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IN-CORE MODERATOR TEMPERATURE MEASUREMENT WITHIN CANDU REACTORS

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The temperature profile of the D_2O moderator inside a CANDU (Canada Deuterium Uranium) reactor, within the calandria vessel, was measured by means of a specially instrumented probe introduced within the core. Measurements were made under steady and transient reactor conditions using two different sensors, viz. resistance temperature detectors (RTD) and type K chromel–alumel thermocouples. The results established the feasibility of in-core moderator temperature measurement and indicated that the thermocouples used were relatively not affected by the intense radiation fields thus producing more accurate data.

1. Introduction

The program required the measurement of the temperature profile of the moderator water (D_2O) inside the calandria vessel of Unit 3 at Bruce nuclear generating station, for various steady and transient conditions.

The purpose of these tests was to obtain practical experimental data of the temperature profile and to verify a theoretical computer code – MODCIR (a Company generated computer program for MODerator-CIRculation).

Attaining more accurate temperature distribution within the calandria vessel (fig. 1) allows greater confidence in assessing the effectiveness of the moderator as a heat sink for specific postulated accident conditions, e.g., a loss of coolant accident.

2. Approach taken

The system devised is shown in fig. 2. The design was to construct a long probe and instrument it with temperature sensors whose sensing elements were located at regular intervals along the length of the probe. The probe and sensors were to be inserted vertically into the calandria so that the sensors were immersed into the

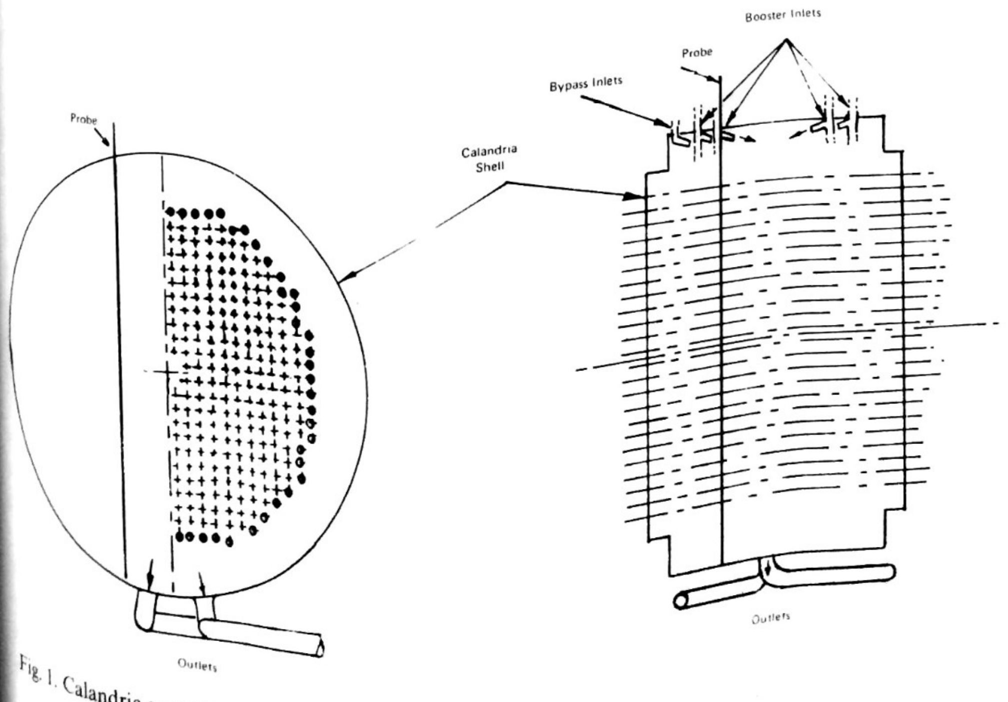

Fig. 1. Calandria vessel in a CANDU reactor.

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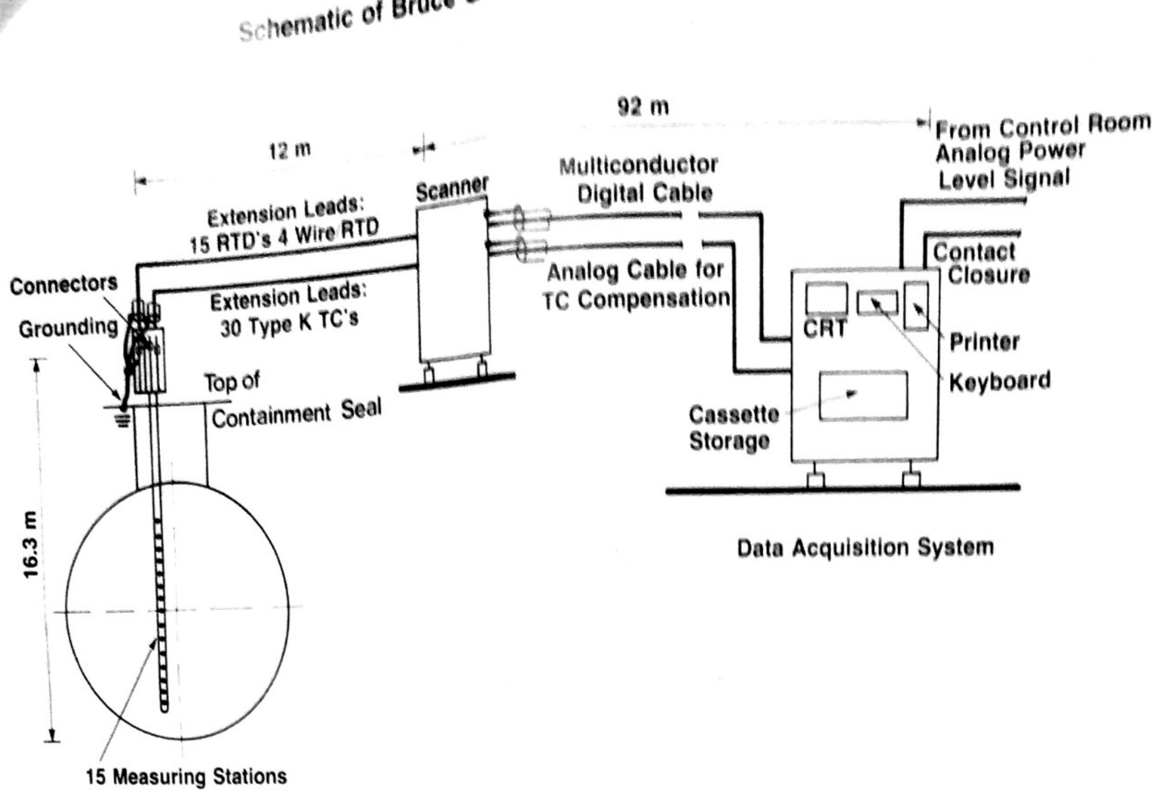

Fig. 2. Schematic of Bruce generating station 'A' temperature measuring probe.

moderator D_2O. The probe would replace a shut-off rod which was to be removed.

A data logging system (a scanner, a microprocessor-based datalogger, a printer, and a tape storage system) would handle the signal processing.

3. Ambient conditions

The radiation conditions within a CANDU reactor at full power can be:
gamma dose rate: 200×10^6 rad/h,
fast neutrons ($E > 1$ MeV): 2×10^{13} n/cm^2 s,
thermal neutrons: 3.6×10^{14} n/cm^2 s,
above the reactor deck: 20 mrad/h.
For the type of sensors selected, the heat generation rate would be about 5 W/cm^3.

The expected temperature range of the moderator was 30–80°C from zero power to full power respectively.

4. Description of the apparatus

4.1. The probe

The probe, 16.2 m (53′2″) long and 92 mm dia. (3 5/8″), basically consisted of two zircalloy adjuster-rods guide tubes welded together to obtain the requisite length. Mounted around the circumference of the probe were 45 temperature sensors at 15 measuring stations each of which comprised 3 sensors (an RTD and two thermocouples of different sizes). The stations were spaced at 50 cm intervals, as in fig. 3. The sensor cables were strapped onto the perforated probe with the sensors' tip location corresponding to the perforations to allow the moderator D_2O to circulate freely through the assembly and around the sensors. A typical measuring station is shown in fig. 4. The probe was made to fi

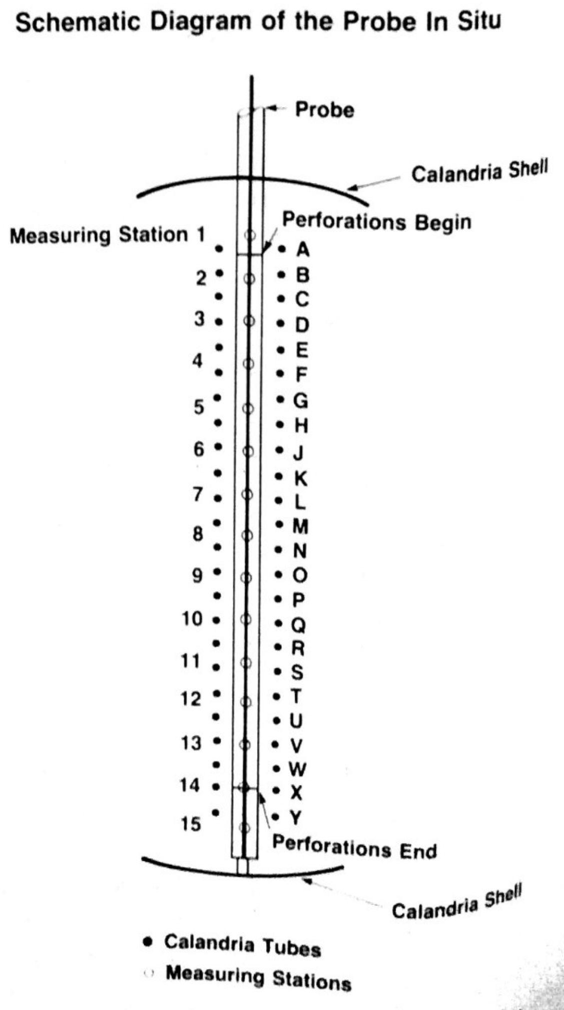

Fig. 3. Schematic diagram of the probe in-situ.

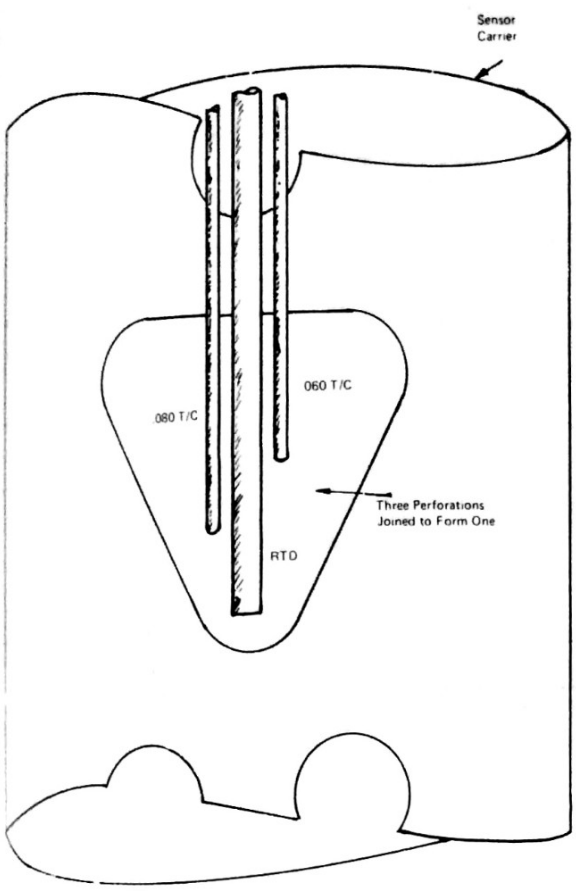

Fig. 4. Close-up of a measuring station.

into a guide tube and kept concentric by means of spring loaded pads.

The sensors emerged out of containment through a cover plate via compression fittings viz Swagelocks which maintained the containment boundary.

Sensor lengths varied from 16.3 m for the longest to 9.3 m for the shortest.

4.2. *The data acquisition system (DAS)*

The DAS consisted of the datalogger which incorporated a programmable microprocessor. Data were recorded by an external printer and on magnetic tape.

Some 92 m away, a scanner detected the e.m.f. signals from the 45 sensors by scanning periodically at pre-programmed times, or continuously, as required, and transmitted them to the datalogger. Scanning was achieved by selectable modes, low resolution (35 sensors per second), and high resolution (10 sensors per second). The slow scan rate was used for measurements during steady power conditions, and the faster scan rate was used during power ramps and reactor trips where fast temperature and radiation level transients usually occur.

Analog-digital conversion of the sensor signals was performed in the datalogger. The digital signals, including contributions from electronic cold junction compensation for the thermocouples, were converted to temperature readings by means of polynominal approximations of the sensor characteristics.

Another input to the scanner was an analog signal from the station computer which indicated the reactor thermal power at every scan in linear correspondence.

The datalogging system was equipped with a line conditioner to minimize power line transients resulting in noise and/or spikes.

5. Temperature sensors

Due to the intense radiation environment within which the sensors have to operate, it was considered prudent to build redundancy into the measuring system should a sensor type fail, as well as to provide the means for comparing measurements.

Study of the literature, refs. [1–6], and communications with various institutions and research facilities, ref. [7], recommended the use of type K chromel–alumel minerally insulated sheathed thermocouples. The high nickel content of chromel–alumel and the fact that nickel has a low neutron capture cross section makes this thermocouple recommendable for use in intense radiation environments. There was reluctance to use resistance temperature detectors (RTD's), but insufficient data to explain the reasons other than that platinum RTD's were not successful in similar environments when measurements were taken at Oak Ridge National Labs.

It was decided to use nickel RTD's instead of platinum, so that transmutation effects would be negligible for the duration of the tests.

Different dimensional sizes were selected to enable cross-correlation of the collected data whereby the radiation effects, which are proportional to the sensors' mass and radiation intensity, could be taken into account, should they be significant.

The sensor cable diameters have been kept to a minimum commensurate with ease of manufacture and yet maintain the required high insulation where $10^{11}\ \Omega$ at 100°C was achieved. Material selection and design criteria took into consideration the possible means of minimizing gamma-ray heating, transmutation effects, radiation-induced current, and alloy inhomogeneity. A strict quality assurance programme was adhered to during the manufacturing processes.

5.1. *Thermocouples used*

Chromel–alumel type K thermocouples were used, each clad in a type 316 stainless-steel sheath, as shown in fig. 5. These were grounded types to ensure good thermal contact with the moderator.

An added feature to the thermocouples was to heat-treat them for 24 h at 430°C to induce short-ranged

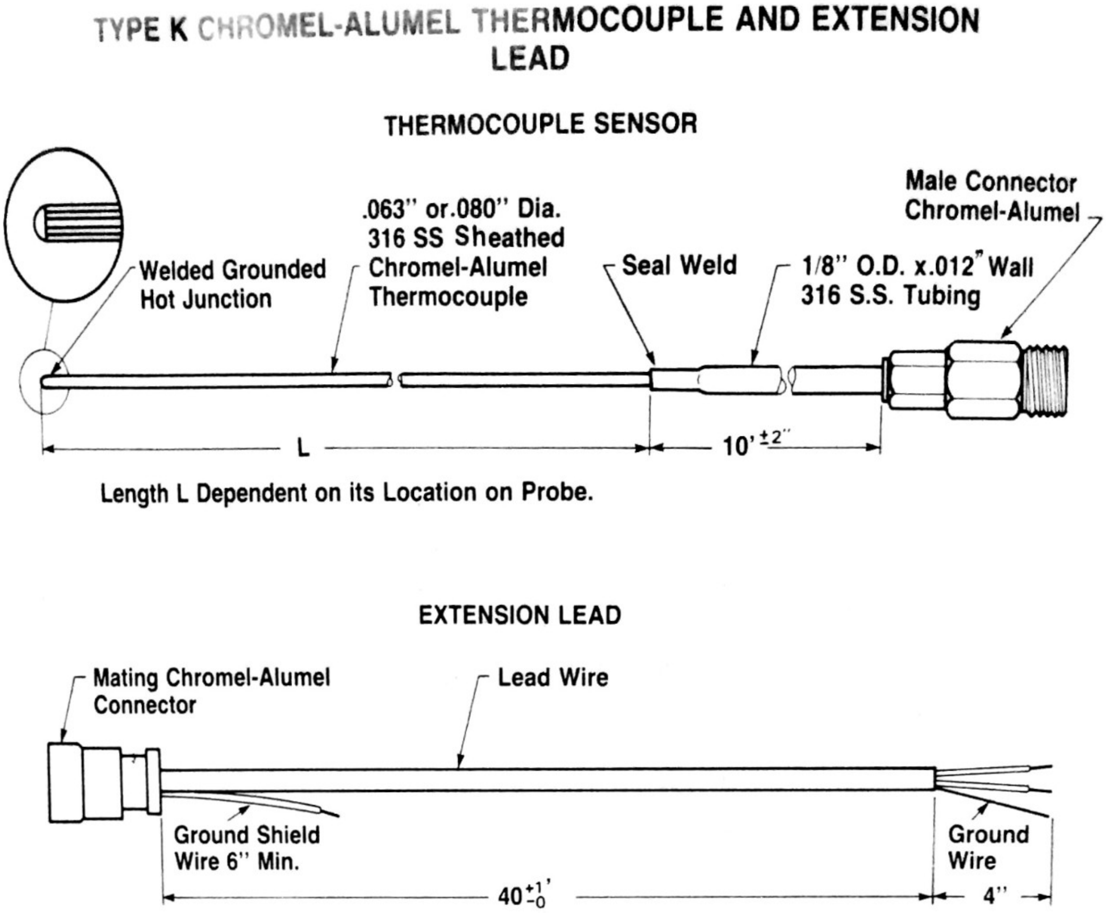

Fig. 5. Type K chromel–alumel thermocouple and extension lead.

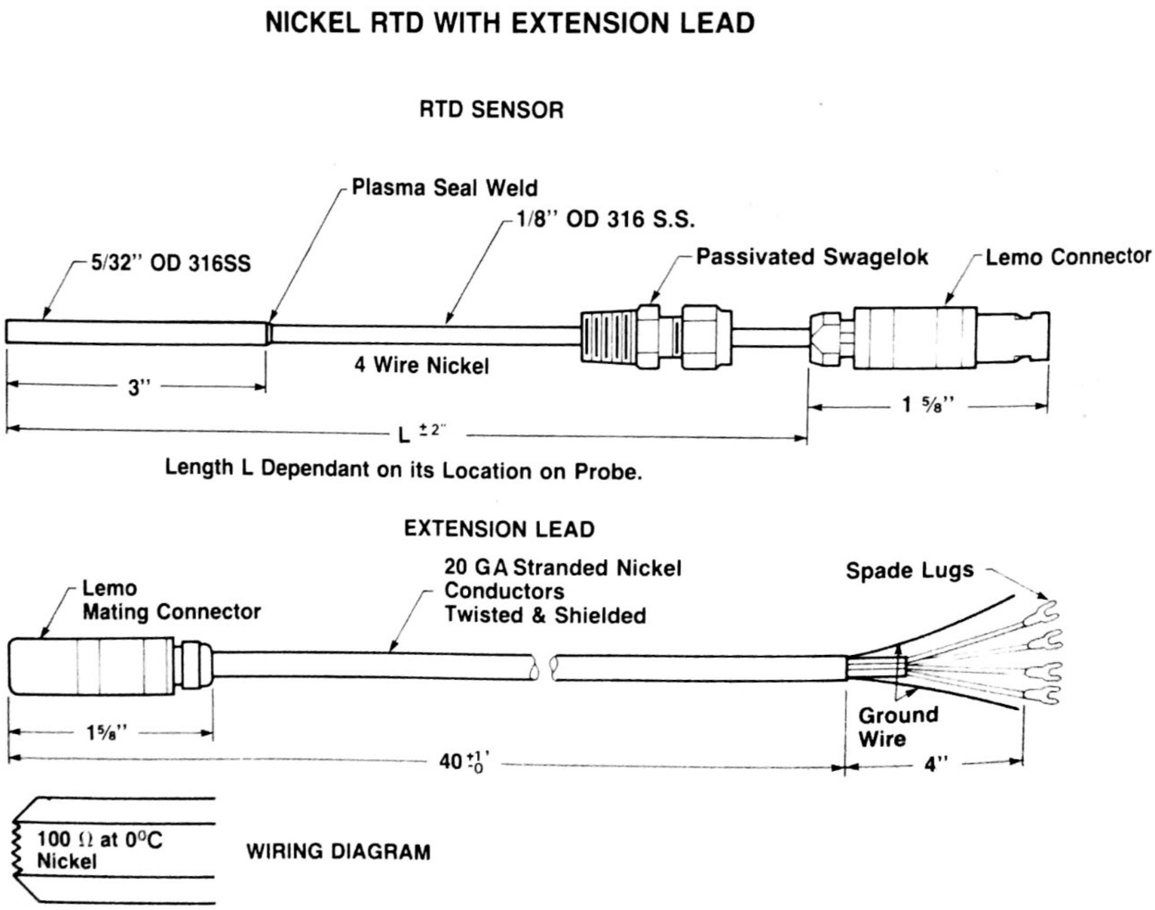

Fig. 6. Nickel RTD with extension lead.

ordering in the chromel, which is a restructuring of the molecule of a binary alloy, ref. [8].

5.2. *Resistance temperature detectors (RTD's) used*

The RTD's were nickel bulb 4-wire types clad in type 316 stainless steel sheath, and having a 1/8″ diameter along its entire length after the bulb and are shown in fig. 6.

5.3. *Grounding*

Each of the sensors was grounded, at the containment boundary, to a common node, fig. 2. The signal cables were shielded, twisted pairs.

6. Possible sources of errors

The main sources of errors were looked into and, generally, these include errors caused by:

6.1. *Gamma-ray heating*

A thermocouple, or RTD, introduced in a very high gamma radiation environment would indicate a higher reading due to the radiation. In a power reactor, typical fields of 200 Mrad/h at full power contribute a heat source term of about 5 W/cm^3 for the sensor materials used causing them to read higher.

The use of grounded thermocouples minimizes this error since the hot junction is in direct contact with the medium it is measuring. A significant error would likely occur if there is poor heat transfer between the measuring element, and the moderator.

Since radiation heating is mass dependent, the sensors used were of different sizes so that this effect would be quantified by cross-correlation.

6.2. *Transmutation*

These are changes in the composition of the sensing elements leading to temperature drifts with time. Transmutation is caused by the absorption of neutrons within the atomic nucleus of the material used, i.e., by neutron capture. From ref. [9] chromel–alumel thermocouples are least affected since they consist largely of nickel which does not undergo significant changes over a long time span (a few years) when irradiated under power reactor conditions. For similar reasons the properties of nickel RTD's would not be expected to change for the duration of these tests.

6.3. *Radiation-induced currents*

These are likely to result from a flow of electrons induced between the core wires and the outer sheath of a thermocouple or RTD cable due to ionization of the cable materials by nuclear interactions. There is conflicting evidence as to the magnitude of these currents where some experimenters have found them severe, whilst others found them negligible.

Since this effect was expected to be geometry dependent, it provided another reason to choose sensors of different dimensions, again for cross-correlation purposes.

6.4. *Calibration errors and material inhomogeneity*

These errors are the deviations from the calibration curves published by the National Bureau of Standards. For type K thermocouples and within 0–250°C the specified accuracy is ± 2°C for standard wire, or ± 1°C for special wire. The thermocouples used were of the premium grade special wire from the same batch.

6.5. *Cold work error*

Care was exercised during the manufacture of thermocouples, and during assembly of the probe, to minimize the possibility of cold working the thermocouples.

A quality assurance test was designed to check for the presence of cold work and material inhomogeneity. A 5 cm section of the thermocouple was heated by hot air flow using a travelling gradient approach, ref. [2].

6.6. *Ice-point resistance (in RTD's)*

This comes from the basic Callender equation relating the element resistance R_T at varying temperatures T.

$$R_T = R_0(1 + aT + bT^2 + cT^3 + \dots),$$

where R_0 is the RTD resistance at 0°C, i.e., the ice-point resistance and a, b, $c\dots$ are first, second and third order temperature coefficients of resistance.

Generally, nickel RTD's are specified to have $R_0 = 100 \pm 0.2\ \Omega$.

Each RTD was individually calibrated to obtain its ice-point resistance, and this error was calibrated out.

6.7. *Self-heating errors (in RTD's)*

To get an output from an RTD, a current must pass through it which induces self-heating. Typically 0.1 mA is used. In the system devised, this was not a continuous current but was only present when the RTD was being scanned.

The error introduced by this magnitude of intermittent power dissipation was difficult to predict as it depended on the thermal conductivity – and hence the compaction of the insulant, as well as the flow of coolant surrounding the RTD.

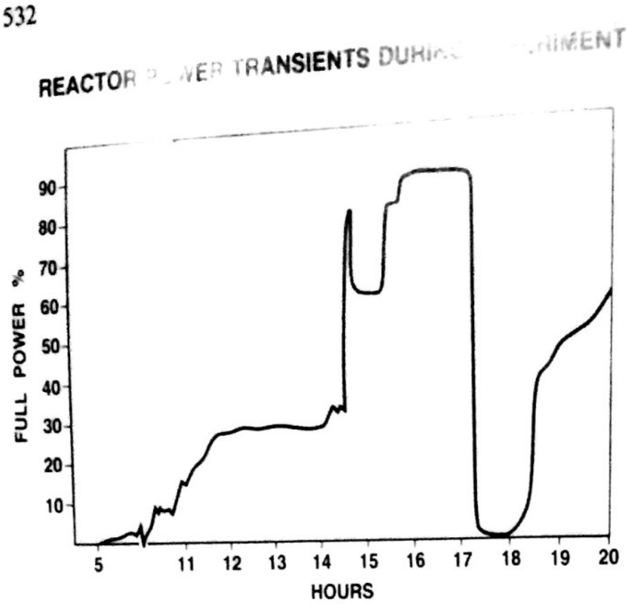

Fig. 7. Reactor power transients during experiment.

6.8. Measuring system error

These are the errors in the data acquisition system and are found noted in the manufacturer's operating manuals as $\pm 0.1°C$ at high resolution (slow scan) and $\pm 0.9°C$ at low resolution (fast scan).

6.9. Common mode errors

The errors arise when voltages which are common to both signal input wires are converted to normal output signals by the measurement system. A typical common mode error is a voltage difference between sensors' ground and the instrument ground resulting in ground current flowing in the sensors' wires.

The common mode rejection for the datalogger used

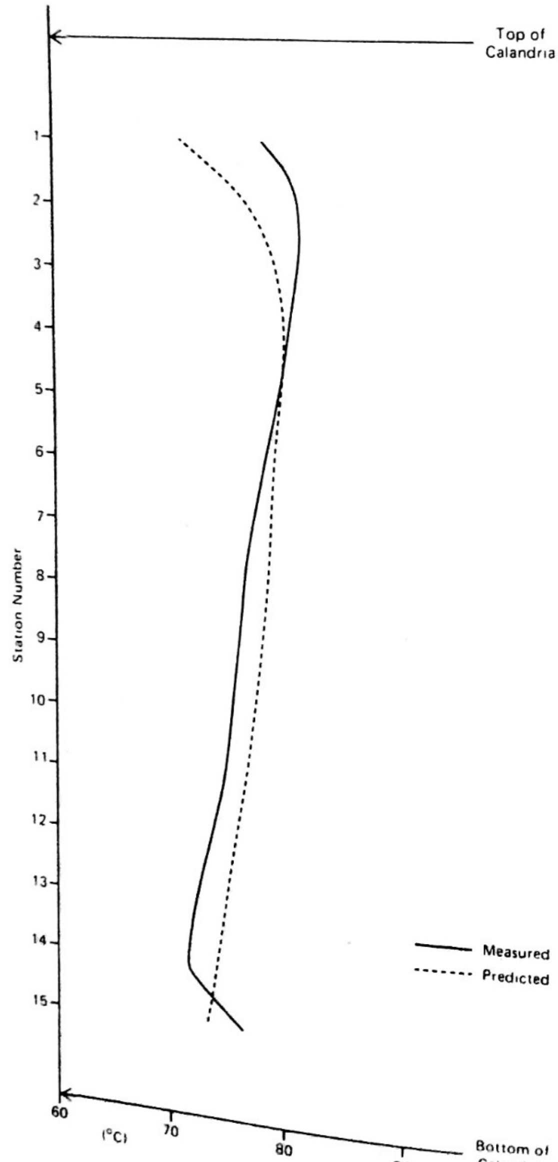

Fig. 8. Measured and predicted temperature profiles along the probe at 88% full-power.

could be translated into a measurement error of 1.0 (fast scan) or 0.4 μV (slow scan) for a common mode signal of 100 V.

7. The test program

Fig. 7 shows the reactor power transient during the test program. The station operating staff required an extended period at low power (hours 12–14) followed by a rapid ramp to almost full power with an immediate setback (hour 15). During these transients, data were continuously recorded.

Though the measurements and data were primarily being recorded from the temperature measuring probe, the entire program was also being verified by on-going parallel measurements by recording heat exchanger service water flow rates, and moderator heat exchanger inlet and outlet temperatures as well as measurements of neutron flux in the vicinity of the probe to record temperature fluctuations with flux intensities.

The reactor was finally brought to full power (hour 16) and moderator temperatures taken at the steady-state condition.

A reactor trip (hour 17 1/2) was initiated so as to enable the assessment of the gamma heating effects which were discussed earlier. The reactor was gradually brought up to power again and the probe was left within the reactor to routinely monitor on a long-term basis till the next shutdown when it will be withdrawn.

8. Discussion

The results of the tests have established the feasibility of in-core moderator temperature measurement (within the range of 30–80°C) and were very close to the data predicted by a theoretical computer code –

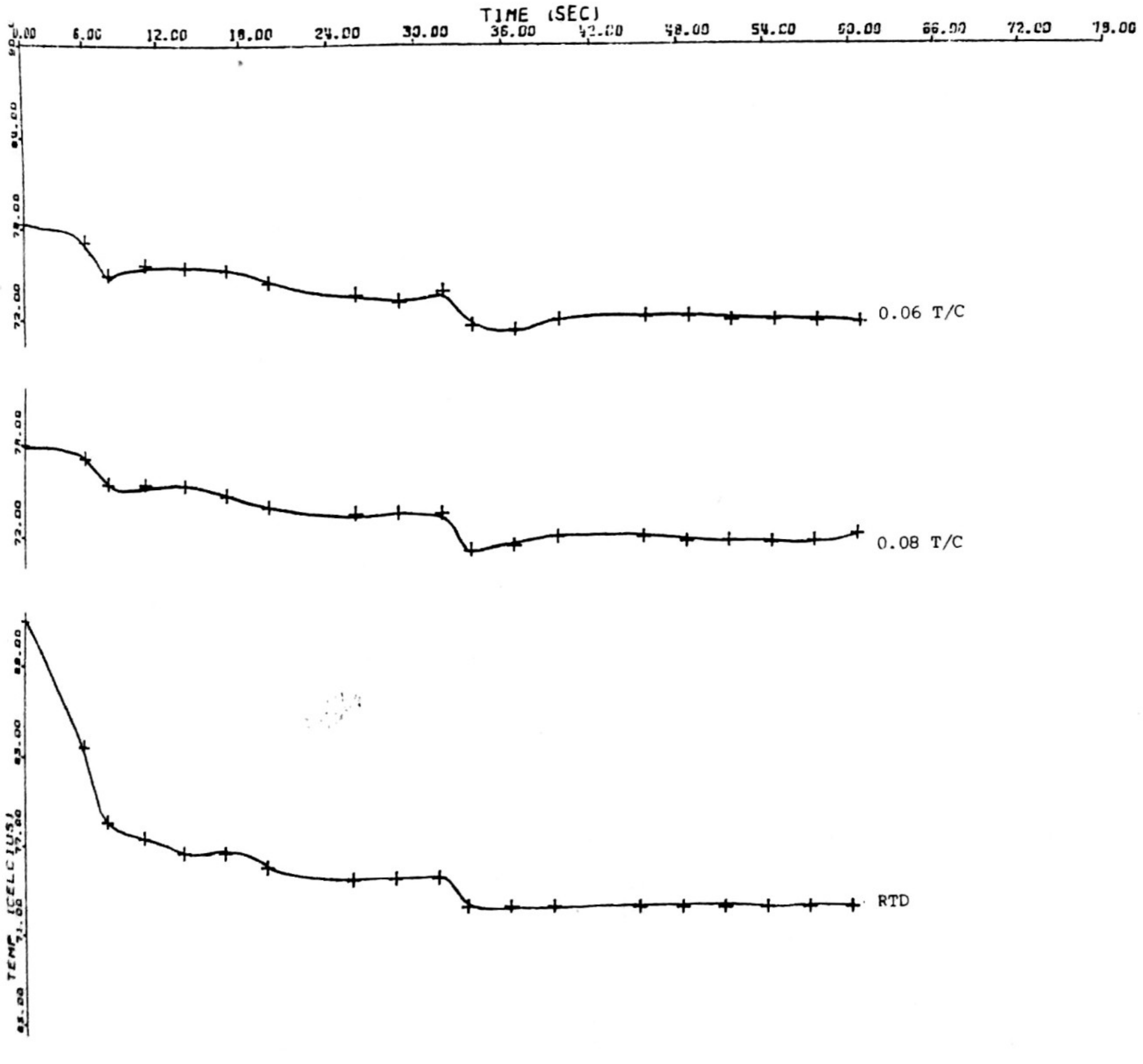

Fig. 9. Temperature readings, after the trip, from the sensors at station 8.

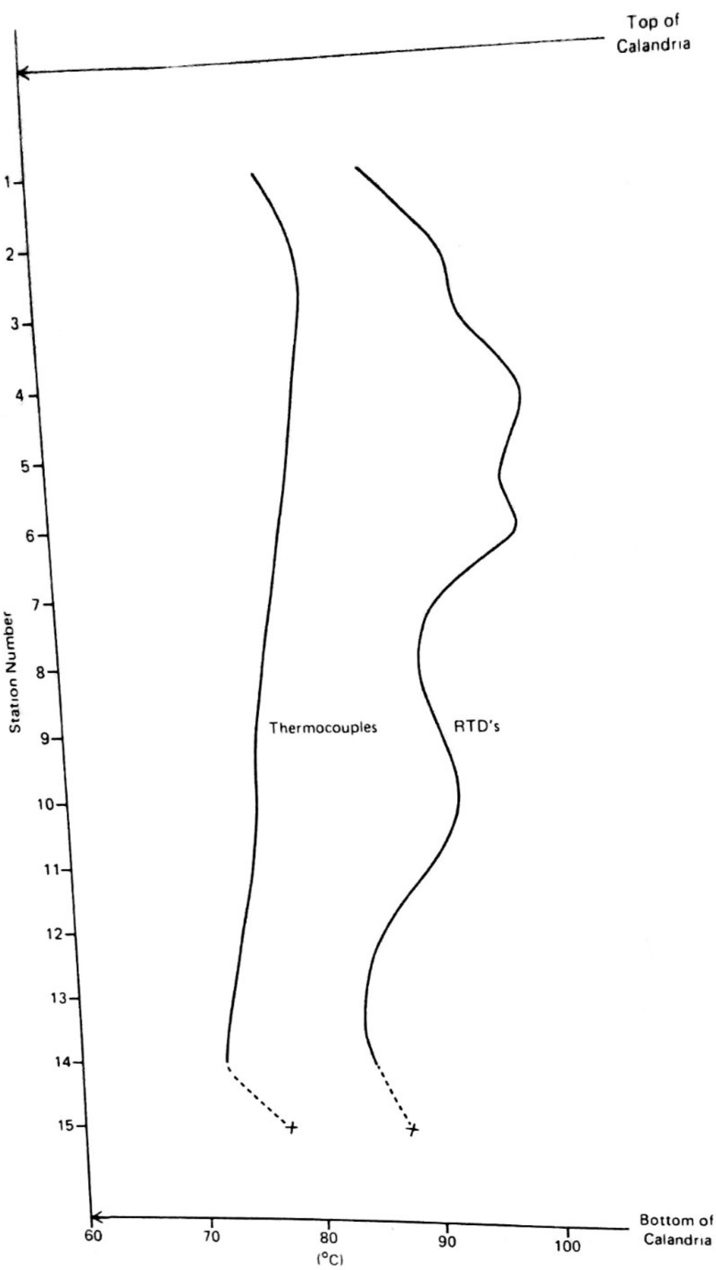

Fig. 10. Comparison of RTD and thermocouple readings at 88% full-power.

MODCIR. This may be seen in fig. 8. The divergence at the top and bottom readings were attributed to modelling constraints on the computer code and to the lack of perforations at either end of the guide tube, thus leaving pockets of relatively stagnant or less circulating moderator fluid.

Throughout the test the standard deviation of the pairs of thermocouple readings was less than 0.8°C of which about 0.5°C was a constant discrepancy between the two thermocouples.

Gamma heating. The RTD readings were close enough to the thermocouples at zero or low power conditions but read proportionately, to power, higher upto an average of 14°C higher at full power conditions indicating gamma heating of the RTD. This was verified after a reactor trip (i.e., scram or shutdown) in which the RTDs began to read closely to the thermocouples, after their time constant.

After a trip is initiated, reactor power drops by an order of magnitude in less than 3 s. This would reveal any gamma heating of the sensors as sharp drops in their readings. Typical time consants of RTD's are about 4 s, and of grounded thermocouples 100–200 ms.

Fig. 9 were temperature readings from the sensors at station 8 which was at the center of the core - a region of most intense radiation and where gamma heating was most evident. Fig. 9 indicated that there were negligible gamma-heating effects on the thermocouples whilst the RTD, which was giving falsely high readings before the trip (fig. 10), gave similar readings to the thermocouples within seconds (due to its time constant) after the trip.

Radiation-induced currents. Since this effect exactly follows the reactor power it would have been observed as

Table 1
Comparison of outputs betweens NBS data and ordered thermocouples (TC)

Temp (°C)	NBS emf (mV)	Average mV output of ordered TCs	Deviation from NBS (μV)	Deviation from NBS (°C)	Random spread between TCs (°C)
0	0.000	0.0021	+2.1	+0.05	±0.05
50	2.022	2.0590	+37.0	+0.88	±0.10
70	2.850	2.8991	+49.1	+1.18	±0.15
100	4.095	4.1680	+73.0	+1.77	±0.15
120	4.919	5.0058	+86.8	+2.10	±0.15
			Systematic shift above NBS		Random spread between TCs
		At 50°C	36.3 μV (0.878°C)		±4 μV (±0.1°C)
		70°C	49.1 μV (1.185°C)		±7 μV (±0.16°C)
Seebeck coeff between 50–100°C			41.5 μV/°C type K from NBS		42.2 μV/°C ordered type K calibrated data

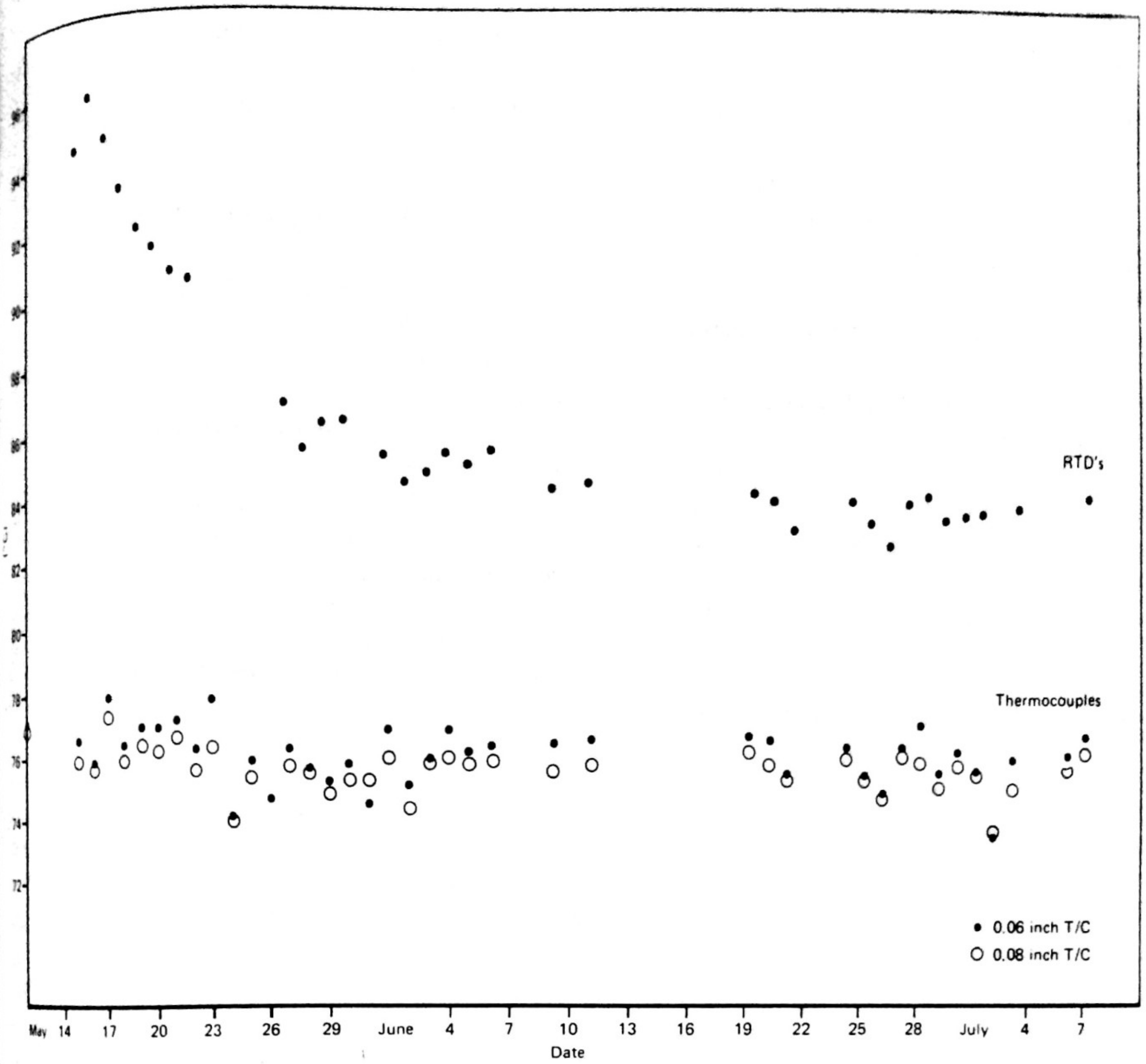

Fig. 11. Trends of peak temperature reading.

an immediate transient during the reactor trip following the electrical inertia, rather than the slower thermal inertia.

No such effect was observed. This may be attributed to designing for the maximum attainable insulation resistance and for grounding detail.

Transmutation. This was not anticipated for the duration of the test, and neither was it observed. But over a period of several months, the thermocouple signals did not degenerate by any significant amount whereas the RTD signals did after about 5 weeks. The RTD readings had dropped by over 10°C after which time they became stable, fig. 11. Though the RTD's are significantly more massive than the thermocouples, this reduction in signal may reflect transmutation and/or deterioration of the insulation.

Short-ranged ordering. The heat-soak, 430°C for 24 hours, was to stabilize the short-range ordering of the chromel thermo-element. The heat treatment increased the output of the thermocouple to cause a systematic shift by +1.85°C, at 70°, above NBS, but the random spread between the tested thermocouples was reduced to +0.16°C. Table 1 summarizes these effects.

Consideration was given to the fact that the thermocouples were heat-treated, but the extension leads were not. In the analysis this produced a discrepancy of about 6 μV.

Data acquisition system. Overall accuracies from sensor to readout was 2°C at high resolution (of datalogger) and 2.3°C at low resolution incorporating the random uncertainties. This was well within the requirement of this program.

The overall program shows that RTD's are unsuitable for in-core temperature measurements, whereas the type K thermocouples proved highly dependable.

The sizes of the thermocouples used did not appear to have measurement signficance, but the recommendation would be to use the smaller size but only because radiation effects are known to be mass dependent.

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