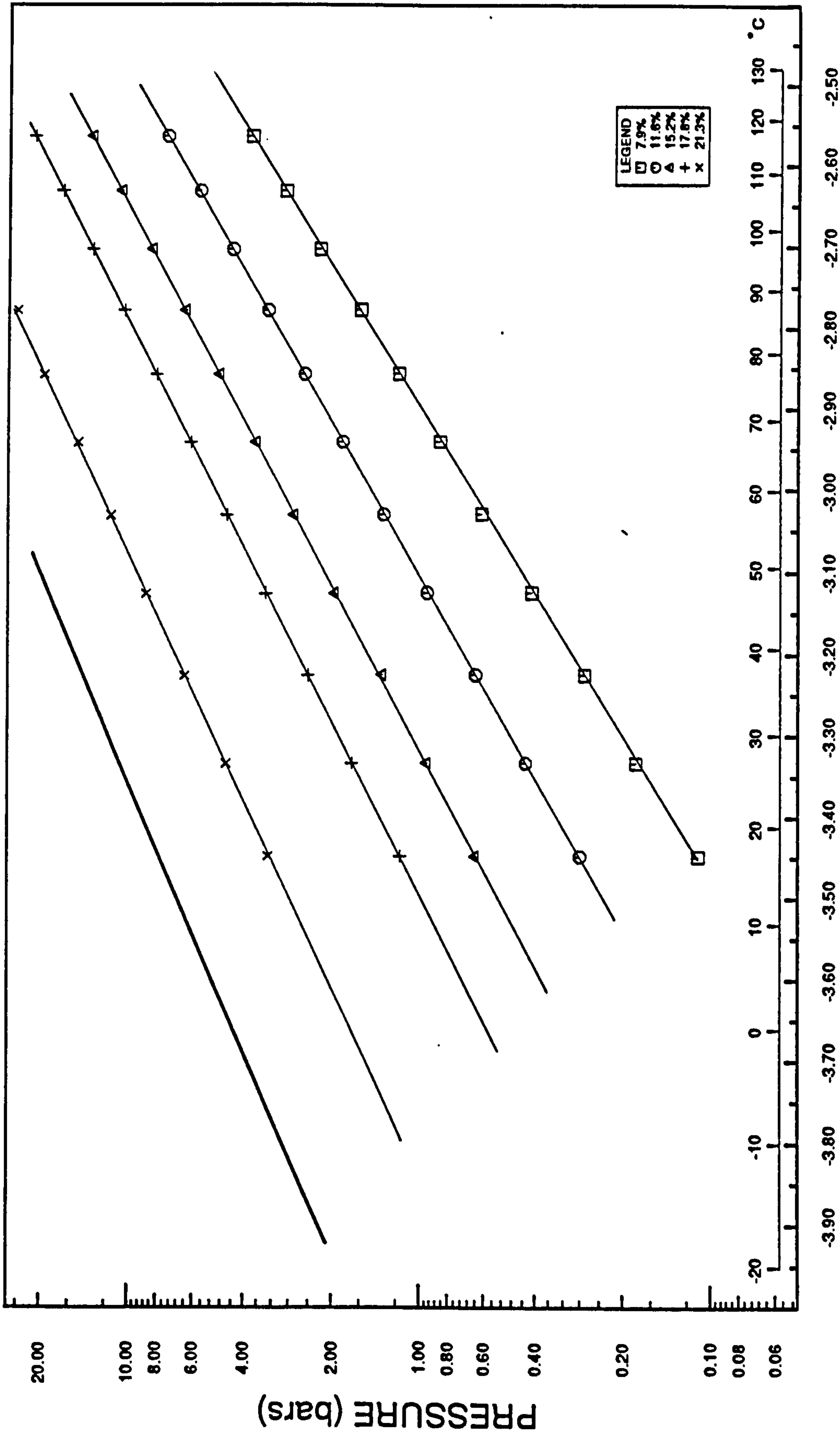


Fig 7.12 Isosteres for the pair activated carbon 208C(old batch)/ammonia

Figures 7.13 and 7.14 were drawn following the procedure described in section 7.5. The maximum adsorbable amount, m_0 , was determined experimentally which was 20.3% and 22.1% for 207C and 208C respectively. Linear regression produced a value for n of 1.97 and 1.98, for 207C and 208C respectively, whereas for E it produced the values of 8.412 and 10.085 kJ/mole.

These results were compared with those from the only published results (to my knowledge) by Critoph [7,9]. The results for 207C compared well with his values of $m_0=19.8\%$, $n=2$, and $E=8.248$ kJ/mole. Critoph's results pertaining to 208C differed in both the references (i.e. ref [7,9]), but he considered his latter work more accurate [7]. Thus the current results were compared with those from ref [7]. His value for $m_0=25\%$ is higher than 22.1 which was obtained during the current experiments. The values of n ($=1.92$) and E ($=7.152$) differed, as well, from the current results.

As 208C is claimed to be more activated than 207C, it should exhibit higher adsorption capacity (which is so in case of Critoph's work). During activation pore size is slightly enlarged due to higher burn off which should reduce, slightly, the value of n and E . But this is not so in the case under discussion.

Same kind of poor results were shown by the 208C with methanol as well (see section 7.6.3 below) which raised suspicion about the quality of the material. On approaching the manufacturers, later, they confirmed that the 208C supplied to us was not of the right

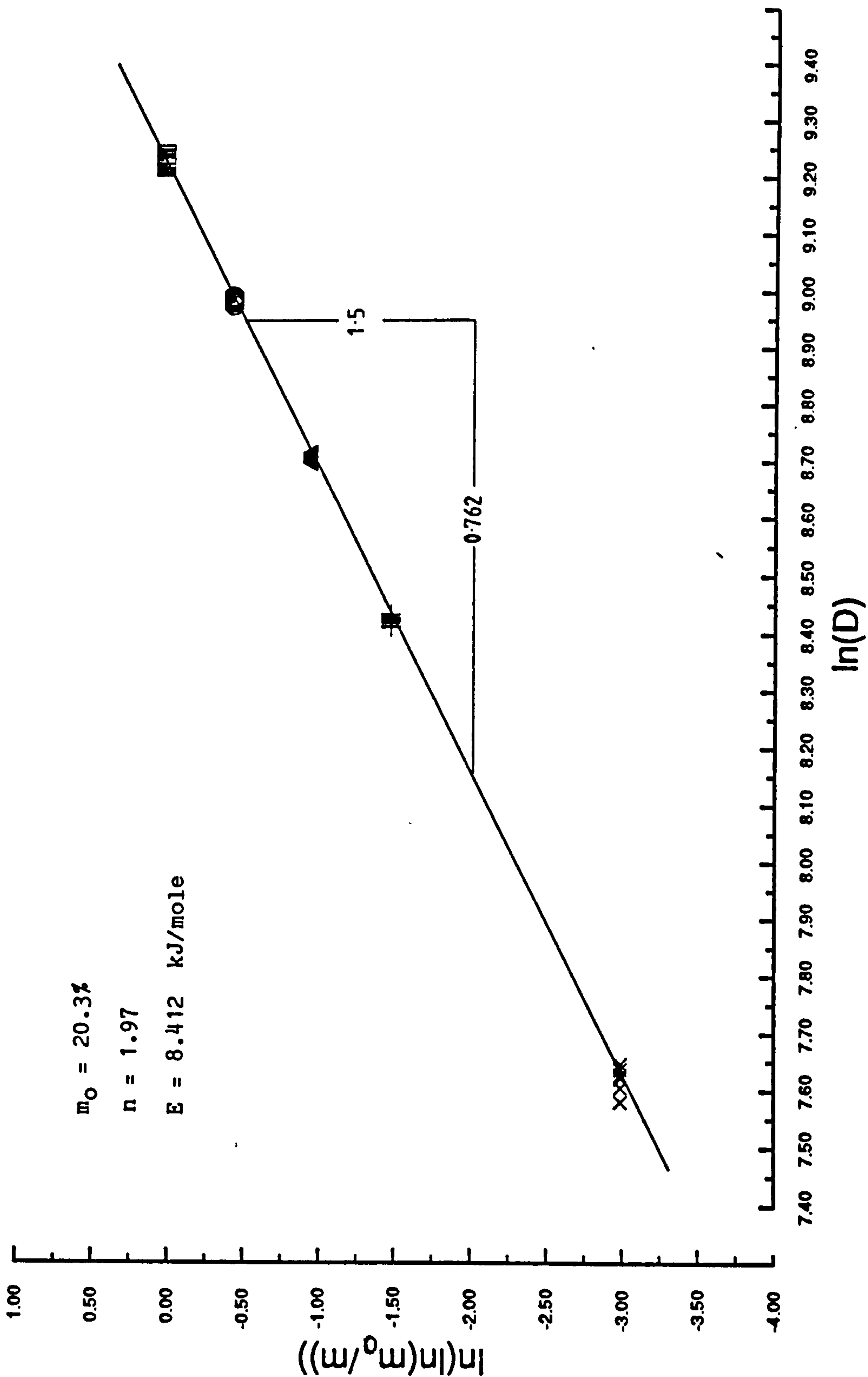


Fig 7.13 Characterization curve for the pair activated carbon 207C/ammonia

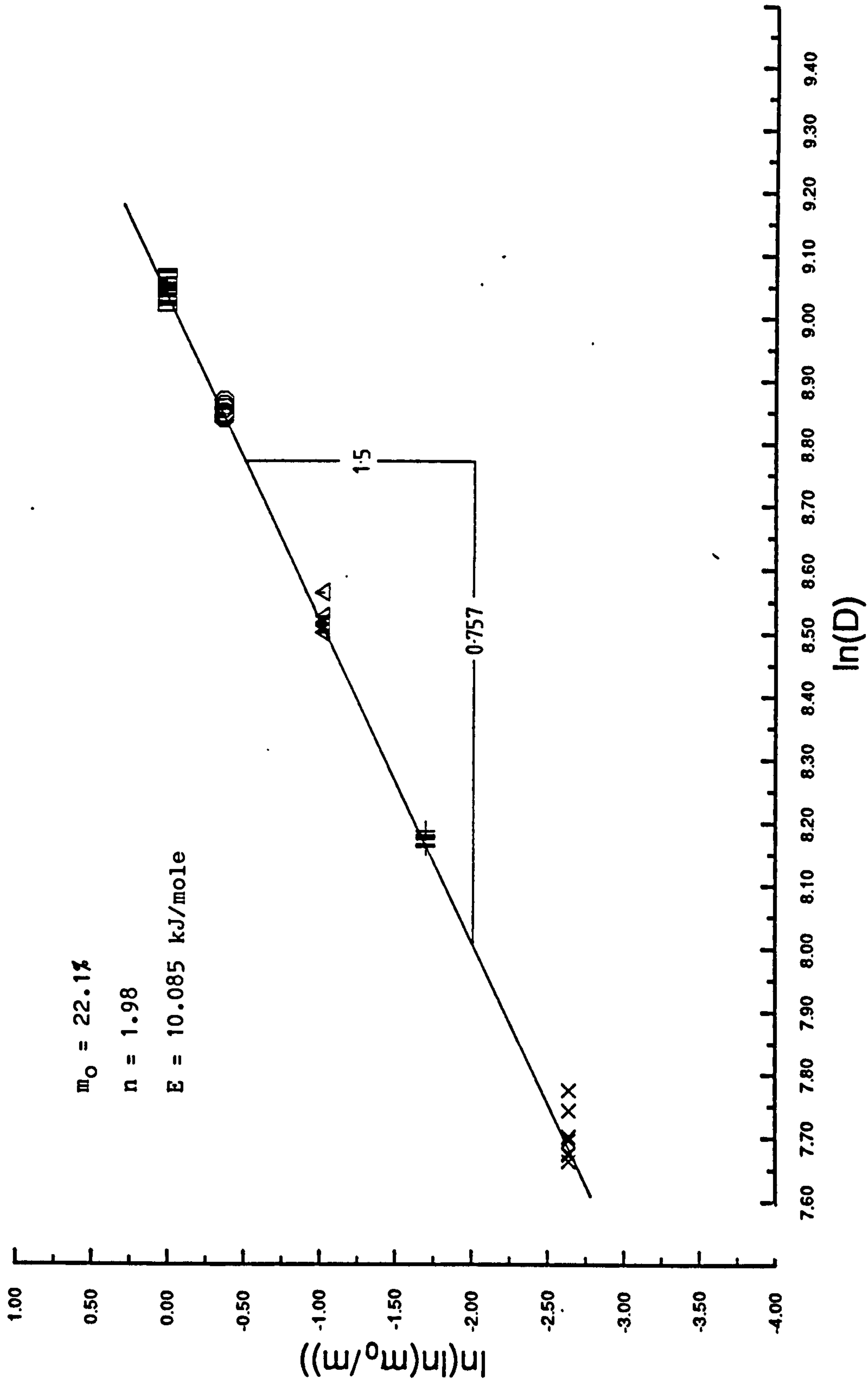


Fig 7.14 Characterization curve for the pair a.c. 208C(old batch)/ammonia

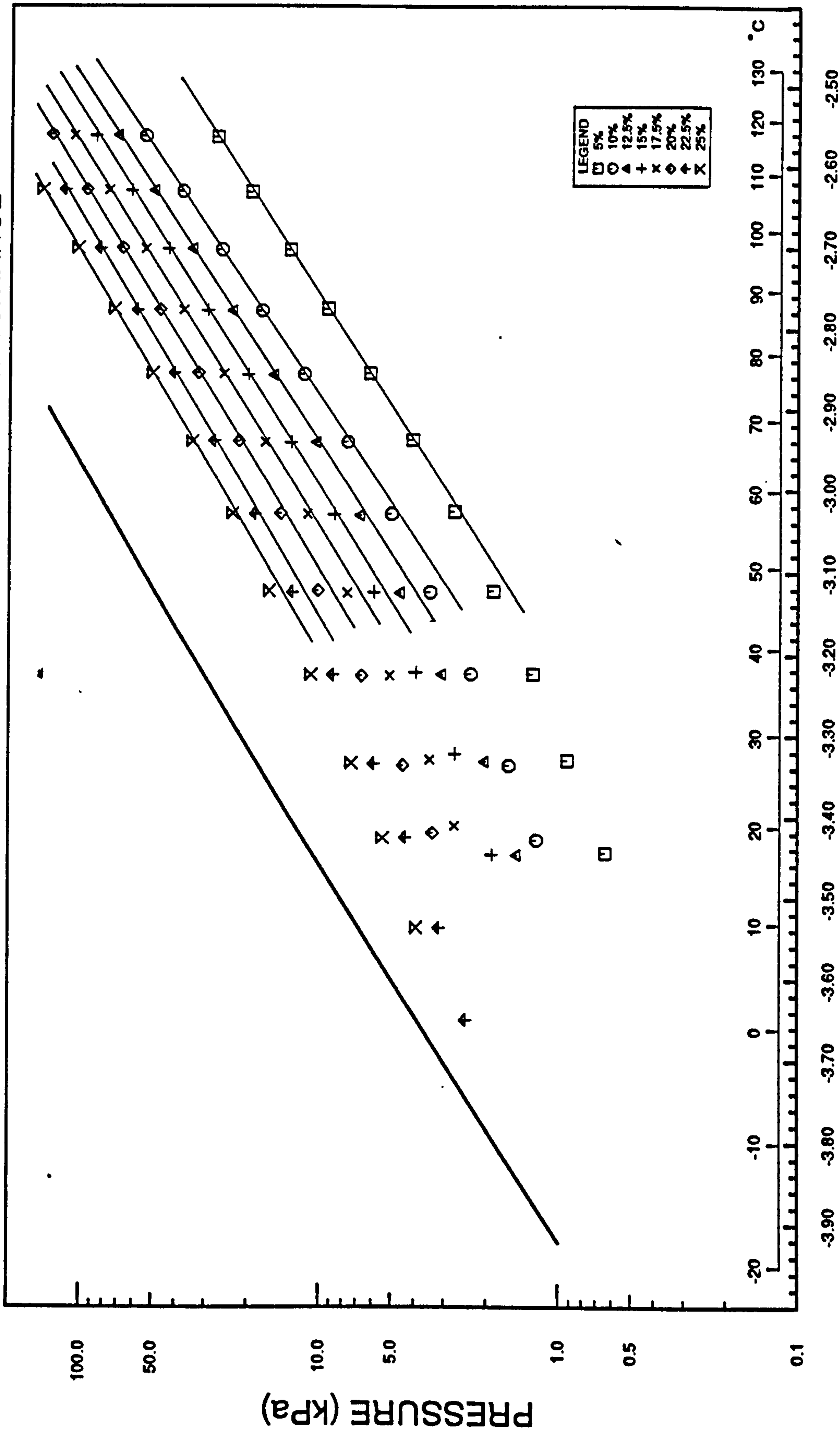
specification. It was found, in the mean time, that ammonia-208C combination is not suited to the envisaged application (see chapter 6). Thus, no further tests, with ammonia as the adsorbate, on the new batch of 208C were conducted.

7.6.3 Activated carbon-methanol

According to a previous investigation [9] 208C was superior in performance to 207C when the refrigerant is methanol. Therefore it was decided to establish the adsorption equilibrium of 208C and methanol only. Due to the irregular crystal structure different batches of the same type of activated carbon could exhibit slightly different properties. Therefore it would be always necessary, in the case of activated carbons, to determine the exact characteristics to ascertain the expected performance.

The equilibrium pressure of adsorbed methanol on 208C, in the range 20 to 120°C, is sub-atmospheric. Therefore at low temperatures and concentrations the measured equilibrium pressure could be much in error if any preadsorbed moisture is present in the system. This was experienced with the old batch of 208C. At the time of experiment the material had been stored in a polythene lined box for the last 6 months. A sample of 400 g of 208C was outgassed at a temperature of 250°C under a vacuum of 0.5 mbar for 24 hours. There was a loss in weight of about 7.5%. The isosteric equilibrium data is presented in fig 7.15 in Clapeyron coordinates. It can be seen that the data points do not converge on a straight line. Especially at low

ISOSTERES FOR THE PAIR ACTIVATED CARBON 208C/METHANOL



NEGATIVE RECIPROCAL TEMPERATURE (-1/K)

Fig 7.15 Isosteric equilibrium data for methanol on activated carbon 208C(old batch); departure from straight line is evident

temperature the equilibrium pressure recorded was too high. This indicated that either some air had been leaked into the system or some of the preadsorbed moisture had not been removed.

To determine the actual cause of the error system pressure was monitored continuously over the next 3 days. No rise in the system pressure was observed which excluded the possibility of any leak into the system. Thus the only source of error could have been the preadsorbed moisture which had not been removed completely.

Therefore a second specimen of 208C was outgassed at a temperature of 350°C and under a vacuum of 0.5 mbar for 36 hours, after which a 10.3% loss in weight was recorded. The isosteres were established again. The data converged to straight lines this time and was shown in fig 7.16. The maximum adsorption was determined experimentally to be (m_0) 28%. The derived parameters for the D-A equation were, $n=1.97$, and $E=6.95$ kJ/mole. The adsorption capacity was much lower than that measured by Critoph (41.9%) [9].

In view of the similar observations when the material was characterized with ammonia (see section 7.6.2 above), it was decided to contact the manufacturers. The research laboratory at Sutcliff Speakman constructed an isotherm at 25°C with methanol for which they used a freshly prepared sample of 208C. Their results (see appendix)indicated that 208C had adsorbed 40.6% methanol under saturation conditions. As a result of their further investigation on the 208C already supplied to us, they concluded that the material was not of the right specification and supplied us a new batch of 208C.

ISOSTERES FOR THE PAIR ACTIVATED CARBON 208C/METHANOL

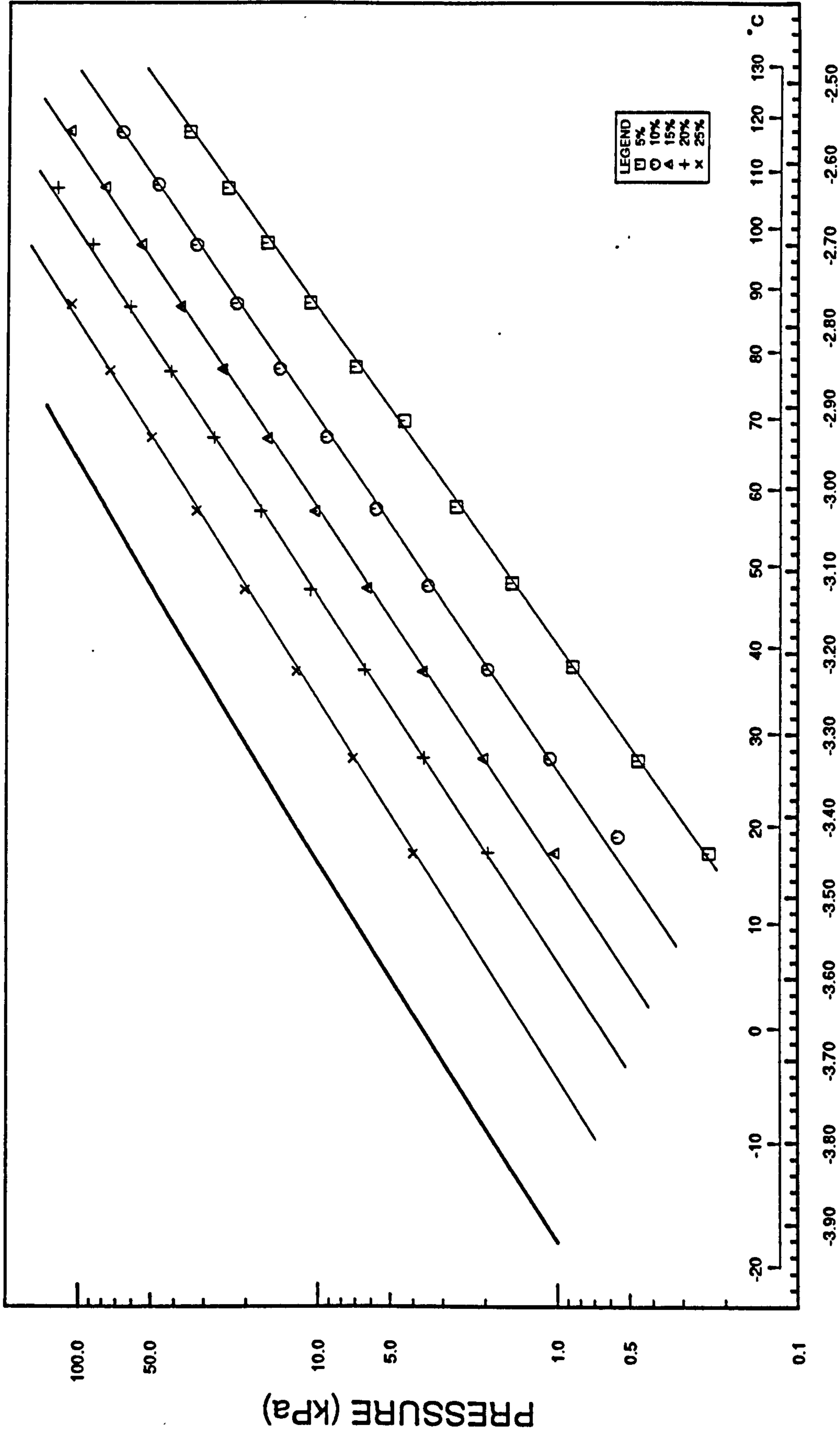
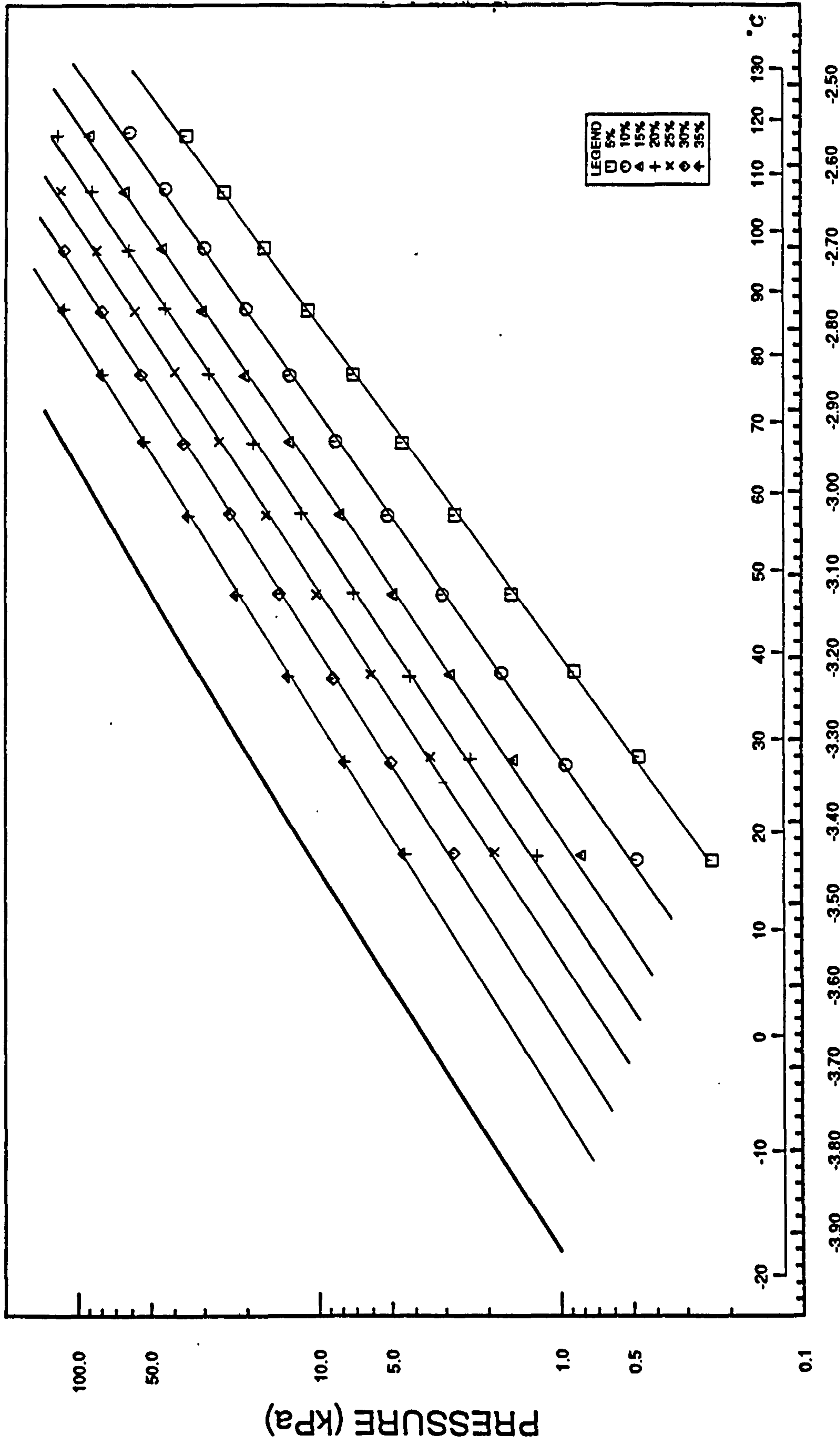


Fig 7.16 Isosteric equilibrium data for methanol on activated carbon 208C(old batch) after prolonged outgassing at high temperature

The new batch of activated carbon 208C showed the promised results. The maximum adsorption of methanol was measured as 40.1%. The measured equilibrium data converged on straight lines in a Clapeyron diagram. The isosteres for the new batch with methanol are shown in fig 7.17. Following the procedure described in section fig 7.18 was prepared. The linear regression produced a value of $n=1.89$ and E was determined to be 6.175 kJ/mole.

ISOSTERES FOR THE PAIR ACTIVATED CARBON 208C/METHANOL



NEGATIVE RECIPROCAL TEMPERATURE (-1/K)

Fig 7.17 Experimental isosteres for activated carbon 208C(new batch)/methanol

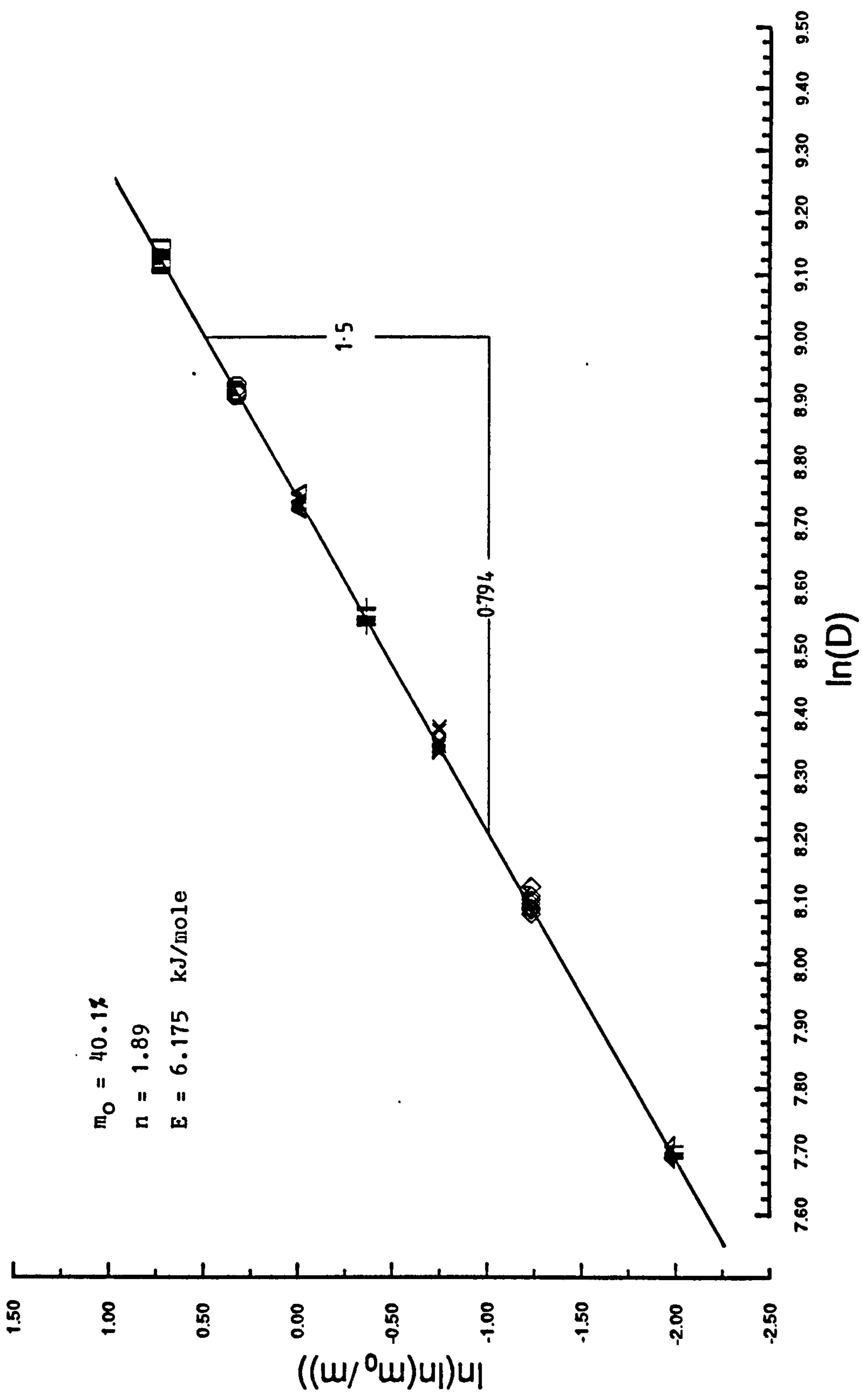


Fig 7.18 Characterization curve for the new batch of 208C with methanol

7.7 Conclusions and summary of results

The experimental rig designed for the characterization of adsorption pairs proved successful. The external-device-control circuitry worked very well and performed its designated function proficiently. Data acquisition system suffered from a few inherent hardware problems which could not be attributed to the general design of the rig itself. The software developed specifically to control the rig worked satisfactorily.

Ammonia attacked the viton 'O'rings and rendered them hard and brittle and were replaced with seals made of teflon. These proved satisfactory but cannot be used again once the seal has been opened. This is because the teflon rings are squashed in the groove and adapt to its shape.

Table 7.1 summarizes the experimental results discussed and presented in graphical form in the previous sections. Isosteres shown for different pairs in these graphs, for the sake of clarity, show the equilibrium data for ascending temperatures only. In each case the data was acquired for ascending and descending temperatures and was found to converge, i.e. no hysteresis was observed.

Activated carbon showed a lesser adsorption capacity for ammonia than for methanol. As the kinetic diameter of ammonia (2.6×10^{-8} cm) is almost half the methanol diameter (5.046×10^{-8} cm), it was expected that more ammonia could be adsorbed than methanol. This anomaly could be explained by the phenomenon of specificity explained by Barrer [10]. The surface of activated carbon is

energetically heterogeneous because of the chemical complexes formed during activation process. These complexes are such that methanol molecules are more attracted in comparison with ammonia and hence the reason for higher adsorption.

Detailed discussion of specificity in adsorption is beyond the scope of this thesis and the interested reader is referred to reference [10] and the other references cited in it.

TABLE 7.1

Summary of results of characterization experiments
for different adsorption pairs

ADSORPTION PAIR	CHARACTERISTIC CONSTANTS IN D-A EQUATION		
	E (kJ/mole)	n	m ₀ (kg/kg)
Zeolite-13X/NH ₃	12.11	3.06	0.215
A.C.207C/NH ₃	8.412	1.97	0.203
A.C.208C/NH ₃ *	7.152	1.92	0.250
A.C.208C/CH ₃ OH	6.175	1.89	0.401

* result from ref [7]

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CHAPTER EIGHT

Design and testing of a novel
Solar Generator Adsorber (SGA)

8.1 Solar thermal adsorption refrigerators

The major advantage of intermittent operation of solid adsorption cycles is the ability to integrate the solar collector, generator and adsorber into one single unit. This simplifies the circuit and reduces the weight and cost of the plant. At the same time due to intermittent operation the total quantity of refrigerant, and therefore adsorbent as well, has to be large which inevitably makes these machines bulky.

A typical intermittent solar adsorption refrigerator is shown schematically in fig 8.1. There are four main components of the system, namely, (1) solar collector-cum-generator-cum-adsorber (SGA), (2) condenser, (3) refrigerant storage, and (4) evaporator. The two control valves, E and C, are used to connect the condenser to and isolate the evaporator from the SGA during the generation period and to connect the evaporator to and isolate the condenser from the SGA during the evaporation period.

The design of SGA for an adsorption refrigerator requires special attention. It combines three separate components into one unit while the requirements of all three are conflicting. Solar collectors become inefficient at higher operating temperatures due to increased energy losses whereas the COP of the refrigerator increases (upto a certain point) as the operating temperatures rise. The SGA has to be well insulated to reduce the losses to the ambient whereas the insulation inhibits the heat of adsorption to be rejected to ambient during adsorption of the refrigerant.

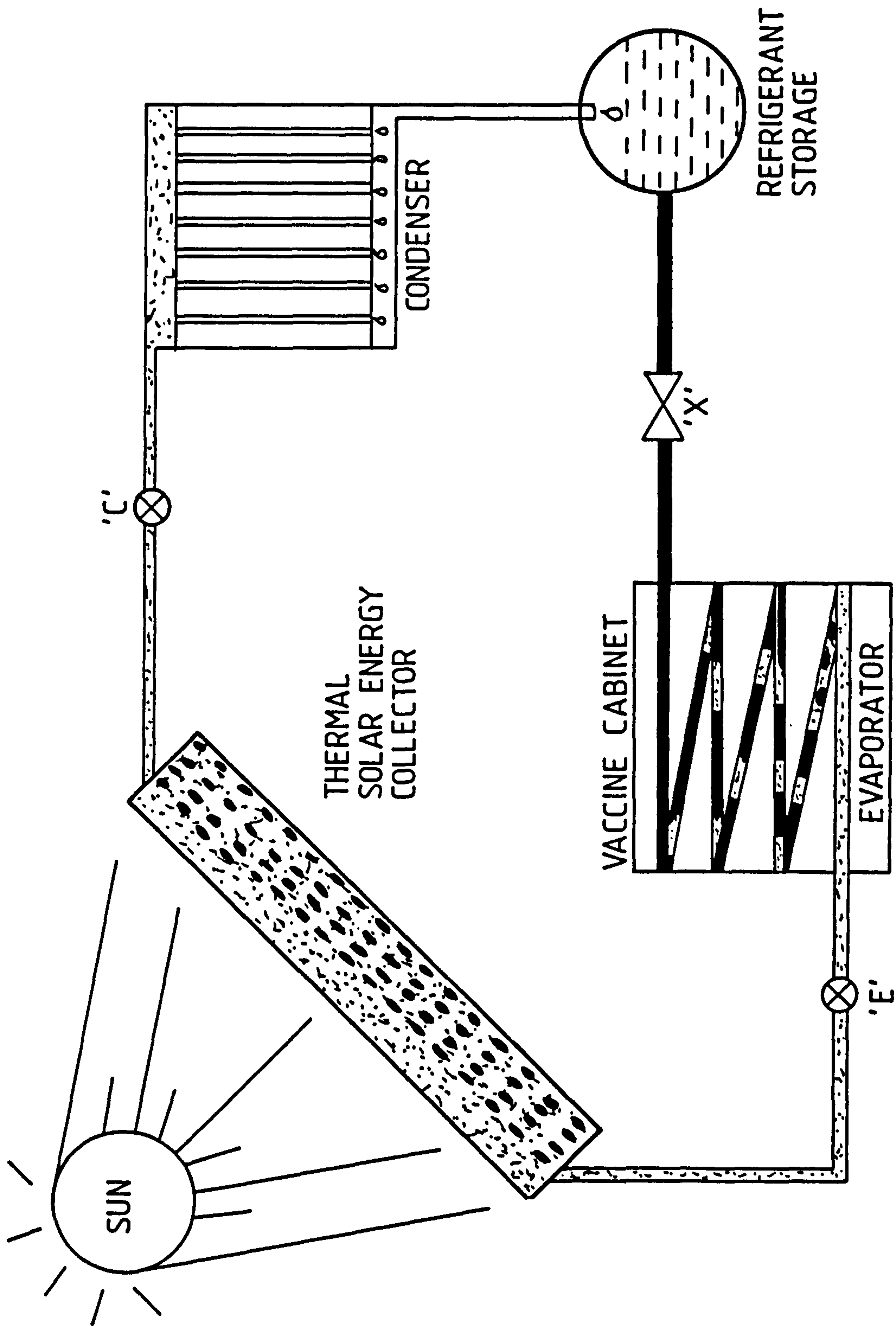


Fig 8.1 Schematic representation of an adsorption refrigerator

8.2 SGA for activated carbon/methanol refrigerator

The conventional designs of an SGA used a metallic box filled with activated carbon enclosed in a single or double glazed insulated outer casing. The top surface of the metal box was coated with a selective surface to reduce the heat loss. A grave problem with this design stemmed from the high contact resistance between the metal box and the carbon granules. A temperature difference of up to 25°C had been experienced [1] between the metal surface and the carbon bed. If this temperature difference could be recovered somehow, the operating temperature of SGA could be lowered and overall efficiency of the refrigerator improved.

It was believed that activated carbon, being black, would be a good absorber of the solar radiation. The temperature differential of 25°C could be recovered if the intervening metal plate was removed and the solar energy was directly absorbed by the carbon bed. Before proceeding further with the idea an estimate of the absorptance of carbon was considered necessary.

8.2.1 Measurement of absorptance of granulated activated carbon

After extensive literature search no figure for the absorptance of activated carbon could be found. But a strong evidence of carbon being a good grey body was found [2]. It was, therefore decided to carry out some tests to ascertain its absorptance. An emissometer, model A.E., produced by Devices and Services Company, Dallas, Texas, USA, was used for the purpose. It was calibrated first against a

standard sample of known emittance (supplied with the instrument) by noting the emissometer's output (in millivolts). Then it was used on the specimen of activated carbon granules. The emittance of the carbon sample and the corresponding output signal would be in the same proportion as were for the standard sample.

As the instrument was designed to measure the emittance of flat surfaces, the activated carbon granules were laid down on the heat sink (part of the instrument) in the shape of a flat bed. A slight variation in the measured values was observed when the orientation of the granules in the bed was changed. This variation was less than 4%. The average value after 10 readings came out to be 0.84. As carbon is a good grey body, its absorptance is equal to its emittance. This value of absorptance was as good as for a selective surface (absorptance = 0.87).

8.2.2 Novel design of SGA

The new and novel design of SGA was based on the philosophy that solar energy would be absorbed directly by the carbon bed. This required a container to hold the carbon with a transparent top. The equilibrium pressure of carbon/methanol mixture in the container would be sub-atmospheric which necessitated a good seal between the transparent cover and the container. The proposal was to make the container from glass and join the transparent glass cover by special welding process as was used in the manufacture of television picture tubes (though for the purpose of experimental rig a metal container with glass cover was the only possible option). Activated carbon

granules were to be placed in the container with a vapour space either at the top of or under the carbon bed. A false bottom made from a perforated metal sheet was proposed for the latter option. It was decided to construct two SGA's, one of each design, and test them under a solar simulator side by side under similar conditions.

Granulated activated carbon bed has a low thermal conductivity and to improve the heat transfer within the bed, fins, attached to the top plate, had been used [3]. This measure increased the heat capacity of the system as well, by increasing the mass of metal in the SGA. There has been some development in producing preformed activated carbon in various shapes [4]. A single one piece solid bed would improve the heat transfer within the bed to a large extent. The proposed design of SGA would be able to take advantage of this new development.

8.3 Experimental rig

The experimental facility was built to study and compare the performance of the SGA as solar collector, generator and adsorber by measuring the kinetics of adsorption and desorption and heat transfer rates within it. A schematic representation of the experimental rig is shown in fig 8.2. The main components of the rig, whose detailed description follows, were SGA, condenser, methanol storage/measurement vessel. Instrumentation and control arrangements have also been described in the following sections.

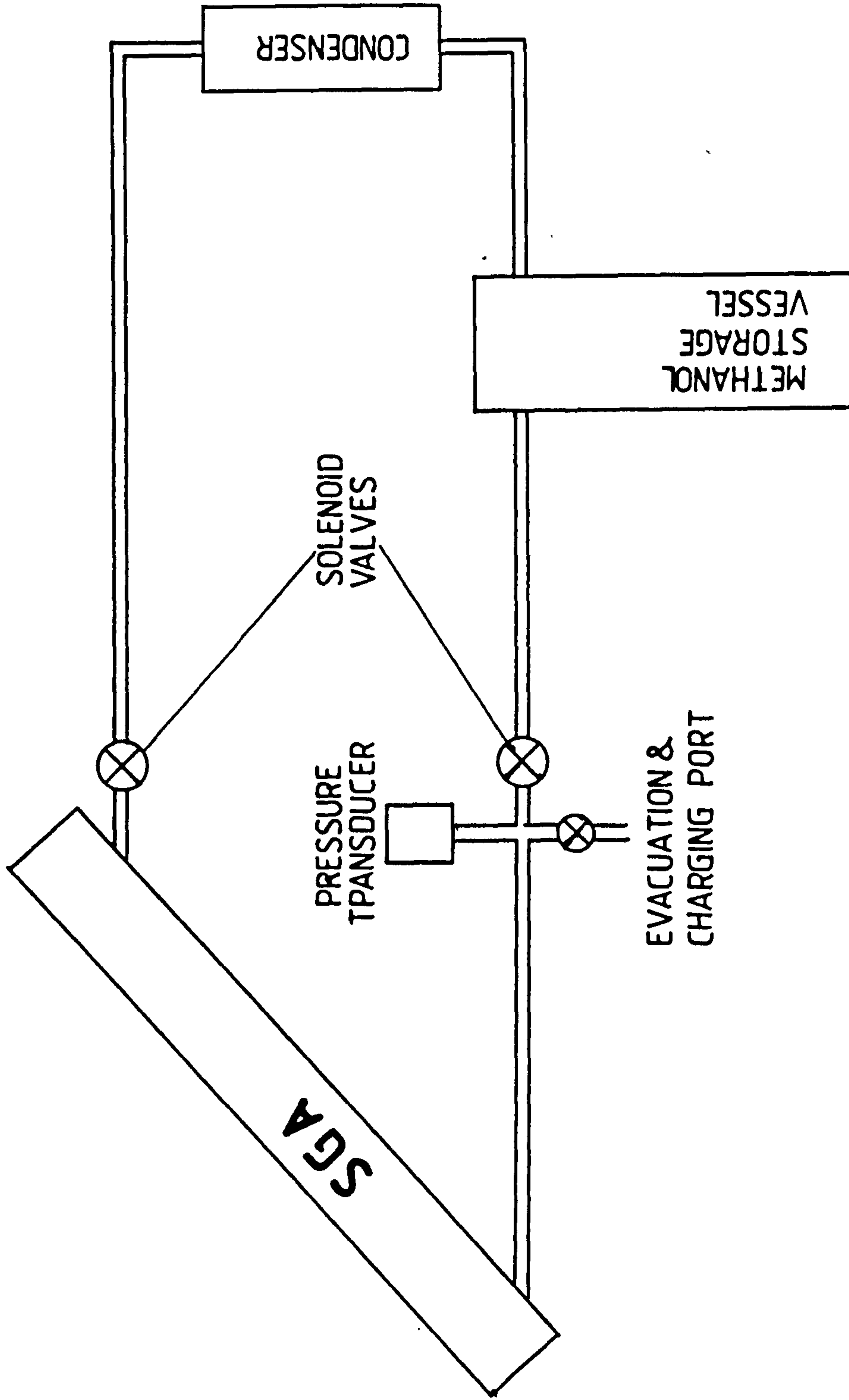


Fig 8.2 Schematic representation of SGA test rig

8.3.1 Solar-generator-adsorber

Because of the limited space in the laboratory, size of the SGA was restricted to 500 mm square. The detailed engineering drawing is shown in fig 8.3. The container was made of 3 mm thick duralumin sheet. A 25 mm wide flange was welded to the perimeter and groove cut in it to accommodate a square section strip-rubber seal. A square angle-section clamp, made from 1.5 mm mild steel sheet, kept the double glazing in place on top of the container. The inner glass cover was held pressed against the rubber seal and was supported at five other locations as shown in fig 8.4

A 6 mm thick clear glass was used initially for the covers. The inner cover became subjected to a large stress when the container was evacuated and shattered. Subsequently it was replaced by a 10 mm thick glass which could withstand the stress without breaking. The vacuum containment did not prove satisfactory. The main reason for the leak was the roughness of the bottom surface of the groove in the flange. It had to be a highly smooth surface to be able to make a vacuum proof seal. Local facilities were not capable of producing such a special surface. It was therefore decided to spray silicon sealant around the seal perimeter which cured the problem.

The false bottom in SGA no. 1 was made from a 1 mm thick stainless steel perforated sheet which was held by five spacer rings placed around the five support pillars. Four and a half kilogram of activated carbon was put into each of the SGA's which made created a 40 mm thick bed.

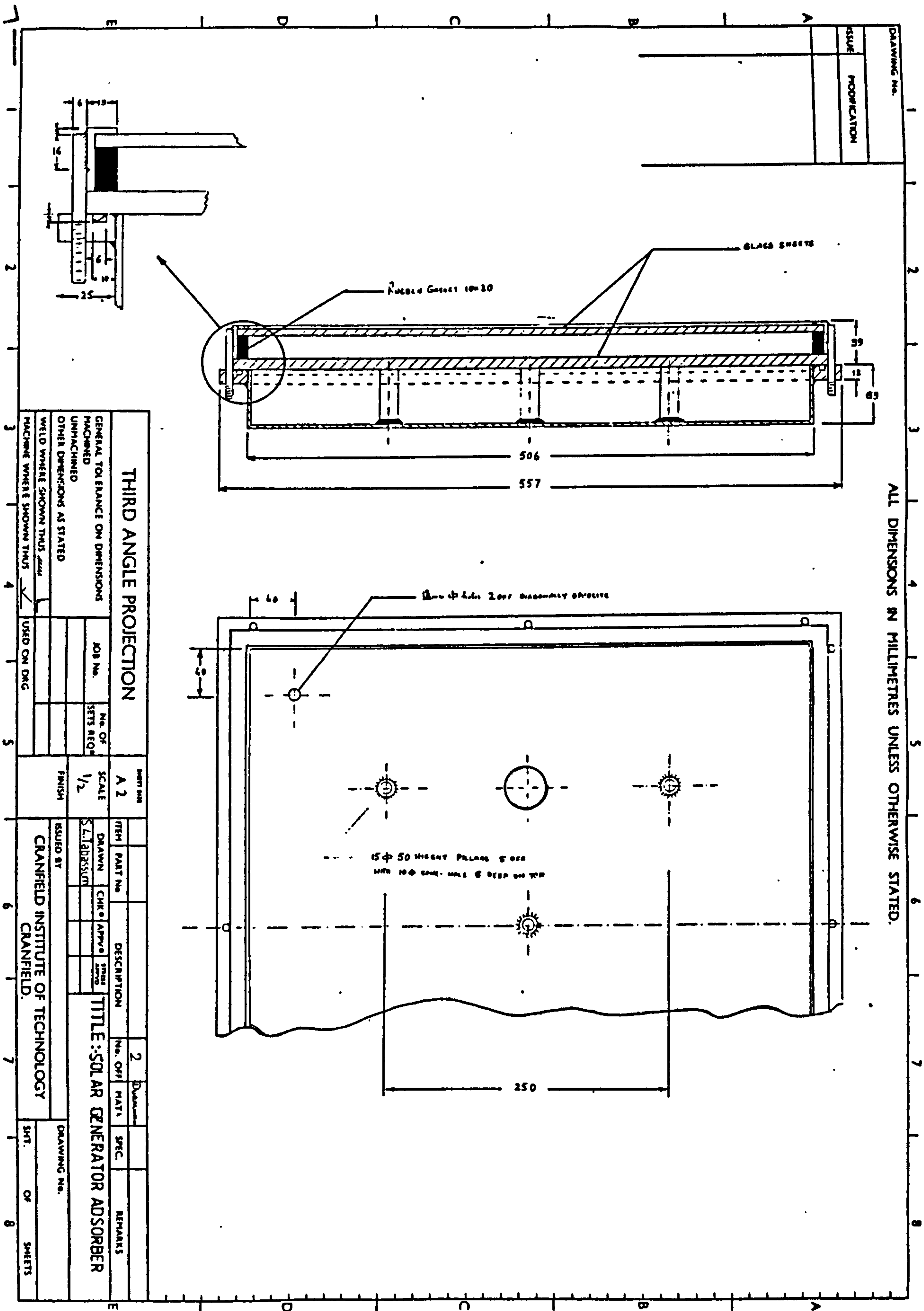


Fig 8.3 Engineering drawing of the SGA

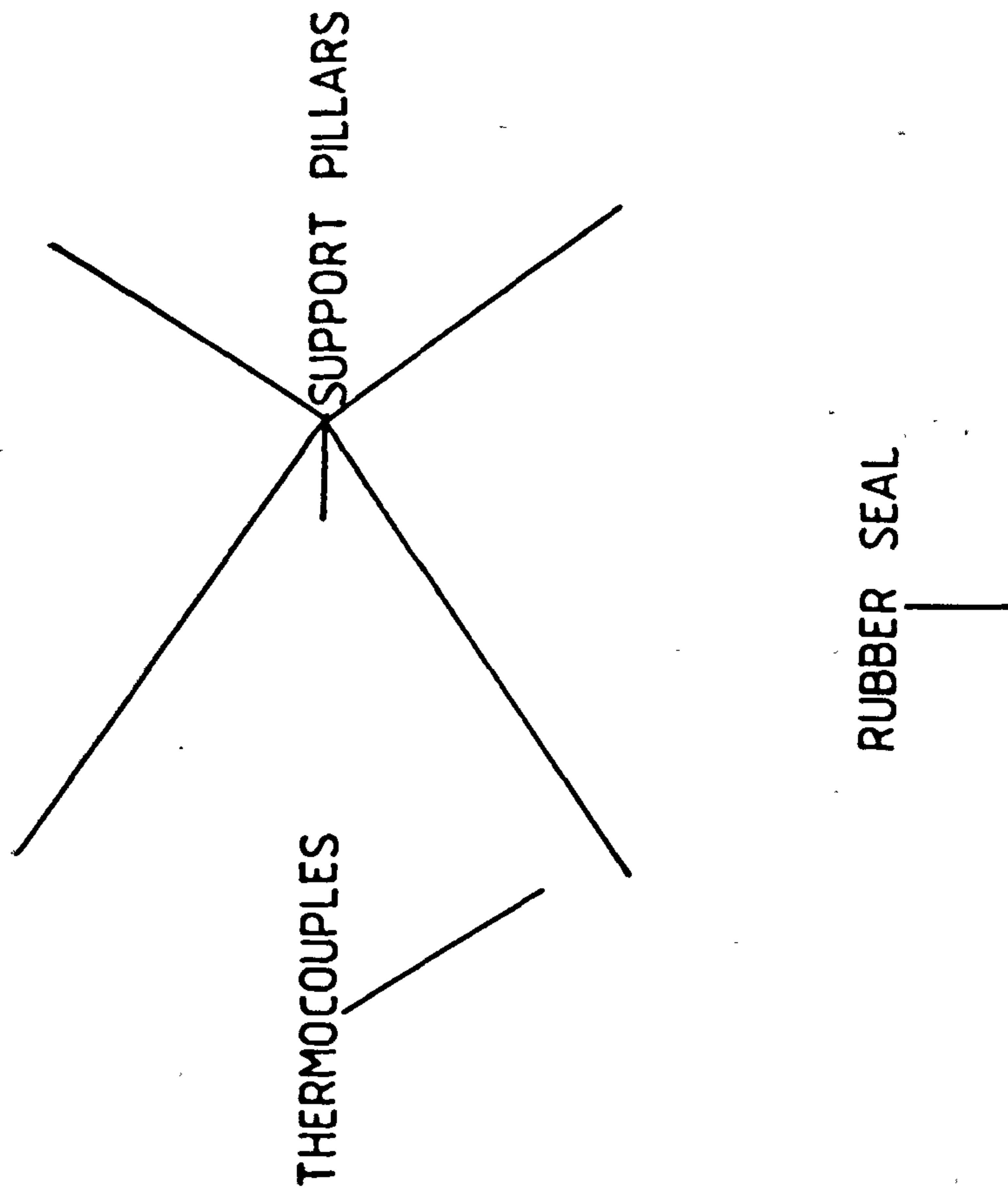
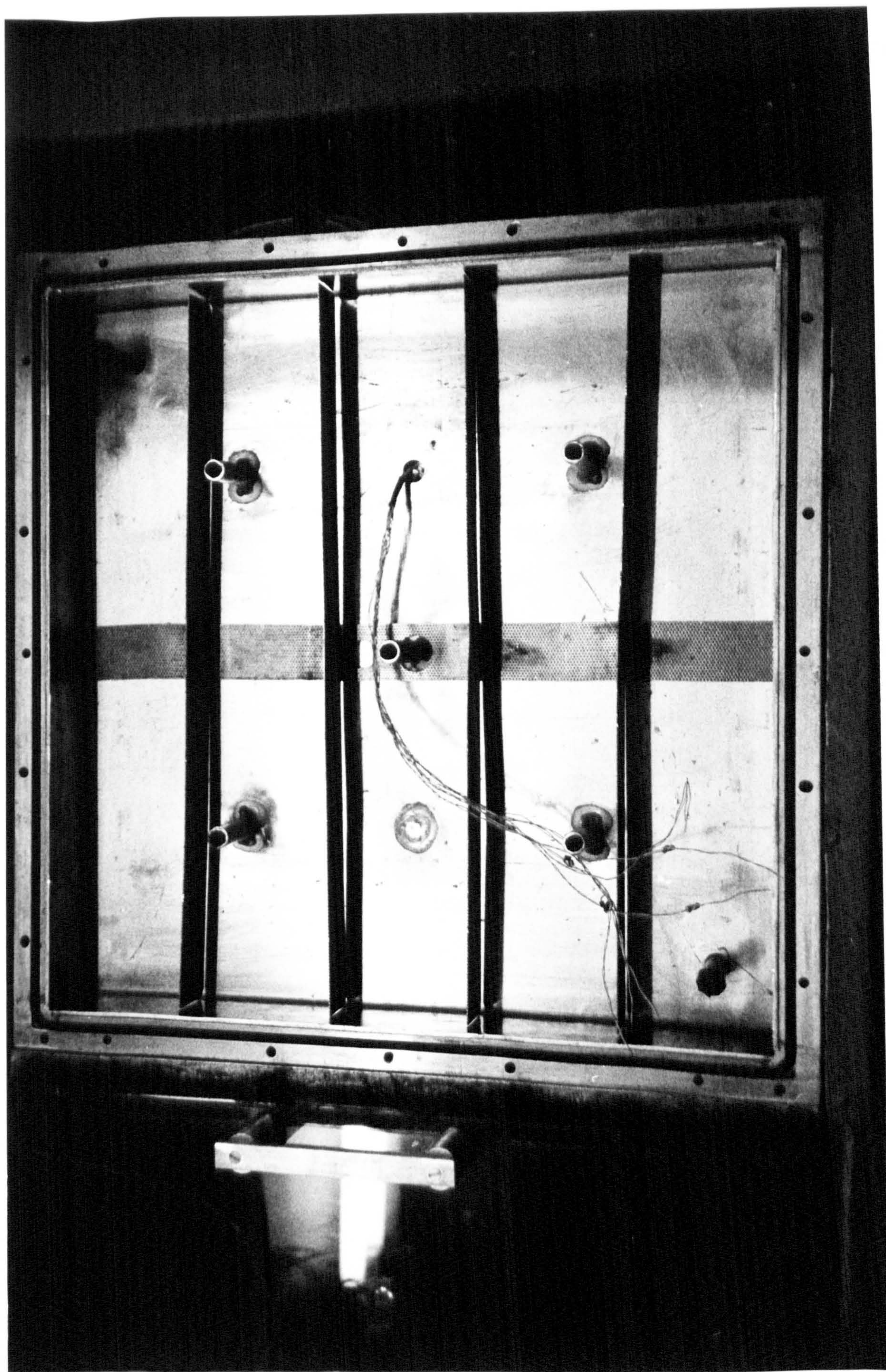


Fig 8.4 Photograph of SGA without glass covers



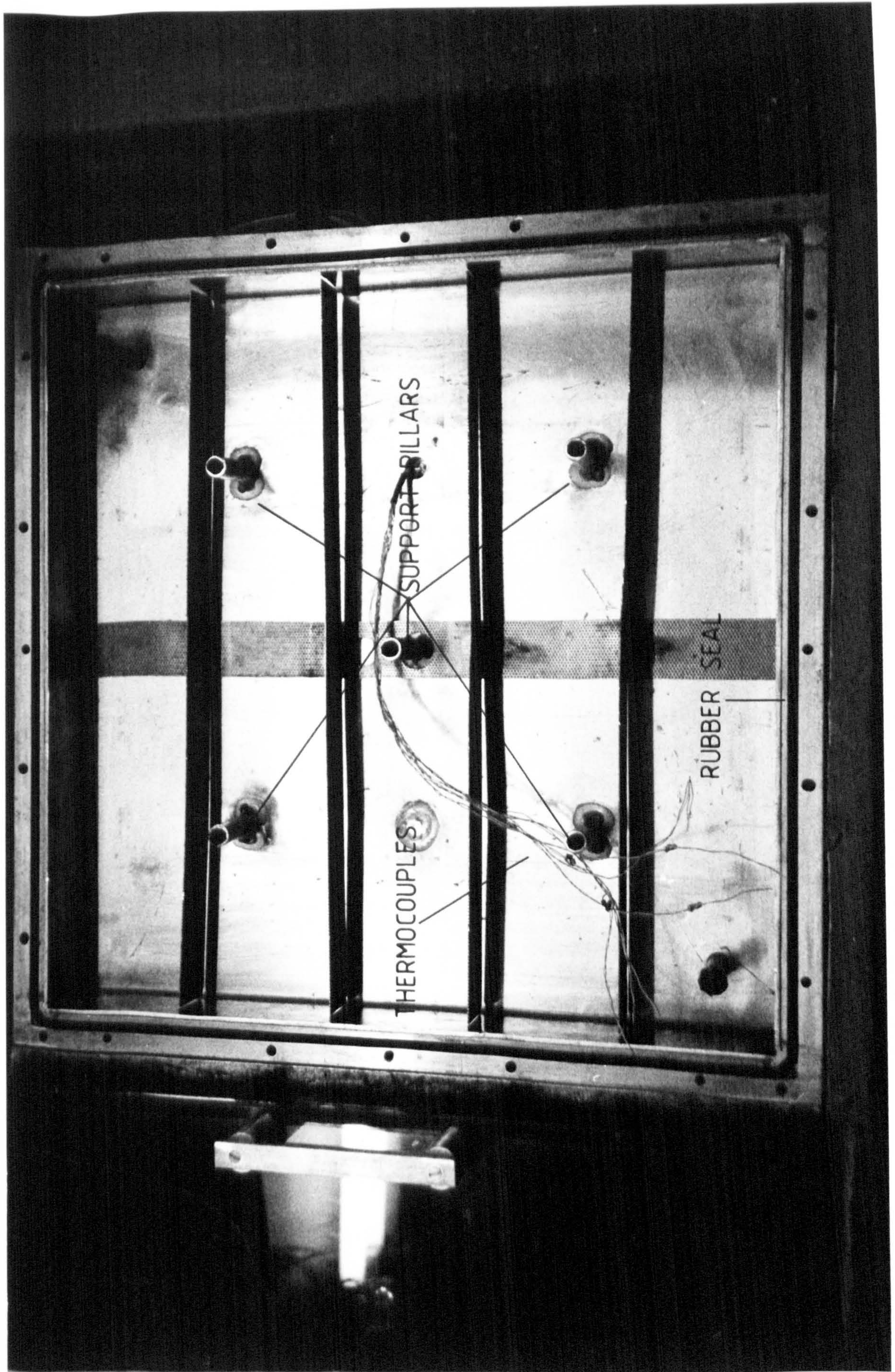


Fig 8.4 Photograph of SGA without glass covers

In SGA no. 2 the vapour space was at the top. The carbon granules would have slid down when the SGA would have been inclined. To stop that happening a grid was so arranged inside the SGA as to divide and separate the total mass of carbon into 4 portions (see fig 8.4). Both the SGA's were insulated on the back and sides by a 25 mm thick closed cell polyurethane sheet.

8.3.2 Condenser

In order to assess the effect of varying ambient temperature on the generation process the condensation temperature had to be varied. It could be done, conveniently, in a water-cooled condenser by varying the cooling water temperature.

The condenser was built by submerging a coil of copper tube, of 12 mm diameter, in a tank of stagnant water. It was connected, at one end, to the SGA through a solenoid valve and a flexible stainless steel pipe. The other end of the condenser was connected to the methanol storage/measurement vessel. An immersion heater was used to vary the temperature of water in the tank.

8.3.3. Methanol storage/measurement vessel

During the generation process, desorbed and condensed methanol was to be collected and stored. A record of the amount desorbed (or evaporated during adsorption period) at regular time intervals was also required in order to determine the kinetics of the desorption (and adsorption) process.

It was decided to make the vessel in the shape of a long cylinder so that a conductance probe can be built into it to measure the volume of the liquid methanol collected. The maximum amount of methanol, which could be desorbed from 4.5 kg of activated carbon, was about 500 ml. Therefore a cylinder with 700 ml capacity was constructed from duralumin pipe of 47 mm internal diameter and 450 mm long by closing both the ends with 3 mm duralumin disc. Two ports near the top end provided connections to the condenser and the SGA. Fig 8.5 shows the sectioned elevation of the vessel and the arrangement of the probe elements.

The conductance probe built into the vessel, for measuring the methanol volume, worked on the principle that the electrical conductance between two electrodes dipped into a liquid varied with the level of the liquid. To implement the principle the vessel body was chosen as one of the electrodes. A copper pipe of 22 mm outer diameter placed inside the duralumin vessel acted as the other electrode. It was held concentric with and insulated from the vessel by the help of two 5 mm tufnol discs fixed at its top and bottom ends (see fig 8.5). An insulated pin, fixed at the top end of the cylinder, provided electrical connection to the copper pipe. Sixteen slits, 30 mm long and 2 mm wide, were cut into the pipe with 25 mm gap, as shown in fig 8.5. The condensed methanol got access through these slits to the space enclosed by the pipe walls. The finished vessel with electrical leads connected is shown in fig 8.6.

All dimensions in millimeters

Material duralumin unless stated otherwise

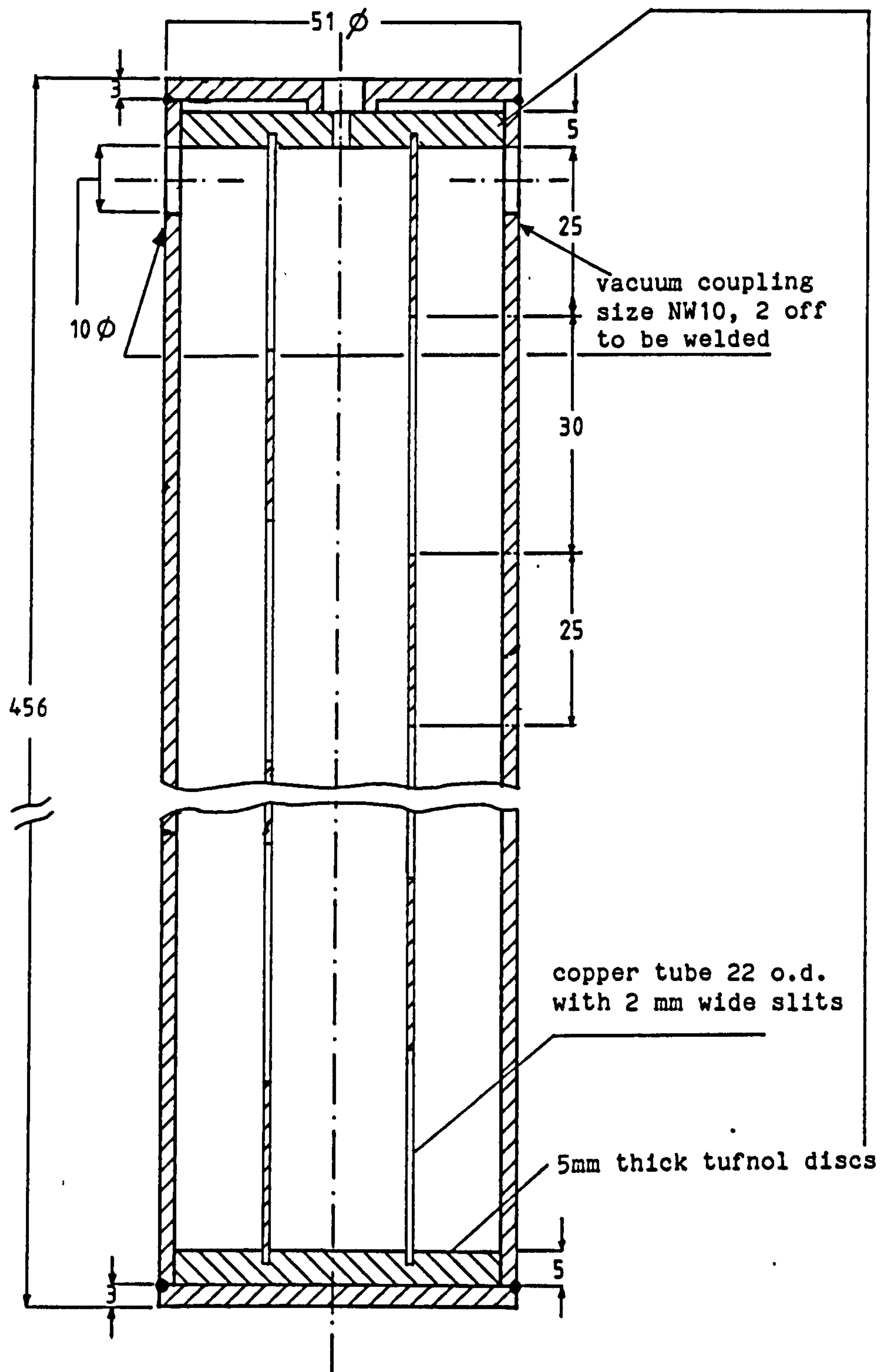
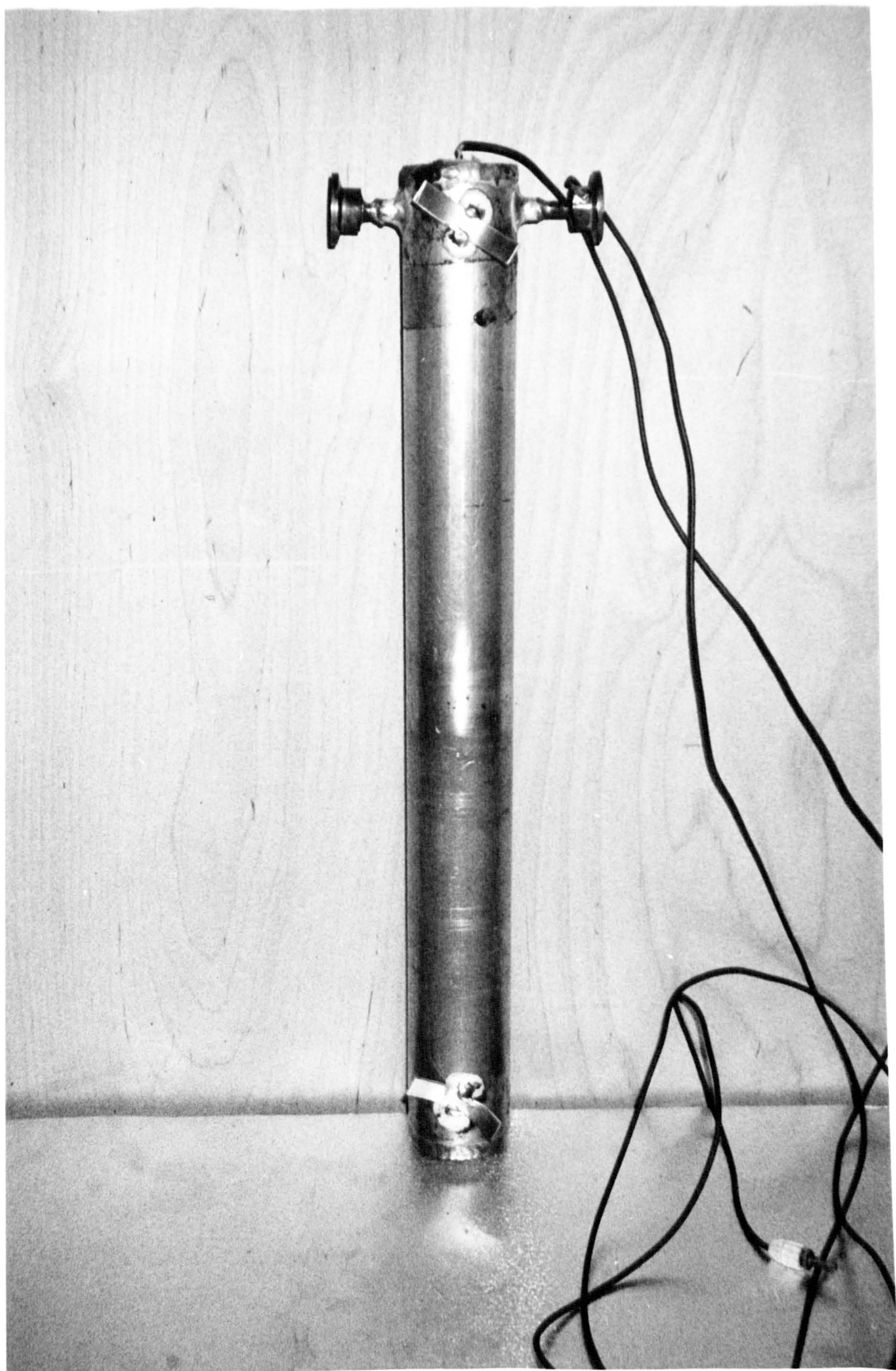


Fig 8.5 Sectioned elevation of methanol storage/measurement vessel

Fig 8.6 Photograph showing the assembled storage vessel



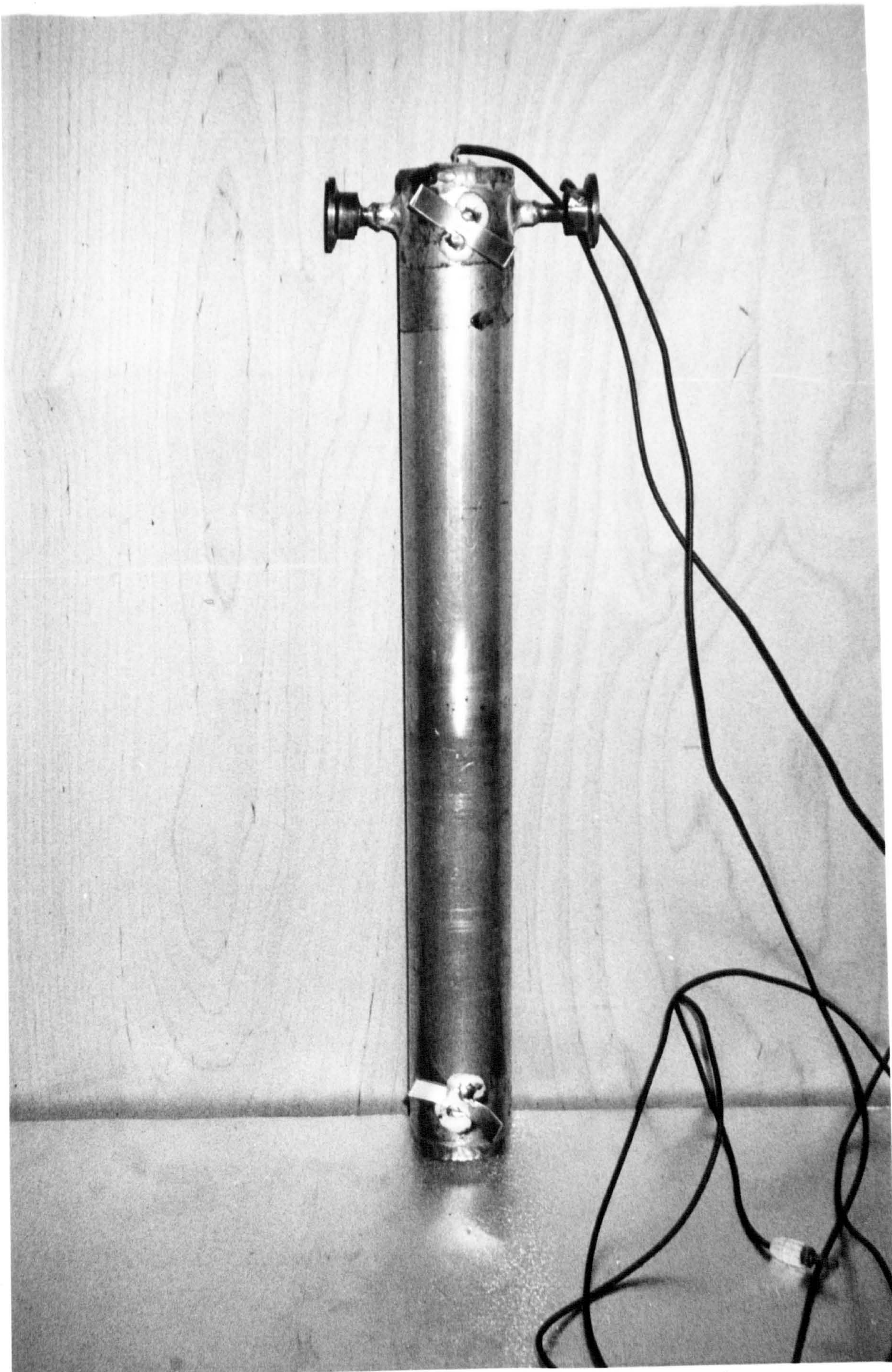


Fig 8.6 Photograph showing the assembled storage vessel

8.3.3.1-Methanol level indicator

The conductance probe built into the methanol measurement vessel can be inserted into one arm of a Wheatstone bridge and variation in its conductance be measured. Supply to the probe must be a.c. A d.c. current across the probe would produce electrolysis. The circuit built for indicating methanol level, converted the changes into conductance between the two electrodes into a voltage signal. It had four main stages as shown in fig 8.7.

Stage one was a function generator which converted the d.c. voltage into a sinewave and fed it to the second stage which is a Wheatstone bridge. The conductance probe constituted one arm of the bridge. The unbalance signal from the bridge went into the next stage which is an instrumentation amplifier. Here the signals were amplified so that those could be measured with more precision. These amplified a.c. signals finally entered into the fourth stage where these were converted into d.c. voltage which could then be measured by any data acquisition system. A voltmeter provided a visual indication of methanol level in the storage vessel.

The storage vessel connected to the level indicating circuit was calibrated by pouring the known quantities of methanol in the vessel and measuring the voltage at the output terminals of the indicator. Two such circuits were built and calibrated for both the SGA's. Calibration curves are shown in fig 8.8 and 8.9. Seventh order polynomials were fitted to those curves whose coefficients were shown on the respective graphs.

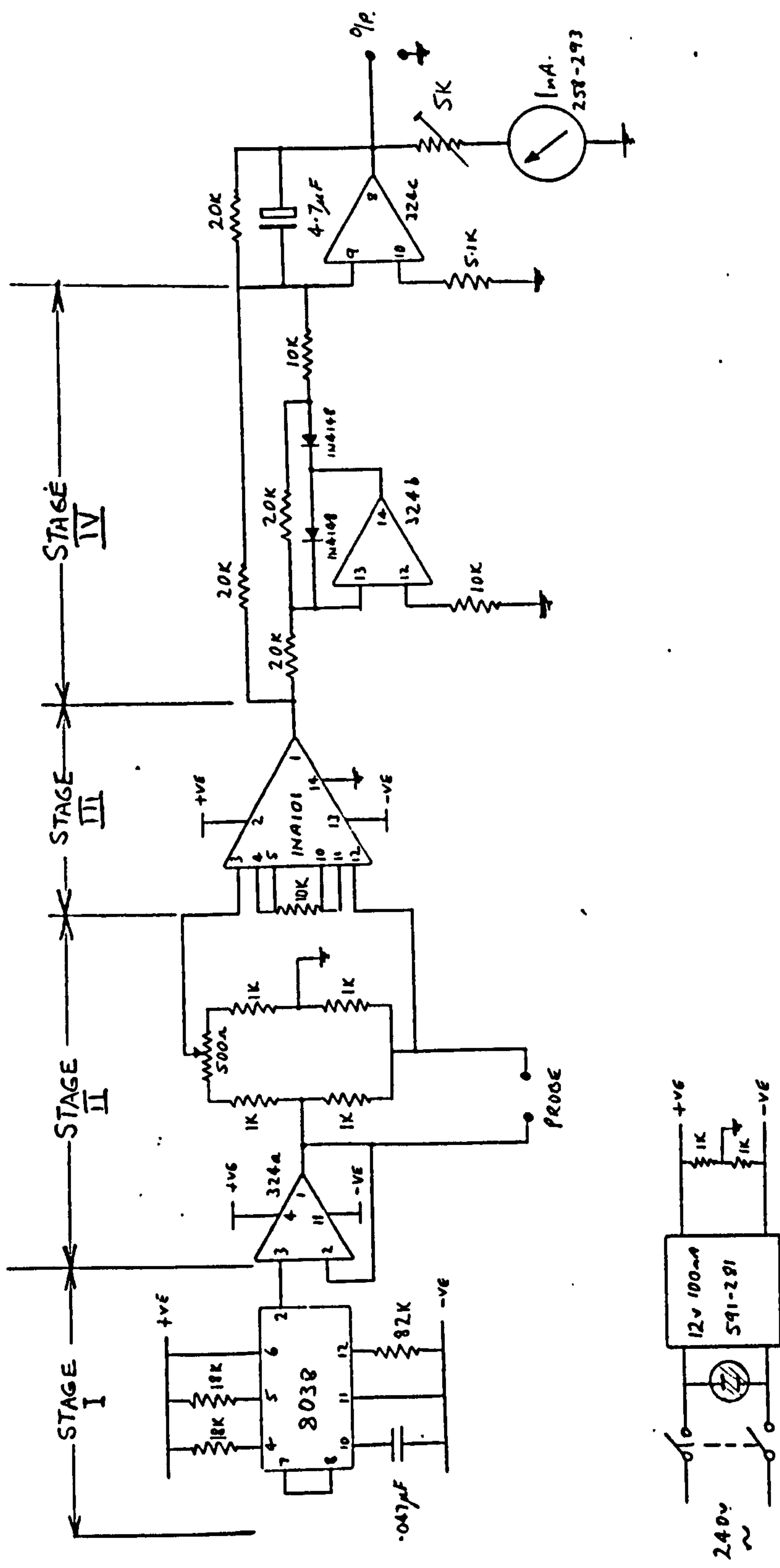


Fig 8.7 Circuit diagram for the methanol level indicator

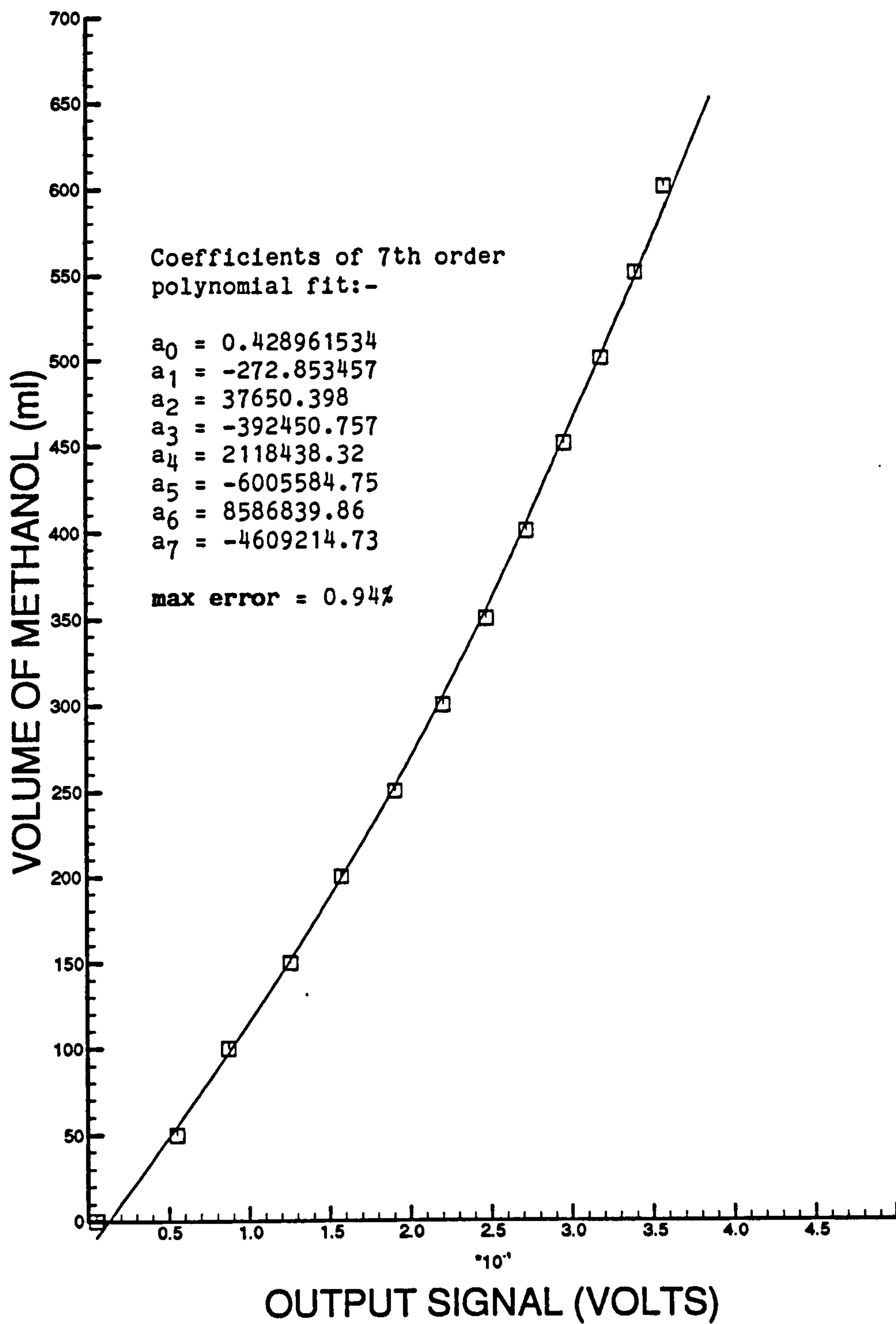


Fig 8.8 Calibration curve for methanol level probe no. 1

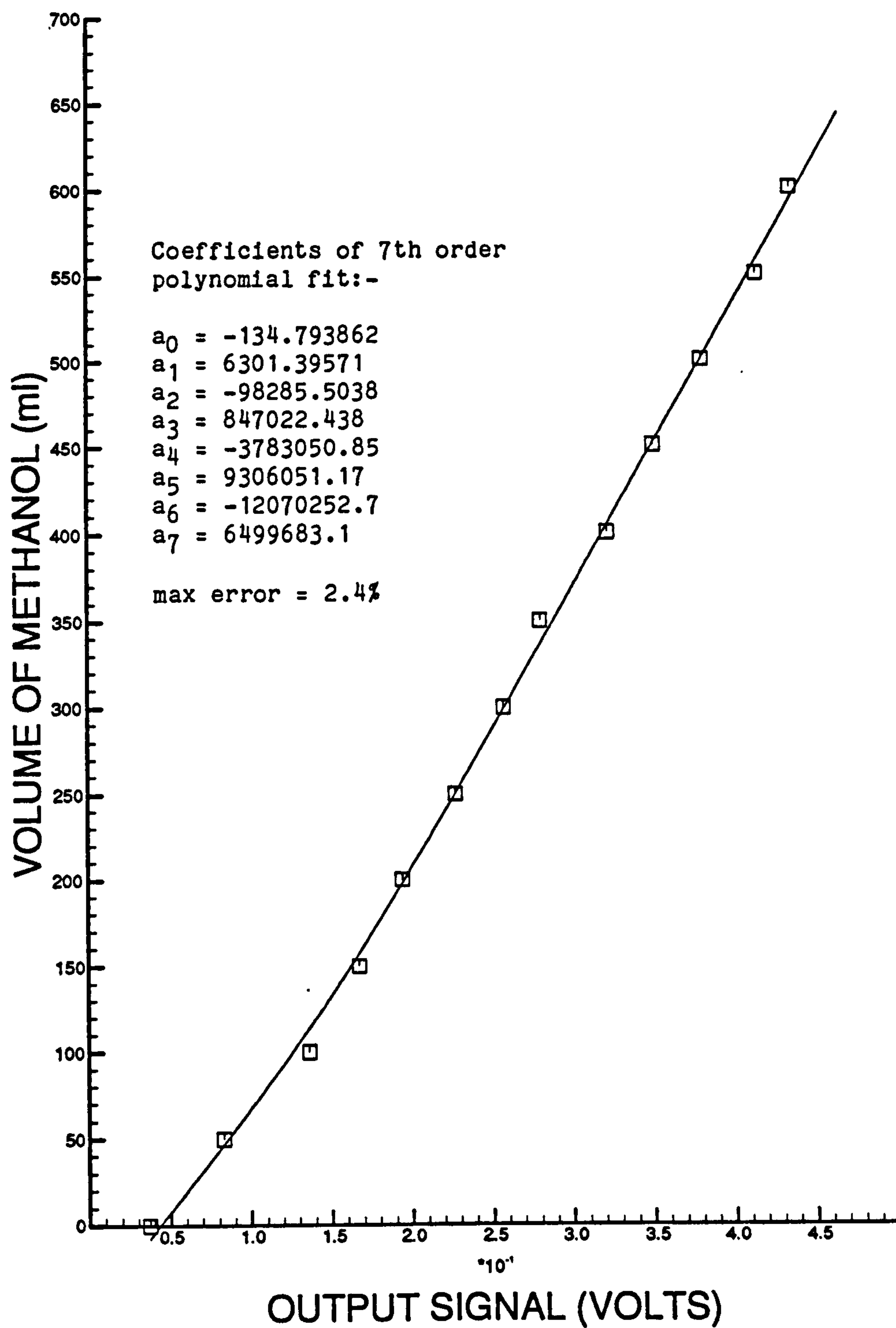


Fig 8.9 Calibration curve for methanol level probe no. 2

8.3.4 Solar simulator

To ascertain the performance of the SGA under real conditions a solar simulator was developed using tungsten-halogen lamps, with parabolic anodized reflector (PAR), made by General Electrics of USA. As both the SGA's were to be tested side by side, 8 lamps of 1000 watts each were arranged as shown in fig 8.10. Each group of four lamps illuminated one of the SGA's. The lamps were placed in a frame measuring 1160 mm in length and 560 mm in width. The distance between the centres of the lamps in each group was kept as 250 mm while both the groups on the frame were at a centre-to-centre distance of 580 mm. This arrangement would have ensured that both the SGA's were illuminated uniformly.

The frame containing the cluster of lamps was hinged at its lower edges to an angle iron frame which was fixed to the wall. At a distance of 150 mm from the top edge of the frame, two eyelets of 20 mm diameter were fixed to both the sides of the frame. Through these eyelets steel pipes, fixed to the wall, could slide. Inclination of the frame could be changed by sliding the pipes through the eyelets and fixing the eyelets to a new location along the pipe.

To simulate real insolation conditions, output from these lamps had to be varied. Eight kilowatt of total load had to be distributed on the three phases. A three phase variac was used to vary the input voltage to these lamps. The operating voltage for the available lamps was 120 volts and therefore these were connected in series-parallel fashion. As all the three phases had to be balanced

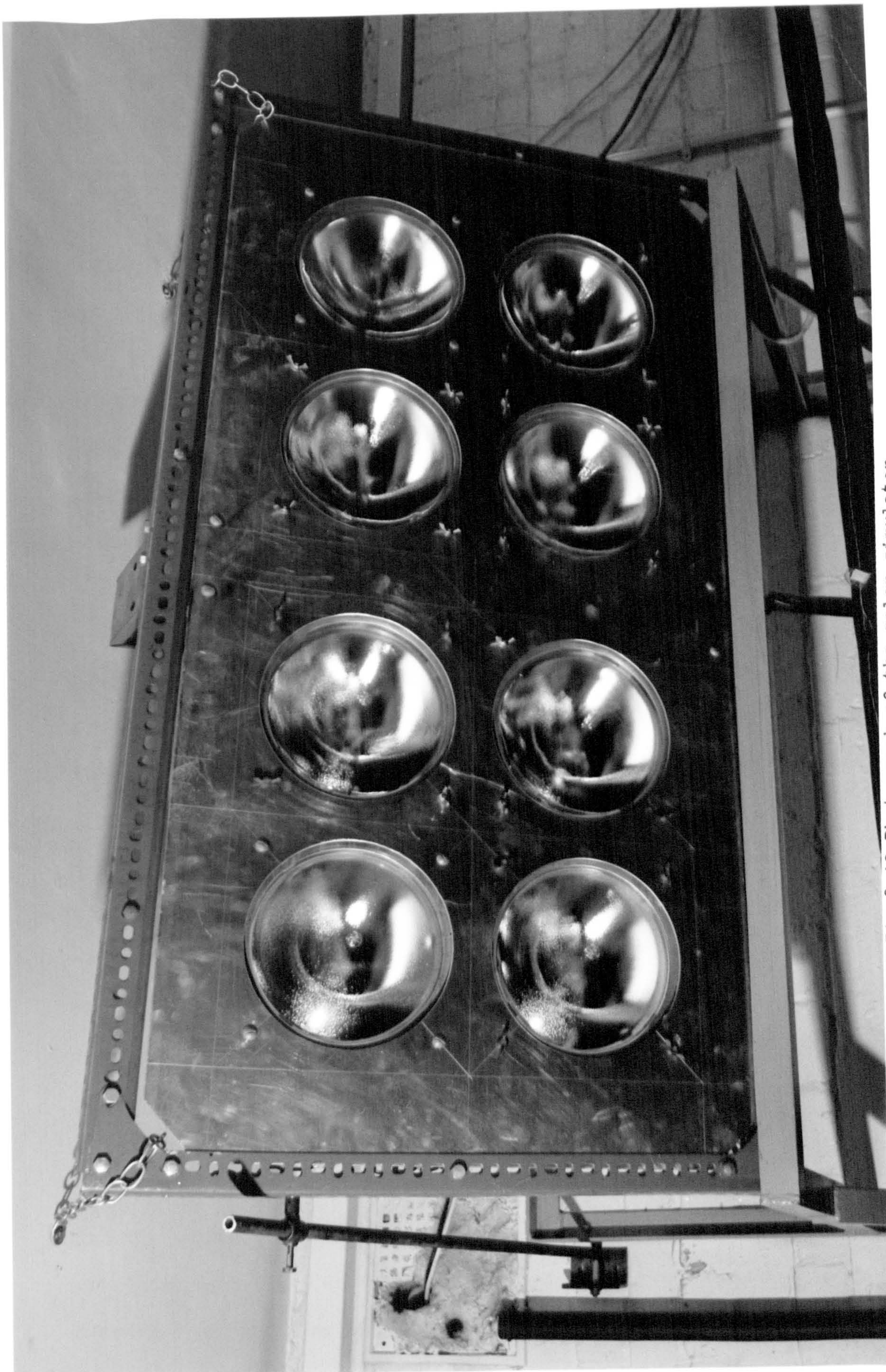


Fig 8.10 Photograph of the solar simulator

for the variac to work properly, a ninth lamp was introduced into the circuit but it did not illuminate the SGA's. Each group of three lamps, connected in series, was supplied by one of the three phases.

Measurement of energy received on the plane of each SGA was carried out behind the double glazing. A grid of 25 squares were marked on the 500x500 mm transparent window and the energy received was measure with a Moll-Gorczynsky pyranometer at the centre of each square. This was repeated for six different voltage inputs to the lamps. Contour maps of energy received were drawn from these measurements for both the SGA's which are shown in appendix I.

The lamps used to build the simulator had already been used in different projects and no record of length of their usage could be traced. The output from these lamps starts declining after about 2000 hours of use. Two contour maps for full voltage input of 225 volts are shown for SGA no. 2 and no. 1 in fig 8.11 and 8.12 respectively. It can be seen that there was a great deal of variation (+25% over the average) in the intensity over the whole measurement field. This variation was observed at other voltage inputs as well (see appendix I). The reason was quite obviously the different span of spent life for each lamp. Within the available resources situation could not be improved any more.

Under natural insolation conditions the heat-transfer in the activated carbon bed would be a one-dimensional phenomenon i.e. heat flowing from the top to the bottom layers. But under the solar

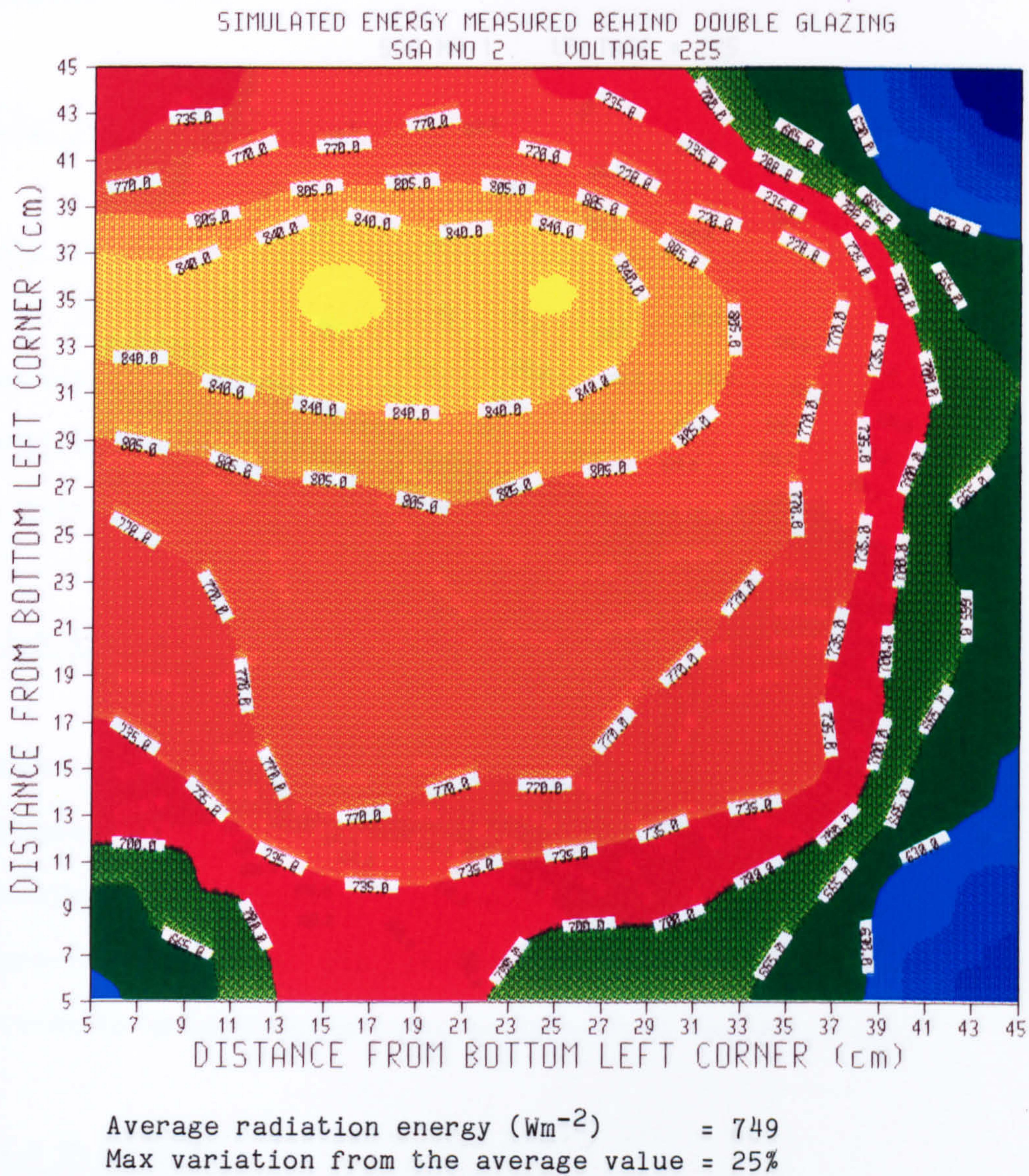
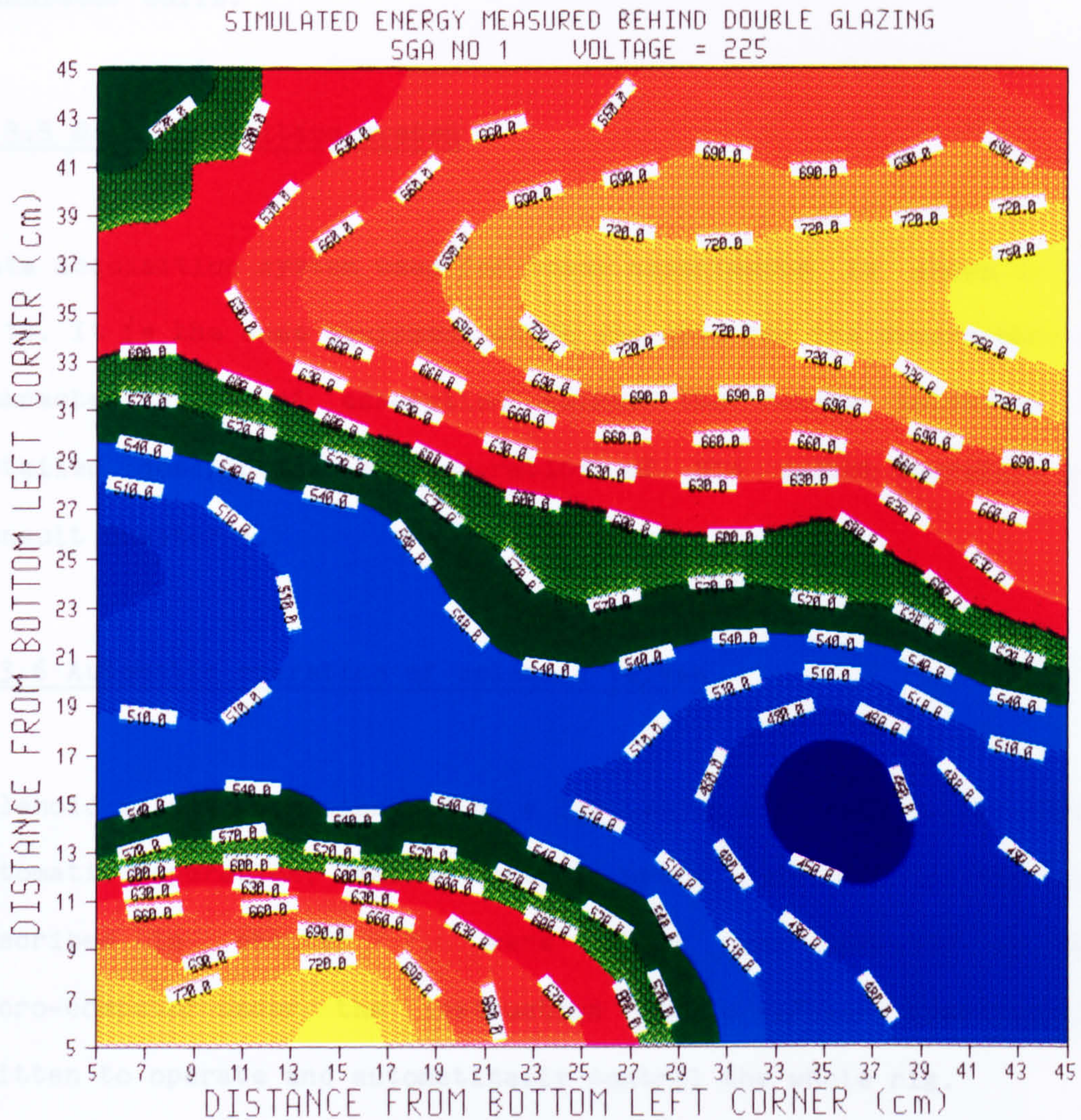


Fig 8.11 Contour map of energy received from the solar simulator
behind the double glazing of SGA no. 2
at full input of 225 volts



Average radiation energy (Wm^{-2}) = 600

Max variation from the average value = 25%

Fig 8.12 Contour map of energy received from the solar simulator behind the double glazing of SGA no. 1 at full input of 225 volts

simulator constructed it would be a three-dimensional flow due to the large variations in the intensity over the whole area of the SGA. In the absence of any alternative it was decided to make use of what was available and the tests were conducted under the solar simulator built.

8.3.5 Data acquisition system

Data acquisition system used for these experiments is shown in fig 8.13. It is the same equipment which was used for the experiments on characterization of adsorption pairs. The reader interested in detailed description and operation of the system therefore may consult chapter 7.

8.3.6 Automatic operation of solenoid valves

Solenoid valves were operated by a 240 volts a.c. signal. For their automatic operation, mains control units, similar to the one described in chapter 7, were built and operated by the micro-computer under the instruction from a software specifically written to operate and automatically control the whole rig.

8.3.7 Evaporator

In order to determine the kinetics of adsorption under different evaporation rates, cooling load on the evaporator was required to be varied. For this purpose no separate evaporator was used. Instead a

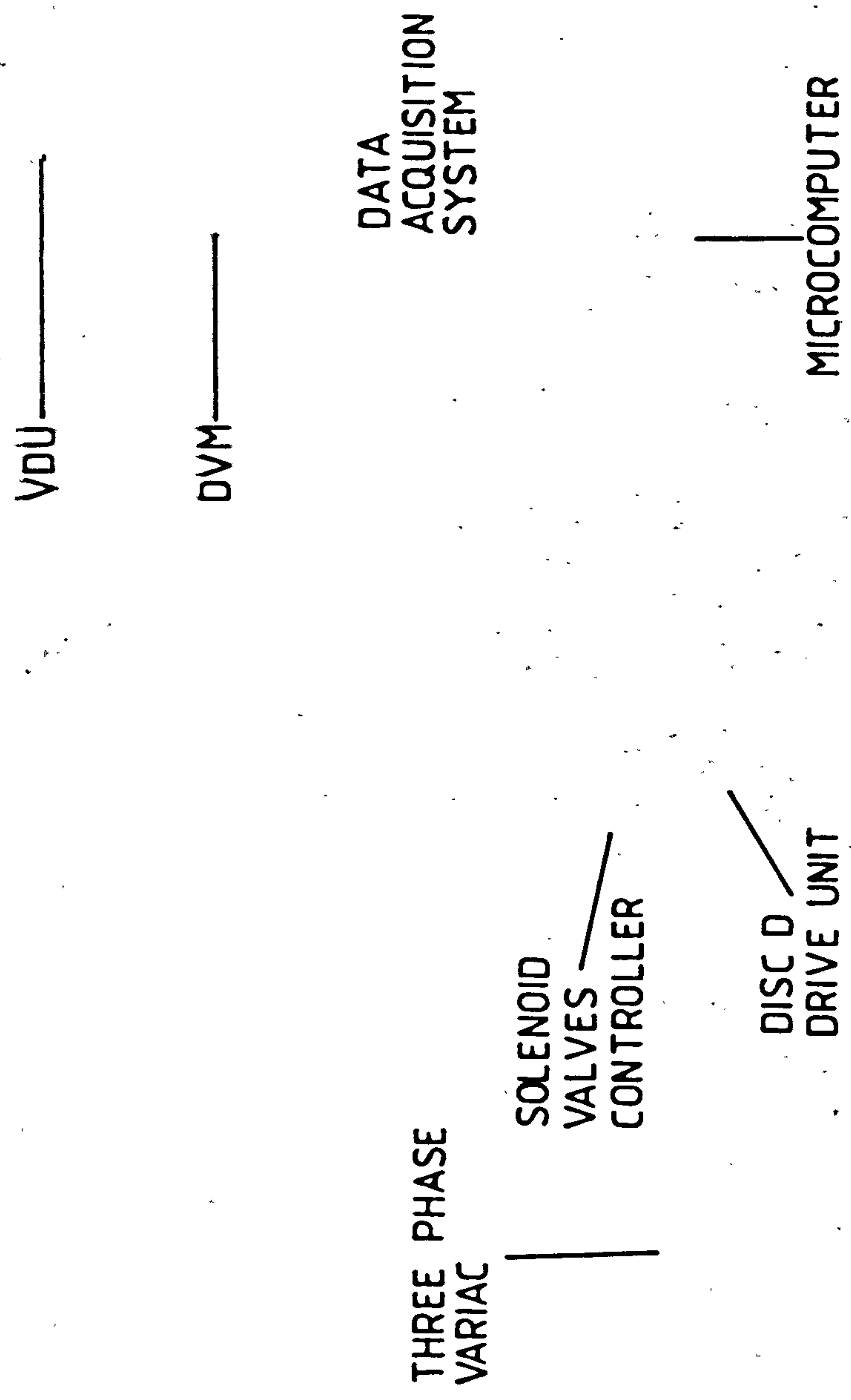
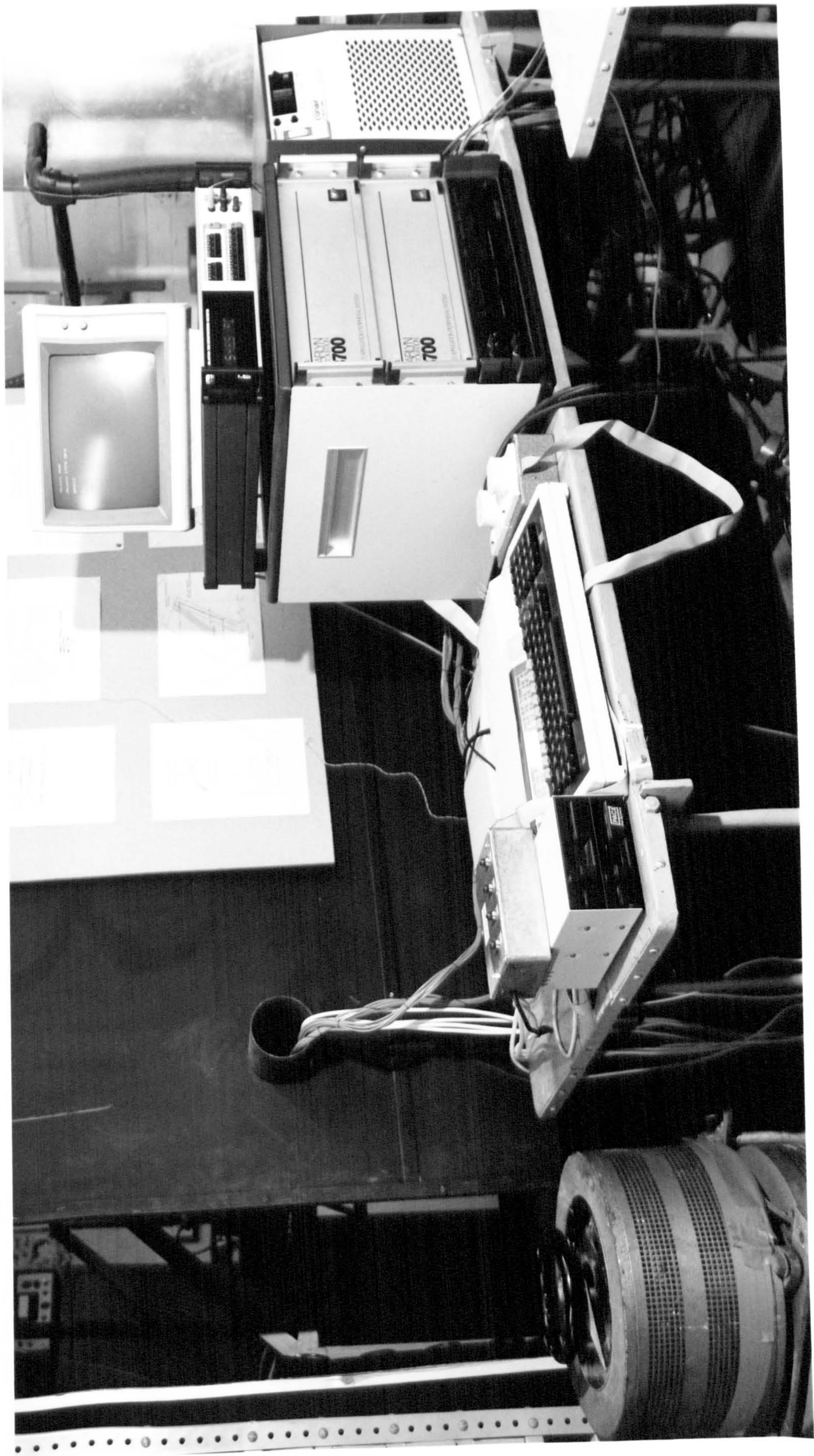


Fig 8.13 Photograph showing different elements of the data acquisition system



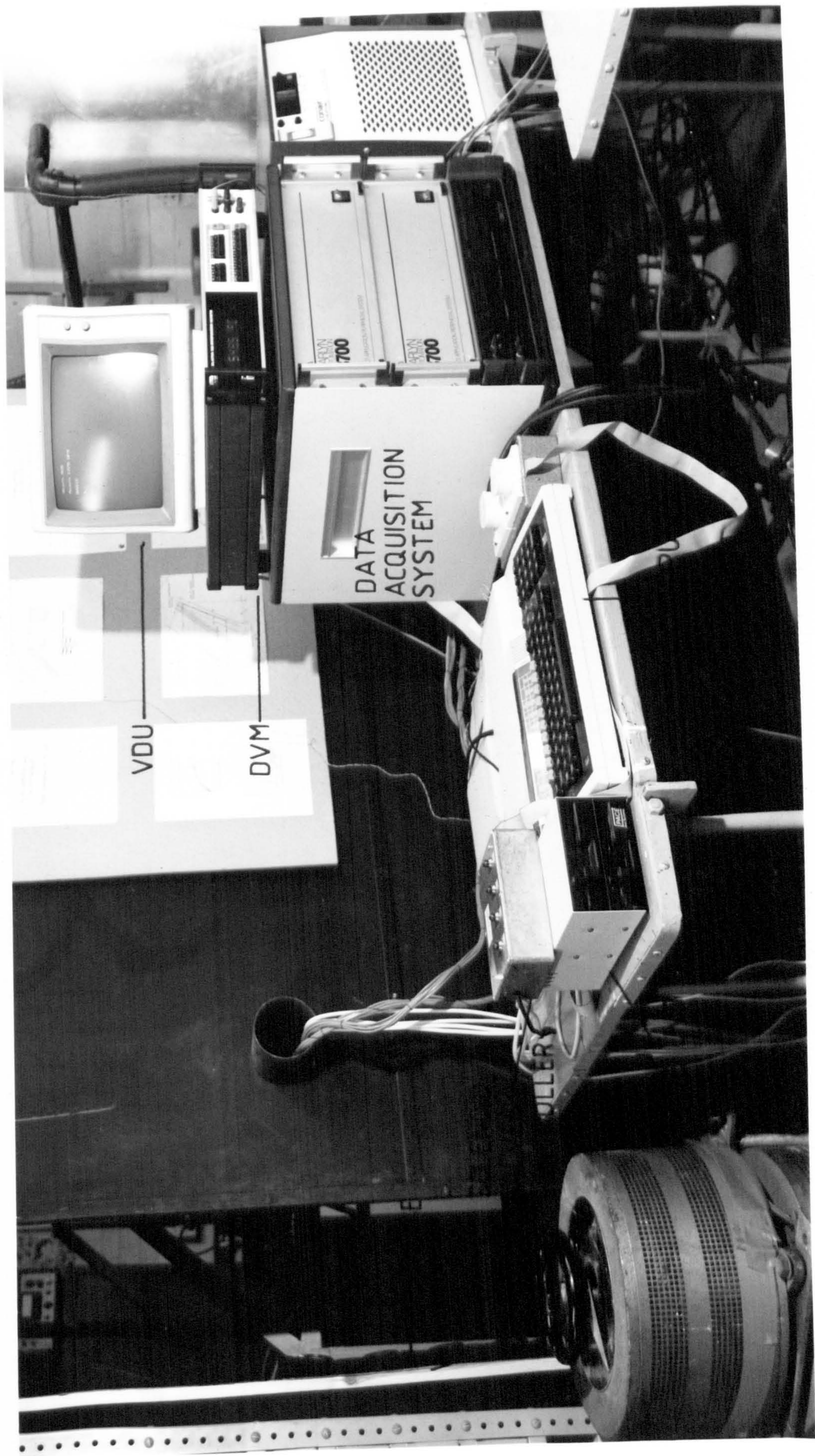


Fig 8.13 Photograph showing different elements of the data acquisition system

heating tape was wound around the storage vessel as shown in fig 8.14. The vessel was then wrapped in a blanket of glass wool and slipped into an outer cylindrical casing as seen in fig 8.15.

The heater power (representing a simulated cooling load) was varied by changing the input voltage through a small variac. An electronic wattmeter was connected to the supply line to the heater in order to measure the simulated cooling load on the evaporator.

8.4 Instrumentation

Pressure and temperature were the two main properties to be measured at various locations in the experimental rig.

8.4.1 Pressure measurement

Equilibrium pressure of methanol in the SGA was measured and recorded. Two vacuum transducers, one fixed to either SGA, were used for this purpose. Transducer fixed on SGA no. 1 was that used on the other rig described in chapter 7. Second one was similar to that and showed very similar characteristics. Reader may see chapter 7 for a detailed description of the transducers.

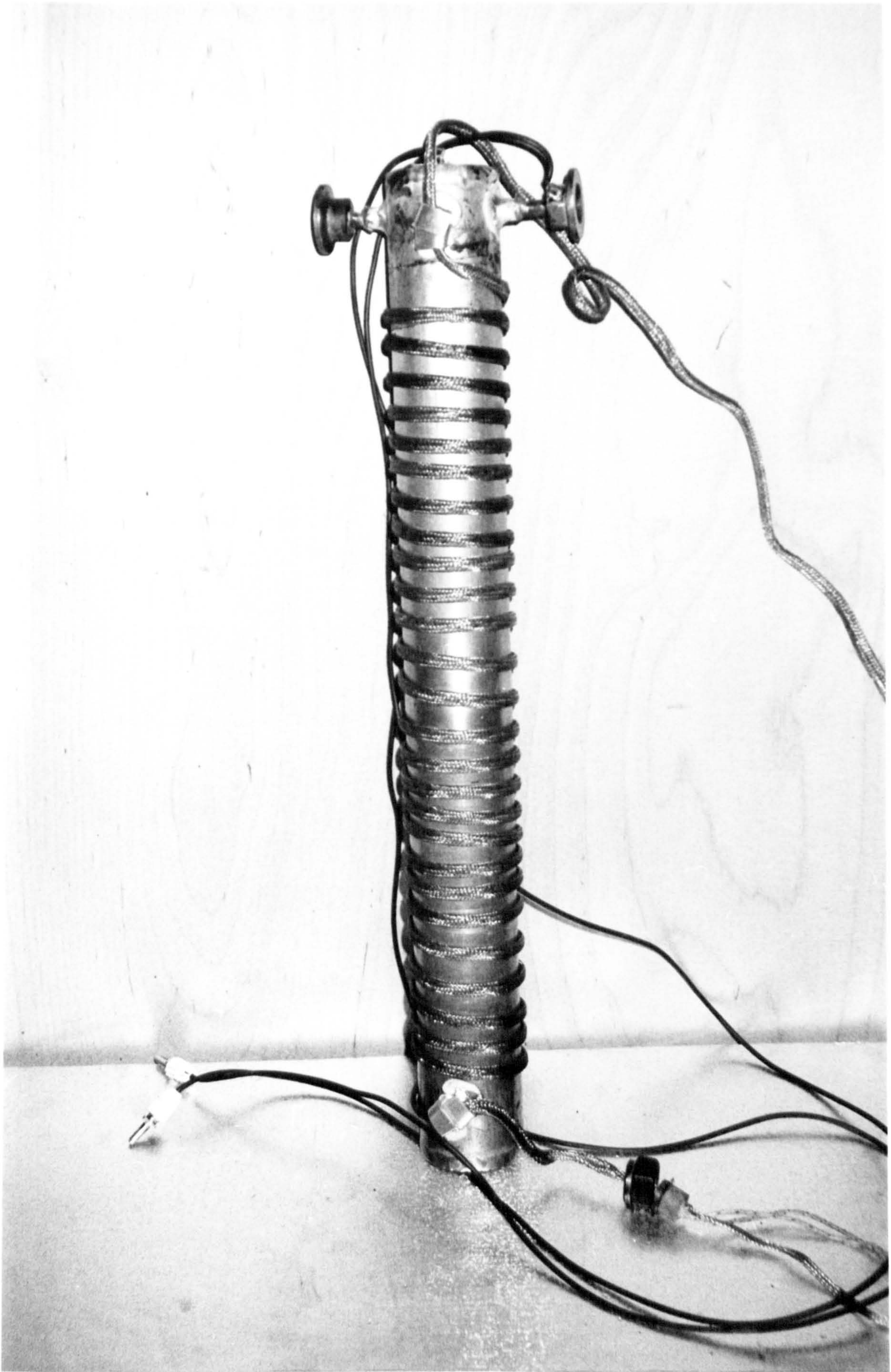
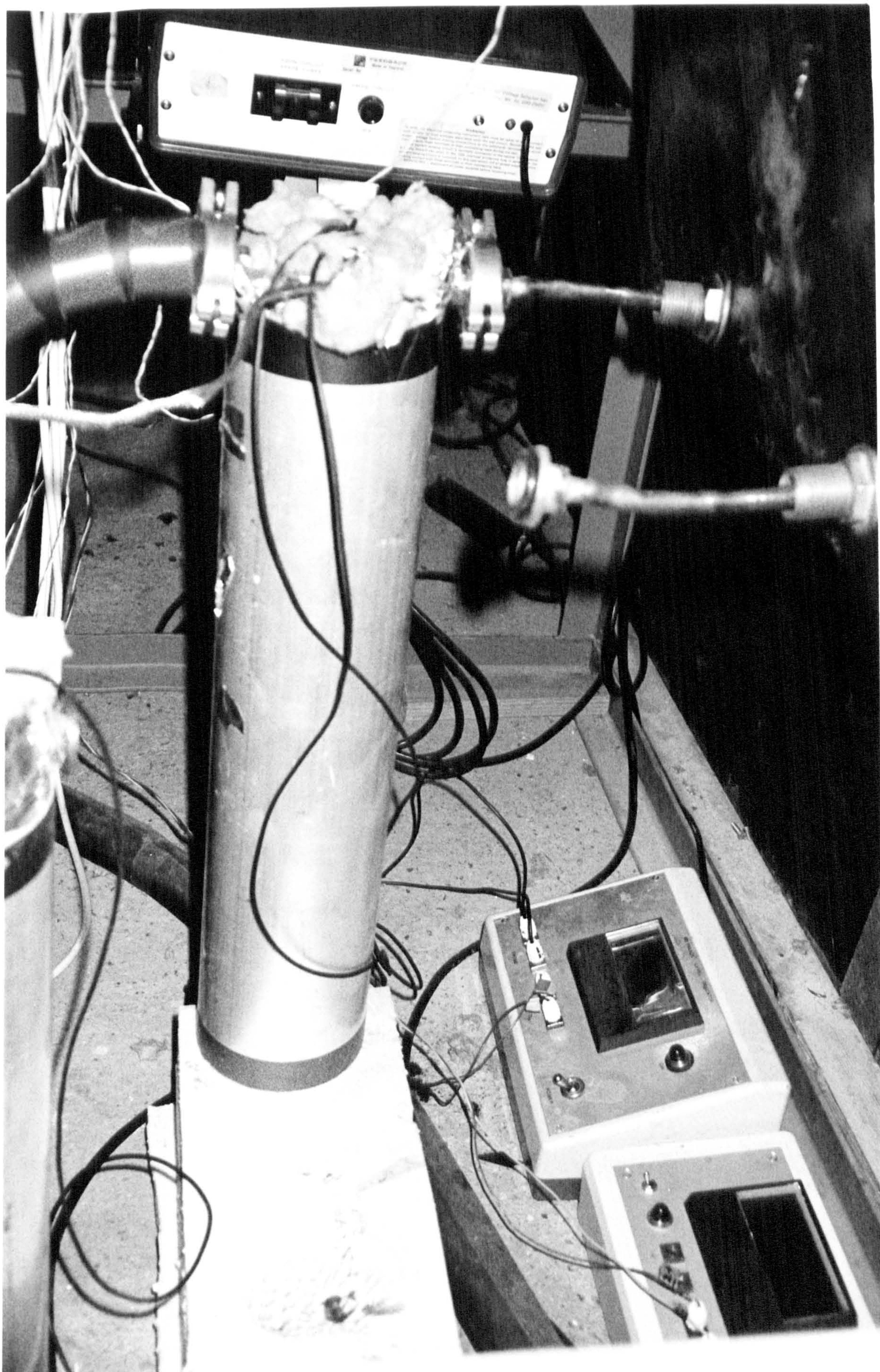


Fig 8.14 Photograph showing the heating tape wound around the methanol storage vessel to simulate cooling load

— METHANOL
STORAGE
VESSEL

INDICATOR
UNIT —

Fig 8.15 Photograph of insulated methanol storage vessel



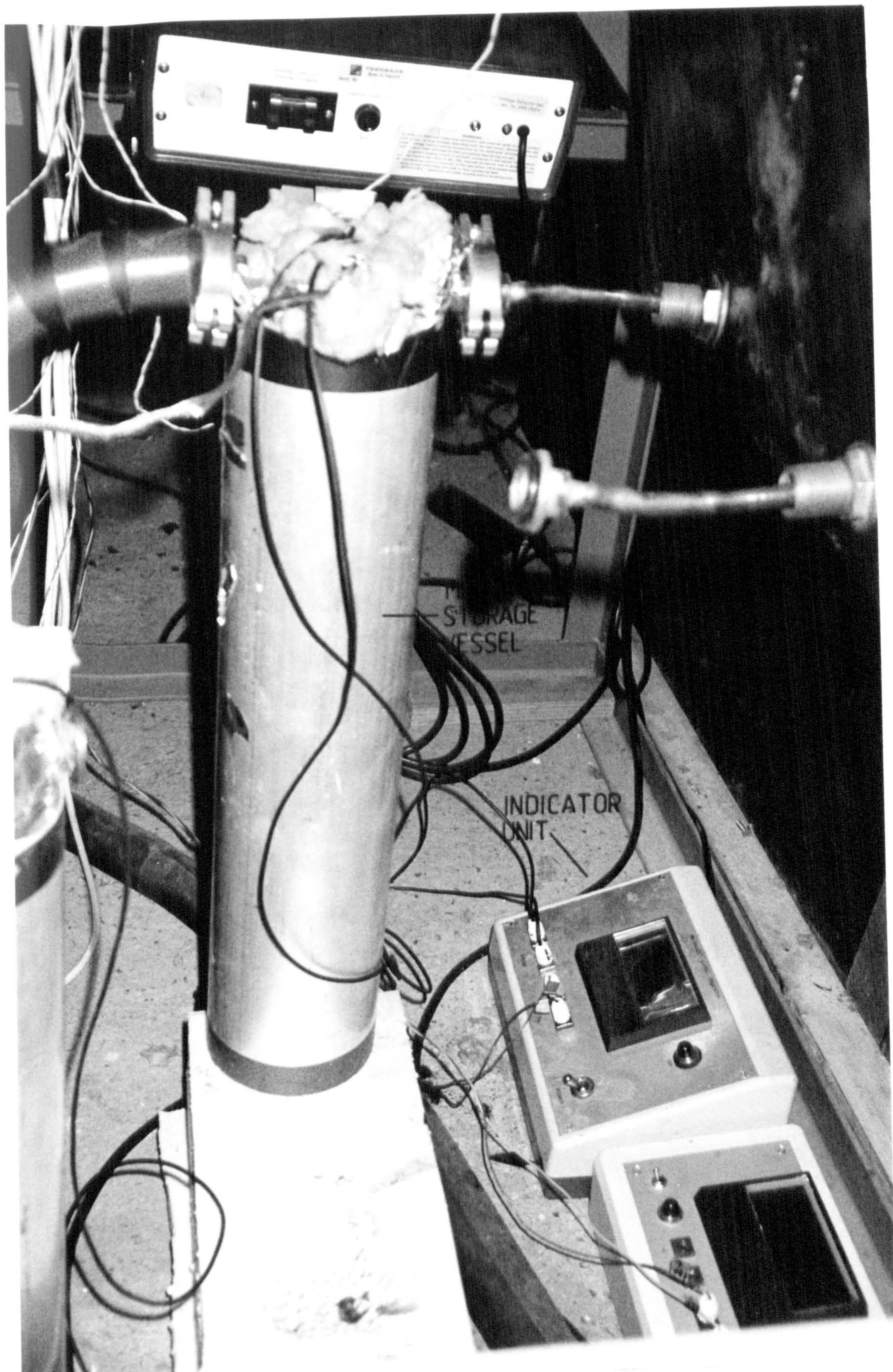


Fig 8.15 Photograph of insulated methanol storage vessel

8.4.2-Temperature-measurement

Teflon sheathed type 'T' thermocouples were used for the measurement of temperature. For thermocouple connections inside the sealed SGA a multipin connector was used. A special housing with an 'O'ring seal was welded at the back of the SGA (see fig 8.16) and a retaining plate held the multipin connector against the 'O'ring to prevent any leaks. Short lengths of the thermocouple wires were soldered to the pins on the inner side. Thermocouple extension leads, connected to the pins from outside, carried the signals to the data acquisition system.

Activated carbon bed was made up of granules of size from 2-6 mm. Thermocouple tips were barely 1 mm in diameter and could have stayed in a gap between the granules, giving a false reading. Therefore it was decided to embed the tips into the granules with the help of some thin adhesive (e.g. Loctite Superglue). The granules would remain fixed at the particular location of interest in the fixed bed of activated carbon and thus the measured temperature would be the representative bed temperature at that point.

8.5-Commissioning-of-the-experimental-rig

Activated carbon was outgassed at 300°C for 48 hours and cooled under vacuum. Then it was transferred to the SGA. SGA was then sealed by fixing the glass covers in place. During this transfer operation activated carbon was liable to adsorb some moisture and air. Therefore the solar simulator was switched on its full power and the

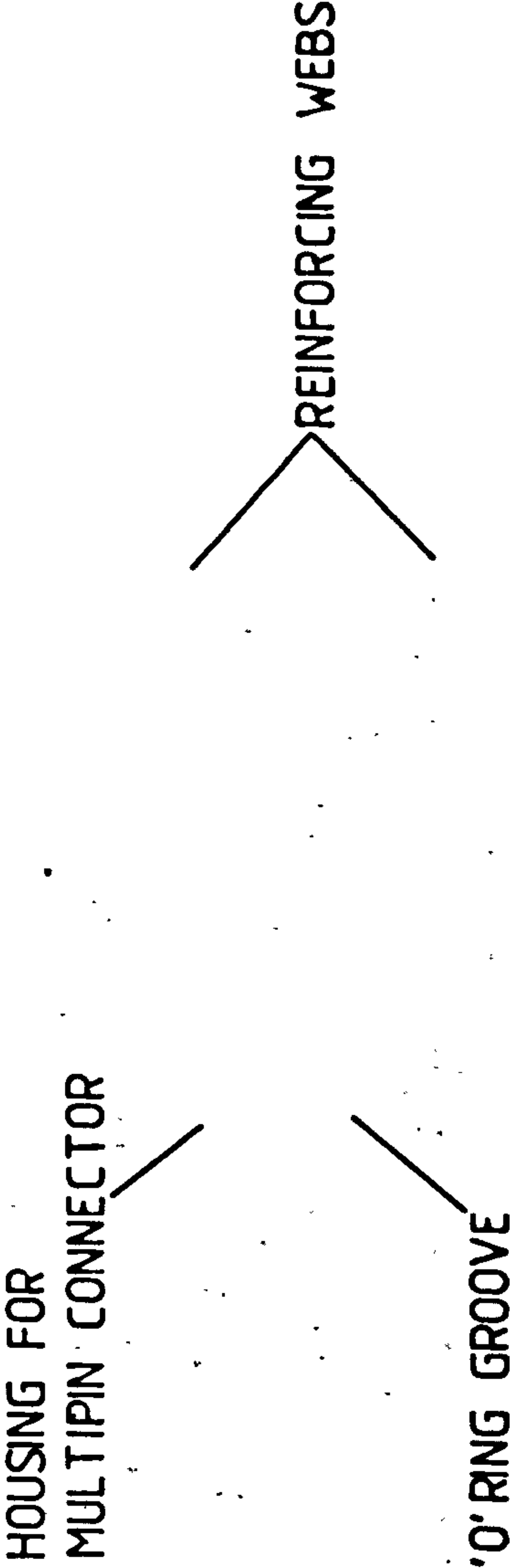
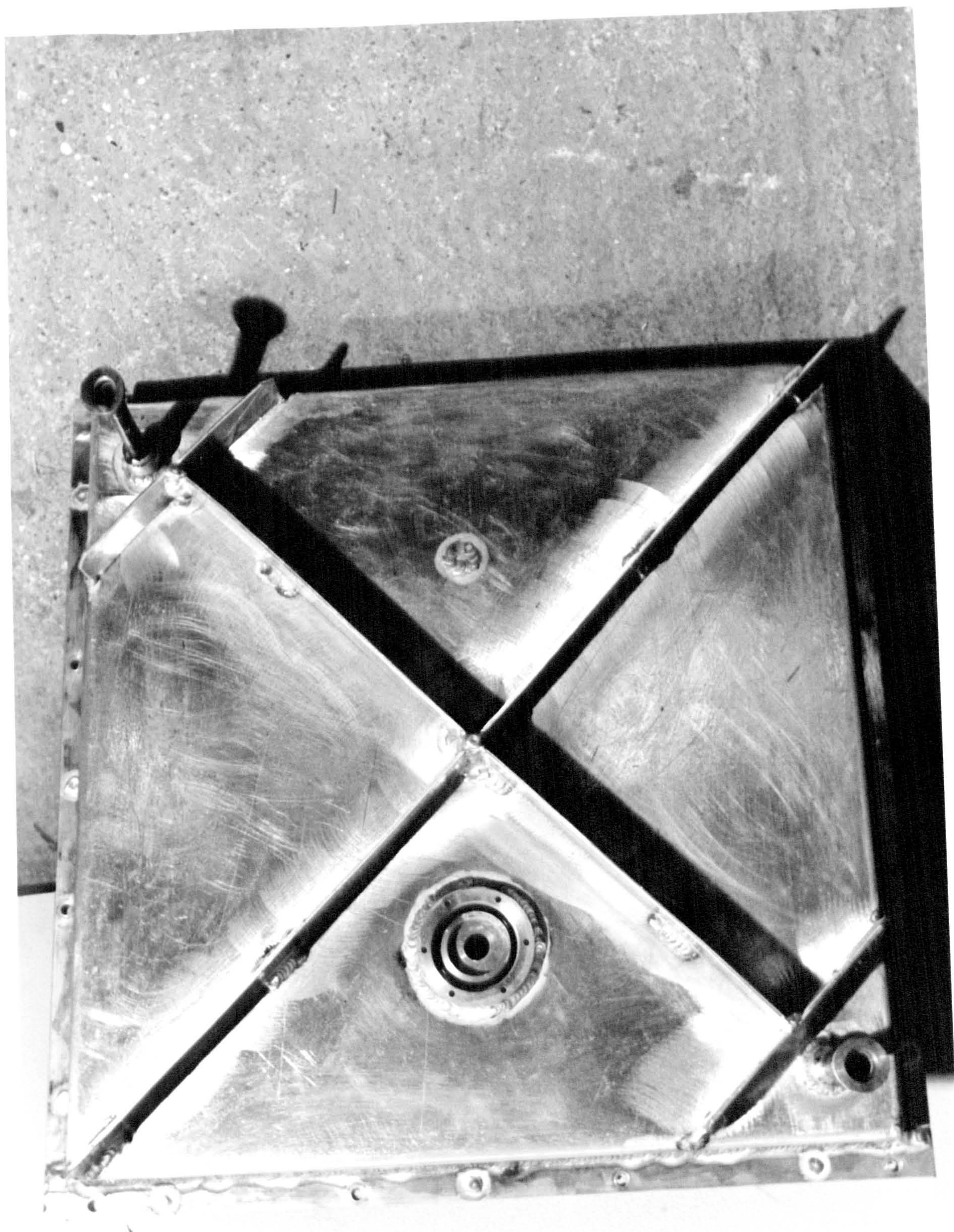


Fig 8.16 Photograph showing the housing for the multipin connector



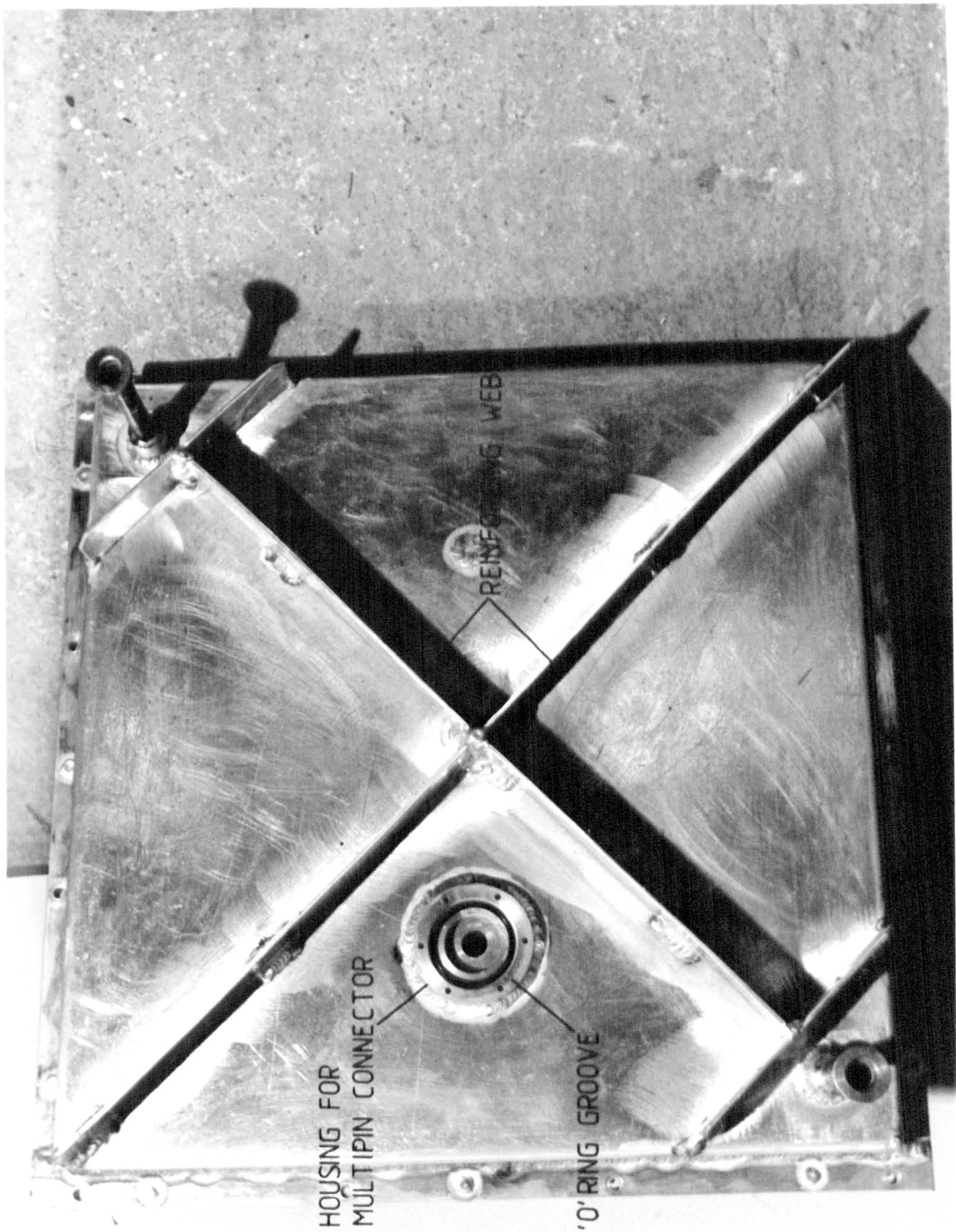


Fig 8.16 Photograph showing the housing for the multipin connector

SGA was kept under constant evacuation. After about 15 minutes the glazing shattered.

After consultation with Pilkington Glass Limited, the manufacturer of the glass sheet, the cause was identified. When the normal float glass sheet is constrained at the ends, it cannot resist a temperature differential of more than 30°C . When the SGA was put under the solar simulator the glass covers were subjected to highly nonuniform intensity of radiation all over its surface. This was bound to create large temperature differentials. The remedy was to use armour plate i.e. toughened glass. Toughened glass sheets of 6 mm thickness could have been used with slight modification in the support design. This would have improved the optical efficiency of the cover system but due to lack of time it was decided to go ahead with 10 mm toughened glass covers.

During the initial outgassing and evacuation of SGA no. 1 (in which the vapour space is under the carbon bed) temperature of the carbon bed and the glass covers was recorded. The results of this test no. 1 are shown in fig 8.17-8.19. It was observed that the temperature of the carbon bed was lower than the glass cover temperature. It was not logically possible as the carbon was directly absorbing the radiative heat from the solar simulator and conducting it to the glass cover. The possible causes included a malfunction of data acquisition system and a local heat junction at the location of thermocouples. After a thorough check of the data acquisition system no reason could be found for such a discrepancy in the measured values. After the check up was complete, another set of results was

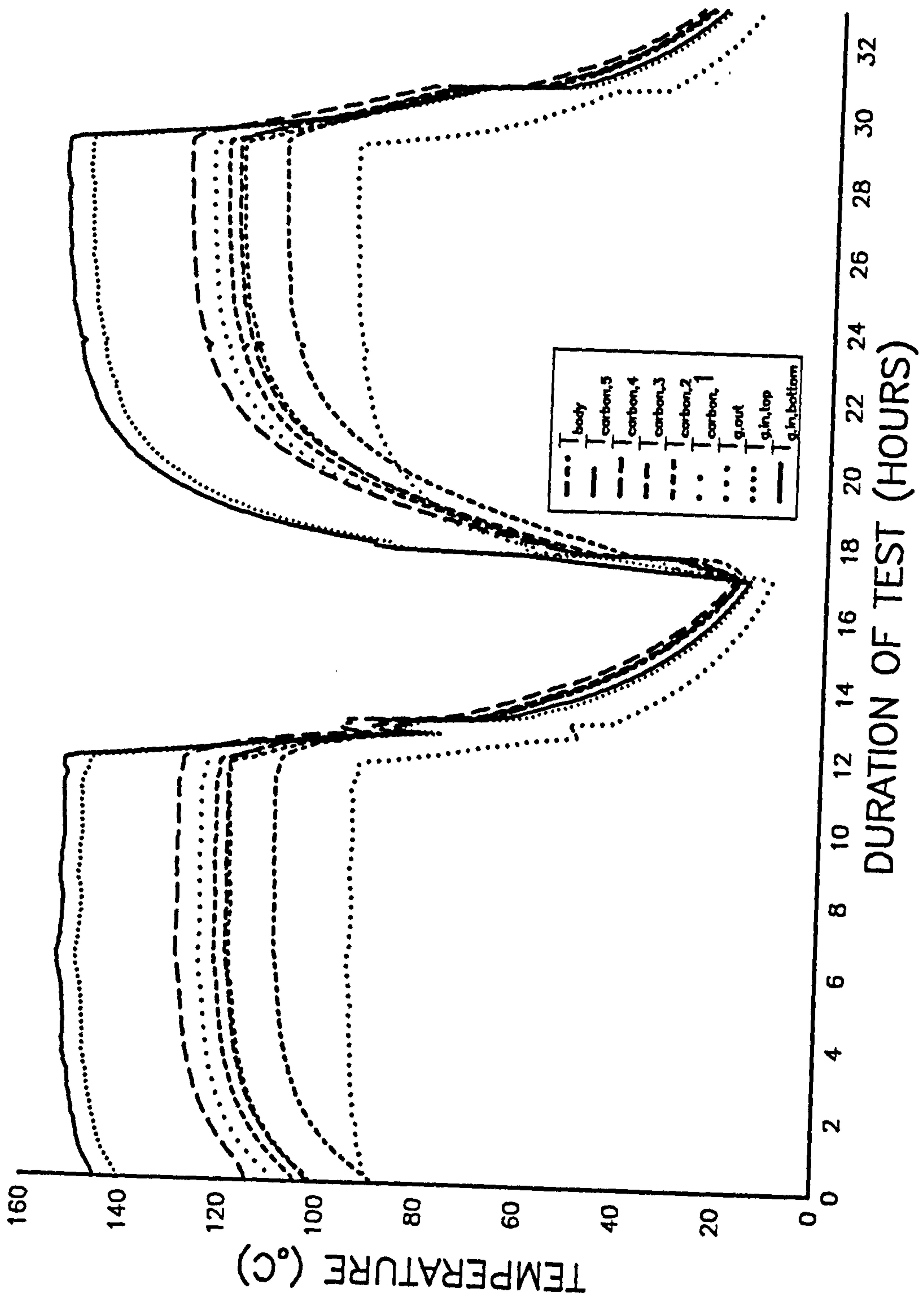


Fig 8.17 Graph showing the erroneous temperatures readings in SGA no. 1 during test no. 1

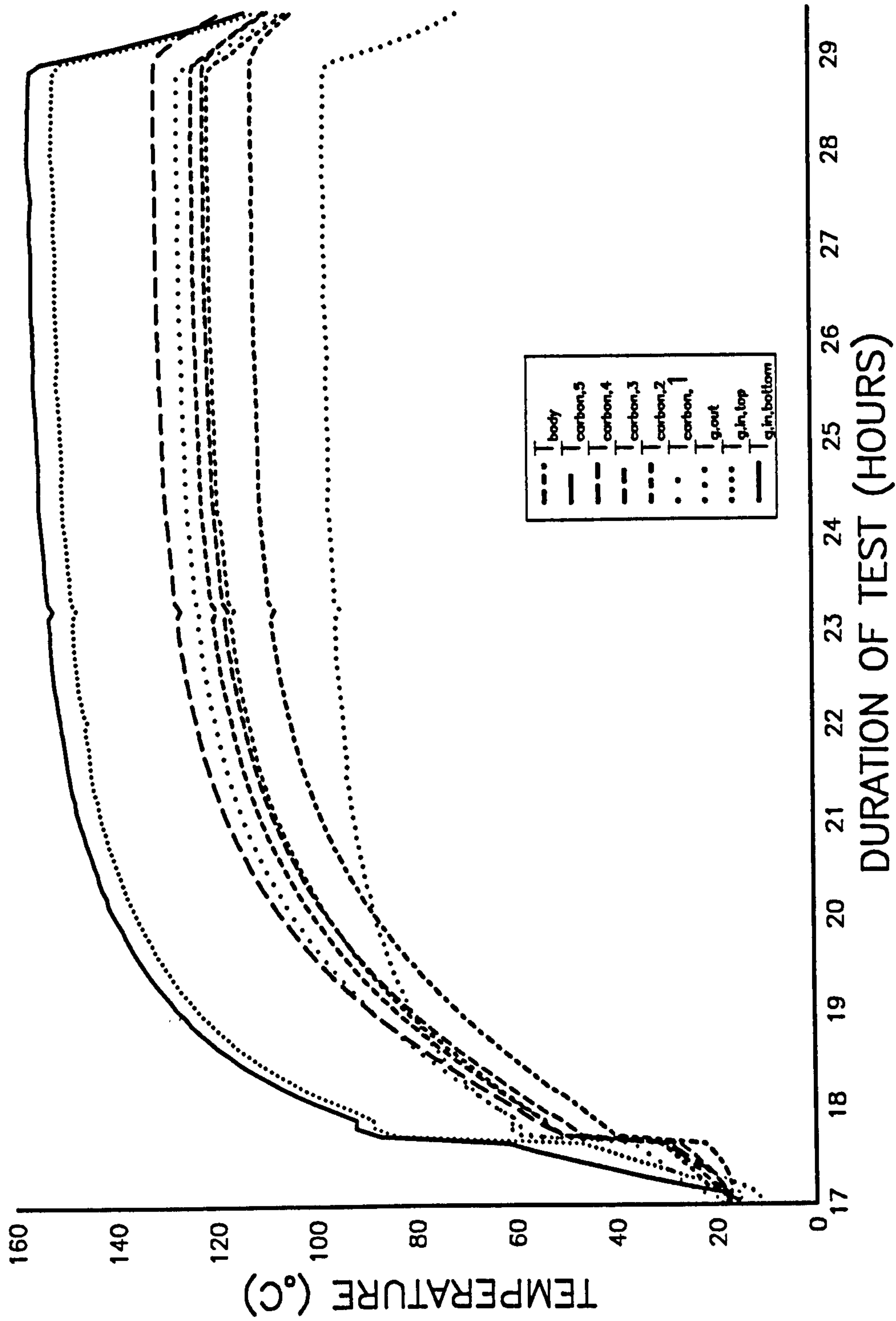


Fig 8.18 Graph showing the heating curve for SGA no. 1 during test no. 1

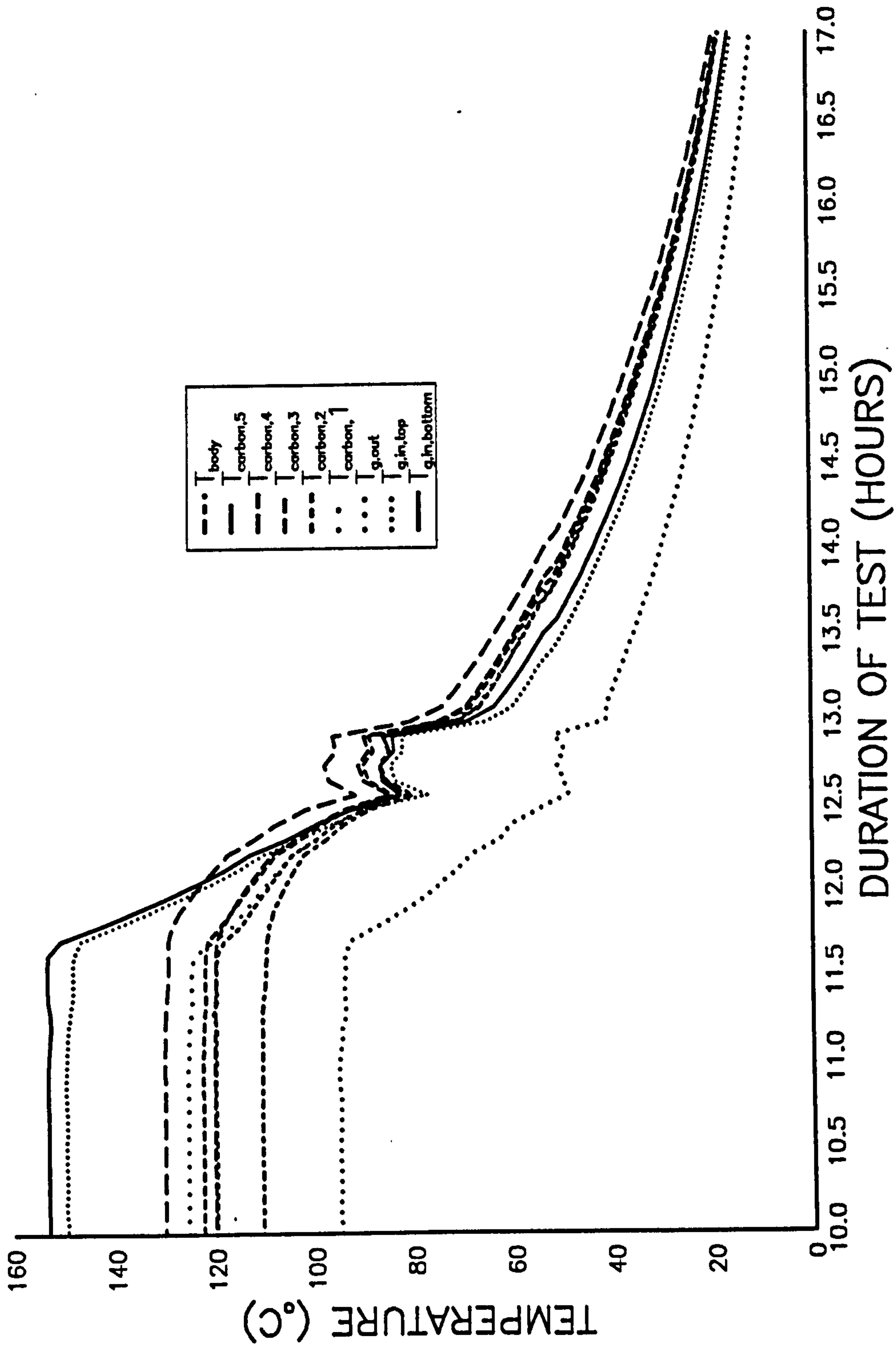


Fig 8.19 Graph showing the cooling of SGA no. 1 during test no. 1

recorded during test no. 2. These results are plotted in fig 8.20 and show no improvement.

Therefore the attention was focussed on the possibility of some local heat junction. The five thermocouples were embeded into the carbon bed near to the central support pillar which was welded to the base of the SGA. This provided a good heat leak passage and reduced the temperature of the surrounding carbon granules. When the thermocouples were moved from the location the problem disappeared. In the subsequent test no. 3 the five thermocouples were placed in the bed away from the pillars as shown in fig 8.21. The results of this test showed that the correct temperature reading had been recorded (see fig 8.22).

The leakage of air into SGA no. 2 could not be remedied for the lack of time. Therefore no test could be conducted on it.

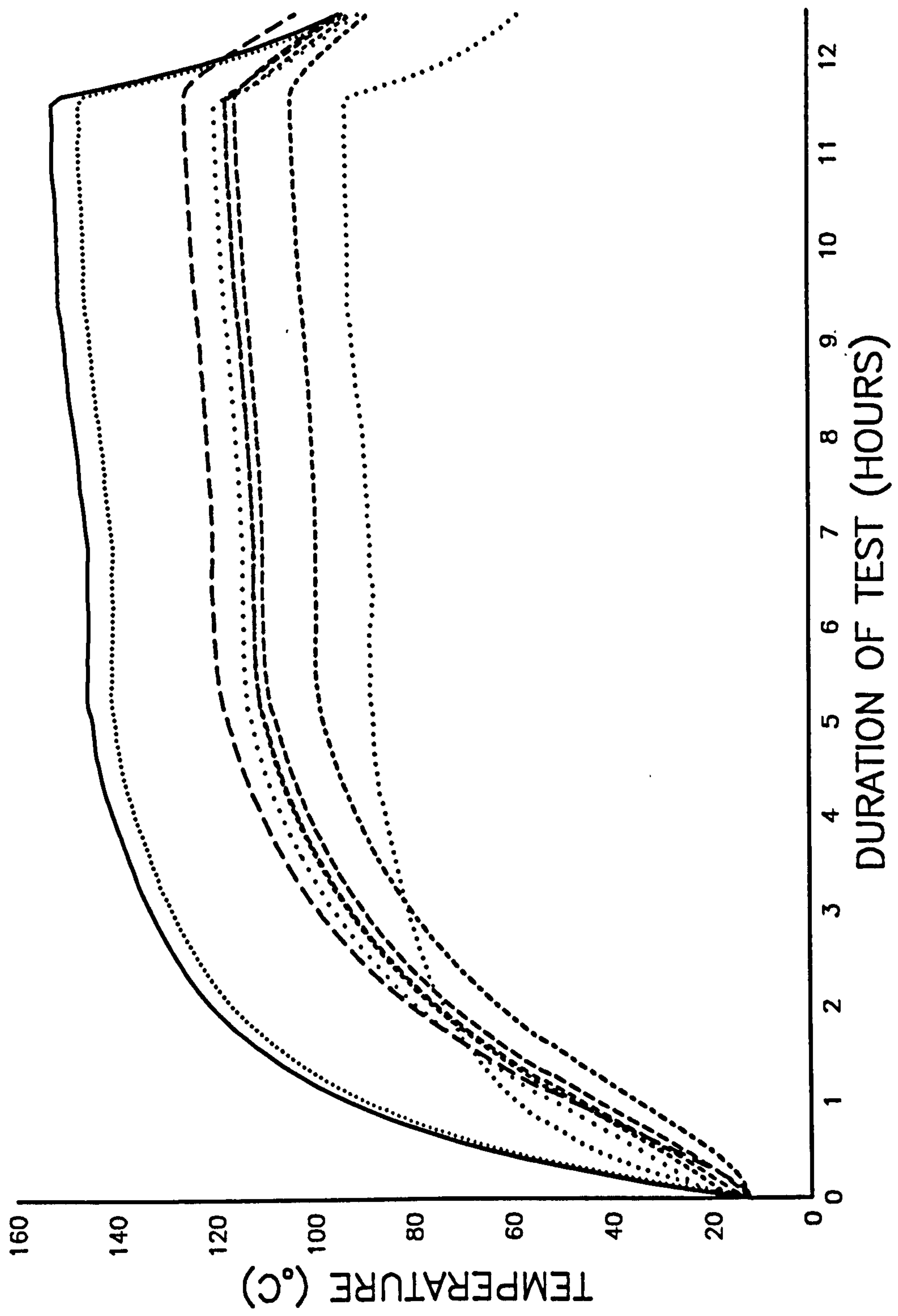


Fig 8.20 Graph showing the error in temperature reading during test no. 2

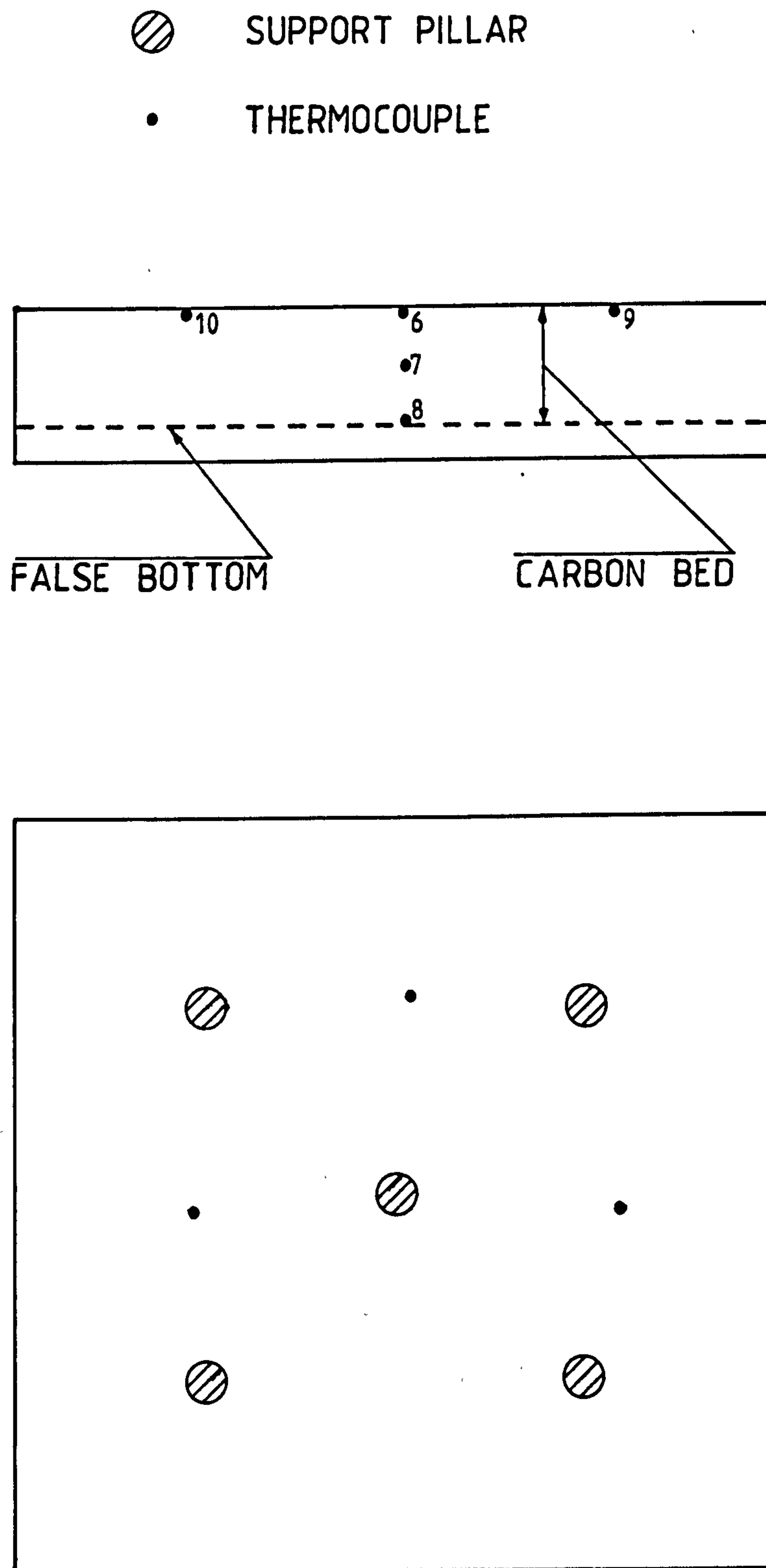


Fig 8.21 Diagram showing the re-location of thermocouples in SGA no. 1

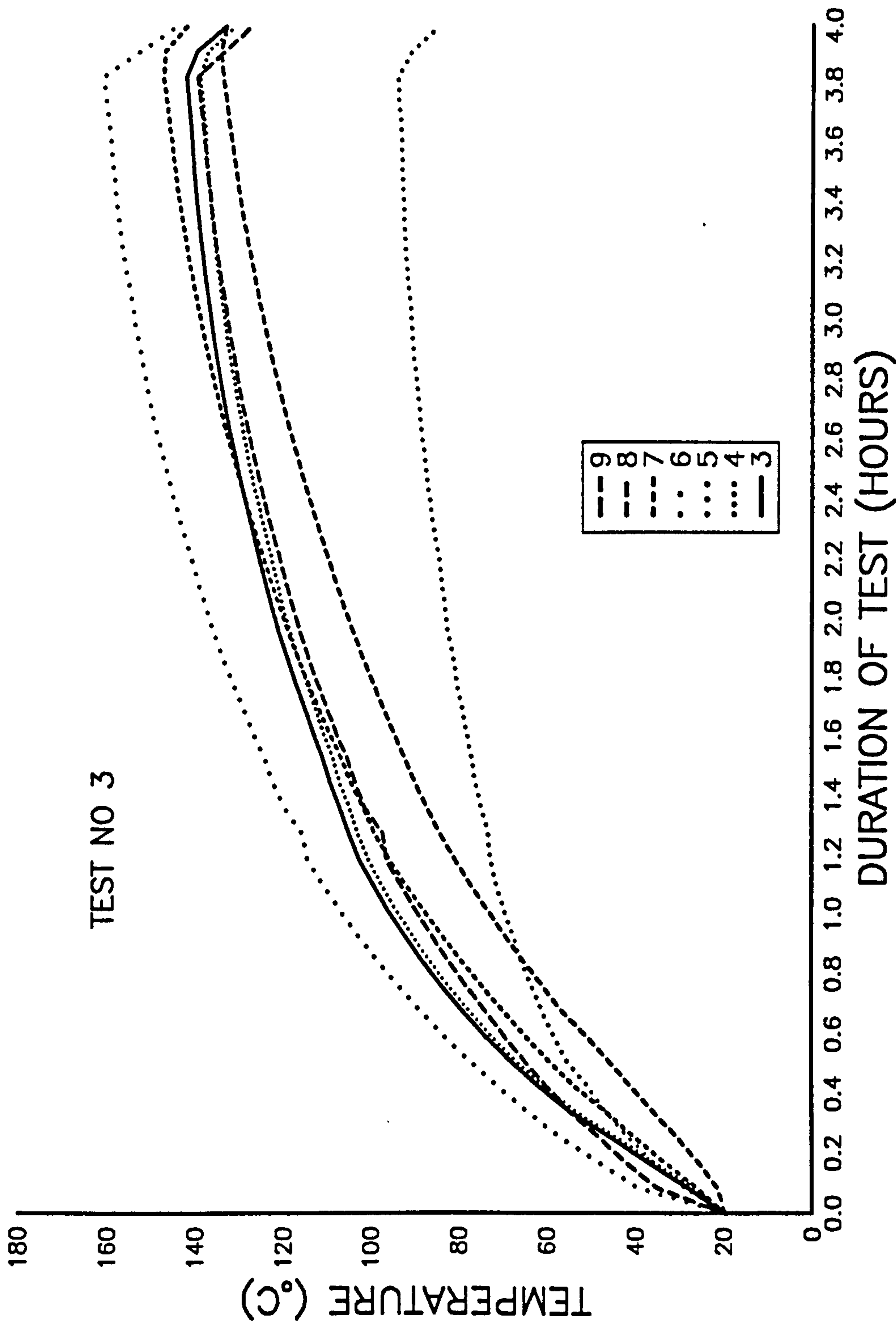


Fig 8.22 Correct temperature distribution recorded after re-location of thermocouples in SGA no. 1

8.6-Discussion-of-the-test-results-from-SGA-no: 1

The experimentation rig work very well. All the instrumentation performed satisfactorily except the methanol level indicator. During calibration the minimum quantity of methanol introduced into the vessel was 50 ml. Because of the approximate fit of the polynomial and the rounding off error (introduced during the internal calculation procedures by the micro computer), the indicator measured a volume of 7.5 ml when the vessel was empty. It was also found during experimentation that the indicator had not followed the calibration curve and showed a negative volume below 10 ml level. The data acquisition equipment failed to work properly during many test periods. Therefore either the data could not be recorded or the data recorded was erroneous in some tests. Complete set of test results are presented in graphical form in appendix J. Some of the typical results are discussed in the following paragraphs.

The SGA contained 4.5 kg of activated carbon-208C and 1.125 kg of methanol was introduced into it on 7.6.89. The first cycle started on 9.6.89. The results of the generation period of this first cycle are presented in fig 8.23. The test was conducted under an ambient temperature of 22°C and an average radiation of 600 Wm^{-2} reaching the carbon bed. At 20°C equilibrium pressure of methanol should be 22 mbar. The pressure curve (1) indicated an initial pressure of 25 mbar which was within the error limits of the instrument. The pressure rose to 200 mbar during the first 0.93 hours of the test when it steadied for about 0.09 hours and then started rising again. At the condenser temperature of 18°C methanol should have started

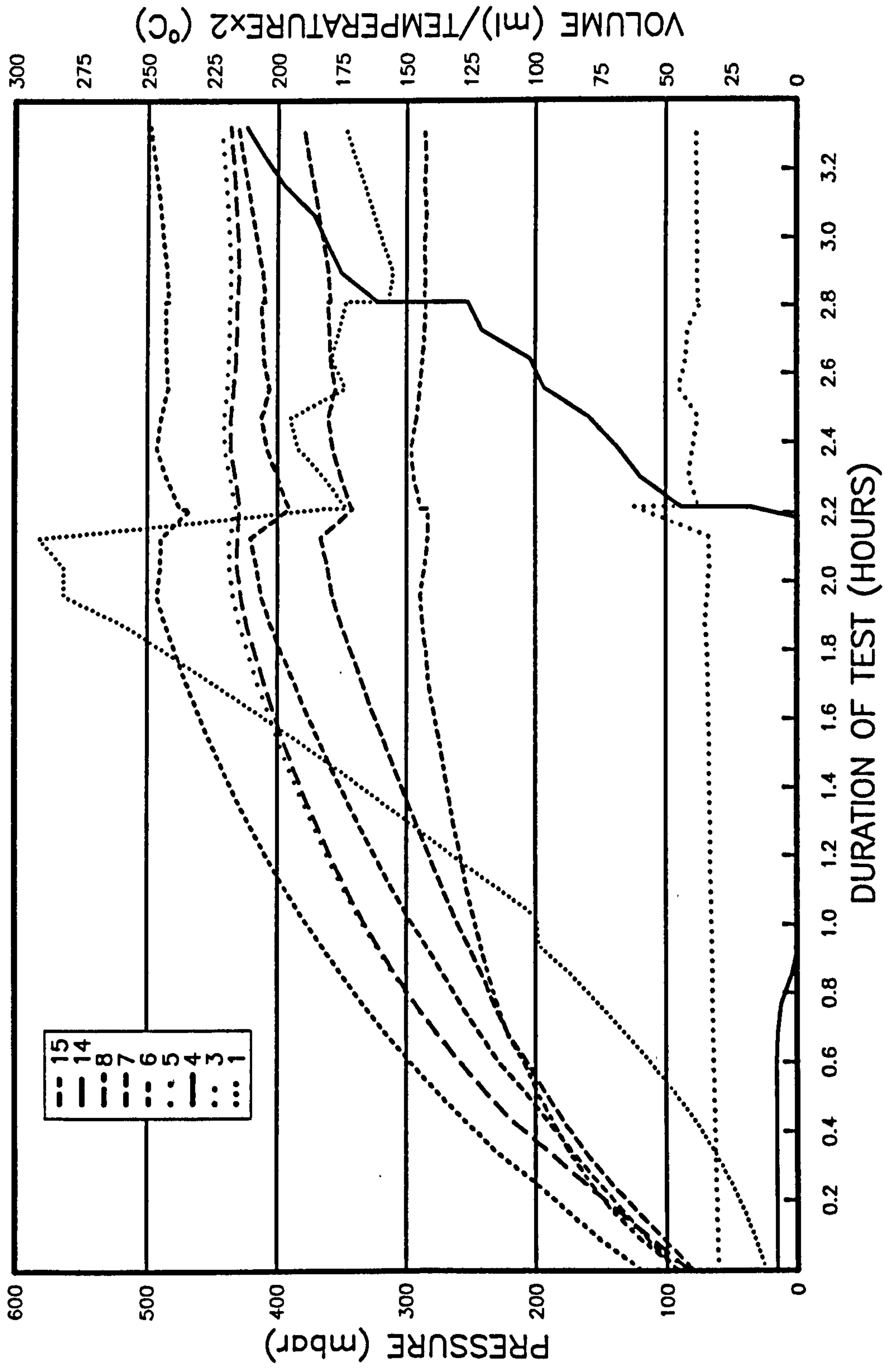


Fig 8.23 Desorption test on 9.6.89. at an average radiation of 600 Wm^{-2}
reaching the activated carbon surface

condensing at below 200 mbar pressure. The process started, as indicated by methanol volume curve (4), at 0.8 hours and the desorbed volume remained below 10 ml level up to 2.2 hours. During this period pressure rose to about 580 mbar. This was a clear indication that condensation was not taking place. This could have happened because of accumulation of some leaked air into the condenser.

To remove the accumulated air from the condenser, it was evacuated at 2.7 hours. The pressure inside the SGA dropped to about 350 mbar and a large amount of methanol condensed. Fig 8.23 indicate that the condenser temperature (curve 3) rose to 32°C during the process. The activated carbon bed temperature (curves 6, 7 & 8) also dropped by about 8°C because of the heat absorbed by the desorption process. The process of removing the air leaked into the system had to be repeated for three times as indicated by the pressure curve and after about 3.3 hours 215 ml of methanol were available in the storage vessel. The SGA was then allowed to cool and adsorb back the condensed methanol. During the adsorption period data acquisition system failed and therefore no results could be recorded.

To stop the ingress of air into the SGA, more silicon sealant was sprayed around the rubber seal and other joints. The second test was done 4 days later on 13.6.89 when the data acquisition system started working again. The results of this test are shown in fig 8.24. Sixty ml of condensed methanol was still in the storage vessel at the start of the generation period. The carbon bed received an average radiation of 506 Wm⁻². The methanol concentration in the bed

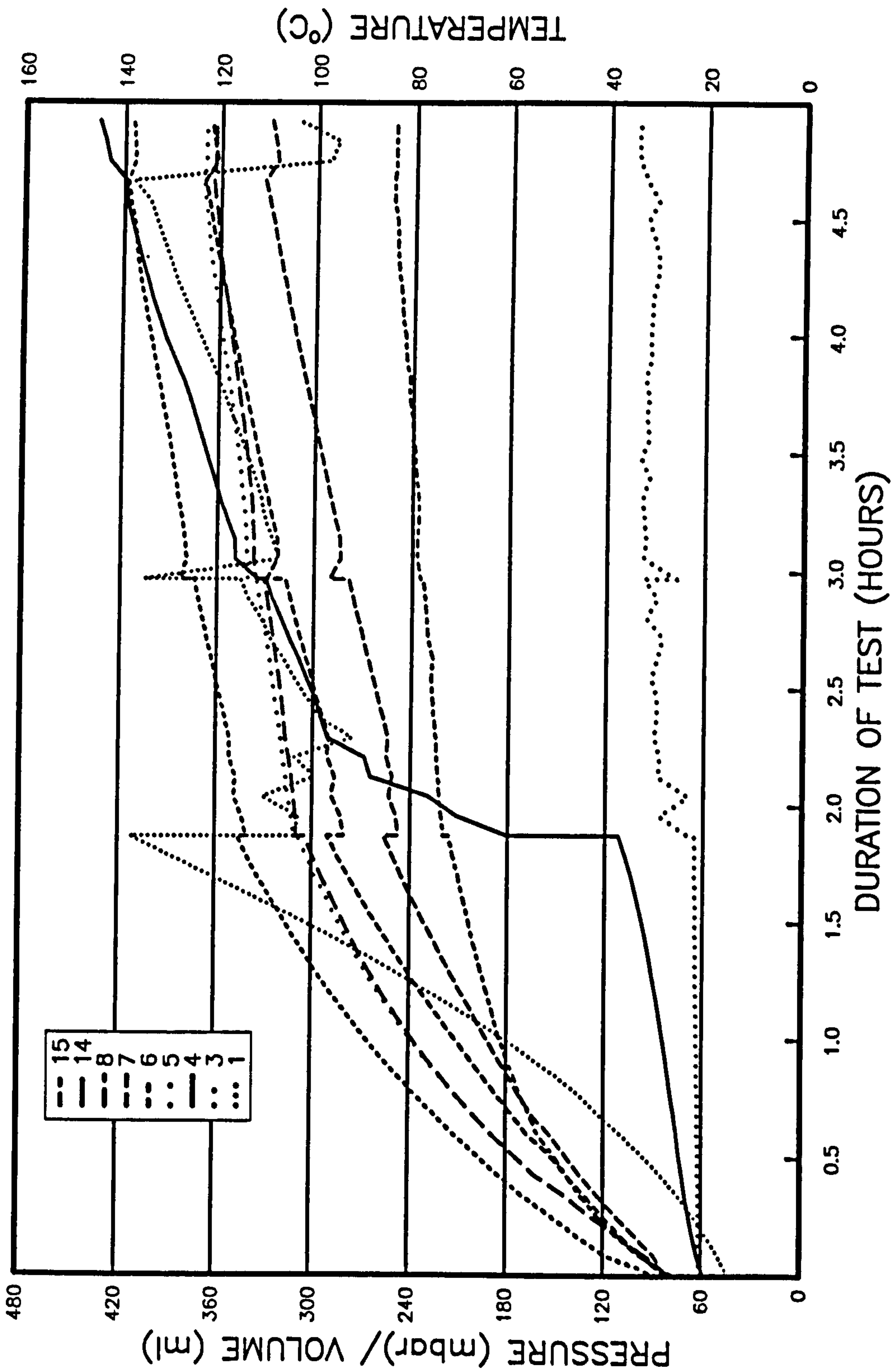


Fig 8.24 Desorption test on 13.6.89. at an average radition of 506 Wm^{-2} reaching the activated carbon surface

was 24% and at equilibrium temperature of 28°C the pressure should have been around 35 mbar. The initial equilibrium pressure within the SGA was 46 mbar which indicate that air had ingressed into the SGA. This was confirmed by continuous rise in the pressure during generation period to more than 400 mbar.

After about 1.8 hours the accumulated air was removed from the condenser by evacuation and the desorption process accelerated. The process of evacuation was repeated for four times and after about 5 hours of heating 440 ml of methanol condensed into the storage vessel. The results of 4 more generation tests, which are shown in appendix J, all indicate that air had been constantly leaking into the system. Therefore the results were not useful for any quantitative analysis.

The results pertaining to the adsorption period indicated that heat transfer from the bed took place through a temperature difference of 16°C when the SGA was double glazed (see fig 8.25) which reduced to 11°C when there was only one cover on it (see fig 8.26). This is a reasonable temperature differential for an air-cooled adsorber and can be improved further by exposing the insulated body of the SGA during adsorption process.

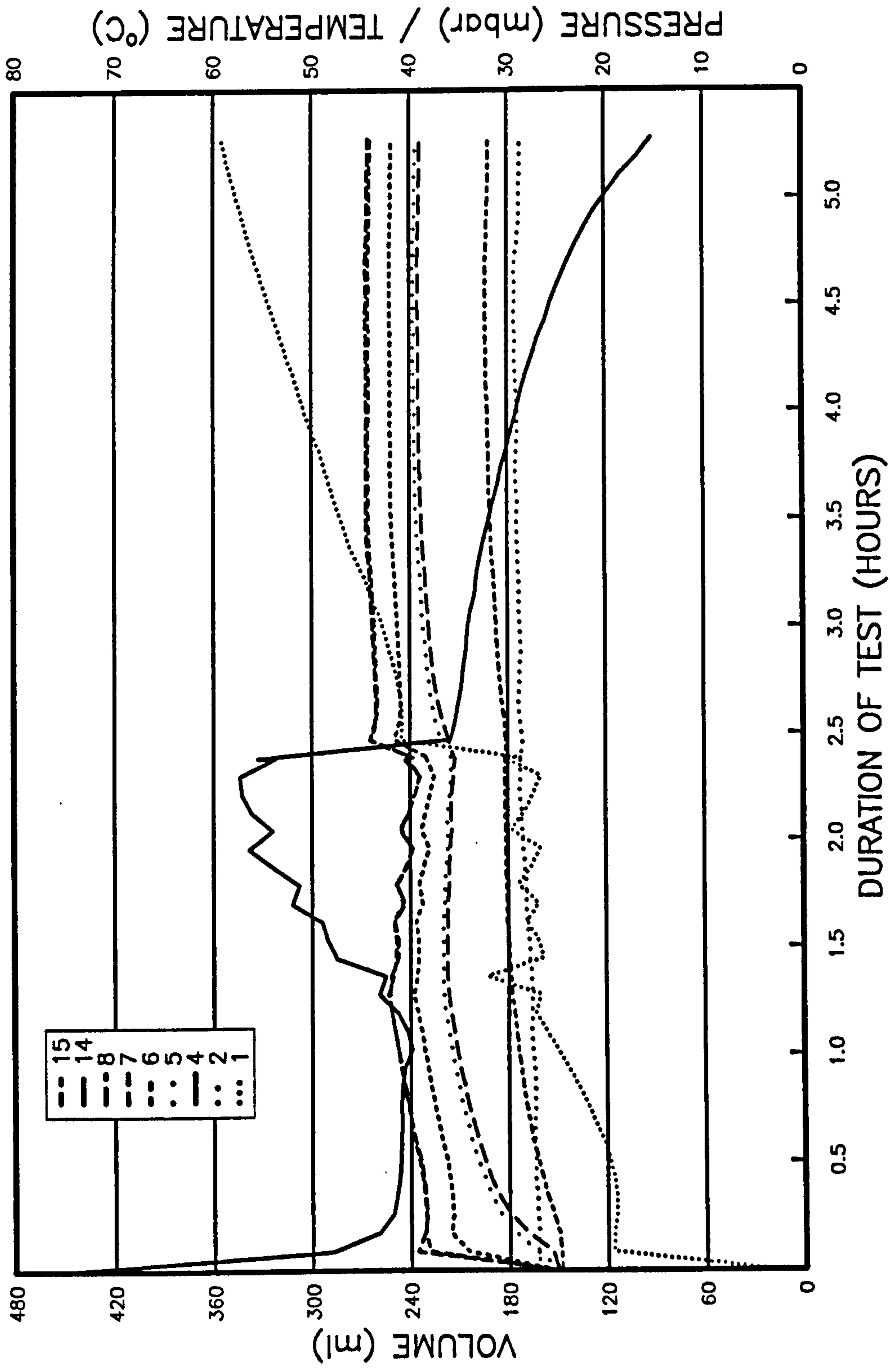


Fig 8.25 Adsorption test on 14.6.89. at 20 W cooling load and double glazing

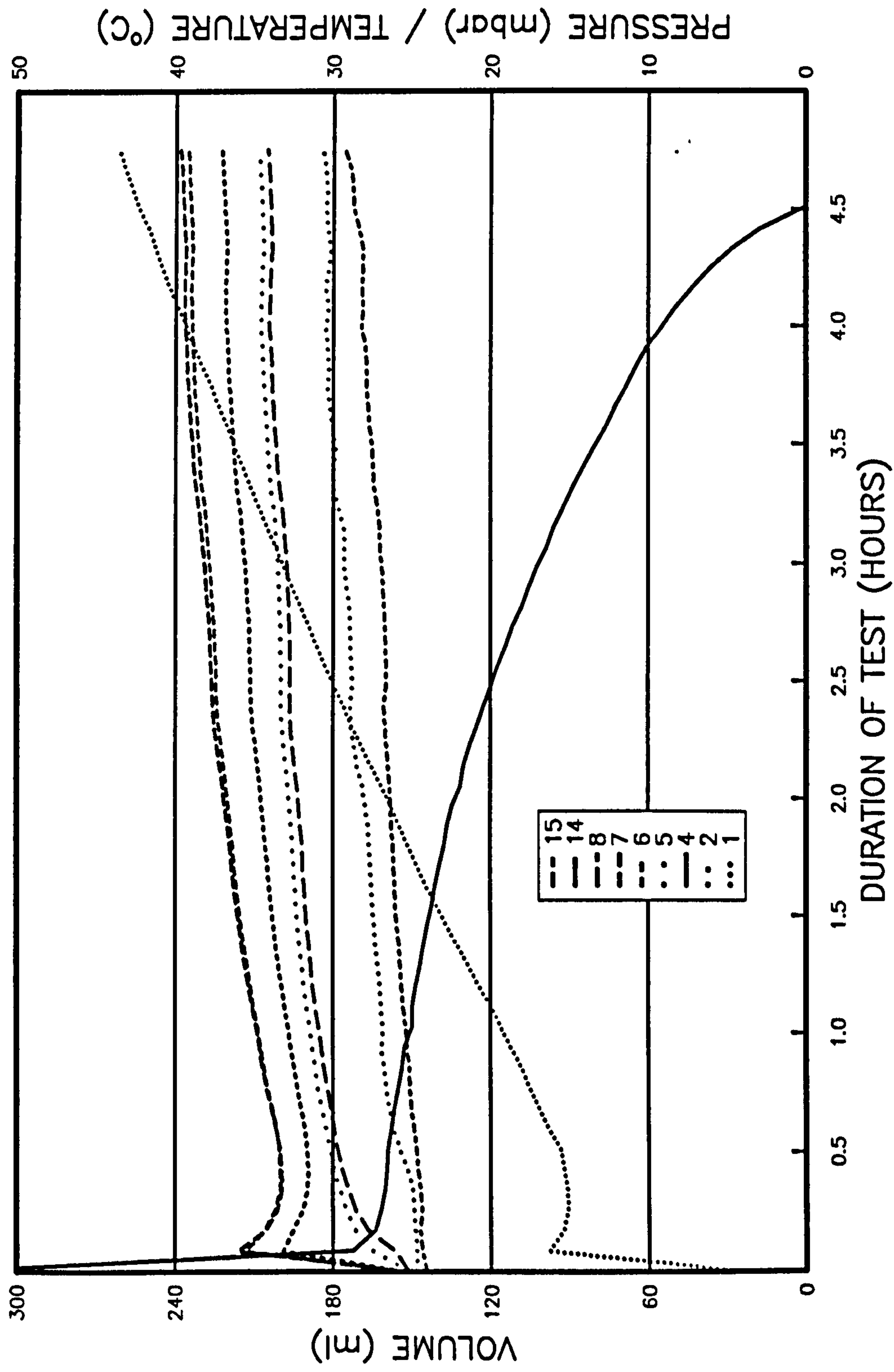


Fig 8.26 Adsorption test on 20.6.89. at 20 W cooling load and single glazing

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CHAPTER NINE

Conclusions and Recommendations

9.1 Conclusions

Three different options for building a solar operated vaccine store had been evaluated. These included a household vapour compression refrigerator operated by the photovoltaic power, an 'Electrolux' absorption refrigerator driven by the heat collected by evacuated tube heat pipe collectors and the intermittent solid sorption refrigerators. Energy from the sun vary in its magnitude by the time of the day, the time of the year and the geographical location. This uncertainty makes it difficult to design a universally applicable design of solar appliances, especially, the solar refrigerators whose performance vary greatly with ambient conditions.

Non of the options considered truly met the suitability criteria developed in chapter five. The technology of photovoltaic vapour compression refrigerators is the most developed at present. It provides a very flexible way of producing cold from the heat of the sun. But it has its drawbacks as well. These include high initial capital cost, recurring capital expenditure, regular maintenance, failure of electronic circuitry and requirement of high technology for the production of PV-arrays. Although there is no easy answer to the question of technology transfer, yet some measures, suggested in the next section, can reduce the size of the PV-array and eliminate the need for battery storage. These measures are hoped to reduce the initial and recurring capital cost and improve reliability.

The solar operation of 'Electrolux' refrigerator was not possible with the present day technology under the WHO/EPI specified

conditions. The generation temperature has to be high (more than what can be achieved through flat plate collectors) to meet the specifications. It was proposed that if the burners of kerosene fueled refrigerators were modified to burn biogas and the gas made available in the areas then it could prove to be a cheaper option.

Solid absorption refrigerators suffered from swelling and eventual compacting of the absorbents which demanded special processing of the absorbents. It did not occur in solid adsorbents which made them more attractive. Activated carbon/methanol pair was found to show the best COP and was chosen for further investigations.

Absorbing solar energy directly into the activated carbon bed was new and novel. The particular flat plate design adopted, in which an insulated metal container held the activated carbon and its top was sealed with a glass cover to let the solar radiation be absorbed directly by the carbon bed, did not prove wholly successful. Nevertheless the merits of the proposal over the conventional design were proven. The all-glass construction of the SGA as a flat plate or tubular design was proposed to overcome the drawbacks of the design.

9.2 Recommendations for future work

There is no option for a solar operated vaccine store which can be favoured outright. There are merits and drawbacks in every option considered. In this section few proposals are made to improve the design and make the options more attractive and practical.

9.2.1 Photovoltaic refrigerators

There is a need to take measures in the way of reducing initial and eliminating recurring capital expenditure.

It is proposed that work should be carried out on the design of an ice-lined refrigerating cabinet. The ice store will replace the battery storage, as the need for the refrigerator to work during the night will be eliminated. This will consequently reduce (i) the size of the array (ii) simplify the electronic circuitry required and (iii) help reduce the initial and eliminate the recurring capital cost.

9.2.2 The 'Electrolux' type refrigerators

Kerosene fueled 'Electrolux' (or diffusion absorption) type refrigerators has been in use in areas where electricity is not available. Their use in EPI faced two major problems. The first one was that the supply of kerosene in the remote areas of developing countries, most of which import oil, was not reliable. The other problem was of unreliable burner design which was aggravated further by the contaminated oil supplies. The refrigerators are, otherwise, very rugged, reliable and cheap. Therefore if these refrigerators can be fueled by a local supply of biogas, which can be produced from organic waste with the help of solar energy, they can prove to be a reliable and cheap vaccine store.

It is proposed that the EPI can coordinate with the general development programs in the area to pave the way for the building of biogas plants. The gas can be used for cooking and lighting purposes as well. The 'Electrolux' type refrigerators equipped with reliable gas burners can then be used in EPI clinics to store the vaccines and there will not be any need for heat or cold storage. This type of vaccine stores can prove to be the cheapest.

9.2.3 Adsorption refrigerators

Activated carbon/methanol adsorption refrigerator can be very rugged, simple and reliable. Based on the experimental work described in chapter eight the following is proposed.

A tubular construction for the SGA is proposed which will utilize the existing technology of evacuated tube collectors. Activated carbon will be filled in a double walled glass tube. The annulus between both the tubes will be evacuated to reduce energy losses. Each tube in a module will be coupled to a common manifold. An elaborate design is shown in fig 9.1-9.2 and described below.

An outer envelope of 100 mm outside diameter is proposed. The inner glass tube of 80 mm diameter will hold the activated carbon and is proposed to be longer in length than the outer tube. A 15 mm dia thin and perforated copper tube is placed eccentrically within the

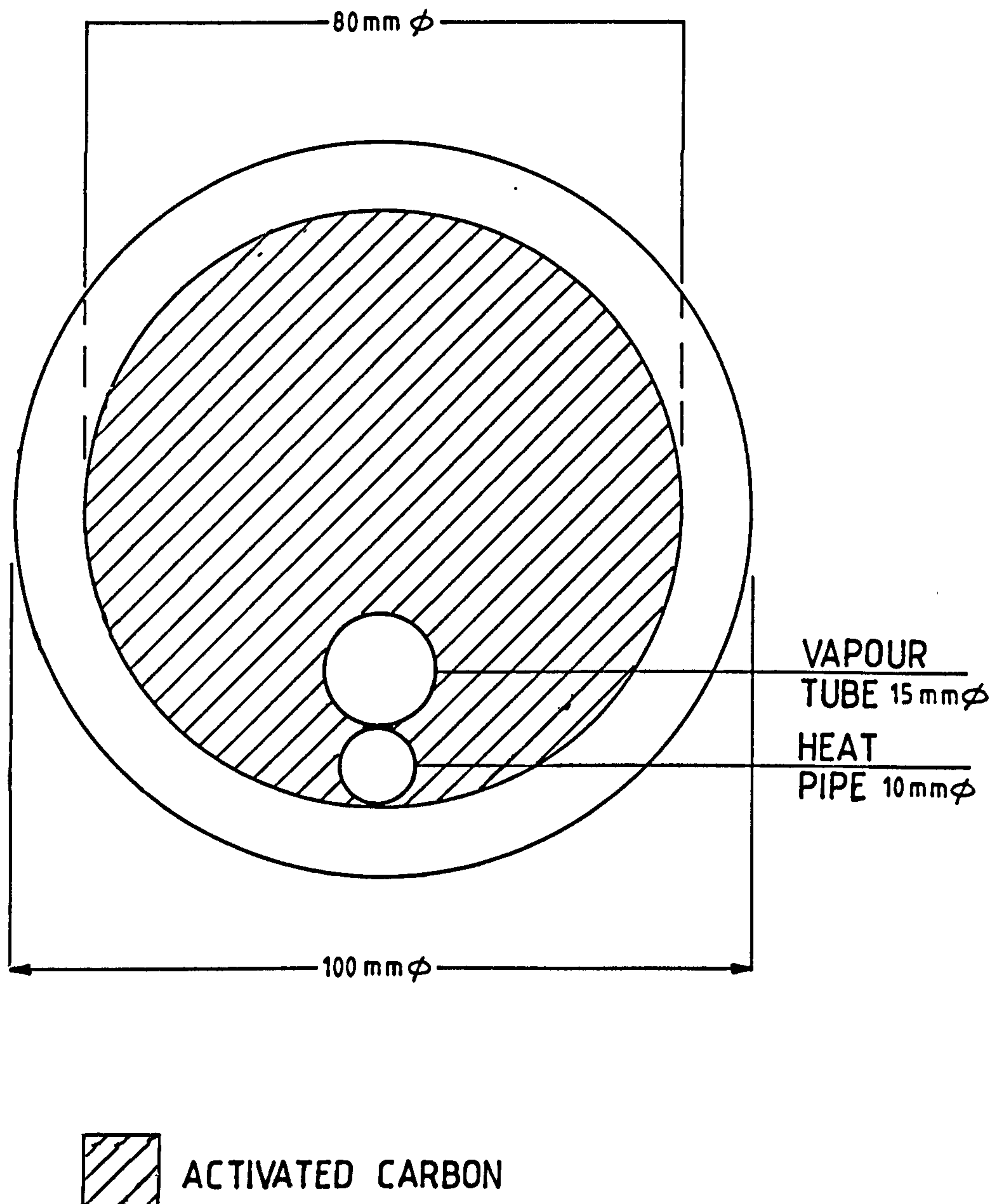


Fig 9.1 Drawing of the evacuated tube for the proposed SGA

carbon bed to facilitate the flow and distribution of methanol vapours. A 10 mm dia heat-pipe is attached to the vapour tube to conduct the heat of adsorption away from the carbon bed. The perforated tube acts as a fin for the heat-pipe. The condensers of the heat pipes are all fixed to rows of rectangular fins for heat dissipation to the ambient.

There is only one metal-to-glass joint at the top end of the inner tube. The open bottom end of the inner tube is connected to a metal manifold which has fins on its surface and will act as the condenser for the refrigeration unit. The actual dimensions of the manifold and other components, and the number of tubes in the module will vary according to the required capacity.

The heat pipes should be designed in such a way that they reach dry out condition at temperatures of more than 60°C . This is necessary to eliminate the possibility of them conducting the heat away during desorption period.

This proposed design has the advantage of directly absorbing the solar radiation into the carbon bed. As the vacuum seal is required around a small length, i.e. the girth of the tube neck, it is, therefore, expected not to suffer from any leaks.

APPENDIX A

HEAT REMOVAL FROM A SOLAR-ENERGY COLLECTOR WITH A HEAT-PIPE ABSORBER

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Abstract—Charts are derived and presented which facilitate the design of solar-energy collectors with heat-pipe absorbers for efficient harnessing of heat.

INTRODUCTION

High-temperature solar thermal applications often employ a solar-energy collector in which an evacuated envelope surrounds a heat-pipe absorber. There are many commercial designs available. A mathematical model for predicting the behaviour of such a collector, under the envisaged operating conditions, is helpful when selecting which particular type to adopt. Such models have been developed by Kamminga [1] who employed a heat balance for the collector and by Hull [2, 3] who undertook a detailed analysis of the problem.

The heat-transfer processes within the heat pipe cannot be simply simulated mathematically. Inside the condenser and the evaporator, the heat transfer phenomena are especially complicated. The system considered here consists of a single fin-and-tube heat-pipe absorber within an evacuated glass sheath. The fin-plate has a selective surface and the condenser of the heat-pipe transfers heat to the fluid via a manifold (see Fig. 1). A simple mathematical model has been developed to study the effects on performance of variations of heat-transfer areas and coefficients of the condenser and the evaporator.

ANALYSIS

Figure 2 shows a simplified resistance network for a heat-pipe solar-energy collector. The rate of radiative heat loss is low (because of the use of selective surfaces

in such collectors) compared with the rate of convective heat loss. The steady-state rate of useful heat gained by the solar-energy collector plate can then be represented by the equation [4]:

$$\dot{Q}_u = A_c [I(\tau\alpha)_{eff} - U_L(T_c - T_a)]. \quad (1)$$

The steady-state rate of heat transfer from collector plate to the fluid within heat pipe can be represented by the equation:

$$\dot{Q}_{c,h} = h_c A_c (T_c - T_h). \quad (2)$$

Assuming $\dot{Q}_u$ equals $\dot{Q}_{c,h}$ and eliminating T_c from equations (1) and (2) we get:

$$\dot{Q}_{c,h} = \frac{h_c/U_L}{h_c/U_L + 1} A_c [I(\tau\alpha)_{eff} - U_L(T_h - T_a)]. \quad (3)$$

The steady-state of heat transfer taking place between the heat pipe fluid and the manifold fluid can be represented by the following equation:

$$\dot{Q}_{h,m} = h_{hm} A_{hm} (T_h - T_{f,l}) \quad (4)$$

where $\dot{Q}_{h,m}$ is the same as $\dot{Q}_{c,h}$. Eliminating T_h between equations (3) and (4), gives:

$$\dot{Q}_{h,m} = \frac{A_c}{(U_L A_c / h_{hm} A_{hm}) + (U_L / h_c + 1)} [I(\tau\alpha)_{eff} - U_L(T_{f,l} - T_a)] \quad (5)$$

or,

$$\dot{Q}_{h,m} = F_r A_c [I(\tau\alpha)_{eff} - U_L(T_{f,l} - T_a)] \quad (6)$$

* Member ISES.

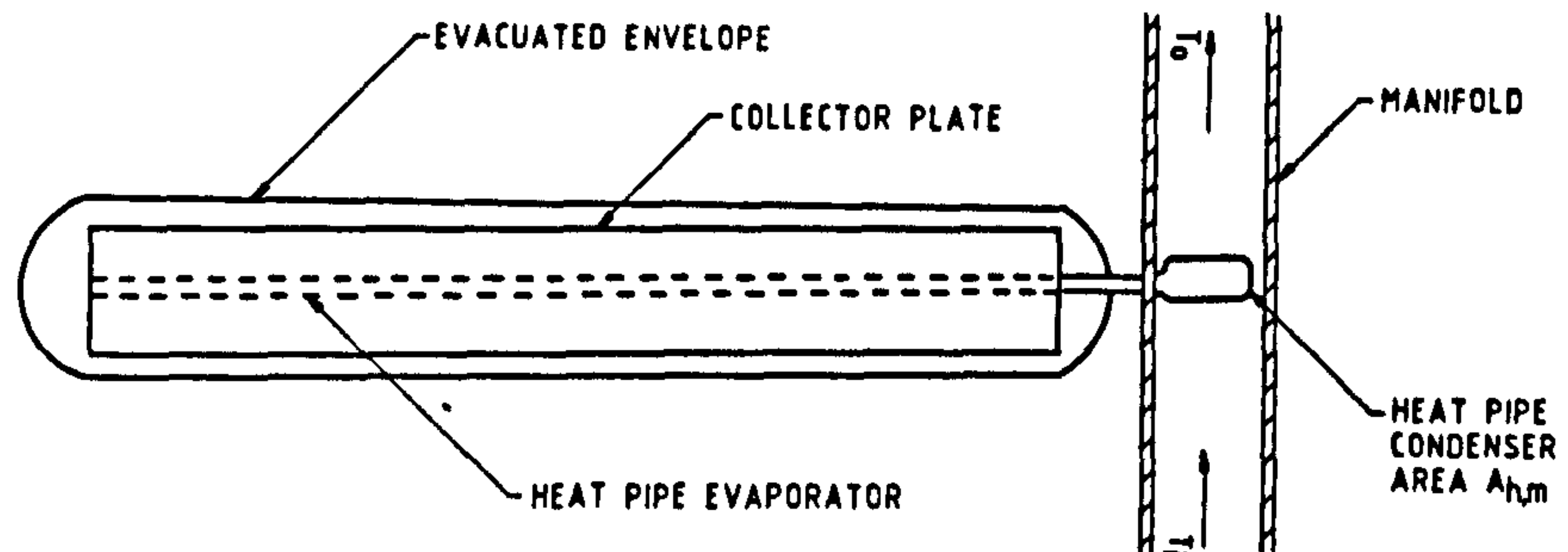


Fig. 1. Arrangement of heat-pipe collector with the manifold.

where,

$$F_r = \frac{1}{(U_L A_c / h_{hm} A_{hm}) + (U_L / h_e + 1)} \quad (7)$$

Defining $\eta = \dot{Q}_{hm} / I A_c$, equation (6) becomes the Hottel-Whillier-Bliss equation of the solar-energy collector, i.e.

$$\eta = F_r (\tau \alpha)_{eff} - F_r U_L \frac{(T_{f,i} - T_a)}{I} \quad (8)$$

A graph of steady-state efficiency vs $(T_{f,i} - T_a) / I$ gives a straight line of gradient $F_r U_L$ and intercept $F_r (\tau \alpha)_{eff}$ [4].

The collector's heat-loss coefficient can be regarded as constant over the working range. Thus the heat-removal factor has a great influence on the shape of the efficiency curve.

RESULTS

The heat-removal factor F_r is dependent on the three ratios U_L / h_e , U_L / h_{hm} and A_{hm} / A_c . Figure 3 shows that when the condenser is not very efficient, i.e. when $U_L / h_{hm} > 0.01$, F_r is relatively insensitive to variations of the ratio U_L / h_e (for a VTR-141 evacuated-tube collector manufactured by Philips, U_L / h_{hm} is 0.0038

[4]). Therefore to gain an insight into the effects of other factors, the value of this ratio is held constant. A value of 0.19, for U_L / h_e has been used to generate Figs. 4 and 5. In Fig. 4, it can be seen that increasing the heat-transfer area of a relatively inefficient condenser (i.e. with $U_L / h_{hm} = 0.04$) from $A_{hm} / A_c = 0.1$ to $A_{hm} / A_c = 0.5$, produces a value of F_r of nearly 0.8. But simultaneously Fig. 5 dictates that, with a relatively efficient condenser (e.g. $U_L / h_{hm} = 0.01$), an increase in the area ratio A_{hm} / A_c beyond 0.035 does not contribute towards further increasing the value of F_r .

Both the parameters U_L / h_{hm} and A_{hm} / A_c may be combined together to form a resistance ratio $h_{hm} A_{hm} / U_L A_c$ [3]. The term $U_L A_c$ is the reciprocal of the thermal resistance to rate of heat loss to the atmosphere and $h_{hm} A_{hm}$ is the reciprocal of the resistance to the transference of heat from the condensate to the fluid in the manifold. Figure 6 illustrates that F_r can have a maximum value slightly in excess of 0.8, for $U_L / h_e = 0.19$, for any value of this ratio of resistances above 17. The value of U_L / h_e imposes a limit on the maximum achievable value of the heat-removal factor F_r . It should be borne in mind that this analysis is based on a single-tube module. The value of F_r increases appreciably when a module of 20 or more tubes is considered due to the increased average heat-

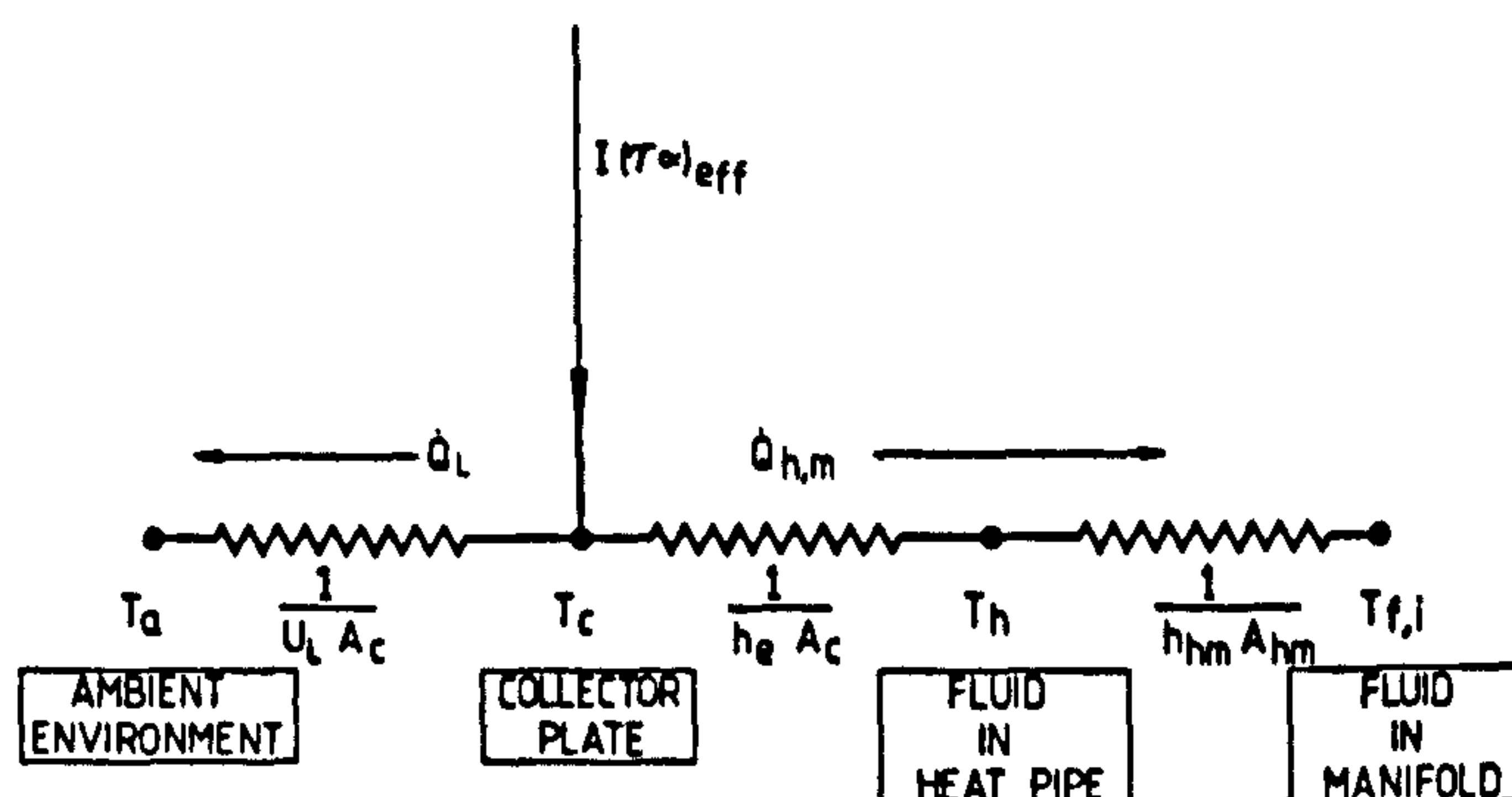


Fig. 2. Heat transport network for a heat-pipe collector.

Heat removal from a solar-energy collector

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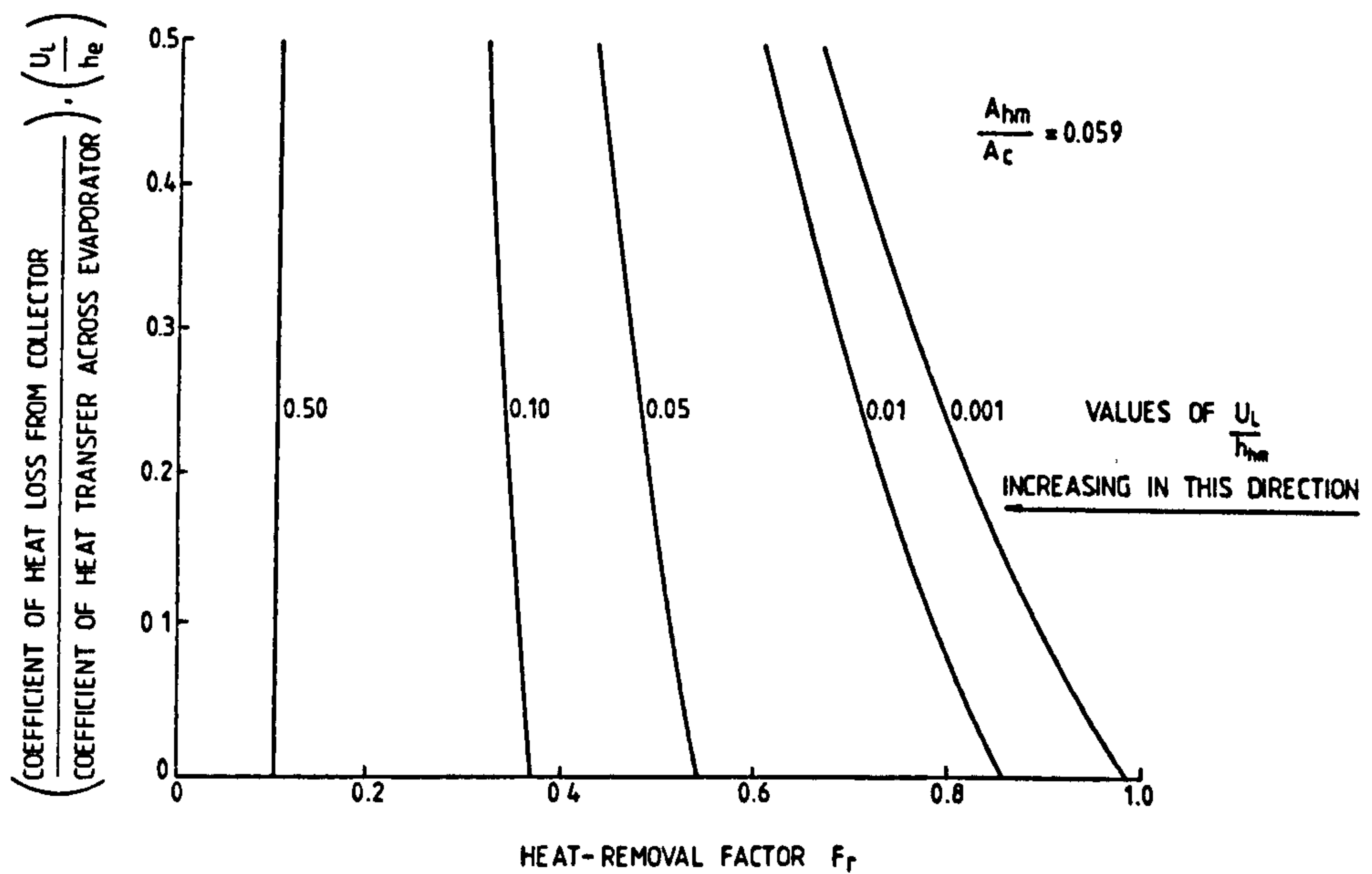


Fig. 3. Effect on the heat-removal factor of varying the ratio of the coefficient of heat-loss from the collector to the coefficient of heat-transfer across the evaporator.

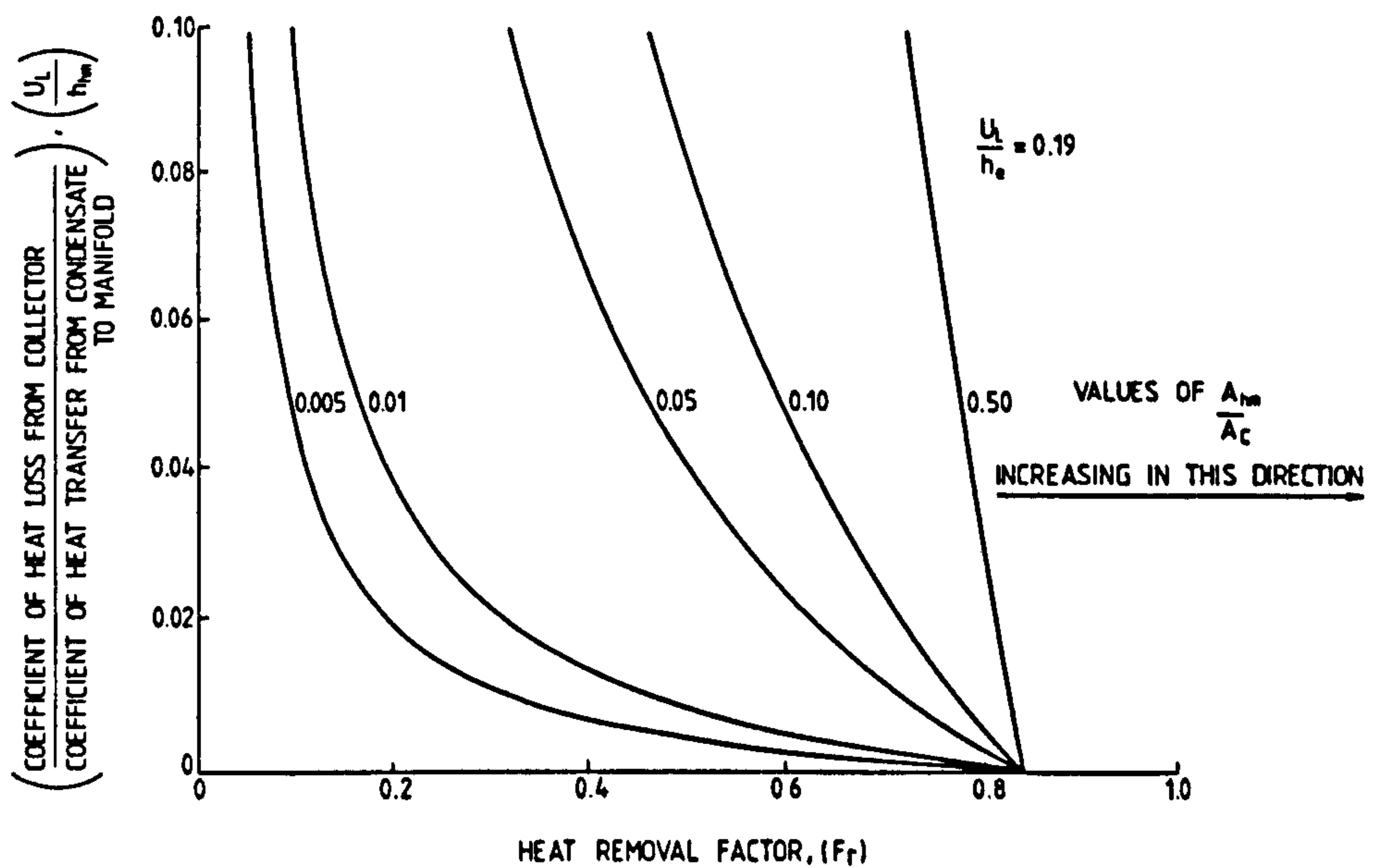


Fig. 4. Effect on the heat-removal factor of varying the ratio of the coefficient of heat-loss from the collector to the coefficient of heat-transfer from condensate to manifold.

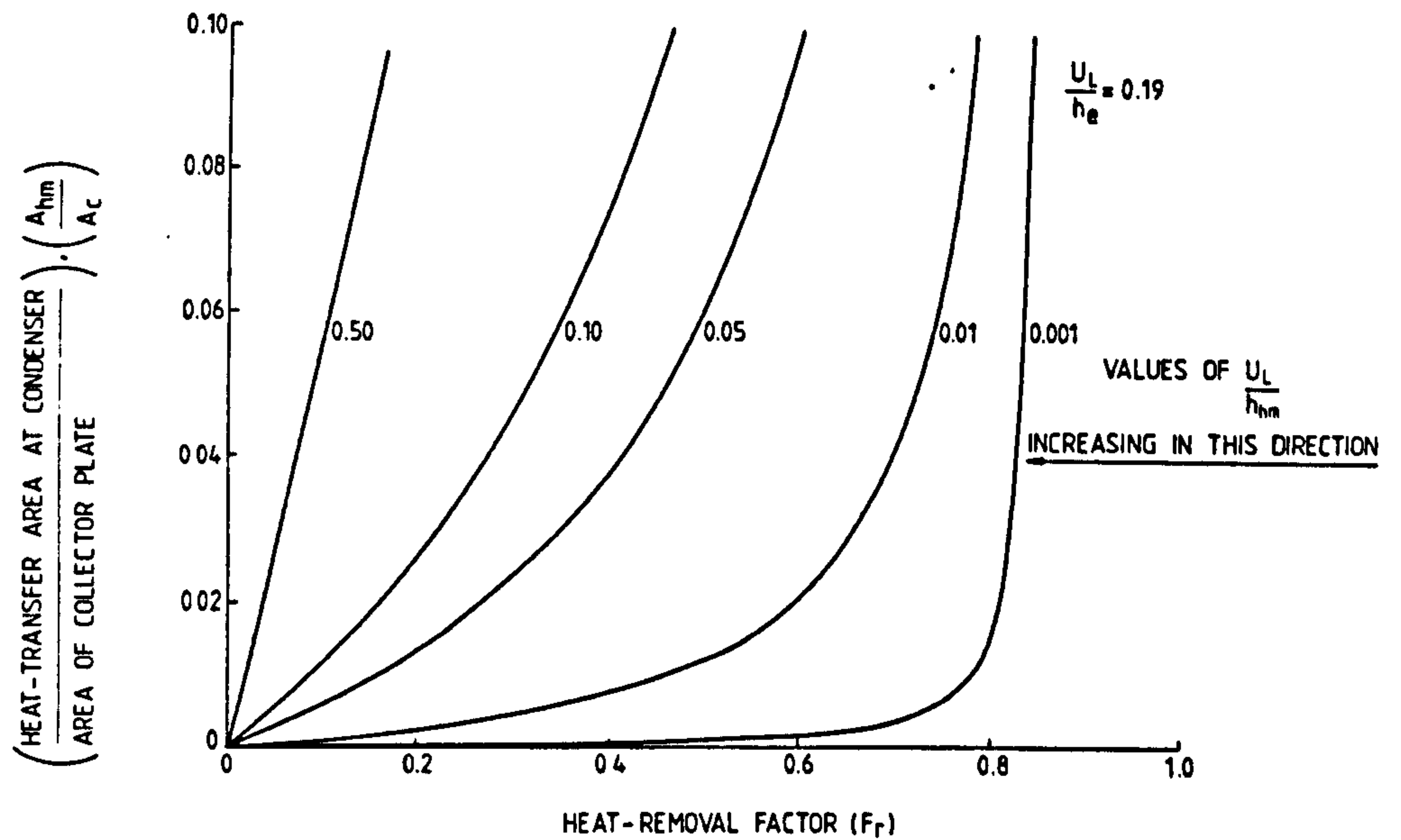


Fig. 5. Effect on the heat-removal factor of varying the ratio of the heat-transfer area at the condenser to the area of collector plate.

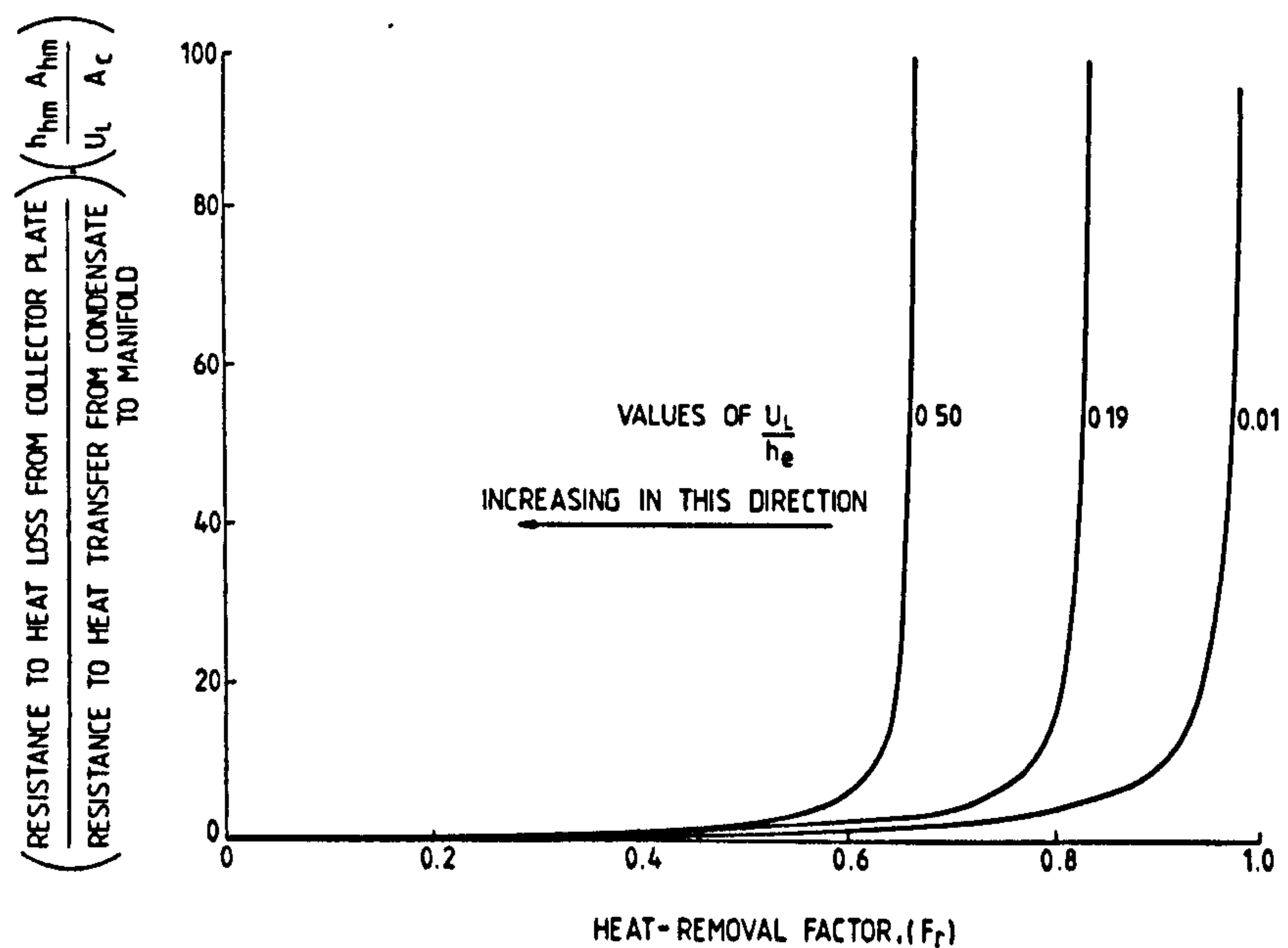


Fig. 6. Effect on the heat-removal factor of varying the ratio of the resistance to heat-loss from collector to the resistance to heat-transfer from condensate to manifold.

transfer then achievable from the condensate to the manifold fluid.

CONCLUSION

The design of a condenser for achieving a high heat-transfer efficiency will be influenced strongly by its economic viability and the limits set by Fig. 6. The first step should be to choose a reasonable value for F_r (i.e. $F_r > 0.8$) which will define the limiting value of U_L/h_e . Increasing the heat-transfer area at the condenser has its practical limitations: for example a manifold has a greater propensity to lose heat if the dimensions are large. It will thus require to be better insulated thermally and thus incur a higher cost. The use of a more efficient condenser has inherent cost implications because special internal and external structures and high thermal conductance materials may be required. Both the afore-mentioned measures have their limitations defined by Fig. 6.

NOMENCLATURE

A	area (m^2)
h	coefficient of heat transfer ($\text{W m}^{-2} \text{K}^{-1}$)
$\dot{Q}$	heat transfer rate (W)

T	temperature (K)
U_L	coefficient of heat loss ($\text{W m}^{-2} \text{K}^{-1}$)
$(\tau\alpha)_{\text{eff}}$	effective transmittance-absorptance product for the collector
F_r	heat-removal factor
I	total incident insolation (W m^{-2})
η	instantaneous efficiency of the solar collector
$\dot{Q}_u$	useful rate of heat gain at collector plate (W)

Subscripts

a	ambient
e	evaporator
h	fluid within heat pipe
m	manifold
c	collector plate
f	manifold fluid
i	inlet.

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1. W. Kamminga, The testing of an evacuated tubular collector with a heat pipe using the Fourier frequency domain. *Int. J. Heat Mass Transfer* **29**, 83-90 (1986).
2. J. R. Hull, Comparison of heat transfer in solar collectors with heat pipe vs flow through absorbers, in *Heat Transfer and Fluid Flow in Solar Thermal Systems* (Edited by T. C. Min and J. P. Chiou), 1-7. U.S.A. (1985).
3. J. R. Hull, Analysis of heat transfer factors for a heat pipe absorber array connected to a common manifold. *ASME J. Solar Energy Engng* **108**, 11-16 (1986).
4. J. A. Duffie and W. A. Beckman, *Solar Engineering of Thermal Processes*. Wiley, New York, U.S.A. (1980).

APPENDIX B

**STANDARD PERFORMANCE SPECIFICATIONS
FOR REFRIGERATORS AND FREEZERS**

SOLAR (THERMAL) REFRIGERATOR AND FREEZER, COMBINED

Specification reference:	E3/RF5.
Test according to:	<i>No Standard Test Procedure available</i>
Type of equipment:	Solar (thermal) refrigerator/freezer (combined). Working with a thermodynamic cycle (adsorption or absorption).
Temperature control:	Temperature of a full vaccine load to remain within the range 0°C to +8°C when maximum daytime temperature is between +32°C and +43°C. Manufacturer should state minimum daytime temperature and minimum day/night-time interval required to maintain this temperature control.
Safe freezing capacity:	More than 3 kg icepacks frozen within a period of 24 hours at +32°C ambient temperature while maintaining the above temperature control.
Holdover time:	72 hours at +32°C ambient temperature.
Corrosion resistance:	Internal and external cabinet, lid and frame to be protected against corrosion to DIN 8985.
Accessories and fittings:	External reading thermometer. Door/lid-lock with key. Fence to protect if installed outside.
Instructions:	Users instructions in English, French, Spanish and Arabic provided. Detailed installation instructions in English, French, Spanish and Arabic provided.

STANDARD TEST PROCEDURES FOR REFRIGERATORS AND FREEZERS

SOLAR (THERMAL) REFRIGERATOR AND FREEZER, COMBINED

Procedure Reference: E3/PROC/

Applies to:

Specification E3/RF5

This type of appliance operates when it is submitted to day/night cycles. During the day the solar energy boils the ammonia or the methanol away from the adsorbing material (Calcium chloride or activated carbon). During the night, the difference of temperature allows the liquid to be released in the refrigerator evaporator, thus cooling the cabinet down.

There is only one cycle per 24 hours, the tests must therefore represent the most critical situation that these appliances will face:

- small day/night temperature difference;
- low insolation during several days and ability to maintain the vaccine temperature until insolation is back to 4.5 kWh/m²/day.

1. COOL DOWN AND STABILIZATION

Test condition: Day/night cycle 43°C and 32°C
Insolation: 4.5 kWh/m²/day.

Procedure:

The test room should be set to +43°C with the appliance empty, the door open and the artificial sun switched off for a period of 48 hours allowing stabilization to take place. The door of the refrigerator/freezer should then be closed, the artificial sun switched on and the day/night cycle started with an insolation of 4.5 kWh/m²/day over the 9 hour day period.

Temperatures should be recorded hourly for 24 hours.

The time required to stabilize the internal temperatures between 0°C and 8°C in the vaccine compartment should be recorded, in terms of the minimum number of day/night cycles required to cool down.

Test criteria for qualification: None.

2. STABLE RUNNING TESTS AT 43°C/32°C

Test condition: day/night cycles
+43°C ±1°C and 32°C ±1°C
Insolation 4.5 kWh/m²/day and 1.5 kWh/m²/day

Procedure:

The appliance should be loaded, as specified in the General Test Conditions, procedure 3. After allowing for stabilization, internal temperatures are recorded. The appliance should then be submitted to consecutive day/night cycles under the artificial sun with a maximum daily insolation of 4.5 kWh/m²/day.

The ambient temperature as well as the insolation are varied to simulate day/night temperatures. Over a 3 hour period the temperature is reduced to $+32^{\circ}\text{C}$ and held at this level for 9 hours before being raised to $+43^{\circ}\text{C}$ over a 3 hour period. It is then held at $+43^{\circ}\text{C}$ for a further 9 hours before being reduced to $+32^{\circ}\text{C}$ again over a further 3 hour period. Seven such day/night cycles are undertaken. During this time the internal temperatures are monitored hourly.

From the results the temperature range of the warmest and coldest recorded temperatures should be found.

Particular attention should be given to monitoring the minimum temperature in the vaccine compartment since there is a risk of this going below 0°C .

This cycle is then followed by a 3 day period (72 hours) at 32°C ambient temperature without sun, i.e. with only $1.5 \text{ kWh/m}^2/\text{day}$ in order to simulate cloudy days.

When this 72 hour period is over the $43^{\circ}\text{C}/32^{\circ}\text{C}$ cycle with $1.5 \text{ kWh/m}^2/\text{day}$ is resumed for a period of 3 days.

See diagram

Criteria for qualification:

All internal refrigerator temperatures to remain in the $[0^{\circ}\text{C}-8^{\circ}\text{C}]$ interval during the whole test.

3. STABLE RUNNING TESTS AT $43^{\circ}\text{C}/15^{\circ}\text{C}$

Test condition: day/night cycles
 $+43^{\circ}\text{C} \pm 1^{\circ}\text{C}$ and $15^{\circ}\text{C} \pm 1^{\circ}\text{C}$
 Insolation $4.5 \text{ kWh/m}^2/\text{day}$

Procedure:

The same test as in procedure 2. above is repeated but with day/night temperatures of 43°C and 15°C . The appliance is submitted to consecutive day/night cycles under the artificial sun with a maximum daily insolation of $4.5 \text{ kWh/m}^2/\text{day}$. The same procedure as in 2. above is applied during a period of only 5 days with the appliance loaded with vaccines but no icepacks.

From the results the temperature range of the warmest and coldest recorded temperatures should be found.

This cycle simulates the best possible conditions for this type of appliance, i.e. good insolation and high day/night temperature gradient. Particular attention should therefore be given to monitoring the minimum temperature in the vaccine compartment since there is a risk of this going below 0°C .

see diagram

Criteria for qualification:

All internal refrigerator temperatures to remain in the [0°C-8°C] interval during the whole test.

4. ICEPACK FREEZING

Test conditions: Day/night cycle 13°C/32°C
Maximum insolation 4.5 kWh/m²/day

Procedure:

The ability of the freezer to freeze icepacks is then measured. Ice making capability is measured in kg per freezing cycle. All icepacks to form part of the freezing load should be pre-conditioned at +32°C. Any air flow restrictor on refrigerators should be used for this test only.

An estimate is first made of how many icepacks can be frozen in 24 hours, based on manufacturers specifications.

Internal refrigerator temperatures should be monitored throughout this test. If the temperatures in the vaccine load exceed the range 0°C to +8°C during the freezing test, the load of icepacks should be reduced and the test repeated.

The greatest load of icepacks which can be frozen without exceeding vaccine storage temperatures is recorded as the "safe freezing capacity".

Test criteria for qualification:

More than 3 kg per 50 litres of gross volume per 24 hours.

4. HOLD OVER TIME AT +32°C

Test condition: +32°C ±1°C.

Procedure:

The appliance is allowed to stabilize loaded with vaccine in the refrigerator but without icepacks in the freezer compartment and then the artificial sun is then switched to 1.5Kwh/m²/day. Internal temperatures are monitored hourly. The time recorded for the warmest point to exceed +10°C is reported.

Test criteria for qualification:

Minimum 72 hours

5. SPECIAL FEATURES:

If the refrigerator cabinet has to be installed outside the health center, a fence should be provided for protection and the refrigerator itself should be provided with a lock.

If the cabinet can be installed inside the health center with the solar collector outside on the roof or on the ground, the maximum allowable distance between the refrigerator cabinet and the collector should be stated by the manufacturer.

6. CORROSION RESISTANCE

Test condition:

Procedure: According to DIN 8985.

Test criteria for qualification: Meet DIN 8985.

APPENDIX C

```
*****
* Listing of the program for calculating environmental gains *
* in a cooling cabinet, discussed in chapter 6                *
*****
```

```

0 REM.....PROGRAM CABGAINS
10 MODE3
20 INPUT"ENTER range of insulation THICKNESS (m)",TL,TH
30 INPUT"ENTER range of ambient TEMPERATURE (C)",TAL,TAH
40 INPUT"ENTER volume of the storage CABINET (cu.m)",V
50 INPUT"ENTER thermal conductivity of INSULATION (W/m-K)",K
60 L=V^(1/3)
70 E=0.5
80 REM.....Temperature loop
90 FOR TA=TAL TO TAH STEP 10
100 REM.....Open output file
110 GOSUB 450
120 REM.....Thickness loop
130 FOR T=TL TO TH STEP .01
140 TSO=TA
150 REM.....Iteration loop starts
160 TSO=TSO-.5:GOTO210
170 TSO=TSO-.1:GOTO210
180 TSO=TSO-.01:GOTO210
190 TSO=TSO+.001
200 REM.....Calculate heat transfer coefficients
210 HCOV=4/6*1.42*((TA-TSO)/(L+2*T))^0.25
220 HCOHT=1/6*0.59*((TA-TSO)/(L+2*T))^0.25
230 HCOHB=1/6*1.32*((TA-TSO)/(L+2*T))^0.25
240 HCO=HCOV+HCOHT+HCOHB
250 HR=5.67E-8*E*4*((TA+TSO)/2+273.15)^3
260 HO=HCO+HR
270 AI=6*L^3
280 AO=6*(L+2*T)^3
290 AM=6*(L+T)^3
300 Q=HO*AO*(TA-TSO)
310 TSI=TSO-Q*T/K/AM
320 IF TSI<=0 THEN GOTO190
330 QI=AI*(4/6*1.42+0.59/6+1.32/6)/L^0.25*(TSI-0)^1.25
340 IF(QI-Q)>5 THEN GOTO160
350 IF(QI-Q)>1.5 THEN GOTO170
360 IF(QI-Q)>.1 THEN GOTO180
370 IF(QI-Q)<0 THEN GOTO190
380 @%=&020408
390 PRINT Q;TAB(10);T
400 NEXTT
410 *SPOOL

```

```
420  NEXTTA
430  END
440  REM.....Output file selection subroutine
450  IF TA=20THEN *SPOOL CAB20
460  IF TA=30THEN *SPOOL CAB30
470  IF TA=40THEN *SPOOL CAB40
480  IF TA=50THEN *SPOOL CAB50
490  RETURN
```

APPENDIX D

Cattaneo's experiment with bubble pumps

Lifting of liquid with the help of its own bubbles (by heating a vertical tube externally) was investigated experimentally by Cattaneo for the first time. This phenomenon was very similar to the bubble pump action used in 'Electrolux' type refrigerators. He determined the feed ratio (defined as the ratio of liquid volume to vapour volume produced), under varying tube diameters d_s , delivery height h_s , and operating temperature T_s . His results are shown in fig D.1 for water at pressure of 1 ata.

The feed ratio 'b' falls with the decreasing operating temperature, and increasing height and diameter of the tube. The drop in value of 'b' is sharp for increasing diameters upto 16 mm. An interesting phenomenon happened when the tube diameter was reduced below 5 mm. A piston of vapours started forming which delayed the liquid pumping action and the flow proceeded periodically or plugwise.

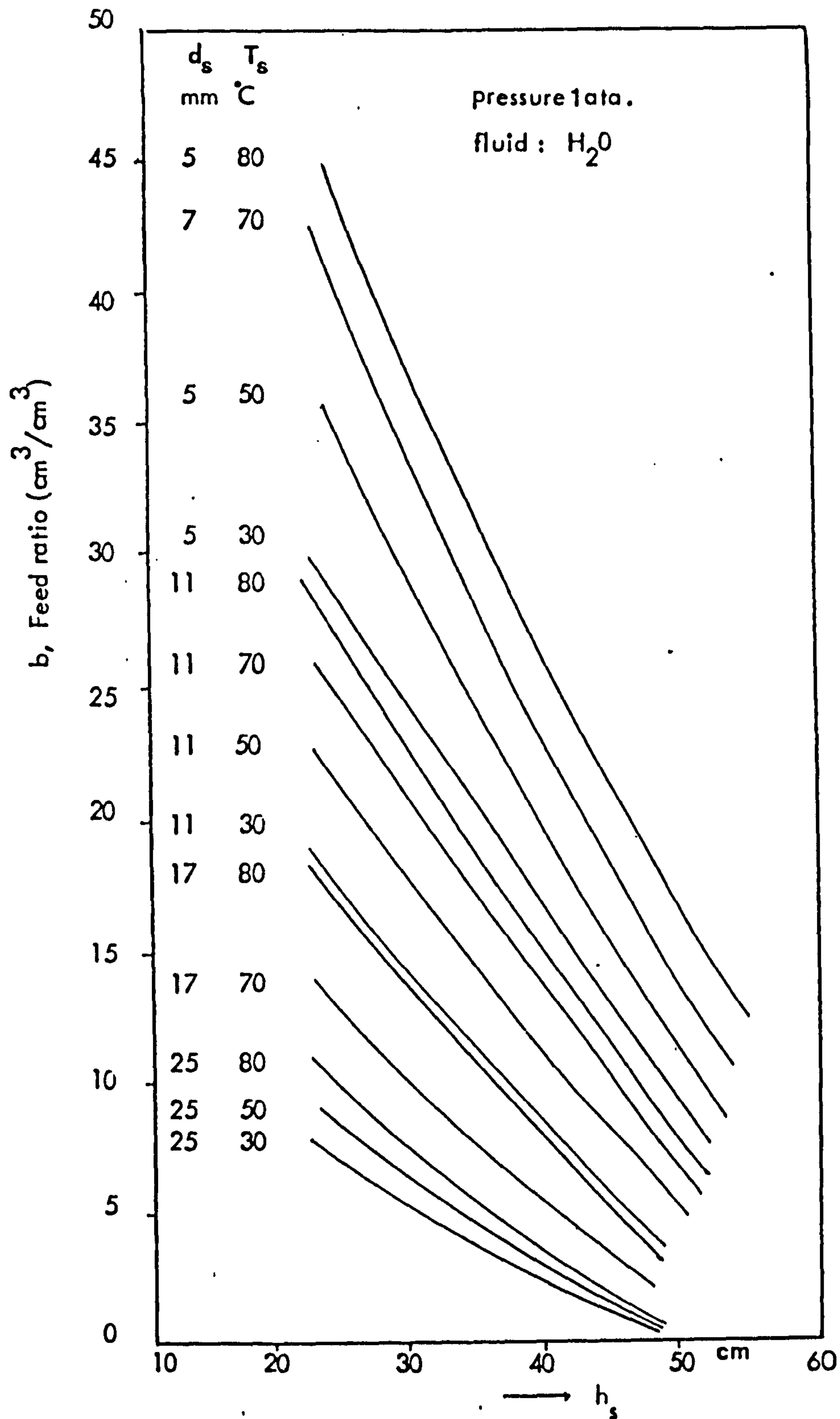


Fig D.1
Thermosyphon pump feed ratio (b) versus tube riser height (h_s)
for various tube diameters (d_s) and operating temperature (T_s)

APPENDIX F

```

*****
* Listing of the program used to control and operate automatically *
* the adsorption pair characterization rig                               *
*****

```

```

10 MODE3
20 DIM T(6),VR(8)
30 PROCinitialise
40 PROCsetup
50 PROCexp
60 *DI.
70 END
80 REM *****
90 REM Procedure which has the overall control of the experiment
100 REM *****
110 DEFPROCexp
120 PROCmeasure:Tadprestep=Tads
130 TIME=0:MINS=0:FLAG=0:C=0
140 PRINTTAB(14,6)"*****"
150 PRINTTAB(14,7)"*                               *"
160 PRINTTAB(14,8)"*           HEATING CYCLE           *"
170 PRINTTAB(14,9)"*                               *"
180 PRINTTAB(14,10)"*****"
190 FOR T=TMIN TO TMAX STEP DELT
200   COUNTER=0:C=C+1
210   PROCmeasure:PROCscreen
220   IF T-To11>3 THEN PROCheat("ON") ELSE PROCheat("OFF")
230   IF To11>T THEN PROCcool("ON") ELSE PROCcool("OFF")
240   IF FLAG=0 THEN PROCdisc
250   IF TIME>=6000 THEN TIME=0:MINS=MINS+1:COUNTER=COUNTER+1:PROCcheck
260   IF PP>0.9 OR ABS(Tads-Tadprestep)<=3 THEN FLAG=1:GOTO210
270   PROCdisc:Tadprestep=Tads
280   NEXTT
290 TIME=0:FLAG=0:C=0
300 PRINTTAB(14,6)"*****"
310 PRINTTAB(14,7)"*                               *"
320 PRINTTAB(14,8)"*           COOLING CYCLE           *"
330 PRINTTAB(14,9)"*                               *"
340 PRINTTAB(14,10)"*****"
350 FOR T=TMAX-DELT TO TMIN STEP -DELT
360   COUNTER=0:C=C+1
370   PROCmeasure:PROCscreen
380   IF To11>T THEN PROCcool("ON") ELSE PROCcool("OFF")
390   IF T-To11>3 THEN PROCheat("ON") ELSE PROCheat("OFF")
400   IF FLAG=0 THEN PROCdisc
410   IF TIME>=6000 THEN TIME=0:MINS=MINS+1:COUNTER=COUNTER+1:PROCcheck

```

```

420 IF PP>0.9 OR ABS(Tads-Tadprestep)<=3 THEN FLAG=1:GOTO370
430 PROCdisc:Tadprestep=Tads
440 NEXTT
450 ENDPROC
460 REM *****
470 REM Procedure to set up and initialize the user port & data system
480 REM *****
490 DEFPROCinitialise
500 *DI.
510 CLOSE#0
520 ?&FE62=&FF:DRB=&FF:?&FE60=DRB
530 *IEEE
540 cmd%=OPENIN("COMMAND")
550 data%=OPENIN("DATA")
560 PRINT#cmd%,"BBC DEVICE NO",0
570 PRINT#cmd%,"CLEAR"
580 PRINT#cmd%,"REMOTE ENABLE"
590 PRINT#cmd%,"UNTALK"
600 PRINT#cmd%,"UNLISTEN"
610 *DI.
620 ENDPROC
630 REM *****
640 REM Procedure which set up the control parameters for the experiment
641 REM & opens a data file to record the measured data values
650 REM *****
660 DEFPROCsetup
670 *DR.1
680 *CAT
690 VDU23,1,0;0;0;0;0;
700 INPUT" INPUT FILE NAME FOR DATA STORAGE "F$
710 CLS
720 INPUT"INPUT REQUIRED INITIAL BATH TEMPERATURE "TMIN
730 INPUT"INPUT REQUIRED FINAL BATH TEMPERATURE "TMAX
740 INPUT"TEMPERATURE STEP BETWEEN STAGES "DELT
750 PRINTTAB(0,8)"DO YOU WANT TO REPEAT DIALOGUE "
760 INPUTX$;
770 IFX$="Y"THEN710ELSEIFX$<>"N"THEN760
780 CLS:INPUT"INPUT CONCENTRATION "C$
790 INPUT"INPUT THE TIME (minutes) BETWEEN EACH DATA RECORDING "D
800 X=OPENOUT(F$)
810 PRINT#X,C$:CLS
820 CLOSE#X
830 PRINT"INITIAL BATH TEMPERATURE (DEG C)"TAB(40);TMIN
840 PRINT"FINAL BATH TEMPERATURE (DEG C)"TAB(40);TMAX
850 PRINT"TEMPERATURE STEP BETWEEN STAGES"TAB(40);DELT
860 ENDPROC
870 REM *****
880 REM Procedure which writes the data to the data file

```

```

890 REM *****
900 DEFPROCdisc
910 *DI.
920 *DR.1
930 X=OPENUP(F$)
940 PTR#X=EXT#X
950 PRINT#X,MINS,COUNTER,To11,T(3),T(4),T(5),T(6),PP,P
960 CLOSE#X
970 *IEEE
980 ENDPROC
990 REM *****
1000 REM Procedure which checks if it is the time to write the data
1010 REM *****
1020 DEFPROCcheck
1030 IF COUNTER MOD D=0 THEN PROCdisc
1040 ENDPROC
1050 REM *****
1060 REM Procedure which displays measured data on the screen
1070 REM *****
1080 DEFPROCscreen
1090 @%=10
1100 PRINTTAB(0,12)"ELAPSED TIME (total)          = ";MINS;" min"
1110 PRINTTAB(0,14)"ELAPSED TIME (step no. ";C;TAB(25)) = ";COUNTER;" min"
1120 @%=&20206
1130 PRINTTAB(0,16)"OIL BATH TEMPERATURE          = ";To11;" deg C"
1140 PRINTTAB(0,18)"ADSORBENT TEMPERATURE         = ";T(3),T(4),T(5),T(6);" deg C"
1150 PRINTTAB(0,20)"ABSOLUTE PRESSURE              = ";P;" bar          "
1160 ENDPROC
1170 REM *****
1180 REM Procedure which scans each channel in turn
1190 REM *****
1200 DEFPROCmeasure
1210 *IEEE
1220 M%=67
1230 FORSCANadd%=65TO69:SCANadd$=CHR$(SCANadd%):PROCscan("7",SCANadd$,"J"):NEXT
1240 FORN%=0TO8
1250   m$=CHR$(M%)
1260   n$=STR$(N%)
1270   PROCscan("7",m$,n$)
1280   PROCdvm(N%)
1290   NEXTN%
1300 Tads=(T(3)+T(4)+T(5)+T(6))/4
1310 To11=(T(1)+T(2))/2
1320 ENDPROC
1330 REM *****
1340 REM Procedure which closes the scanned channel for measuring
1341 REM the analogue signal on the it.
1350 REM *****

```

```

1360 DEFPROCscan(IEEEadd$,SCANadd$,SCANchan$)
1370 SCAN%=OPENIN(IEEEadd$)
1380 PRINT#cmd%,"LISTEN",SCAN%,"EXECUTE"
1390 PRINT#data$,SCANadd$+SCANchan$+"T"
1400 PRINT#cmd%,"UNLISTEN"
1410 CLOSE#SCAN%
1420 ENDPROC
1430 REM *****
1440 REM Procedure which controls the immersion heater
1450 REM *****
1460 DEFPROCheat(COM$)
1470 ?&FE60=DRB
1480 IF COM$="ON" THEN DRB=254:ENDPROC
1490 IF COM$="OFF" AND DRB=253 THEN COM%=253 ELSE IF COM$="OFF" AND
DRB=254 THEN COM%=255
1500 IF COM$="OFF" AND DRB=255 THEN COM%=255
1510 DRB=COM%
1520 ENDPROC
1530 REM *****
1540 REM Procedure which controls the refrigerating cooling coil
1550 REM *****
1560 DEFPROCcool(COM$)
1570 ?&FE60=DRB
1580 IF COM$="ON" THEN DRB=253:ENDPROC
1590 IF COM$="OFF" AND DRB=254 THEN COM%=2544 ELSE IF COM$="OFF" AND
DRB=253 THEN COM%=255
1600 IF COM$="OFF" AND DRB=255 THEN COM%=255
1610 DRB=COM%
1620 ENDPROC
1630 REM *****
1640 REM Procedure which interrogate the DVM to measure the analogue
1641 REM signals present at the channel and pass it on to the
1642 REM computer for further processing
1650 REM *****
1660 DEFPROCdvm(chan%)
1670 @%=&2060C
1680 OSCLI"FX3,7"
1690 IFchan%>0 THEN GOTO1720
1700 VDU76,49,69,49,80,35,82,48,89,49,84,48,72,48
1710 IFchan%=0 GOTO1760
1720 IFchan%=1 GOTO1760
1730 IFchan%=2 PRINT"P#1[46.10466;3;39.6145]":GOTO1760
1740 IFchan%>3 THEN GOTO1760
1750 PRINT"P#3[";ZERO;"8;0";T(0);"]"
1760 OSCLI"FX21,1"
1770 PRINT"G"
1780 OSCLI"FX3,6"
1790 OSCLI"FX2,1"

```

```
1800 INPUT A$
1810 VR(chan%)=EVAL(MID$(A$,6,14))
1820 IF chan%=0 THEN T(0)=10*VR(0):GOTO 1860
1830 IF chan%=1 THEN ZERO=VR(1):GOTO 1860
1840 IF chan%=2 THEN P=VR(2)/14.5+1.0086:GOTO 1860
1850 T(chan%-2)=VR(chan%)
1860 OSCLI"FX3,4"
1870 OSCLI"FX2,0"
1880 IF chan%<>8 THEN ENDPROC
1890 IF T(3)>T(4) THEN Tmax=T(3):Tmin=T(4)
1900 IF T(4)>T(3) THEN Tmax=T(4):Tmin=T(3)
1910 IF T(5)>Tmax THEN Tmax=T(5) ELSE IF T(5)<Tmin THEN Tmin=T(5)
1920 IF T(6)>Tmax THEN Tmax=T(6) ELSE IF T(6)<Tmin THEN Tmin=T(6)
1930 PP = Tmax - Tmin
1940 ENDPROC
```

APPENDIX G

Test results from Sutcliffe Speakman Carbons Ltd

Methanol Adsorption/Desorption data at 25°C

Desorption

P (mm Hg)	% Sorption
108.0	39.5
88.0	38.2
74.5	36.5
58.2	35.2
43.9	34.1
39.1	33.6
35.3	33.1
34.3	32.8
31.8	32.4
30.5	32.4
17.5	28.7
8.2	21.2
3.84	12.9

Sorption

P (mm Hg)	% Sorption
11.9	25.6
27.2	32.5
35.5	33.5
44.7	34.5
122.0	40.6

MeOH radius 2.523×10^{-8} cm
 dia. 5.046×10^{-8} cm
 area 19.988×10^{-16} cm²

Langmuir monolayer sorption X_m = 0.2692
 specific surface area = 1011 m²/g
 BET C const. = 23
 Heat of adsorption = 10,503 cal/g mol

N₂ Sorption

Dubinin micropore vol = 0.421 ml/g
 Pore vol mercury 3.7-7500 nm = 0.234 ml/g (Carlo Erba Model 200)

Coconut shell carbon has very restricted macroporosity, much less than normal coal-based materials, due to the initial structure of the raw product.

Progressive activation stages enlarge micropores but the material does not produce significant mesoporosity, a feature which is illustrated by the inability of the carbon to adsorb molecules of relatively large size such as colour bodies. Shell carbons do not exhibit a molasses decolour value.

Average values for specific heat and thermal conductivity obtained from the literature are as follows:-

sp. ht. 0.16 cal/g
 conductivity 0.35 BTU/hr/ft²

APPENDIX H

```

*****
*   Program for computing the coefficient of performance of an *
*   intermittent adsorption refrigeration cycle. The program   *
*   is based on the model developed in chapter 4 and used in   *
*   chapter 6 part III                                         *
*****

```

```

10 MODE3
20 INPUT"IS A PRINTER CONNECTED (Y/N)",P$:VDU2,1,27,1,78,1,3:VDU3
30 PROCDATA
40 PROCKELVIN
50 PROCCYCLES
60 END
61 REM*****
62 REM Procedure which gets the data about the refrigerant
63 REM and adsorbent and information about the cycle temperatures
64 REM *****
70 DEFPROC DATA
80 CLS:PRINT"REFRIGERANT INPUT DATA" " "
90 INPUT"REFRIGERANT NAME ",R$
100 IFR$="METHANOL" THEN PROC METHANOL
110 IF R$="AMMONIA" THEN PROC AMMONIA ELSE GOTO 130
120 GOTO 220
130 INPUT'"LIQUID DENSITY IN kg/m3 "',DENL,'"HARLACHER CONSTANT A
",HARA
140 INPUT'"HARLACHER CONSTANT B "',HARB,'"HARLACHER CONSTANT C "',HARC
150 INPUT'"HARLACHER CONSTANT D "',HARD
160 INPUT'"LIQUID Cp (kJ/kg-K) "',CPL,'"MOLECULAR WEIGHT "',MW
170 INPUT'"LATENT HEAT OF VAPORIZATION (NBP) "',HNBP
180 INPUT'"NORMAL BOILING POINT (KELVIN) "',TNBP
190 INPUT'"CRITICAL TEMPERATURE (KELVIN) "',TCRIT
200 INPUT'"IS DATA O.K.(Y OR N) "',D$

```

```

210 IFD$<>"Y"THEN GOTO 80
220 IF P$="Y"THEN CLS ELSE GOTO 320
230 VDU2:PRINT"REFRIGERANT INPUT DATA"'"_____'"
240 PRINT'"REFRIGERANT NAME ",R$',"LIQUID DENSITY IN kg/m3 ",LDEN
250 PRINT'"HARLACHER CONSTANT A ",HARA'"HARLACHER CONSTANT B ",HARB
260 PRINT'"HARLACHER CONSTANT C ",HARC
270 PRINT'"HARLACHER CONSTANT D ",HARD
280 PRINT'"LIQUID Cp (kJ/kg-K) ",CPL,'"MOLECULAR WEIGHT ",MW
290 PRINT'"LATENT HEAT OF VAPORIZATION (NBP) ",HNBP
300 PRINT'"NORMAL BOILING POINT (KELVIN) ",TNBP
310 PRINT'"CRITICAL TEMPERATURE (KELVIN) ",TCRIT:VDU3
320 CLS:PRINT"ADSORBENT DATA"'"_____'"
330 INPUT'"ADSORBENT NAME ",C$
340 IF C$="208C"AND R$="METHANOL" THEN PROC208CMETH:GOTO430
350 IF C$="208C"ANDR$="AMMONIA" THEN PROC208CAMMONIA:GOTO430
360 IF C$="ZEOLITE"AND R$="AMMONIA" THEN PROCZEOLITEAMMONIA ELSE
GOTO380
370 GOTO430
380 INPUT'"ADSORPTION CAPACITY in kg/kg ",MO
390 INPUT'"E (in m=m0*EXP(-(D/E)Δn) )",E,'"n (in m=m0*EXP(-(D/E)Δn)
)",N
400 INPUT'"SPECIFIC HEAT ",CPS
410 INPUT'"IS DATA OK (Y OR N) ",D$
420 IF D$ <> "Y" THEN GOTO 320
430 IF P$="Y" THEN VDU2 ELSE GOTO480
440 PRINT'"ADSORBENT DATA"'"_____'"ADSORBENT NAME ",C$
450 PRINT'"ADSORPTION CAPACITY in kg/kg ",MO
460 PRINT'"E (in m=m0*EXP(-(D/E)Δn) )",E,'"n (IN M=MO*EXP(-(D/E)Δn)
)",N
470 PRINT'"SPECIFIC HEAT ",CPS:VDU3
480 CLS:PRINT"CYCLE TEMPERATURES"'"_____'"
490 INPUT'"MIN. EVAP. TEMP. (DEG C) ",TMIN
500 INPUT'"MAX. EVAP. TEMP. (DEG C) ",TEMAX
510 INPUT'"MIN. COND. TEMP. (DEG C) ",TCMIN

```

```

520 INPUT "MAX. COND. TEMP. (DEG C) ",TCMAX
530 INPUT "MIN. GEN. TEMP. (DEG C) ",TGMIN,"MAX. GEN. TEMP. (DEG C)
",TGMAX
540 INPUT "MIN. ADS. TEMP. (DEG C) ",TAMIN,"MAX. ADS. TEMP. (DEG C)
",TAMAX,
550 INPUT "IS DATA OK (Y OR N) ",D$
560 IF D$ <> "Y" THEN GOTO 480
570 IF P$="Y" THEN VDU2 ELSE ENDPROC
580 PRINT "CYCLE TEMPERATURES" " "
590 PRINT "MIN. EVAP. TEMP. (DEG C) ",TEMIN
600 PRINT "MAX. EVAP. TEMP. (DEG C) ",TEMAX
610 PRINT "MIN. COND. TEMP. (DEG C) ",TCMIN
620 PRINT "MAX. COND. TEMP. (DEG C) ",TCMAX
630 PRINT "MIN. GEN. TEMP. (DEG C) ",TGMIN,"MAX. GEN. TEMP. (DEG C)
",TGMAX
640 PRINT "MIN. ADS. TEMP. (DEG C) ",TAMIN,"MAX. ADS. TEMP. (DEG C)
",TAMAX
650 VDU3:ENDPROC
651 REM *****
652 REM Procedure which calculates the vapour pressure of saturated
653 REM vapours from Harlacher coefficients
654 REM *****
660 DEFFNPSAT(T)
670 PVP=0
680 PVP1=EXP(HARA+HARB/T+HARC*LN(T)+HARD*PVP/T^2)
690 IF ABS(PVP1-PVP)>(0.01*PVP1)THENPVP=PVP1:GOTO680
700 =PVP1/750
705 REM*****
710 DEFPROCKELVIN
720 TEMIN=TEMIN+273:TEMAX=TEMAX+273:TCMIN=TCMIN+273:TCMAX=TCMAX+273
730 TGMIN=TGMIN+273:TGMAX=TGMAX+273:TAMIN=TAMIN+273:TAMAX=TAMAX+273
740 ENDPROC

```

```

741 REM *****
742 REM Procedure that calculates the concentration of adsorbate at
743 REM given pressure and temperature using D-A equation
744 REM *****
750 DEF FNCONC(P,T)
760 D=8.314*T*LN(FNPSAT(T)/P)/1000
770 PROD=(D/E)*N
780 =M0*EXP(-PROD)
781 REM *****
782 REM Procedure that determines the temperature of mixture for
783 REM the given concentration and pressure
784 REM *****
790 DEF FNTEMP(M,P)
800 TEMP=TGMAX+50
810 FORJ=1 TO -1 STEP-1
820   TEMP=TEMP-10*J
830   IF FNCONC(P,TEMP)<M THEN GOTO 820 ELSE TEMP=TEMP+10*J
840   NEXT
850 =TEMP
860 DEFPROC METHANOL
870 LDEN=791:HARA=72.268:HARB=-7064.2:HARC=-7.68:HARD=1.86
880 CPL=2.55:MW=32.042:HNBP=1222:TNBP=337.8:TCRIT=512.4
890 ENDPROC
900 DEFPROC AMMONIA
910 LDEN=681:HARA=51.947:HARB=-4104.67:HARC=-5.146:HARD=.82
920 CPL=1.0:MW=17:HNBP=1200:TNBP=239.7:TCRIT=405.6
930 ENDPROC
940 DEFPROC 208CMETH
950 CPS=0.7:M0=0.401:E=6.175:N=1.89
960 ENDPROC
970 DEFPROC 208CAMMONIA
980 CPS=0.7:M0=0.25:E=7.152:N=1.92
990 ENDPROC

```

```

1000 DEF PROCZEOLITEAMMONIA
1010 CPS=0.92:M0=0.215:E=12.11:N=3.06
1020 ENDPROC
1030 DEFPROCCYCLES
1040 IF P$="Y"THEN VDU2
1050 PRINT' '      TE      TC      TA      TG1      TG2      T4      M12
M34
COP''
1060 @%=&01020308
1070 FOR TC=TCMIN TO TCMAX STEP 10
1071   FOR TE=TEMIN TO TEMAX STEP 10:PROCLATHEAT(TE)
1080     FOR TA=TAMIN TO TAMAX STEP 10
1081       FOR TG=TCMIN TO TGMAX STEP 10
1090         PROCCYCLE
1100         IF FLAG=1 THEN
PRINT(TE-273),(TC-273),(TA-273),(T2-273),(TG-273),( T4-273),M12,M34;"
M34>M12" ELSE PRINT(TE-273),(TC-273),(TA-273),(T2-273),(TG-273
),(T4-273),M12,M34,COP
1110           NEXT TG
1111         NEXT TA
1112       NEXT TE
1113     NEXT TC
1120   VDU3
1130 ENDPROC
1131 REM *****
1132 REM Procedure which performs the cycle calculations and gives
1133 REM COP value for the operating conditions
1134 REM *****
1140 DEFPROCCYCLE
1150 FLAG=0
1160 P14=FNPSAT(TE):P23=FNPSAT(TC)
1165 M12=FNCONC(P14,TA):M34=FNCONC(P23,TG)
1170 T3=TG:T2=FNTEMP(M12,P23):T4=FNTEMP(M34,P14)
1180 IF M34>M12 THEN FLAG =1:ENDPROC

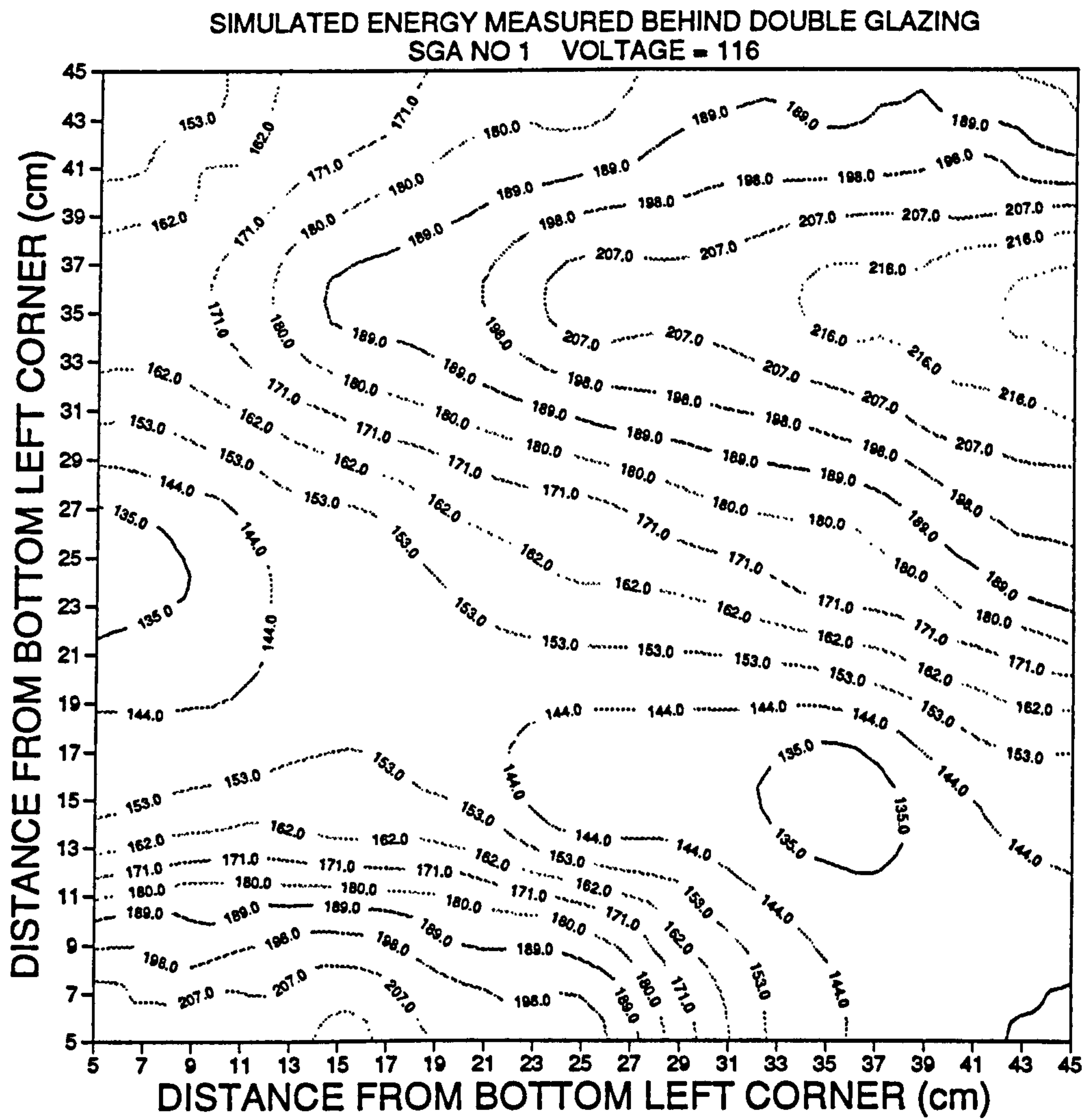
```

```

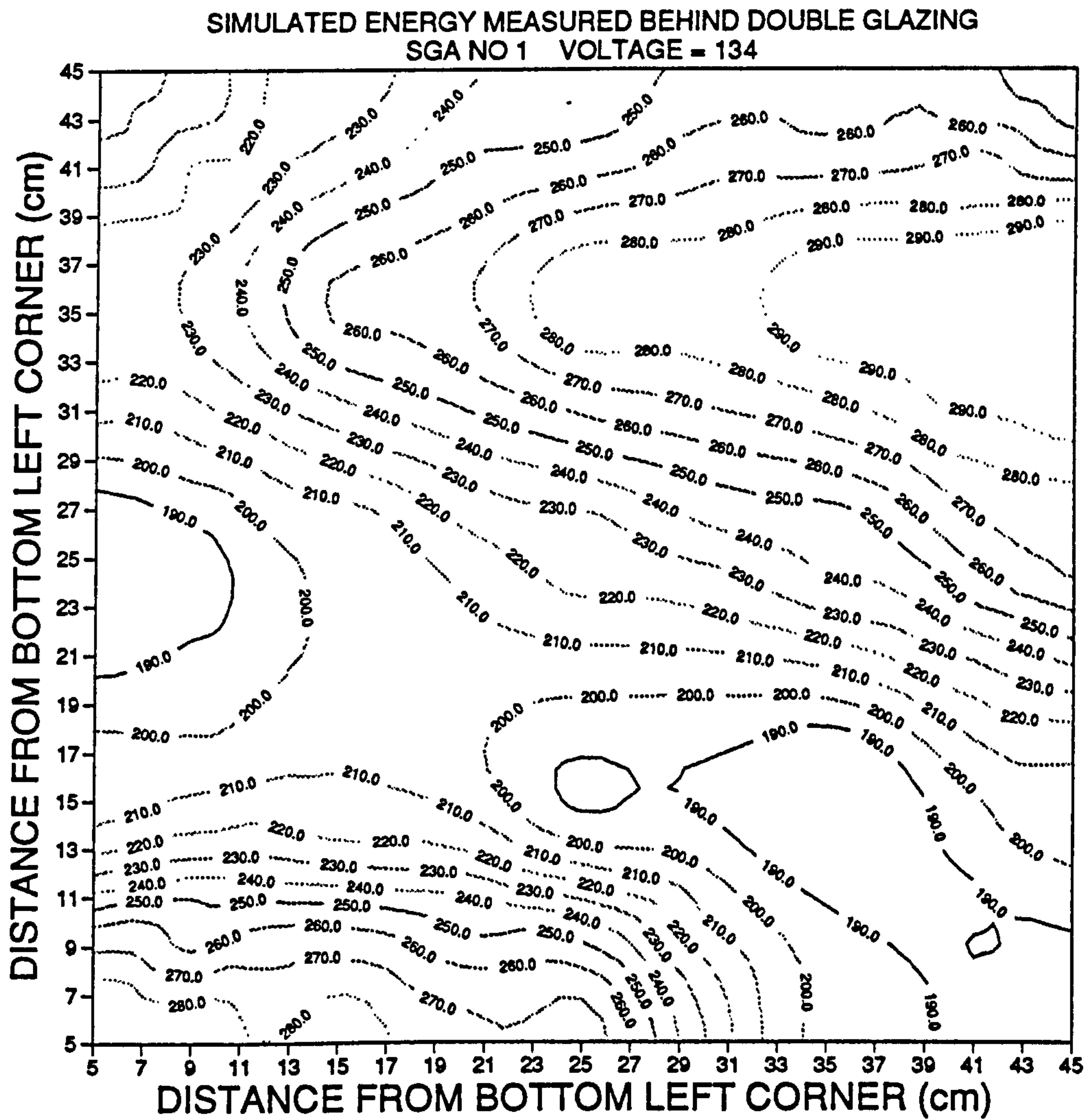
1190 H12=(T2-TA)*(CPS+M12*CPL)
1200 H23=CPL*(T3-T2)*(M12+M34)/2+CPS*(T3-T2)
1210 DH1=8.314/MW*LN(P23/P14)/(1/TA-1/T2)
1220 DH2=8.314/MW*LN(P23/P14)/(1/T4-1/T3)
1230 H23=H23+(DH1+DH2)/2*(M12-M34)
1240 CP34=CPS+M34*CPL:CP12=CPS+M12*CPL
1250 COOL=(M12-M34)*(H-CPL*(TC-TE))
1260 COP=COOL/(H12+H23)
1270 ENDPROC
1271 REM *****
1272 REM Procedure for obtaining latent heat of vaporization at the
1273 REM given temperature when a value at some other temperature is
1274 REM known
1275 REM *****
1280 DEFPROCLATHEAT(T)
1290 TR=T/TCRIT:TRN=TNBP/TCRIT
1300 H=HNBP*((1-TR)/(1-TRN))Δ0.38
1310 ENDPROC

```

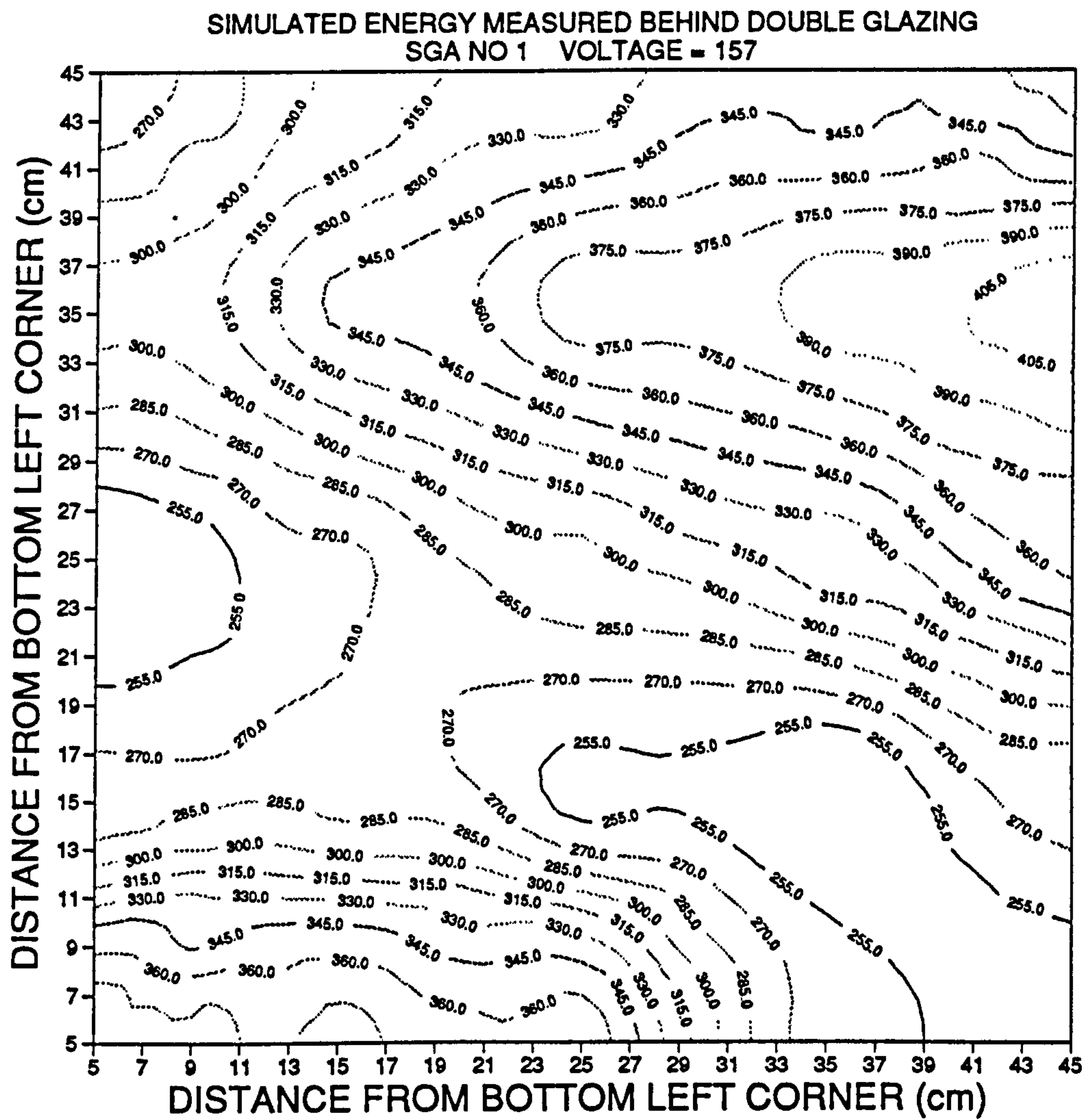
APPENDIX I



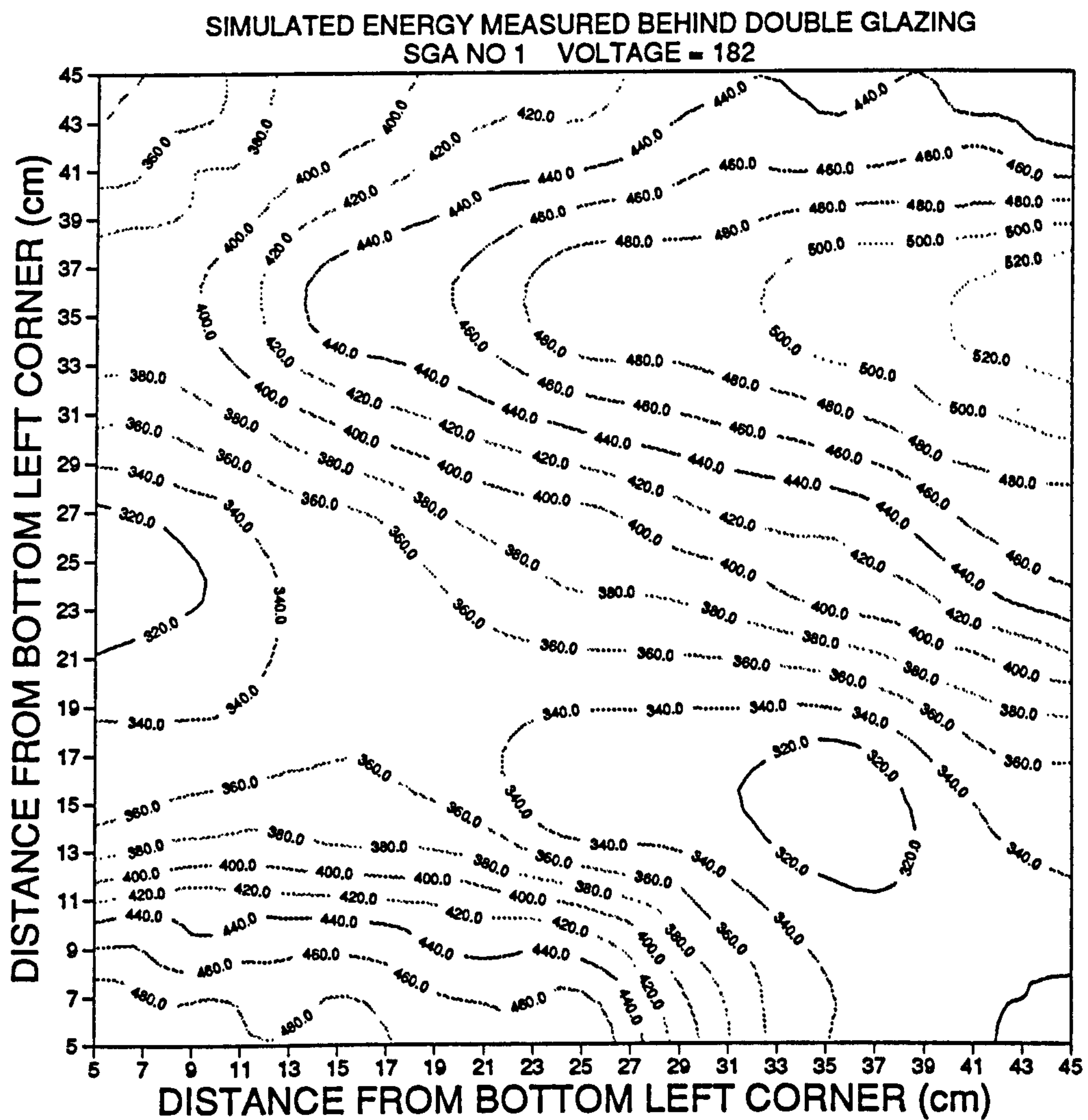
Average radiation energy (Wm^{-2}) = 172.17



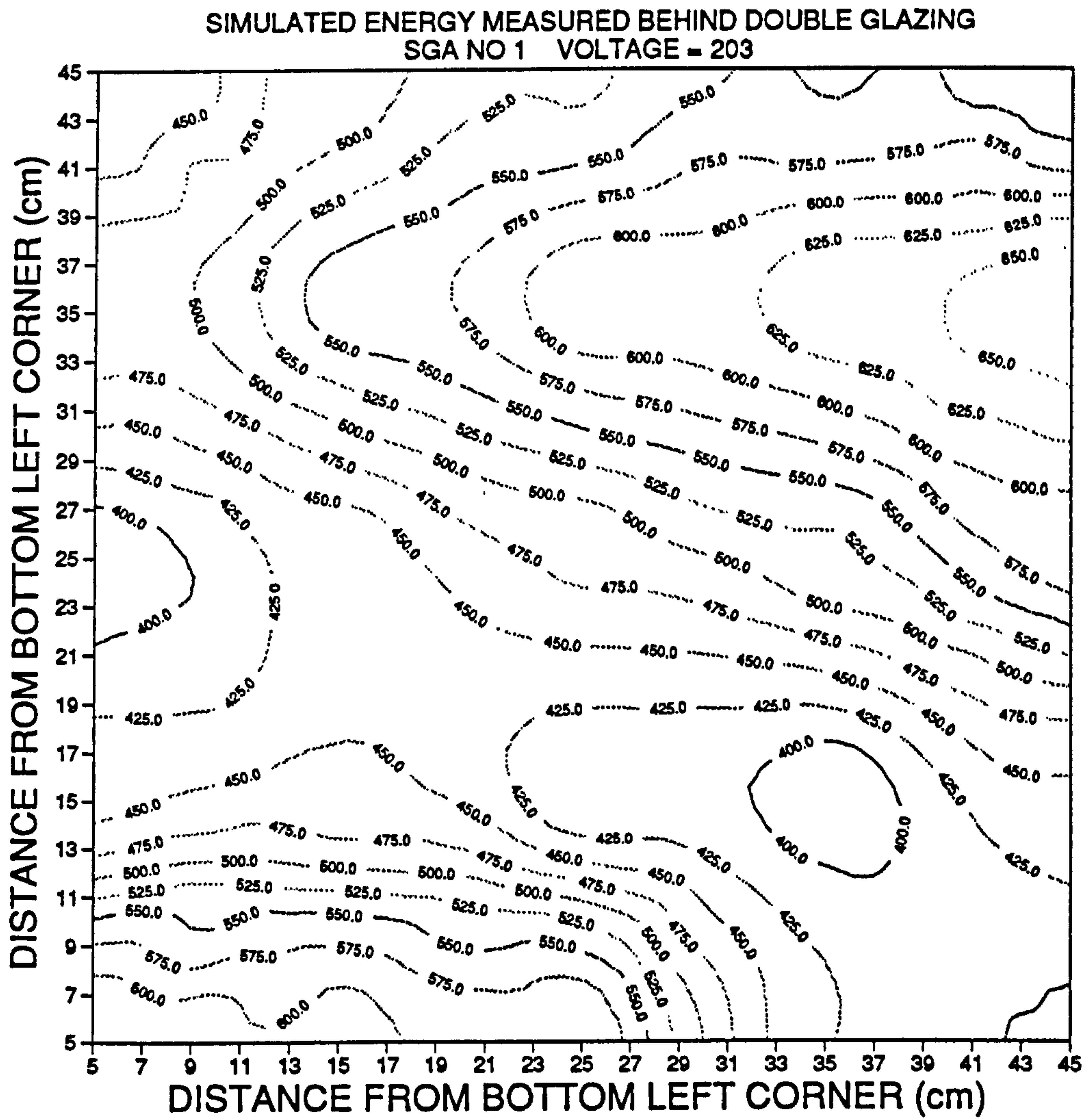
Average radiation energy (Wm^{-2}) = 235.02



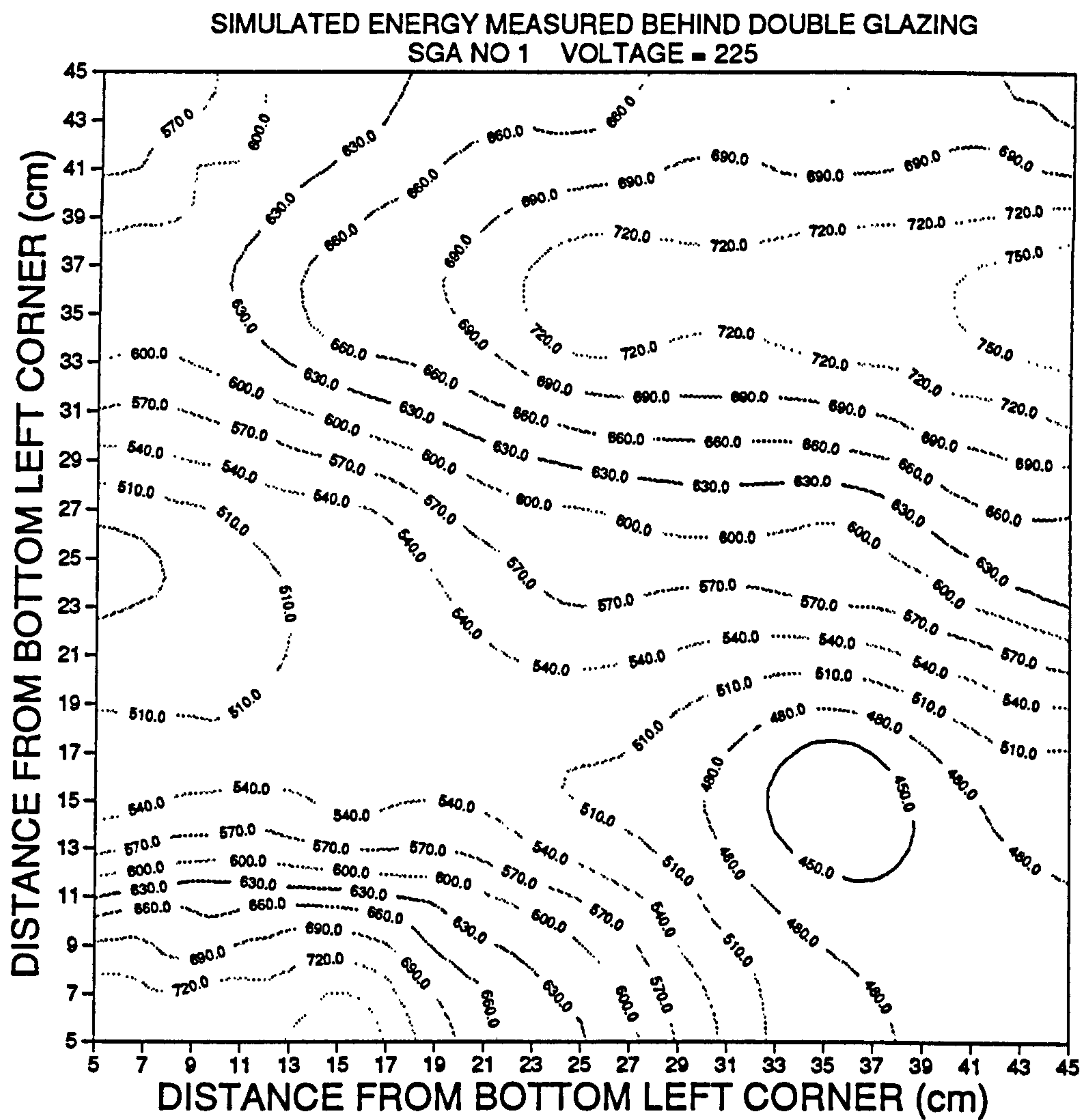
Average radiation energy (Wm^{-2}) = 313.13



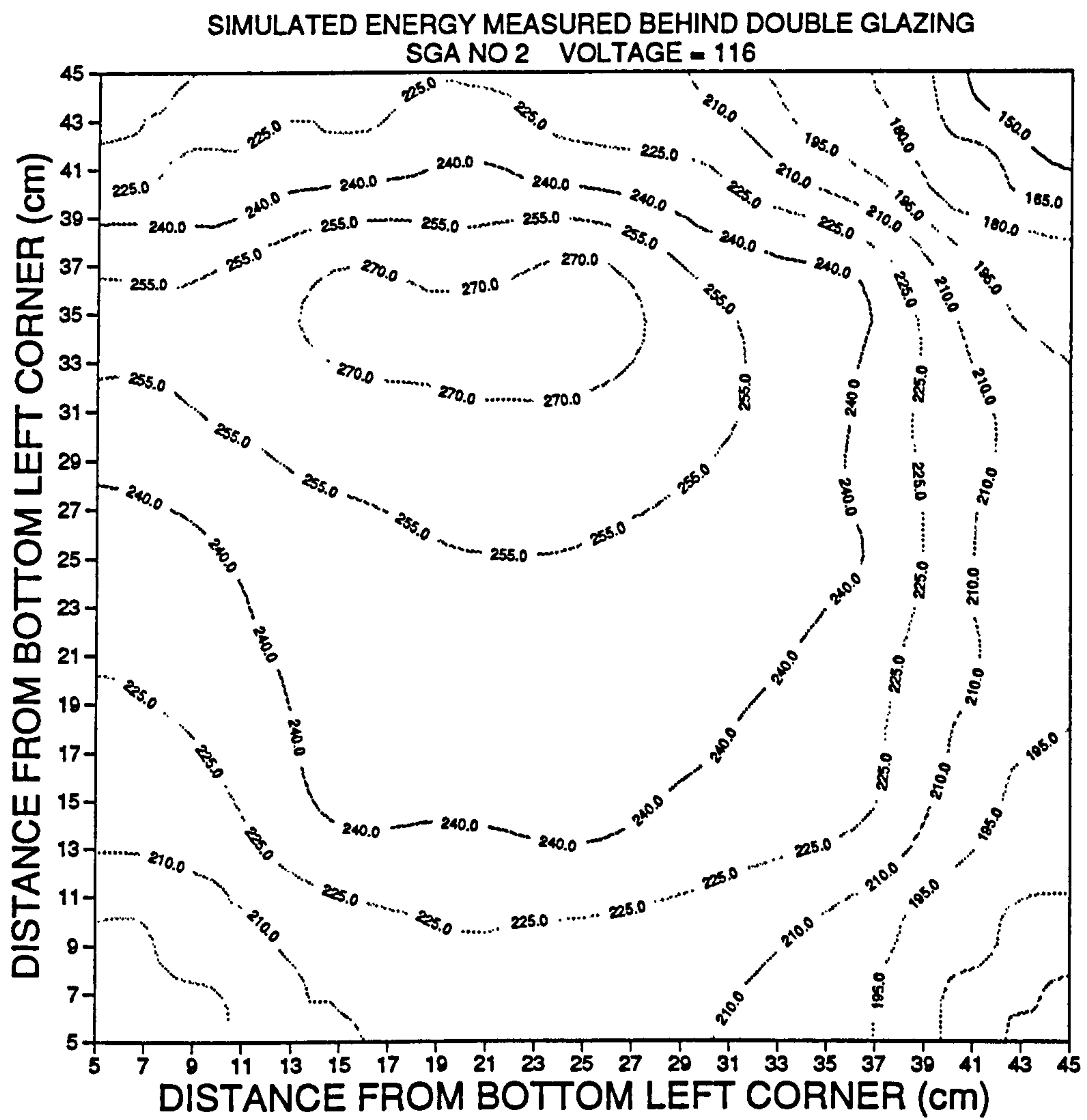
Average radiation energy (Wm^{-2}) = 403.17



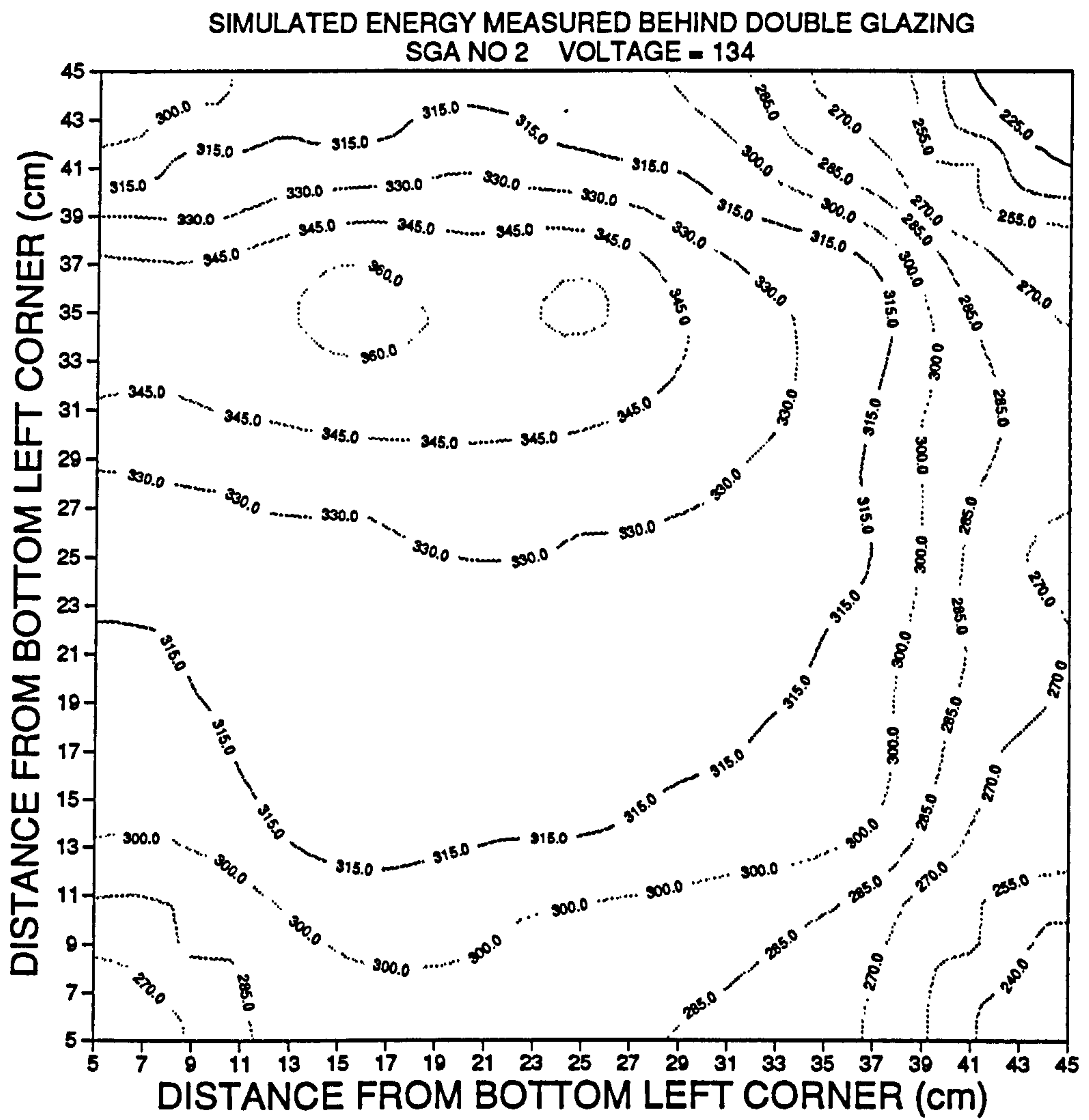
Average radiation energy (Wm^{-2}) = 506.61



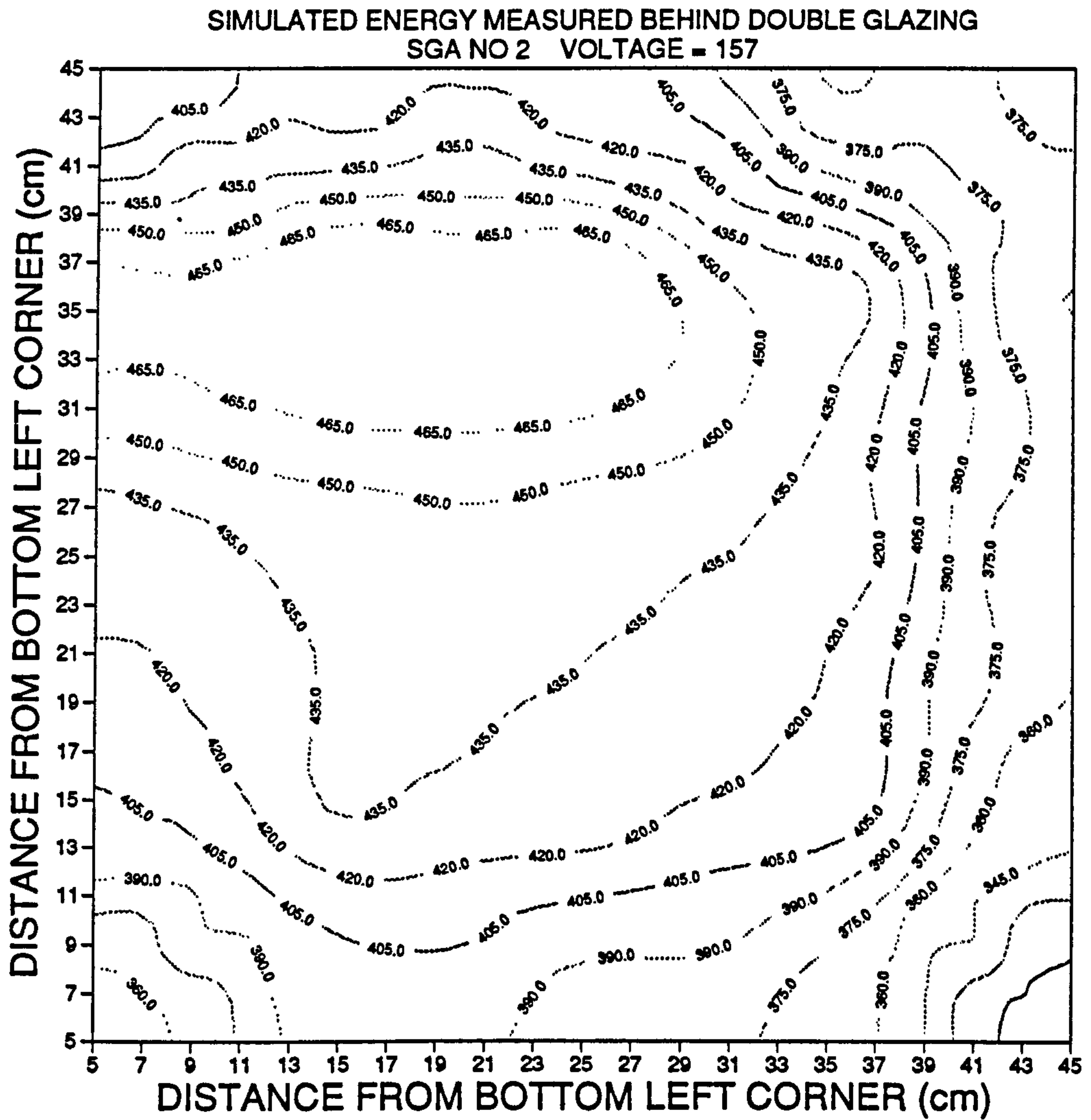
Average radiation energy (Wm^{-2}) = 600



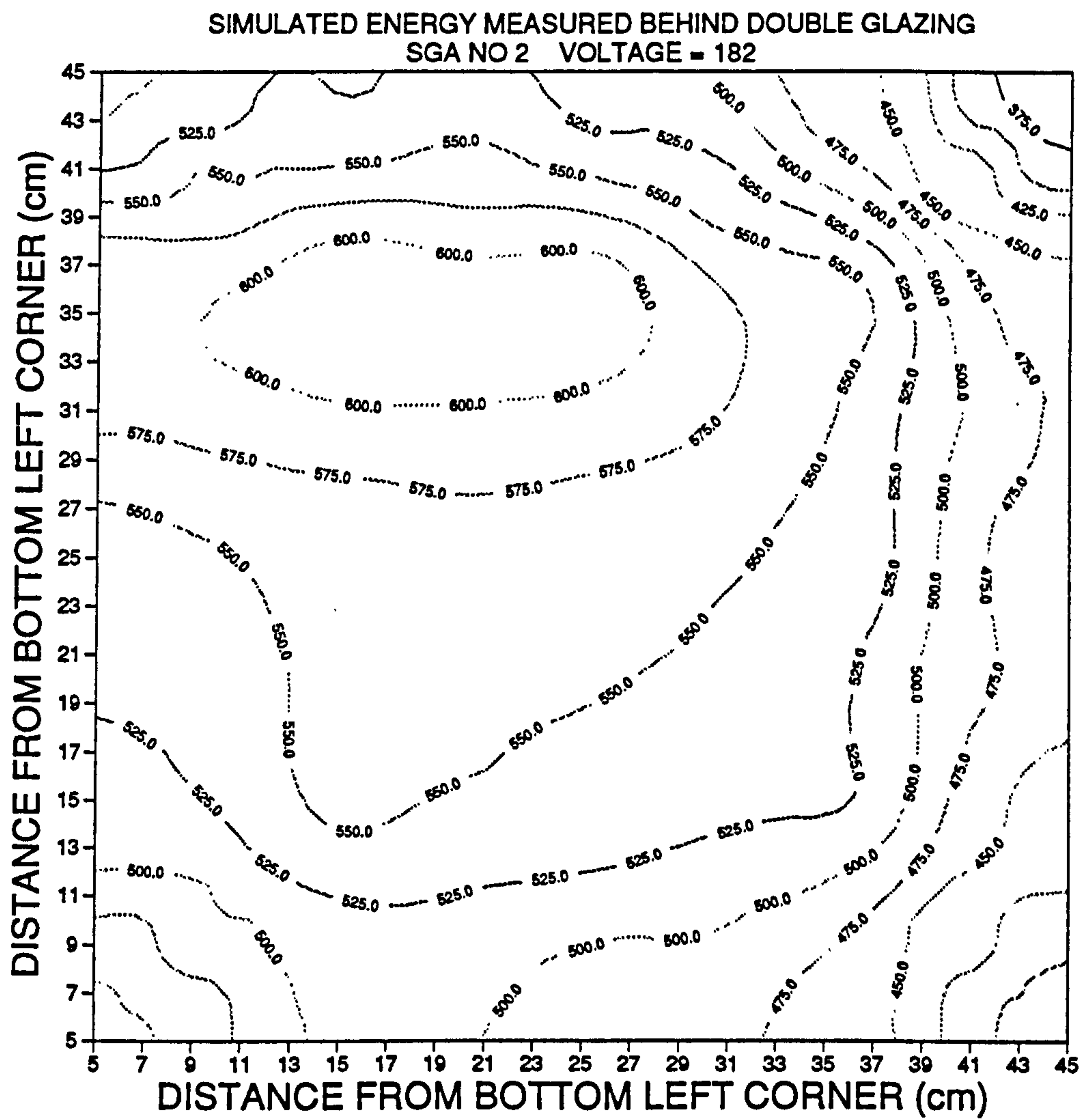
Average radiation energy (Wm^{-2}) = 229.86



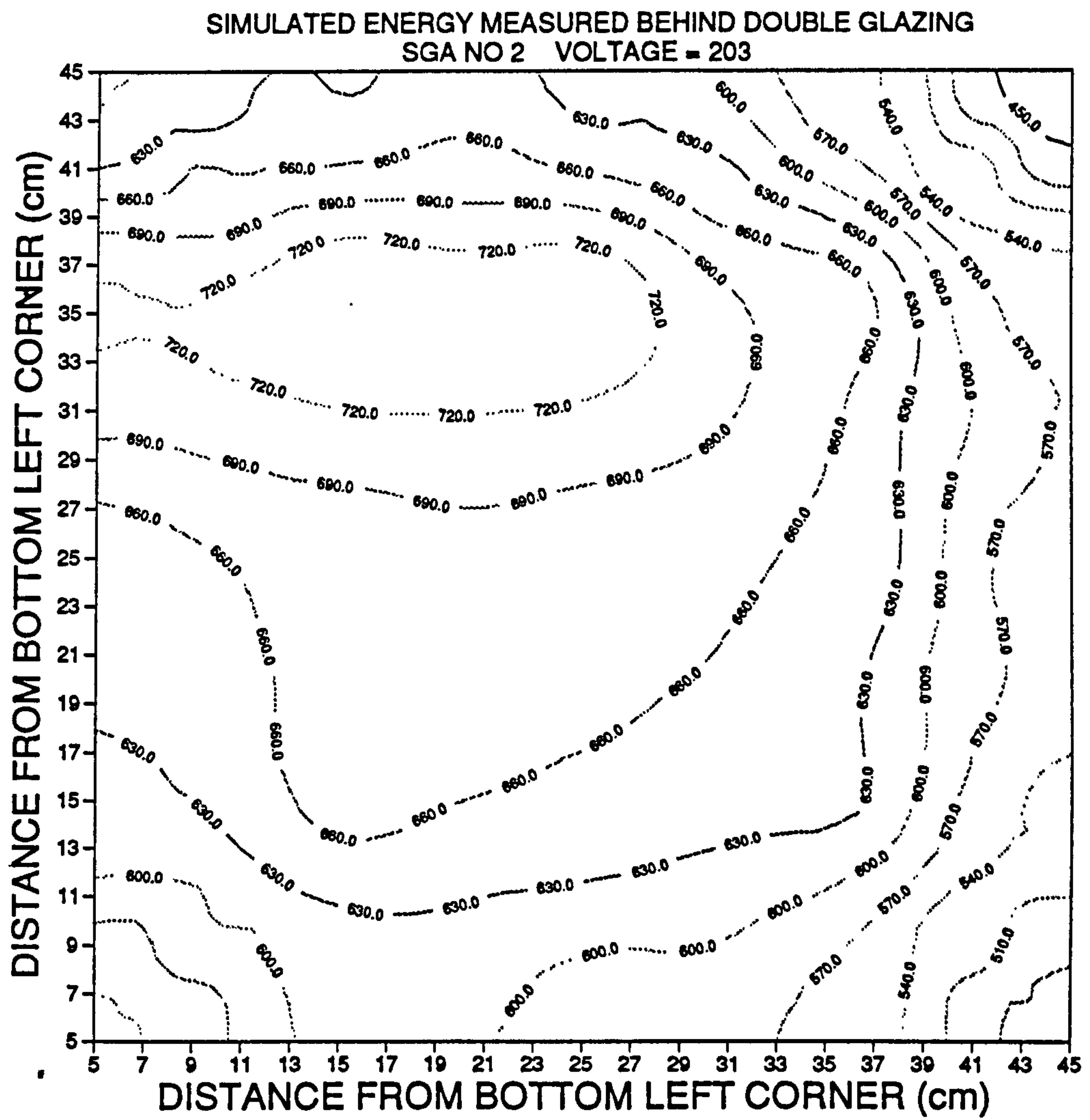
Average radiation energy (Wm^{-2}) = 310.31



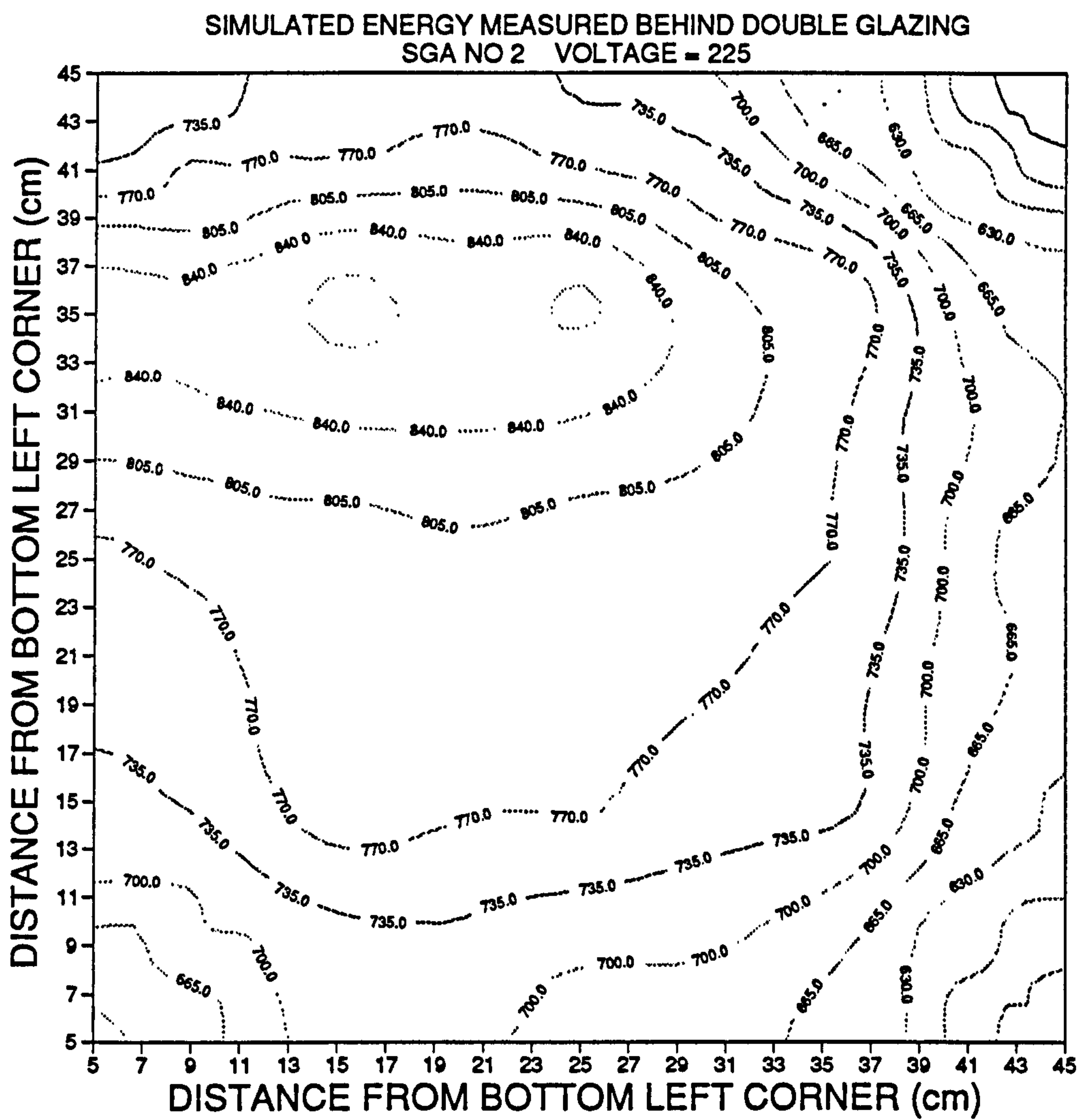
Average radiation energy (Wm^{-2}) = 417.79



Average radiation energy (Wm^{-2}) = 529.24



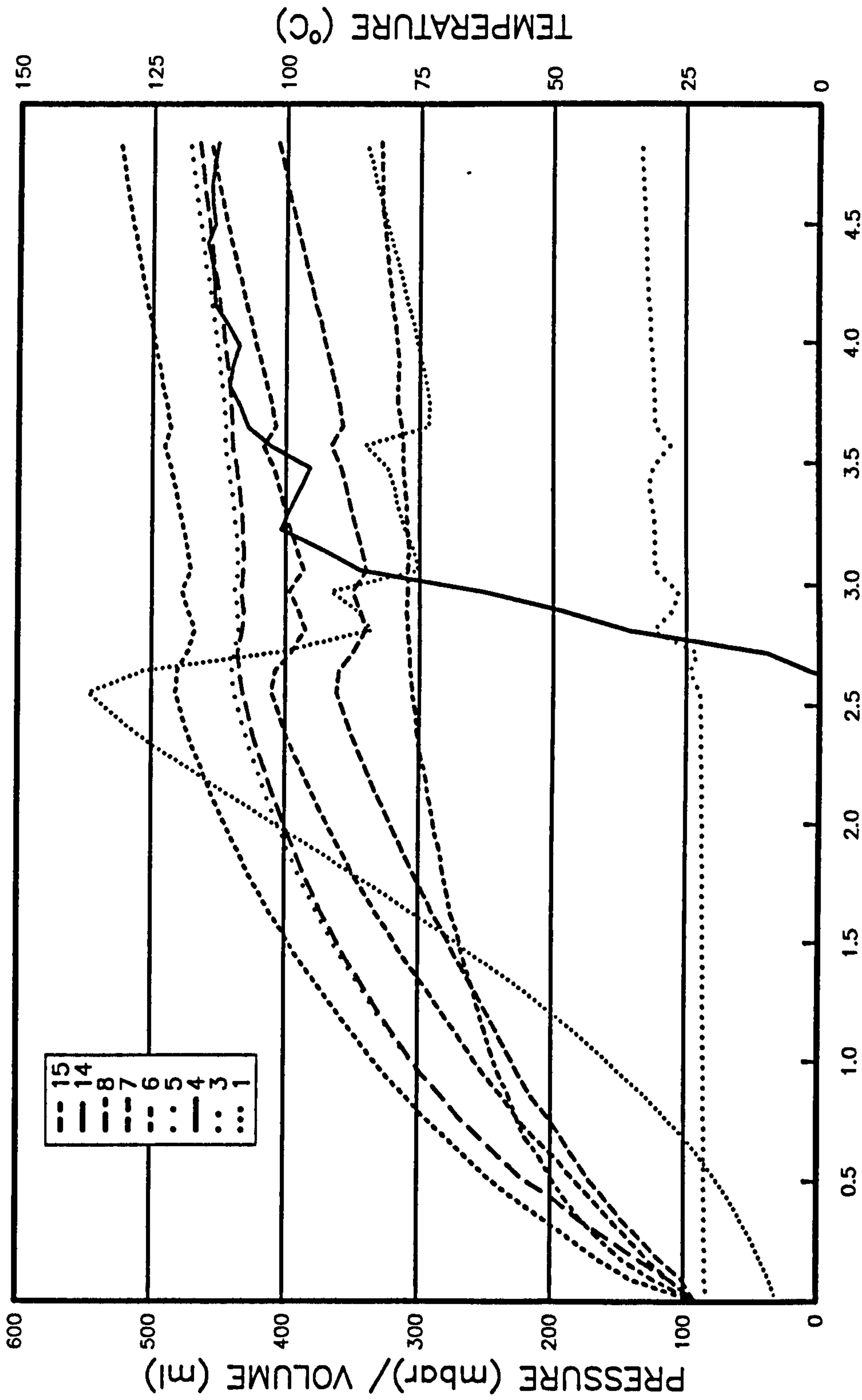
Average radiation energy (Wm^{-2}) = 637.69



Average radiation energy (Wm^{-2}) = 749.02

APPENDIX J

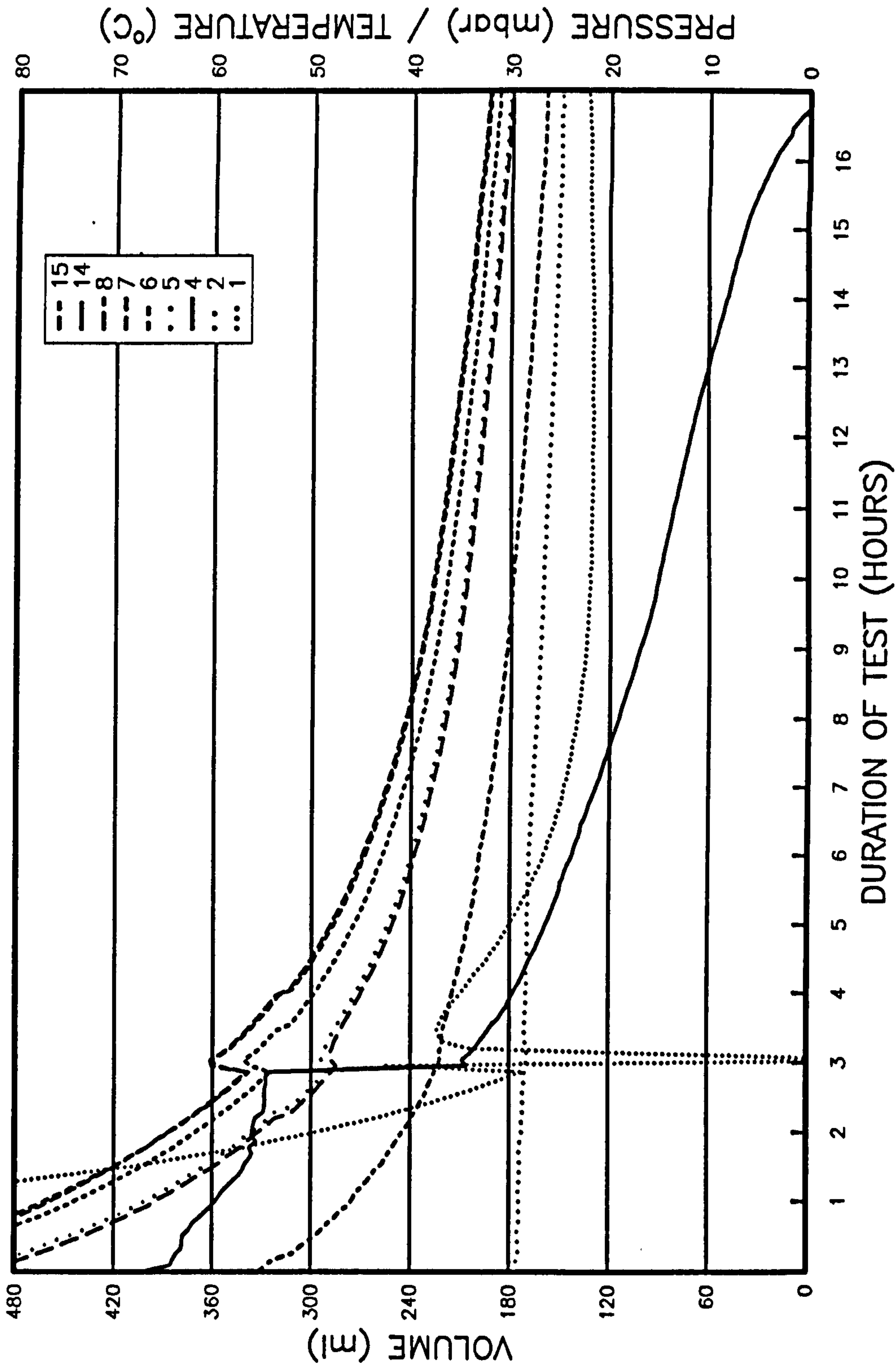
TEST DATE:16.6.89



DURATION OF TEST (HOURS)

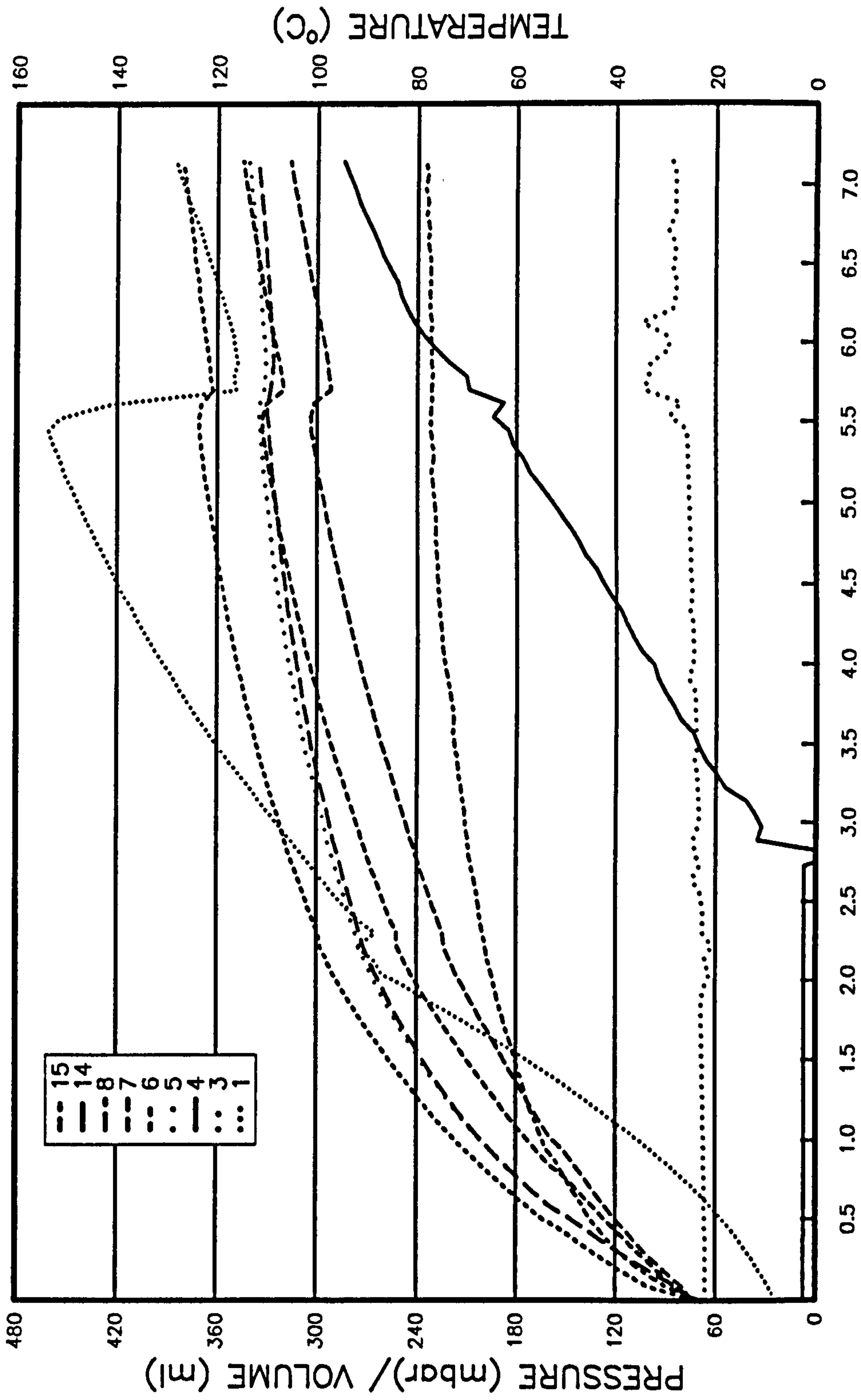
RADIATION = 506 Wm² COVER = DOUBLE

TEST DATE:16.6.89



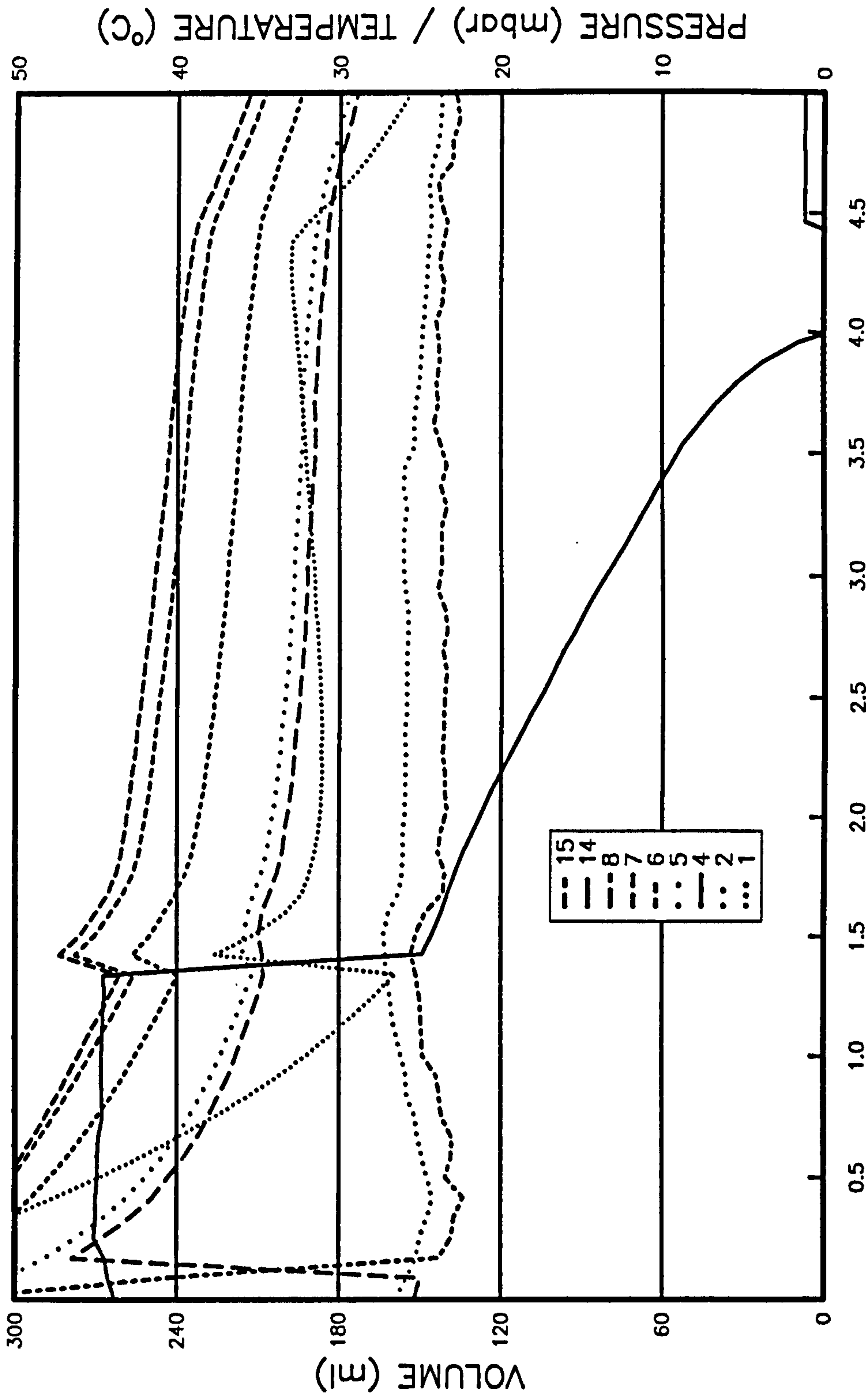
LOAD = 20 W COVER = DOUBLE

TEST DATE:19.6.89



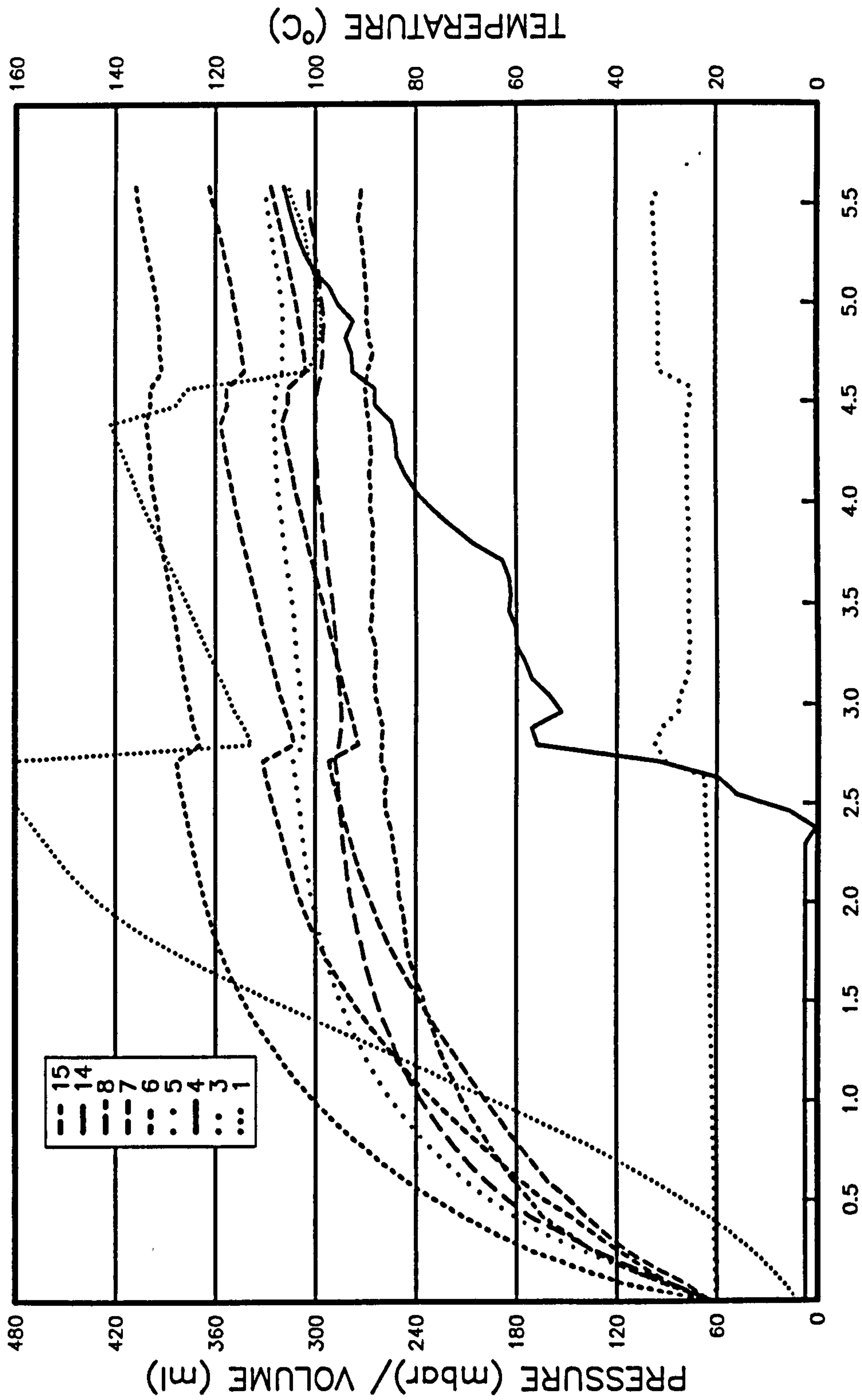
RADIATION = 403 Wm² COVER = DOUBLE

TEST DATE: 22.6.89



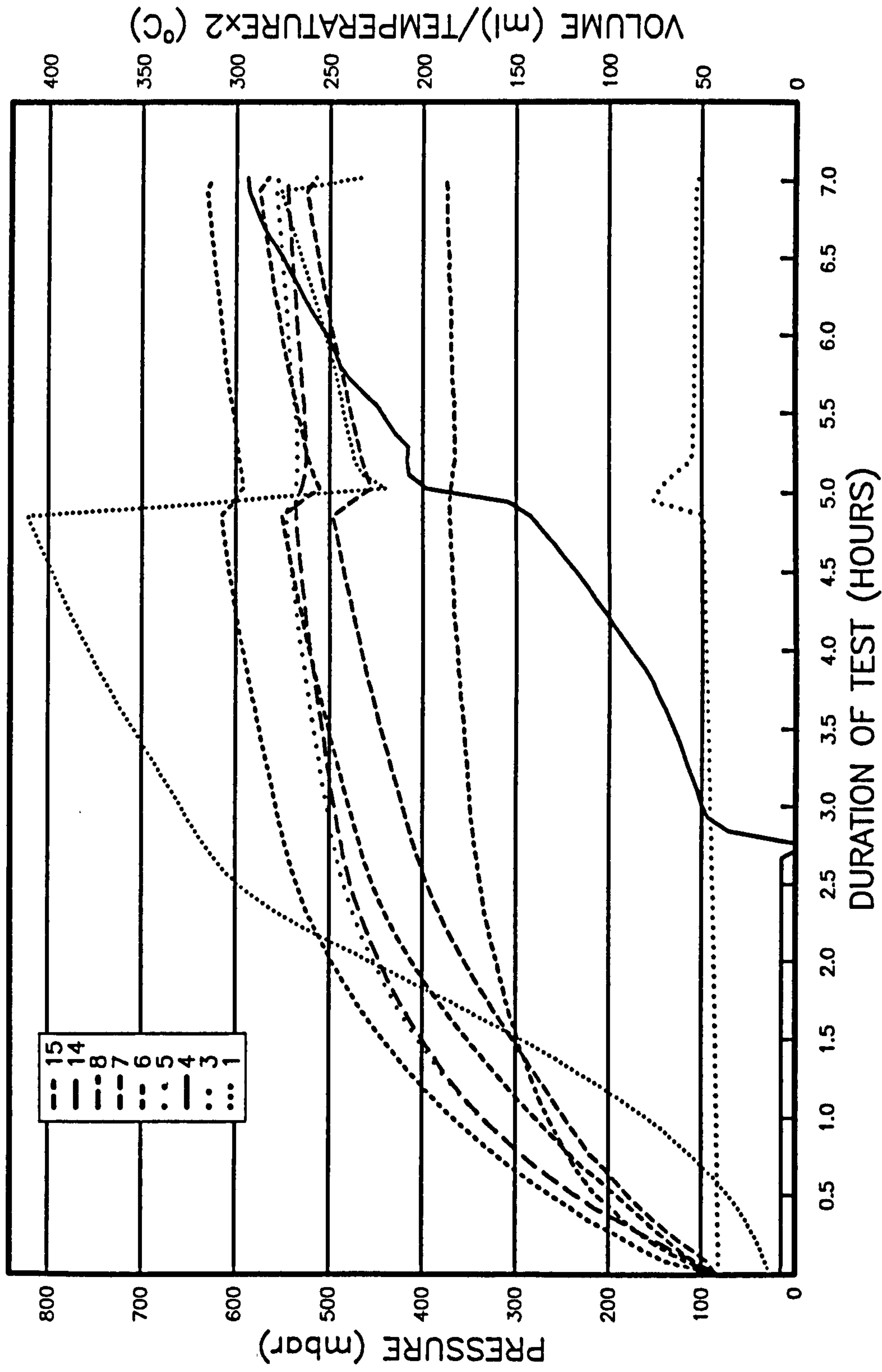
LOAD = 20 W COVER = SINGLE

TEST DATE: 23.6.89



RADIATION = 600 Wm² COVER = SINGLE

TEST DATE: 27.6.89



RADIATION = 600 Wm² COVER = DOUBLE