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Core Physics Tests of THTR Pebble Bed Core at Zero Power

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1. Introduction

The commissioning of the THTR 300, the prototype of the HTR pebble bed line, was started in August 1983. The THTR represents the second step of the HTR development in the FRG after the 15 MWe AVR. Full-power operation is scheduled for late 1985.

Initial criticality of the THTR reactor was achieved on September 13, 1983, with 198.180 spherical elements loaded. The core was fully loaded with 674.200 spherical elements on October 11, 1983.

The core physics tests were divided into three steps. The first step (OI) included the core loading up to initial criticality, the second step (OII) included full core loading. The second step was completed in November 1983. The third and last step (OIII) of the physics tests was started in August 1984 by warm test operation and a great number of tests under nitrogen atmosphere (up to 16 bar). The zero power tests were completed in January 1985.

2. Core Performance

The initial THTR core consists of a loose bed of spherical elements of 6 cm diameter as a mixture of fuel, graphite and absorber elements:

- 358,200 fuel elements (FE) (53 %)
- 272,500 graphite elements (GE) (40%)
- 43,500 absorber elements (AE) (7 %)

Each fuel element contains 0.96 g of 93 % enriched uranium 235 as fissile material and 10.2 g of thorium 232 as fertile material in the form of coated particles. The absorber elements contain boron and hafnium as neutron absorbers. The initial core is designed as a radial two-zone core. The desired flux-flattening is obtained by different mixtures for the inner and outer core zone. The outer zone contains more fissile material.

Mixing ratio:
Inner zone of core AE: GE: FE: 1:6:5
Outer zone of core AE: GE: FE 1:6:12

3. Core Loading

To build up the specific configuration of the initial core, a special loading facility was developed. Using this facility, the spherical elements were loaded into the core by gravity from the 48 m platform above the PCRV*). After passing through headers of loading lines for the different spherical elements, the spheres passed through release valves, pneumatic decelerators and telescopic tubes into the turnable switch (Fig. 1) where they were distributed to the individual 15 loading pipes (3 of them for the inner core).

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*) Prestressed Concrete Reactor Vessel

In the first step of the nuclear commissioning program the core was filled with elements to such a level as to reach criticality with no absorber rods inserted. The inner and the outer core zone were separated by separating sheets up to a cylindrical height of 2 m (Fig. 2).

During this phase frequent entering of the core was necessary (Fig. 3).

In the second step, all incore rods were inserted and the further loading of the core was performed in subcritical conditions.

The filling factor of the pebble bed influences the reactivity by neutron leakage (Fig. 4). Therefore subsequent measurements of the filling factor were obtained. In the lower part of the core a value of 0.643 was achieved which was higher than the expected value of 0.62 from mock-up measurements due to frequent entering the pebble bed surface. In the upper part (approx. 300,000 loaded spheres) the expected filling factor of 0.62 was obtained. This effect caused a step in the density of the pebble bed which has to be taken into consideration in comparison with predicted results.

4. Initial Criticality

In the course of loading the reactor it was ensured by using the method of the inverse counting rate that the reactor did not reach uncontrolled criticality. In a subcritical assembly the inverse counting rate of a detector is proportional to $(1-K_{eff})$:

$$\frac{1}{Z} \sim 1- K_{eff}$$

A Cf-252 source having a source strength of approximately 230,000 neutrons/s was inserted as an auxiliary start-up neutron source in a central position at the core bottom. The neutron flux density induced by this neutron source and increased by the pebble bed was measured and controlled by three high-sensitivity BF_3 detectors located in the pebble bed (Fig. 5). Figure 6 shows the measured inverse counting rates of the three detectors as a function of the number of the spherical elements loaded. The curves demonstrate the expected convergent shape showing the same critical number of spherical elements in approaching criticality. The first self-sustained nuclear chain reaction was reached on September 13, 1981 at 1.10 hours with the loading of 198,180 spherical elements. According to a filling factor of 0.643, a critical number of 204,000 spherical elements had been predicted. The difference of 5800 elements corresponds to a reactivity equivalent of appr. 0.004 Δk.

The tolerable margin was ± 0.02 Δ k.

The calculation method, which had been tested at the KAHTER-facility (1) in Juelich consists essentially of the following features:

- Spectrum calculation in 200 energy groups on the basis of ENDFB IV library with the GGC5-Code (2)
- Evaluation of the heterogeneity of the absorber elements in 50 energy groups (3)
- Diffusion calculation with 15 energy groups (4).

The KAHTER experiments which simulated the THTR initial core by using original fuel and absorber elements (but not with the THTR mixture) already showed small differences between calculated and measured K_{eff}-values. The main point of inaccuracy is the neutron absorber hafnium which covers appr. 0.2 Δk reactivity of the core. Presently the hafnium data have obviously an inaccuracy of 3 - 5 %. Therefore a calibration factor was used known from KATHER to achieve the good prediction.

In the range of the initial criticality the ratio $\Delta\rho/h$ was determined. This can be done using the equation

$$\Delta\rho_2 = \frac{\frac{1}{Z_3} - \frac{1}{Z_4}}{\frac{1}{Z_1} - \frac{1}{Z_2}} \Delta\rho_1$$

i.e. differences of the inverse counting rates in connection with a known reactivity effect. The known reactivity effect was the reactivity worth of the reflector rods which had been independently measured using the inverse kinetic method. The result was 125 Nile/cm compared with a predicted value of 122 Nile/cm.

After having reached initial criticality, the effectiveness of the reflector groups was measured. For this purpose the critical state was first established using the incore rods with the reflector rods completely withdrawn. The reactivity changes were calculated by the inverse-kinetic method from the changes in the counting rates during rapid insertion of the reflector rods. It was the objective of this step to verify the method, especially the accuracy of the point kinetic method which must be used with calibration factors to take into account flux deviation by inserted rods at the detector position. For this purpose incore detectors were available.

Figure 7 shows counting rate and reactivity during insertion of all 36 reflector rods. The incore detector was located at a radius of 1970 mm.

The measured reactivity worth was 0.0085 ΔK, averaged over a number of measurements it was 0.00820 ΔK. It was known from diffusion calculation that insertion of the reflector rods does not influence the flux at this location. Figure 8 shows a measurement using a detector located outside the side reflector. After insertion of the rods the flux reaches very low values so that statistical effects of the counting rate can be seen. The (uncorrected) reactivity worth was measured to be 0.019 ΔK. Diffusion calculations showed that at this location, due to shadowing of the inserted reflector rods, a flux shape correction factor of 2.7 is necessary which corrects the above value to 0.00705 Δ K.

The calculated reactivity worth of the reflector rod at initial criticality was 0.0072 Δ K. This shows the importance of the spatial correction factor. Another difficulty was the influence of the neutron source in the inverse kinetic equations, which produces an equivalent reactivity when the source term is neglected. To identify the value of the source term studies were made until the reactivity curve could be evaluated after rod insertion, when it had stabilized (horizontal).

5. Core after Complete Loading

On September 20, 1983 further loading of the reactor core was initiated. On October 11, 1983 the reactor core was completely loaded. The critical state in the completely loaded initial core represented a milestone in the THTR commissioning phase. Now the start-up neutron source (Cf-252, 10^9 neutrons/sec) was used, which was located in the side reflector. Two critical rod configurations were obtained in air atmosphere (Fig. 9 shows the rod arrangement of the THTR core):

Configuration I

Inserted 12 R2-rods
12 R3-rods
6 reflector rods 66 %

Configuration II

Inserted 12 R2-rods
12 R3-rods
6 R4-rods 85 %
6 Reflector rods 37 %

Table 1: Critical rod configuration, core fully loaded

Predicted values calculated with a filling factor of 0.62 led to excess reactivities of 0.005 Δk for the above rod configurations. Evaluations with correct filling factors showed deviations of no more than 0.0013 Δk and 0.0004 Δk respectively. Due to the higher density of the pebble bed, the reactivity was 0.0065 Δk higher. This will lead to a corresponding reactivity drop during shuffling of the elements.

From these measurements a shutdown margin of 0.05 Δk at 1 bar air may be obtained. Again a number of measurements for reactivity worths of different groups of reflector rods were performed. 6 detectors had been located in the reactor, 3 in the core axis, the remainder outside the reflector. The measurements showed a strong dependence of the flux shape. With calculated correction factors for flux correction and correct source terms good agreement with the predicted values could be achieved:

	$\Delta\rho$ measured	$\Delta\rho$ calculated
6 reflector rods (1 group)	0.0125 ± 0.0005	0.0130
36 reflector rods	0.0475 ± 0.0015	0.0480

Table 2: Reflector rod worths, core fully loaded

This method is proven now to be used later during reactor operation, when no incore detectors are available.

6. Temperature Coefficient Measurements

The ceramic internals were dried by operating the circulators. The core was heated up to 210 °C. During this period a measurement of the temperature coefficient was performed at 1...1.5 bar nitrogen. The procedure started with a critical rod configuration (12 reflector rods inserted, the definite incore rod configuration was determined during the experiments). After a step-wise temperature increase by appr. 20 °C the critical status was obtained again by moving of 6 (1 group) reflector rods. The difference in insertion depth is then measured with the inverse kinetic method. Fig. 10 shows measured and calculated results. The inaccuracy of the measured values is ± 15 % and depends mainly on the uncertainty of the measured temperature distribution in the core/reflector range and on source term concerns in the evaluation of the inverse kinetic results. The calculated values are based on the MUPO-Spectrum code, which compared to GGC is a simplified spectrum code. It is known that in this temperature range MUPO calculates about 10 - 15 % less negative temperature coefficients. Due to the small temperature steps which correspond to 0.002 Δk steps, numeric problems originated in the calculations resulting in ± 10 % inaccuracy. Taking into consideration these facts, the measured and calculated values are in good agreement.

7. Measurements under High Nitrogen Pressure

After the temperature coefficient measurements 20,000 spheres were recirculated according to schedule in order to loosen the density of the pebble bed compactness. This causes, on the other hand, uncertainties in the prediction of values measured subsequently due to the modified filling factor distribution. A reactivity drop of 0.002 Δk was observed.

The following measurements were performed in N_2-atmosphere using N_2 as an absorber gas. The procedure is similiar to the temperature coefficient measurements, however, instead of heating up the core, it was filled with N_2. Thus the reactivity worth coefficient of N_2 could be measured as a function of the N_2 pressure (inaccuracy ± 5 %) (Fig. 11). Contrary to the temperature coefficient measurements the incore rods were withdrawn. At a N_2 pressure of 16.4 bar all rods were withdrawn.

Thus the excess reactivity at ambient temperature could be determined to be $\Delta\rho = 0.0112 \pm 0.0005$. The predicted value was $0.0104\,\Delta\rho$ with a lower filling factor. Taking into account the higher filling factor $\sim 0.0110\,\Delta\rho$ is predicted. During slow depressurizations the reactivity worths of different rod configurations were measured by determining the corresponding N_2 pressures. The reactivity worths were evaluated using the known N_2 coefficient.

The subsequent Table 3 shows the results:

Group	Measured Group Worth $\Delta\rho$	Predicted Group Worth $\Delta\rho$
All groups in sequence		
1st group of refl. rods	0.0076 ± 0.0004	0.0078
2nd group of refl. rods	0.0070 ± 0.0004	0.0081
24 reflector rods	0.0191 ± 0.001	0.0187
6 R3	0.0234 ± 0.002	0.0238
6 R2 in sequence to 12 reflector rods	0.0281 ± 0.0015	0.0291

Table 3: Comparison of Predicted and Measured Rod Group Worths

It should be noted that the predicted values are calculated on the basis of a lower filling factor. In general it can be stated that the prediction is in the range of the inaccuracy of the measured values, i.e. better than 5 %. One interesting result was the reactivity effect of helium due to neutron moderation and subsequent influence on the neutron leakage. 22 bar helium at 29 °C delivers 0.00225 ± 0.000550 Δk, the predicted worth on a basis of 1-d (radial) calculation was 0.0007 Δk.

8. Conclusion

The nuclear performance of the initial THTR core corresponded to the predictions. Good agreement between measurements and calculation was obtained for initial cold criticality (within 0.004 Δk), control rod worth (within 5 %) and temperature coefficient (within 10 %).

9. References

1. Drüke et al., "KAHTER", Jül-1621 (1979), Jül-Spez-187 (1982)
2. D.R. Mathew et al., "GGC5", GA-8871 (1971)
3. W.W. Engle, Jr., "ANISN", AEC-Report K 1693 (1967)
4. A. Hassit, "CRAM", TRG Report 229 (R) (1962)
5. J. Schlösser, "MUPO", Dragon Project Report 172 (1963)

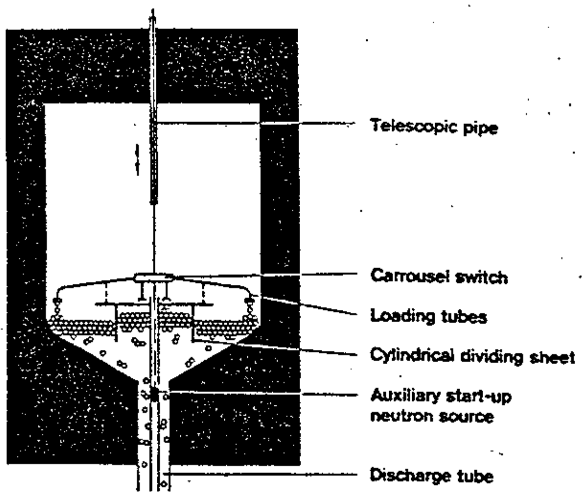

Fig. 1 Schematic View of Loading

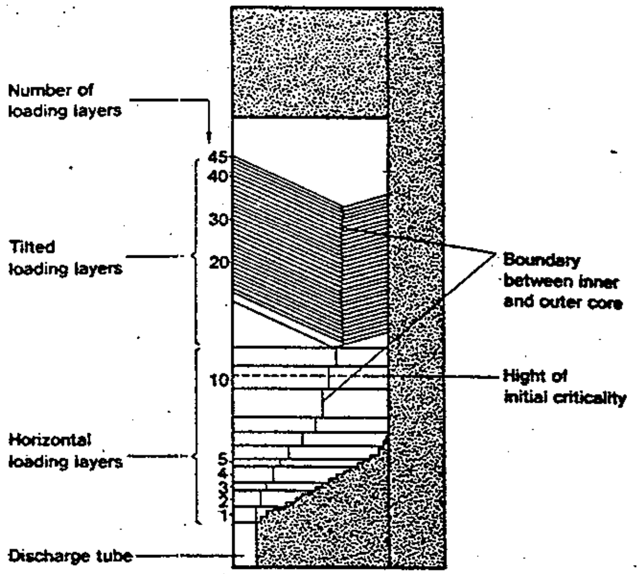

Fig. 2 Loading of THTR Initial Core

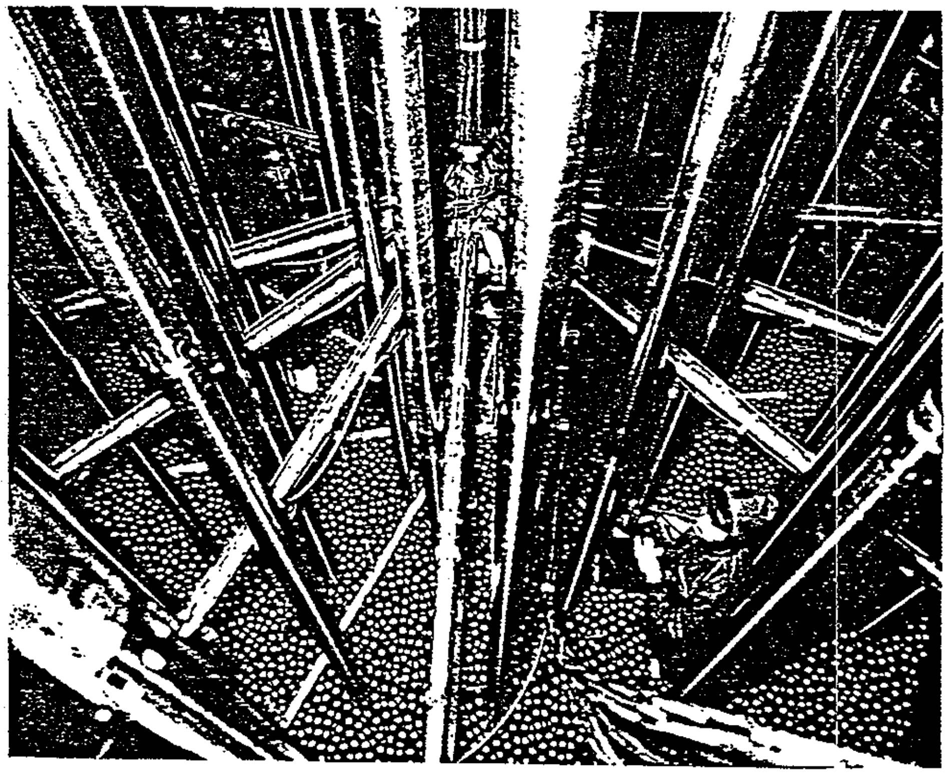

Fig. 3

Reactor Core during Initial Loading Operations Personnel Performing Radiation Measurements

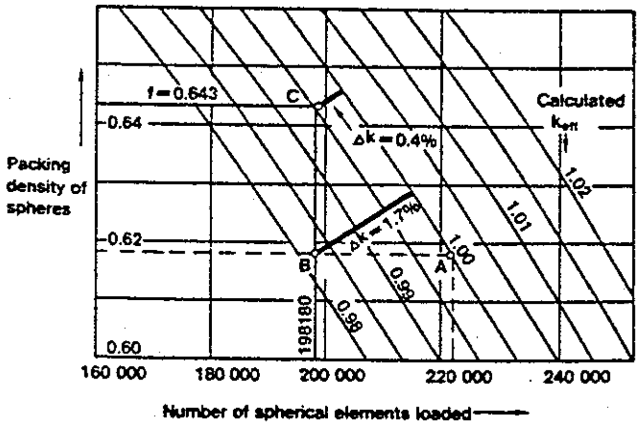

Fig. 4 Influence of Packing Density of Spheres on k_{eff}

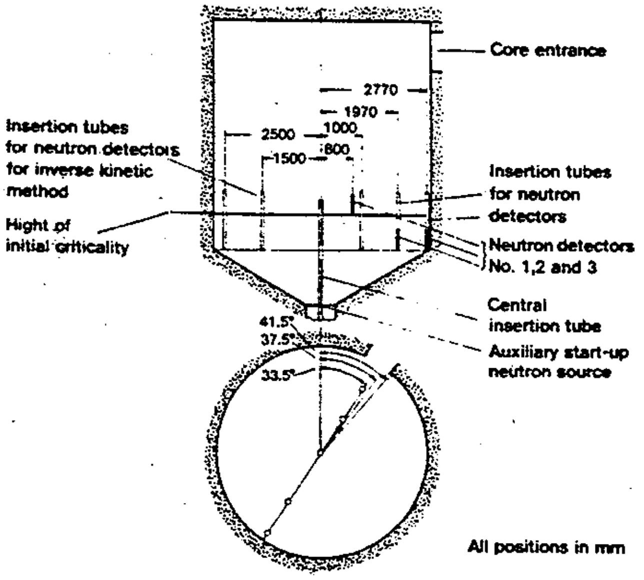

Fig. 5 Positions of Neutron Detectors

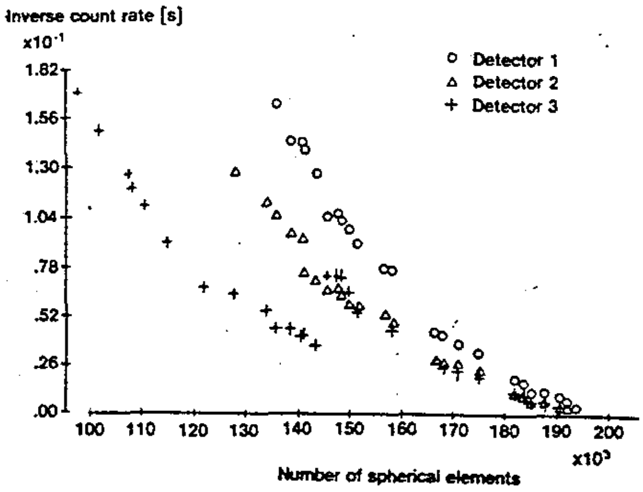

Fig. 6 Inverse Count Rate as Function of the Number of Spherical Elements Loaded

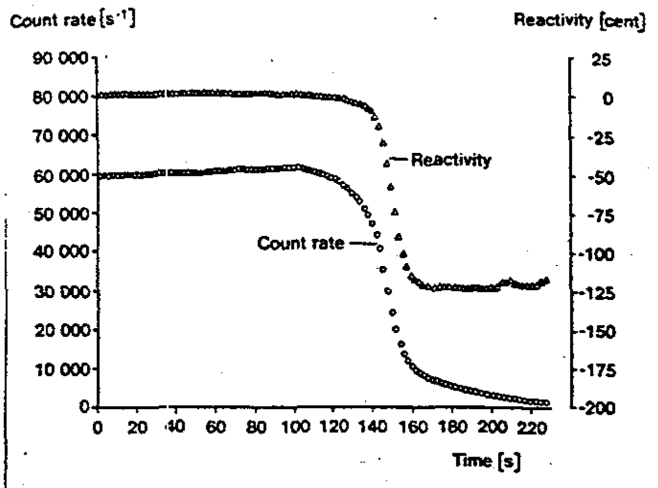

Fig. 7 Count Rate and Reactivity versus Time during Insertion of 36 Reflector Rods, Detector Located inside Core

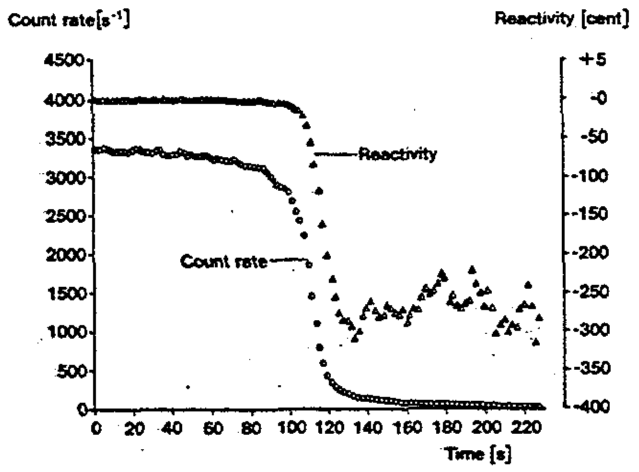

Fig. 8 Count Rate and Reactivity versus Time during Insertion of 36 Reflector Rods, Detector Located outside Graphite Reflector

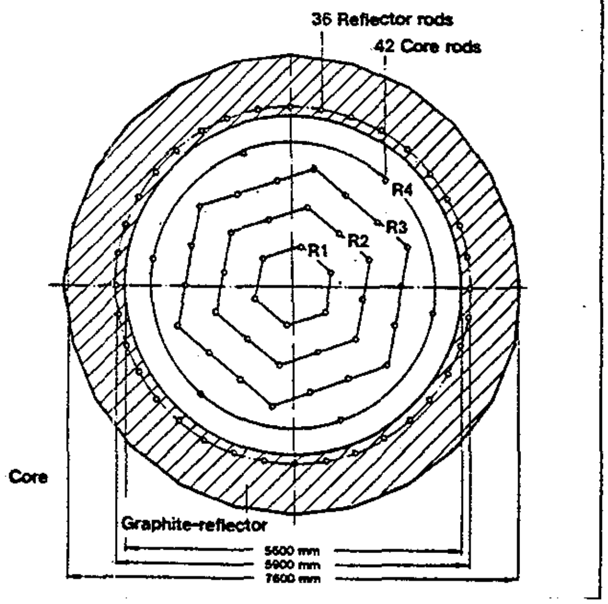

Fig. 9 Positions of Core and Reflector Rods

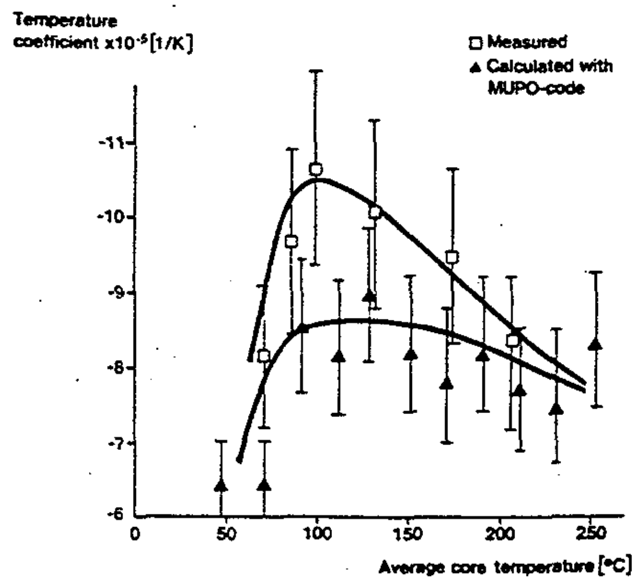

Fig. 10 Temperature Coefficient at 1 bar N_2

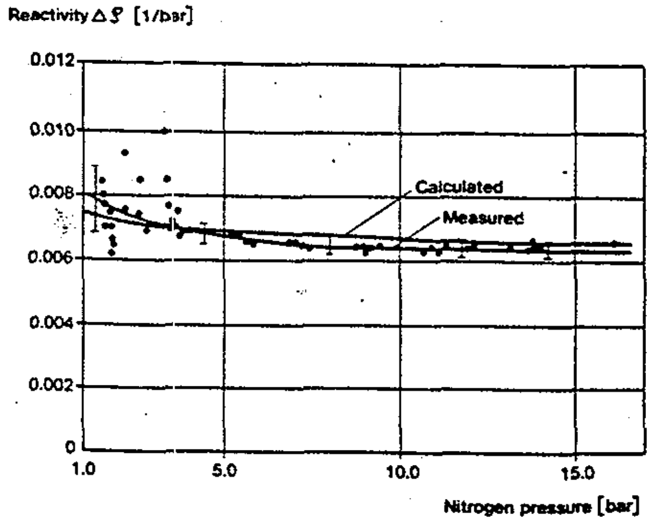

Fig. 11 Reactivity Worth of Nitrogen