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Experiments on Thermohydraulically Induced Fuel Rod Oscillations in a Sodium Flow
Final Report

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KERNFORSCHUNGSZENTRUM KARLSRUHE

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Abstract:

The KNK II reactor in Karlsruhe experienced fuel element damage which could not be traced back to hydraulically excited vibrations. Instead, some indications pointed to low-frequency fuel rod oscillations caused by temperature differences over the circumference of the fuel rod as a result of the high specific rod power and the clearance of fuel rods in their spacers.

In 1988, specific experiments were started in the sodium loop of the IMF III to investigate this phenomenon (THIBO experiments). The rod movements were made visible and detected in a reproducible way.

In 1989, another series of tests, THIBO II, have been run in a second test section. In this case, the cooling channel area was reduced so much that the thermohydraulic conditions very closely approximate those existing in the KNK II reactor. The experiments have shown that fuel rods may start moving already at relatively low sodium temperature increase and low partial loads, respectively, even if the rod clearance in the spacer was set to realistically low levels.

THIBO-Experimente:

Thermohydraulisch induzierte Brennstaboszillationen in Schnellen Natriumgekühlten Reaktoren

Abschlußbericht

Zusammenfassung:

Im KNK II-Reaktor in Karlsruhe sind Brennelementschäden aufgetreten, die nicht mit hydraulisch angeregten Vibrationen erklärbar sind. Es gab vielmehr Hinweise dafür, daß niederfrequente Brennstaboszillationen auftreten. Ursachen hierfür sind Temperaturunterschiede am Brennstabumfang bedingt durch die hohe spezifische Stableistung und das Spiel der Brennstäbe in den Abstandshaltern.

Zur Untersuchung dieses Phänomens wurden im Jahr 1988 gezielte Experimente im Natrium-Loop des IMF III (THIBO-Experimente) aufgenommen. Die Stabbewegung konnte in reproduzierbarer Weise sichtbar gemacht und nachgewiesen werden.

In 1989 wurde mit einer zweiten Teststrecke eine weitere Testserie THIBO II durchgeführt. Dabei wurde die Kühlkanalfläche soweit verringert, daß die thermohydraulischen Verhältnisse denen im KNK II-Reaktor sehr nahe kommen. Die Experimente haben gezeigt, daß Brennstäbe schon bei relativ kleinen Natriumaufheizspannen bzw. bei geringer Teillast in Bewegung geraten können, auch wenn das Stabspiel im Abstandshalter auf realistisch kleine Werte eingestellt ist.

TABLE OF CONTENTS

1 INTRODUCTION

Fuel elements irradiated in the sodium cooled KNK II reactor were found to show wear marks and cracks in the fuel rod claddings (Fig. 1). Wear induced damage was also observed in the spacers. The fuel rods of these fuel elements are 7.6 mm in diameter with a rod pitch of 8.8 mm (Fig. 2). The fuel rod bundle is equipped with eight spark eroded honeycomb shaped grid type spacers. The three support pads are situated on a circle of 7.7 mm diameter.

There are some indications to the damage being produced not by hydraulically excited vibrations, but by powerful low-frequency fuel rod oscillations caused by special thermohydraulic and geometric conditions. This means that the rod power, the sodium mass flow and the flow rate, the clearance of the fuel rod in the spacer system, and the fuel rod structure play the decisive roles in this phenomenon. The movements are the consequence of differences in temperature over the rod circumference causing rod bowing which, in turn, influences the temperature distribution in the cooling channel.

In 1988, the phenomenon was made visible and detected unambiguously and reproducibly in the THIBO I* experiments in a sodium loop of KfK (IMF III).

In 1989, another test series, THIBO II, has been caried out with a new test section. The test section, the test program, and the results and experiences with THIBO II are described in this report. Where necessary, reference is made to the differences relative to THIBO I. The THIBO experiments have been finished at the end of 1989. The program included approximately 50 experiments.

2 DESIGN OF THE THIBO II TEST SECTION

The THIBO experiments are single-rod experiments with an electrically heated fuel rod simulator in a ring shaped cooling channel. Fig. 3 shows the fuel rod simulator, and Fig. 4 gives a schematic representation of the test section. The dimensions of the rod are identical with those of the KNK II/2 fuel rods (600 mm heated length, 1560 mm total length, 7.6 mm diameter). The linear rod power is constant over the entire heated length.

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*) THIBO is the German acronym standing for thermohydraulically induced fuel rod oscillations.

Also the axial distribution of the spacers corresponds to the arrangement in the KNK II/2 fuel element. The spacer grids of the fuel element are replaced in the THIBO test section by three pads radially adjustable by means of micrometer screws (Fig. 5). Three thermocouples are arranged at a pitch of 120° at six levels in the cooling channel. In addition, the sodium inlet and outlet temperatures as well as the heater rod power and the sodium flow are measured. The relevant measured data are recorded directly by line recorders and, in addition, are stored by a data acquisition system.

Rod movements can be detected indirectly through measurements of the periodic temperature changes in the cooling channel. They can also be made visible on an X-ray image intensifier system coupled to a video recorder (Fig. 6). In addition, they can be evaluated quantitatively by means of a digital TV width measurement system connected in series with the X-ray facility.

There are two major differences between the THIBO I and THIBO II test section:

The cooling channel outside diameter was reduced from 12 mm in THIBO I to 10 mm in THIBO II. This decreases the cooling channel area from 67.7 mm^2 to 33.2 mm^2 and causes the thermohydraulic conditions, especially the product of the increase in sodium temperature and the sodium flow rate at a given power, to approach those in a KNK II fuel rod bundle (cooling channel area per rod: 21.7 mm^2). Table 1 shows the comparison of the operating data of the THIBO test sections and the KNK II/2 fuel element.

Another modification is found in the design of the test section outer tube. In THIBO I it had a single wall 2 mm thick. The THIBO II test section is a double walled structure in the region of the heated zone and above it (inner pipe, 0.8 mm; outer pipe, 2.0 mm thickness). Between the pipes there is a gas gap of 0.2 mm. The outer support pipe thus is thermally insulated from the sodium flow. The relatively large oscillatory movements of the test section pipe observed in THIBO I were avoided in this case. The amount of heat exchanged cyclically between the test section shroud and the coolant during the temperature oscillations is reduced, as is the damping effect of the pipe upon oscillations of the test rod.

3 TEST PROGRAM

The test program provided for a variation of all those operating parameters which, in the light of the experience accumulated with the THIBO I test series, can influence the intensity and frequency of fuel rod oscillations. On the one hand, these are the rod power and the coolant flow rate and the sodium temperature increase dependent on it, respectively, and, on the other hand, it is the amount of clearance between the spacers and the test rod. The operating parameters chosen will be explained in greater detail below.

3.1 Spacer setting

This operating parameter can be changed only before the sodium system is started up, for the system is installed in a safety containment which, for safety reasons, is flooded with an inert gas during operation.

In the THIBO I test section mainly one spacer setting had been studied in which the rod, as is shown in Fig. 7, was held tight in spacers 1 and 7 at the bottom and the top (cell diameter, 7.7 mm), while it had much more clearance in all other spacers (cell diameter, 8.6 mm). In that case, very pronounced, almost circular, rod oscillations and the corresponding temperature curves had resulted. This type of rod holding is not typical of a fuel element with grid type spacers.

In fresh KNK II/2 fuel elements the clearance is very small. At a rod diameter of 7.6 mm, the cell diameter in the spacers is 7.7 mm. Fuel elements irradiated for several thousand hours of operation and examined in the hot cells showed cell expansions due to wear of up to 8.2 mm diameter at the upper four spacers. In addition, cladding tube wastage in the region of the spacer pads was found to amount to a maximum of approx. 40 % of the wall thickness, which is tantamount to a reduction in the fuel rod outside diameter to 7.2 mm. If extrapolated to THIBO conditions, the clearance thus produced in the upper support levels would correspond to a spacer diameter of 8.6 mm at a test rod diameter of 7.6 mm.

The two lower spacers, 1 and 2, in the fuel element, which are arranged between the rod fixation at the bottom and the heated zone, did not show any wear under visual inspection, nor were any friction marks found on the cladding tube in this area. In the next spacers, 3 and 4, and on the cladding tube, respectively, minor traces of wear were visible. However, they were not determined quantitatively.

In THIBO II, in principle two basically different spacer settings were used, namely the THIBO I setting for comparison of the temperature curves and rod movements with the findings made in the THIBO I experiments. In this case, as is shown in Fig. 7, the spacer clearance was varied between 8.6 mm/7.6 mm and 8.0 mm/7.6 mm. In addition, another series of tests were run in which the rod, as is shown in Fig. 8, was held only in the two spacer levels 1 and 2 below the heated zone with 7.7 mm/7.6 mm, while all the other spacers had been set with larger clearances varying between 7.9 mm/7.6 mm and 8.6 mm/7.6 mm. Only the results obtained in the second test series will be discussed below, as it simulates as well as possible conditions in fuel elements in actual reactor operation.

An additional test was run in which the spacer cells, offset by 60° each from bottom to top, had been shifted 0.3 mm off the center of the cooling channel, Fig. 9. A similar measure is being taken in the fuel elements for the third core of KNK II. It can be said right away that no rod oscillations occurred in this experiment.

3.2 Rod power

In the THIBO II tests described in this report the rod power was set in steps at 13, 16, 17, and 21 kW. At each power step, several sodium temperature increases between 230 K and a minimum of approx. 70 K were attained by varying the sodium flow.

The rod power of 21 kW roughly corresponds to the fuel rod power in the KNK II reactor at full load operation. The effects part load operation has on rod oscillations was to be studied at the lower power levels.

3.3 Coolant flow rate

In the experiments discussed here, the coolant flow rate varied between 1.5 and 5.5 m/s, which corresponded to a sodium flow of 0.05 to 0.2 l/s. Temperature increases by some 200 K, which are typical of reactor conditions, were achieved at a flow rate of 2.8 m/s at 21 kW rod power; in the part load regime at rod powers of 17 and 13 kW, the corresponding coolant flow rates were 2.2 and 1.7 m/s, respectively.

4 RESULTS OF THE THIBO II TEST SERIES

As had been found already in the THIBO I experiments, fluctuations of the cooling channel temperatures and corresponding periodic movements of the test rod were generated and influenced by changes in the operating parameters.

The maximum changes in circumferential temperature in the THIBO II tests were measured exclusively in the measuring plane at spacer 5. In the THIBO I tests, the maximum temperature amplitudes had been recorded some 150 mm higher up in the region of spacer 6.

The influence of the operating parameters on the oscillations of the rod and the temperature, respectively, will be briefly discussed below.

4.1 Rod clearance

The tests have demonstrated that oscillations occur even if the clearance of the rod in the spacers is minimal. Figure 10 is a plot of the maximum circumferential temperature changes over the sodium temperature rise as a function of rod clearance in the rod clamped at the bottom, while Fig. 11 shows the same situation for the rod clamped twice (at the bottom and at the top). Both diagrams clearly indicate the influence of rod clearance on the temperature amplitude. As the rod clearance becomes smaller, rod movement is restricted and also the amplitude of the circumferential temperature are reduced. In priciple, it can be said that the rod clamped at the bottom exhibited much higher amplitudes of the circumferential temperature than the rod clamped both at the bottom and at the top. At 21 kW rod power, a characteristic sodium temperature increase of about 200 K, and a spacer diameter of 8.6 mm, the rod clamped at the bottom showed maximum temperature amplitudes of 123 K, while the rod clamped at the bottom and at the top exhibited 94 K. In a comparable THIBO I experiment, the maximum temperature amplitude had been 75 K. This indicates the attenuating effect on rod movement of the single-tube arrangement in THIBO I.

The rod clamped at the bottom begins to oscillate even at minimum clearance. Thus, amplitudes of the circumferential temperature of 11 K were measured at 7.9 mm spacer diameter and operating conditions typical of those existing in a reactor, namely 21 kW rod power and 200 K temperature rise. The rod clamped at the bottom and at the top showed no oscillations at this small clearance.

As mentioned above, the maximum temperature amplitude always occured at the level of spacer plane 5 (thermocouples 14, 15 and 16), roughly in the middle of the heated zone. For the rod clamped at the bottom, Fig. 12 and 13 show the curves of these temperatures as a fuction of time, with spacer diameters of 8.2 mm and 7.9 mm. In both experiments, the rod power had been 21 kW and the sodium temperature increase had been roughly 200 K. The difference by more than 20 K in the average temperatures in the plane of measurement is indicative of permanent rod bowing. The phase shift in temperature oscillation of thermocouple 16 relative to the two others seems to be due to a pronounced elliptical, or reciprocating, rod movement in the plane of measurement. In the THIBO I experiments, however it was possible to construe a helical rod movement. The temperature curves in Fig. 14 show that the rod follows a circular orbit in the plane of measurement. In this THIBO I test series, also rod movements were determined quantitatively by means of the TV width measuring system. Figure 15 shows rod movements and temperature curves in the region of the plane of measurement at spacer 6. The amplitude of the rod movement was approximately 1.3 mm at a circumferential temperature amplitude of 50 K. It is seen that the temperature recorded by thermocouple TE20 and the rod movement develop in perfect synchronicity, with a period of 4.35 s.

Temperature curves recorded at five planes of measurement located one above the other are plotted in Fig. 16. In this THIBO II-experiment, spacers 3 to 8 had been set at 8.0 mm diameter. The rod power was 13 kW and the sodium temperature increase was 200 K. The temperature developments at the measuring points located one above the other along the test rod are characterized by the same dashed curve. From the phase shift of the temperature cycles between the different planes of measurment it can be concluded that the rod undergoes helical movements over the entire heated length.

As the rod clearance decreases, the frequency of the temperature oscillations increases both in the rod clamped only at the bottom and in the rod clamped at the bottom and the top. This is shown in Fig. 17, 18 and 21, in which the frequency is plotted versus the sodium flow rate and the temperature increase, respectively, with the rod clearance acting as a parameter. For a fuel element, this would imply that rod movements would slow down with increasing wear.

Also spacer geometries other than those treated in this chapter were studied both in the THIBO I and THIBO II test sections. Figure 19 provides a summary overview, indicating at which spacer settings there were rod oscillations and at which there were none.

4.2 Rod power, sodium temperature increase, and sodium flow rate

The three operating parameters, rod power, sodium temperature increase, and sodium flow rate, are interdependent. In general, the temperature amplitude was found to increase over the rod circumference as a function of the increase in sodium temperature (Fig. 10 and 11). Also the rod power (or the sodium flow rate) influences the temperature oscillations. All temperature amplitude data obtained at higher powers are situated more in the lower range of the scatter band. In the rod clamped at the bottom, Fig. 10, this phenomenon is more pronounced in the presence of a larger rod clearance than it is in the rod clamped at the bottom and at the top. Fig. 11. It is also interesting to note that rod oscillations begin already at less than 70 K sodium temperature increase at medium and higher sodium flow rates. This is even true at a relatively low clearance of 8.2 mm/7.6 mm. In the THIBO I tests, a sodium temperature increase of clearly more than 100 K had been required to trigger oscillations of the rod. Another cause, besides the larger width of the cooling gap, had certainly been the damping effect of the single-walled shroud of the test section.

The frequency of the rod movement depends on the sodium flow rate and on the rod clearance (Fig. 17 and 18). In principle, the frequency rises with increasing sodium flow rate.This finding can also be derived from Fig. 20. In this diagram, the frequency has been plotted versus the sodium temperature increase as a function of rod power as determined in a test series with 8.0 mm spacer diameter. When the rod power is raised from 13 to 21 kW, while the temperature increase is kept konstant at, e.g., 200 K, the frequency of the rod movement rises from 0.33 to 0.56 Hz because of the increased sodium flow rate. It can also be seen from the same diagram that the frequency increases overproportionally as the sodium temperature rise becomes smaller.

That the rod movements are no hydraulically excited vibrations is evident from Fig. 22. If the rod power is reduced while the sodium flow rate is kept constant, the oscillations stop as soon as a sodium temperature increase of approx. 60 K is underrun. When the rod power is raised again, the oscillations start as soon as the temperature increase reaches the level mentioned above. It is also evident from this diagram that the rod movements are easily reproducible.

5 CONCLUSIONS

On the basis of the observations described above, which were made in the course of the THIBO tests, the following conclusions can be drawn:

- Plots of the rod circumferential temperature amplitudes over the sodium temperature increase (Fig. 10 and 11) show considerable variation of the measured points. This is due to the fact that not only the sodium temperature increase, but also the clearance between the spacer and the rod as well as the rod power have an influence on rod movement. In the fuel element, there is the added influence of adjacent rods.
- The THIBO II tests have shown that fuel rods can begin to move even at low sodium temperature increases and low partial loads, respectively, even if the rod clearance in the spacers has been set to realistically low levels. This may be important for the startup procedure.
- The cycle time of the rod of approx. 5 to 0.7 s differs considerably from the holding time of the coolant in the cooling channel along the heated zone, which was between 0.6 and 0.1 s. Consequently, the rod movement cannot be explained solely by axial heat transport.
- The test results suggest that sodium cross flow in the cooling channel caused by the bowing rod could be one of the causes of the relatively slow rod movement.

6 REFERENCES

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Experimente zu thermohydraulisch induzierten Brennstaboszillationen (THI-BO) in natriumgekühlten Reaktoren
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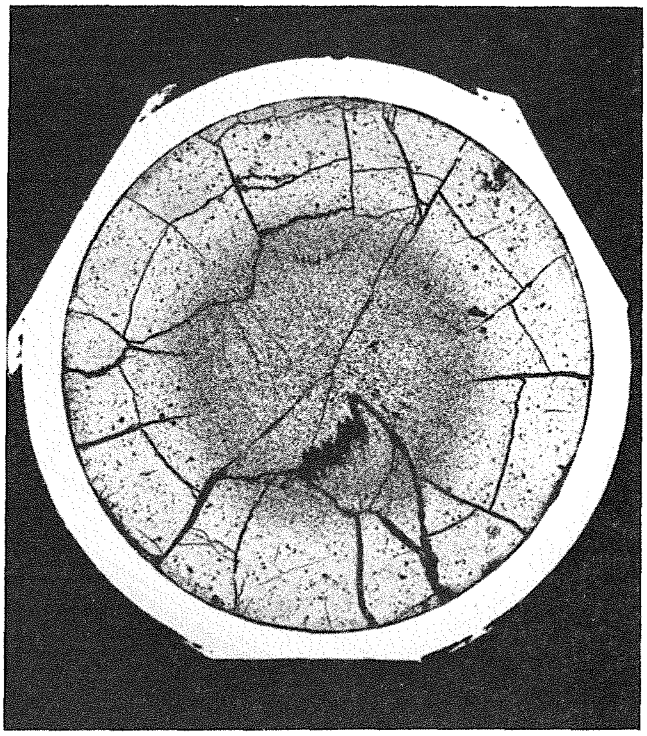
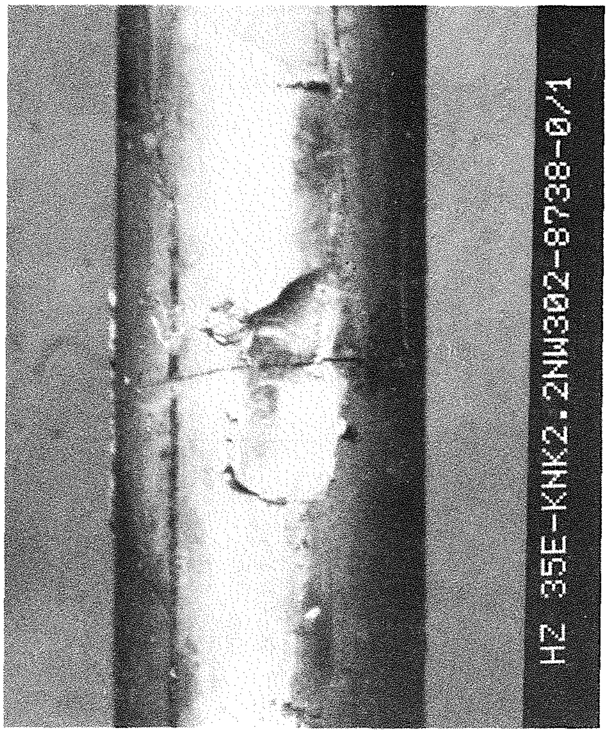
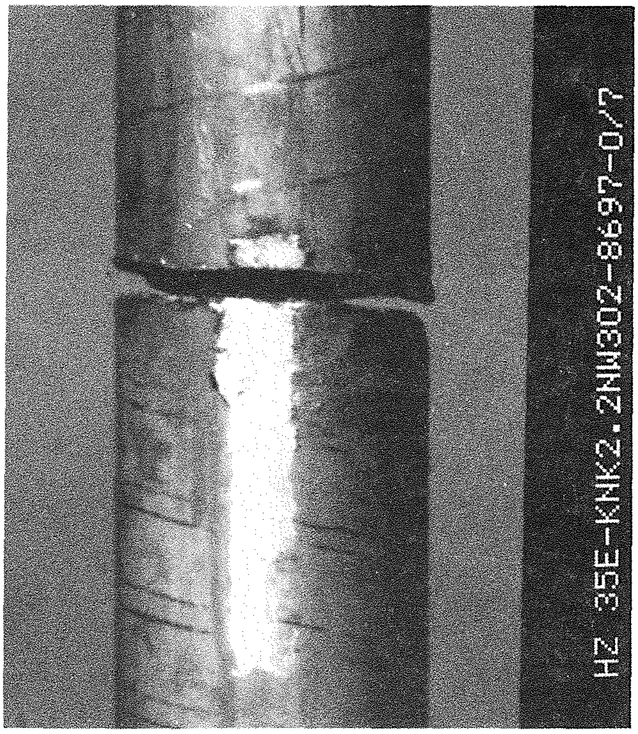
2. E. BOJARSKY, H. DECKERS, H. LEHNING, P. NORAJITRA, D. PIEL, H. REISER, L. SCHMIDT
THIBO Experiments: Thermohydraulically Induced Fuel Rod Oscillations in Sodium Cooled Reactors
International Conference on Fast Reactor Structural Behaviour, 4-6 June 1990, Inverness, UK



Wear marks on a KNK II/2 fuel rod





Cracks on a KNK II/2 driver fuel rod

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Fig. 1: Damaged KNK II/2 fuel rod claddings

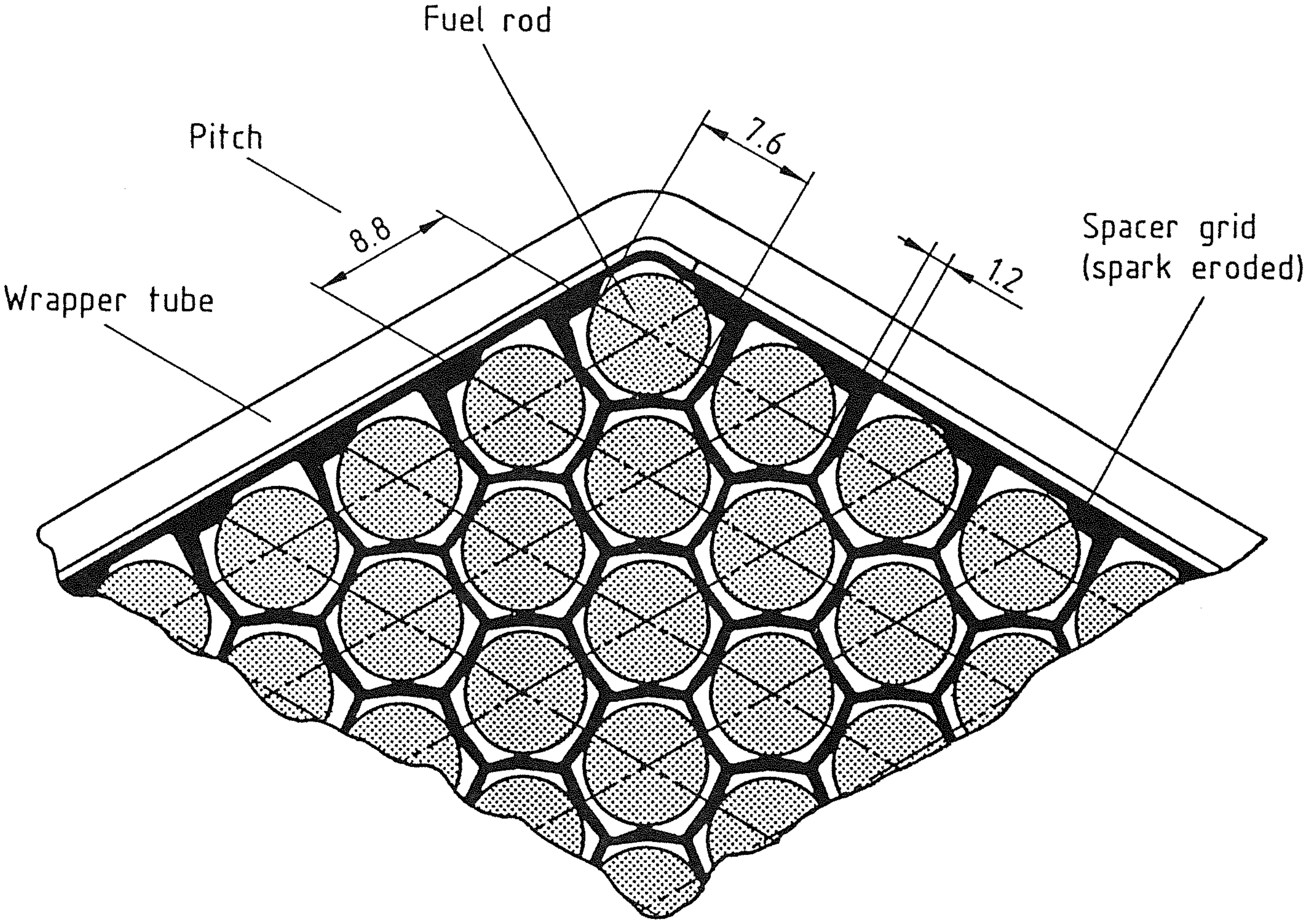

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Fig. 2: Sector of the cross section of a KNK II/2 fuel element

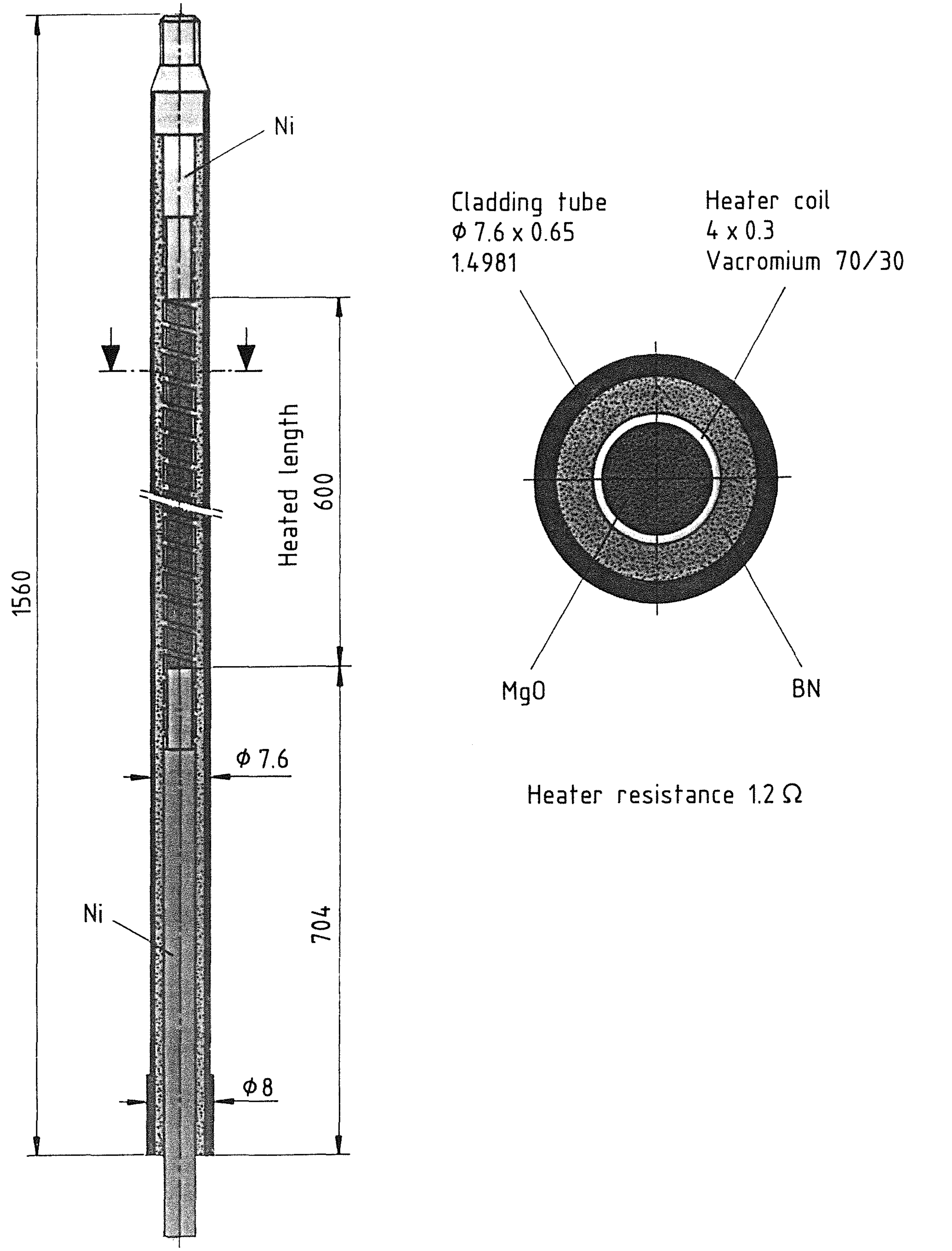

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Fig. 3: Electrically heated fuel rod simulator

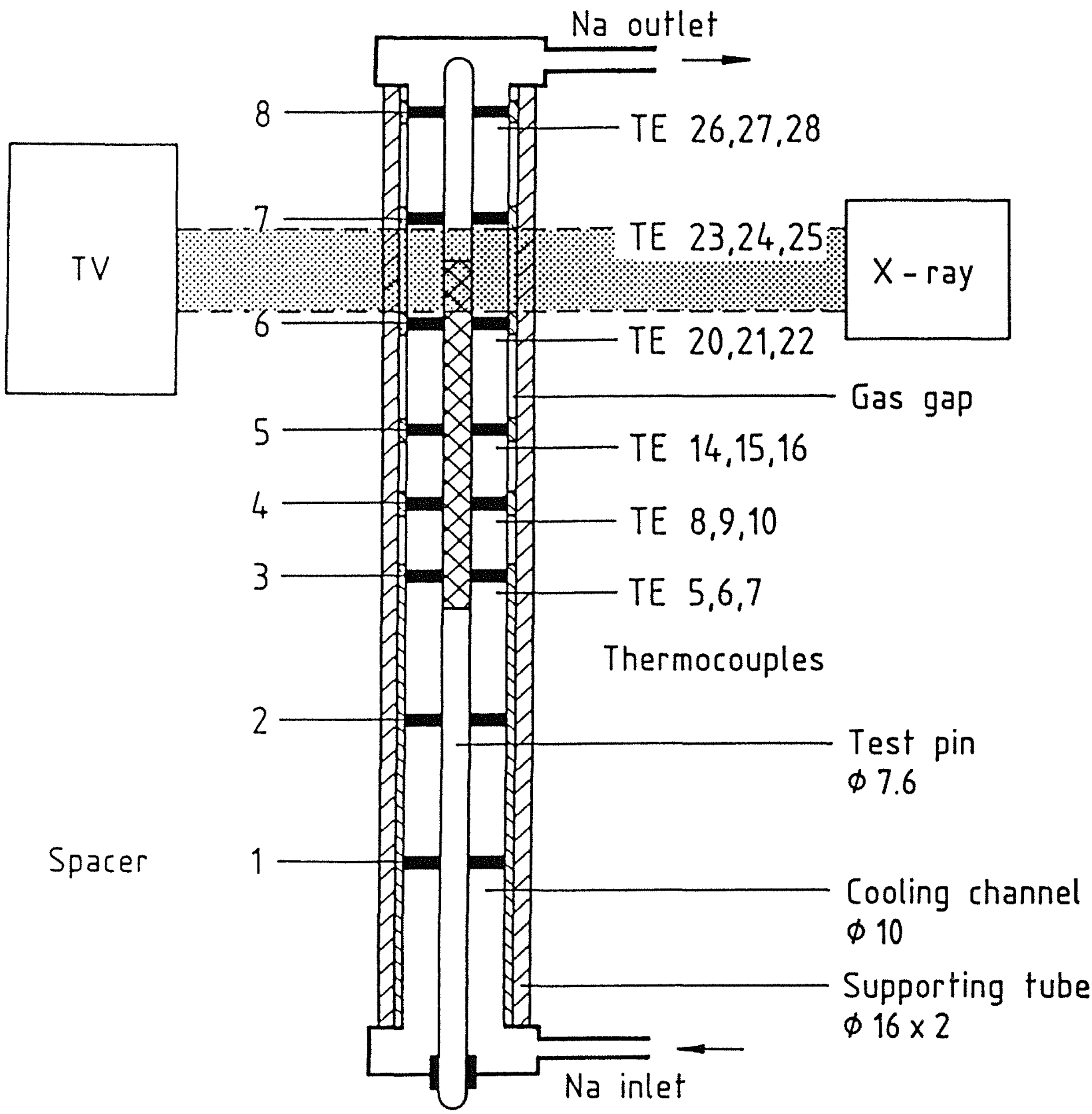


Fig. 4: Test section (cooling channel diameter 10 mm)

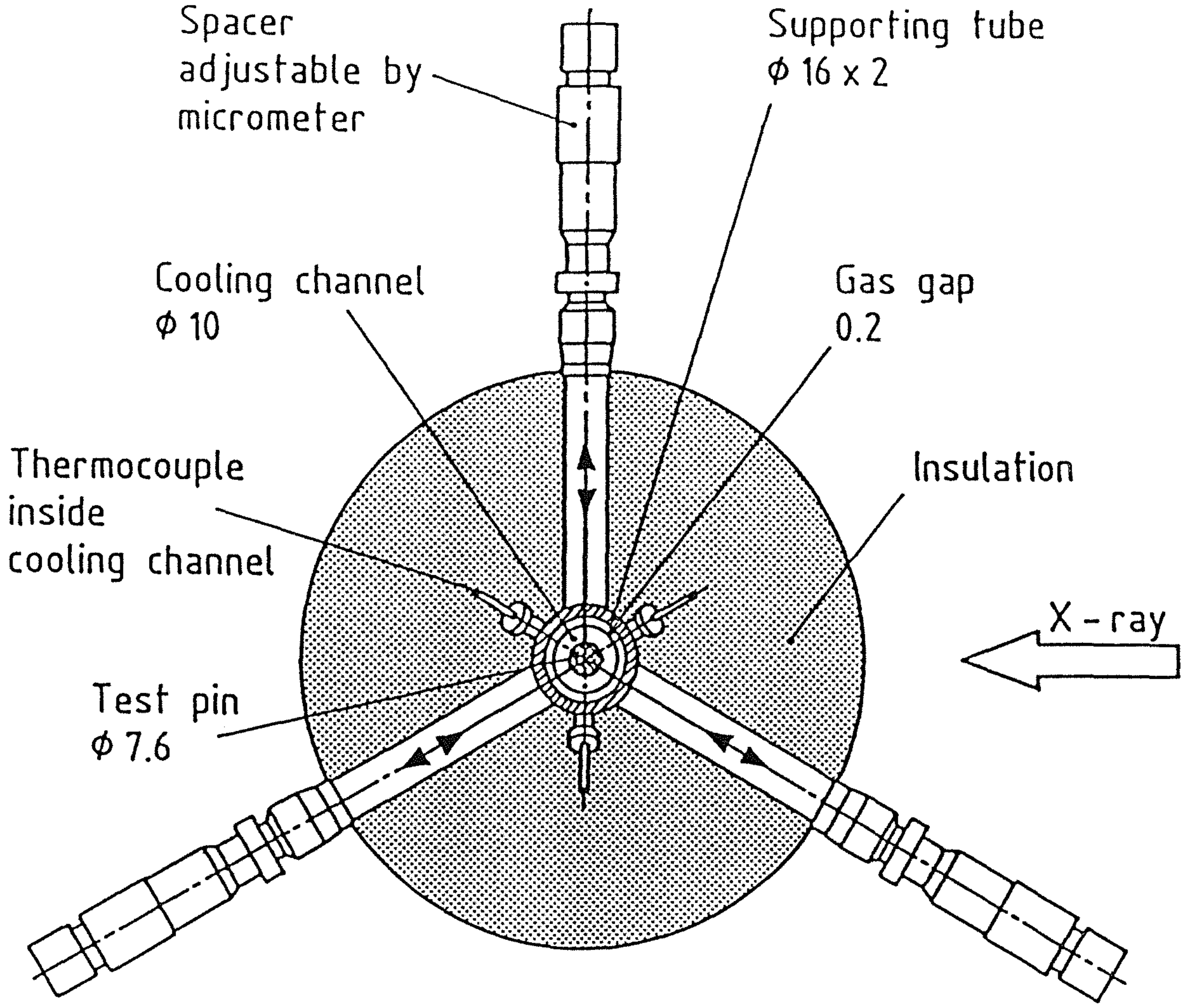


Fig. 5: Cross section of the test section (cooling channel diameter 10 mm)

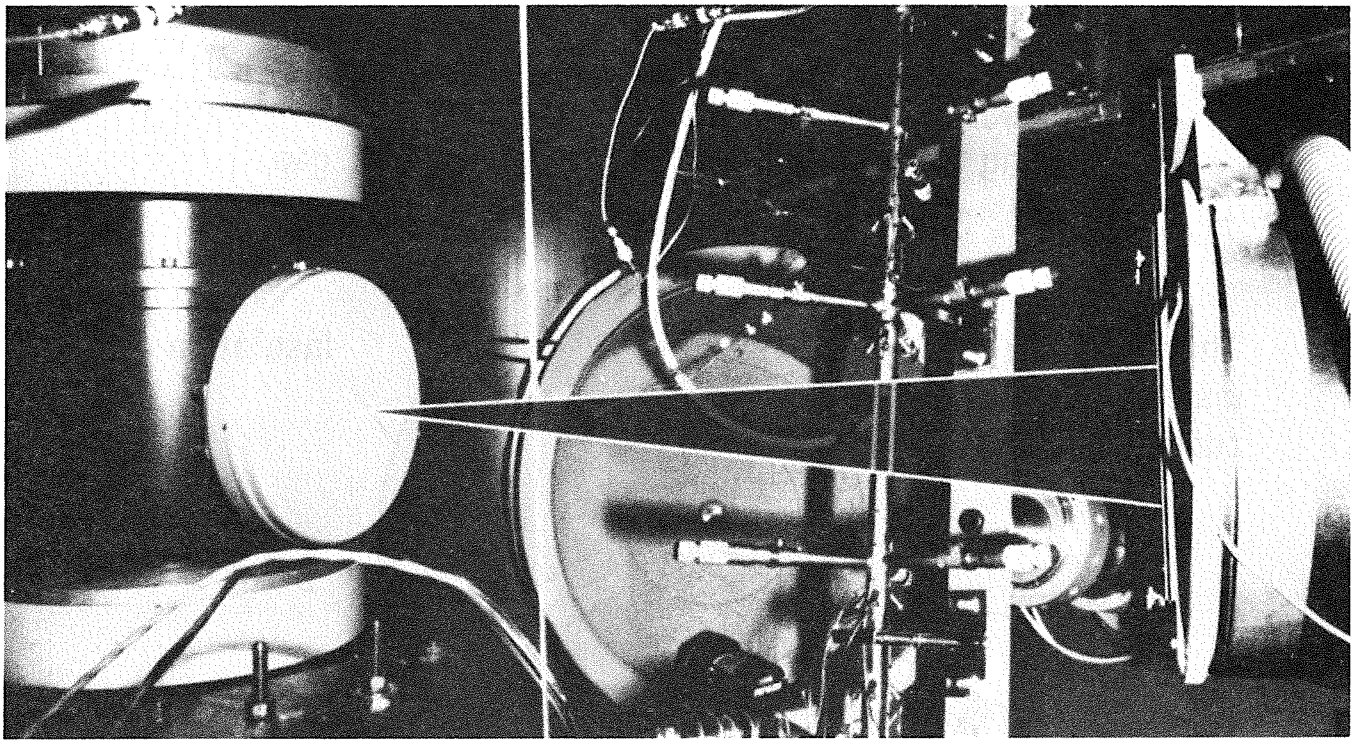


Fig. 6: THIBO test section with X-ray image intensifier system

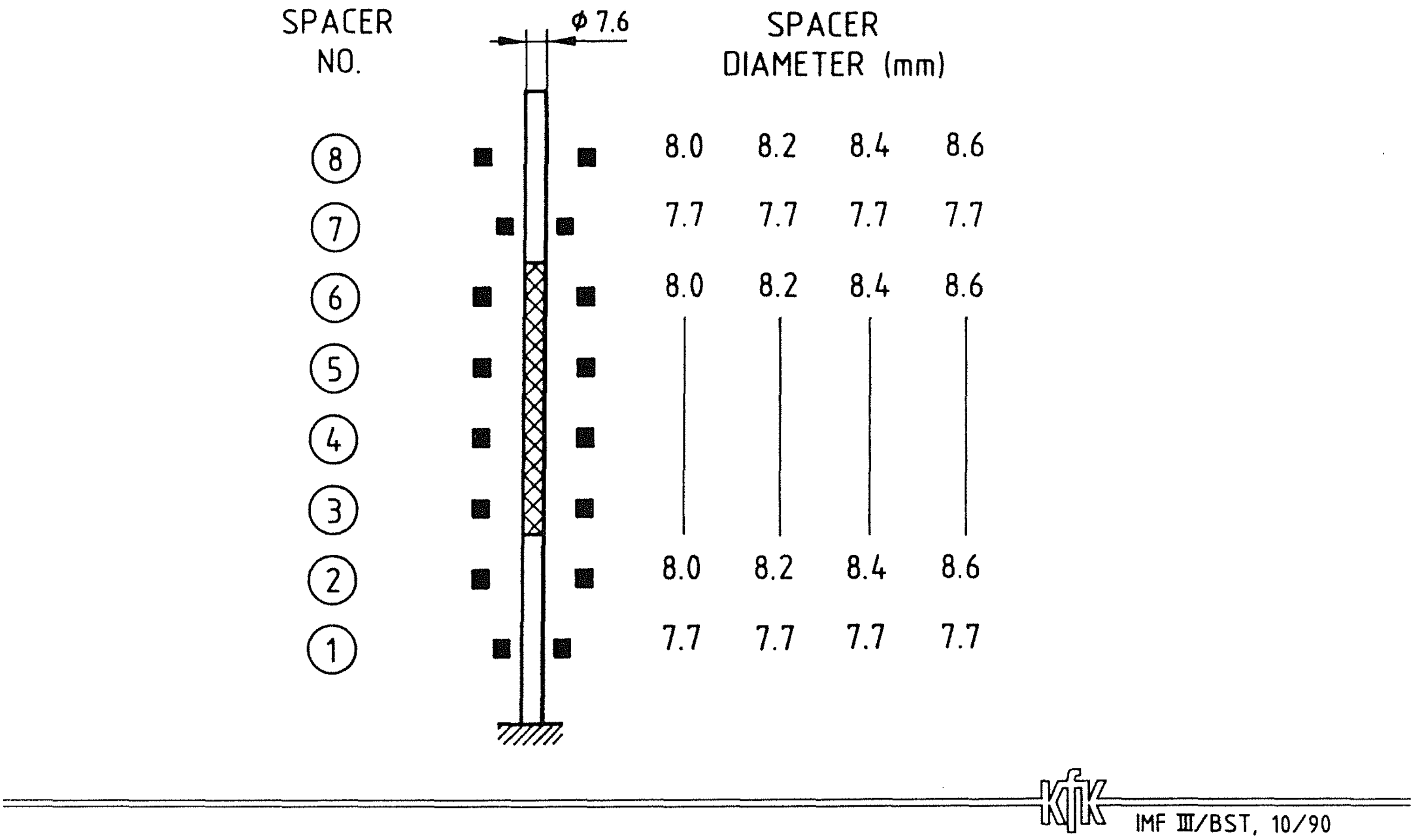


Fig. 7: Spacer setting, test rod held at the bottom and the top

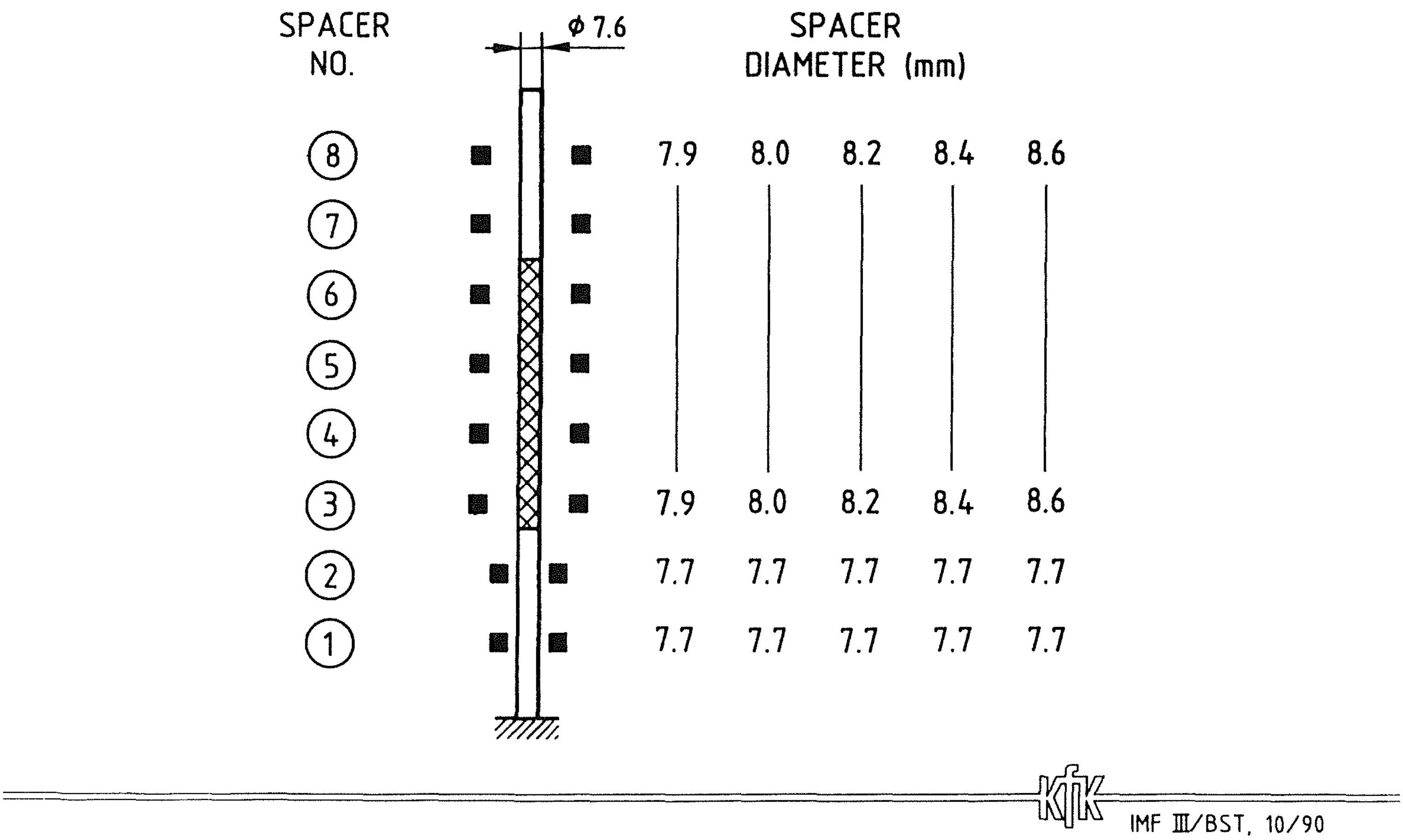
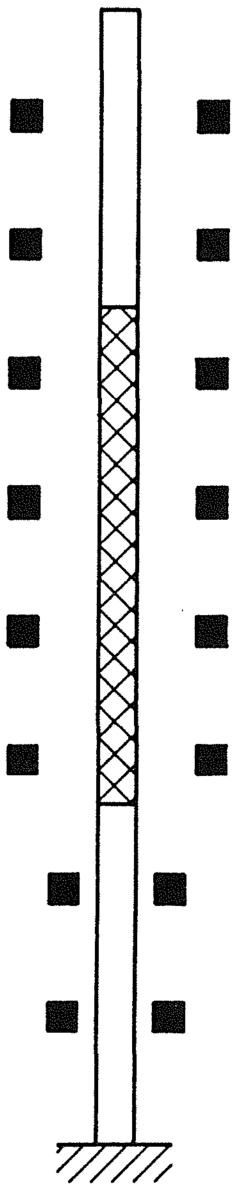


Fig. 8: Spacer setting, test rod held at the bottom

Spacer No.	Spacer Diameter (mm)	Spacer Shifting Eccentric (mm)	Spacer Shifting Angle
8	8.0	0.3	60°
7	8.0	0.3	360°
6	8.0	0.3	300°
5	8.0	0.3	240°
4	8.0	0.3	180°
3	8.0	0.3	120°
2	7.7	0.3	60°
1	7.7	0.3	0°



Rod power	21 kW
Na velocity	2,51 m/s
Na increase	225 K
No oscillations!	

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Fig. 9: Test with shifted spacers (KNK II/3 version)

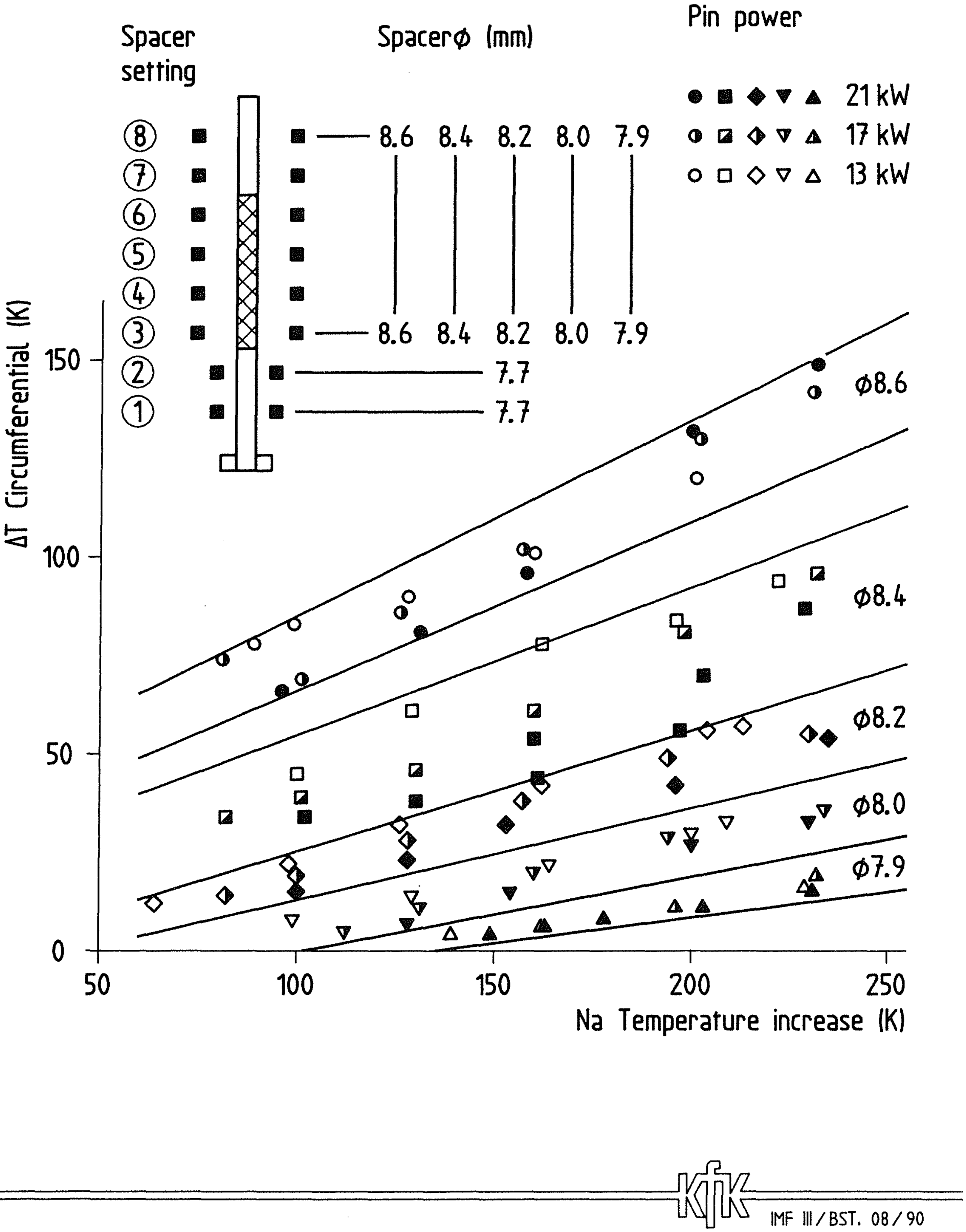

Fig. 10: Circumferential temperature changes as a function of sodium temperature increase and rod clearance

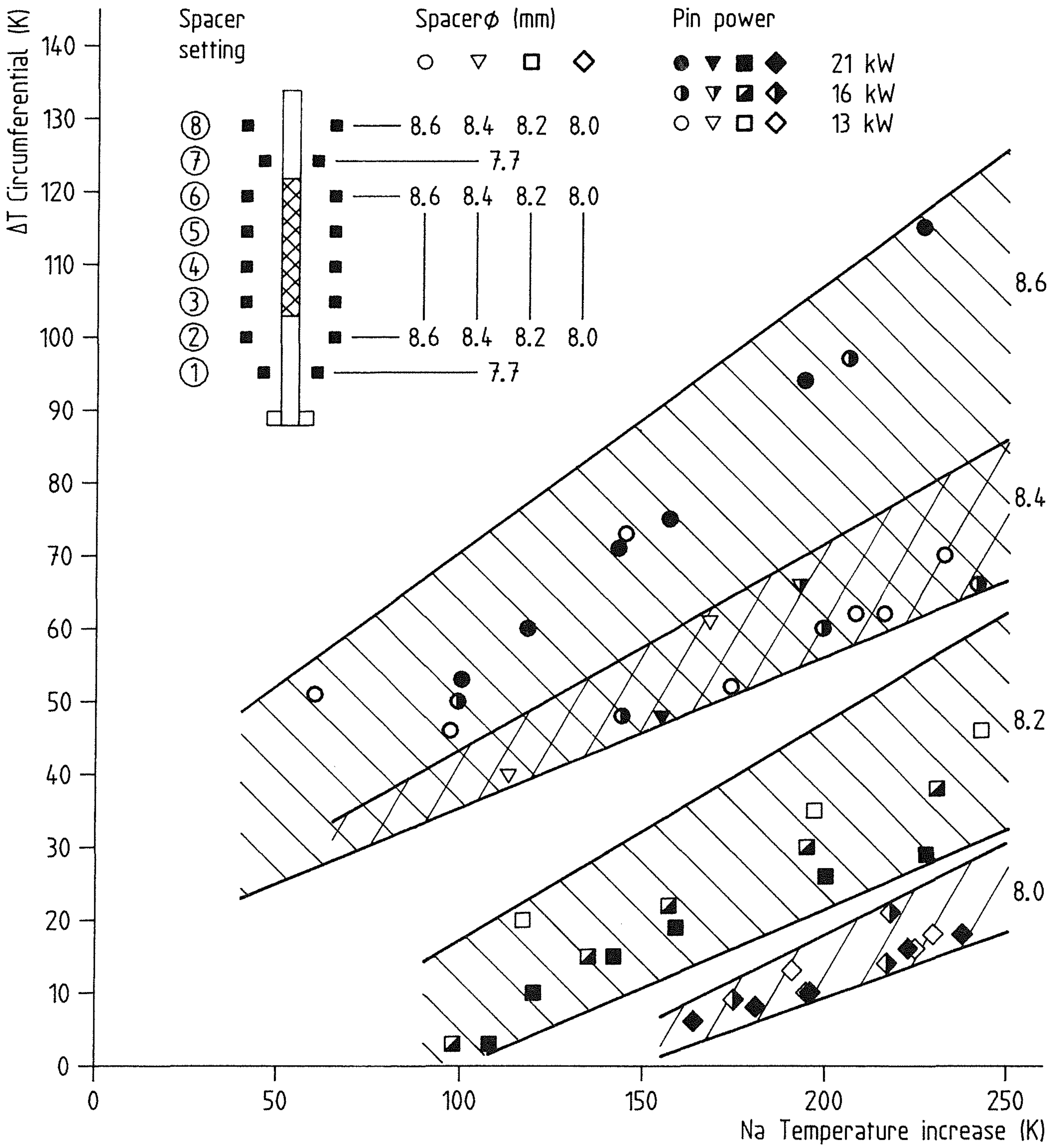

Fig. 11: Circumferential temperature changes as a function of sodium temperature increase and rod clearance

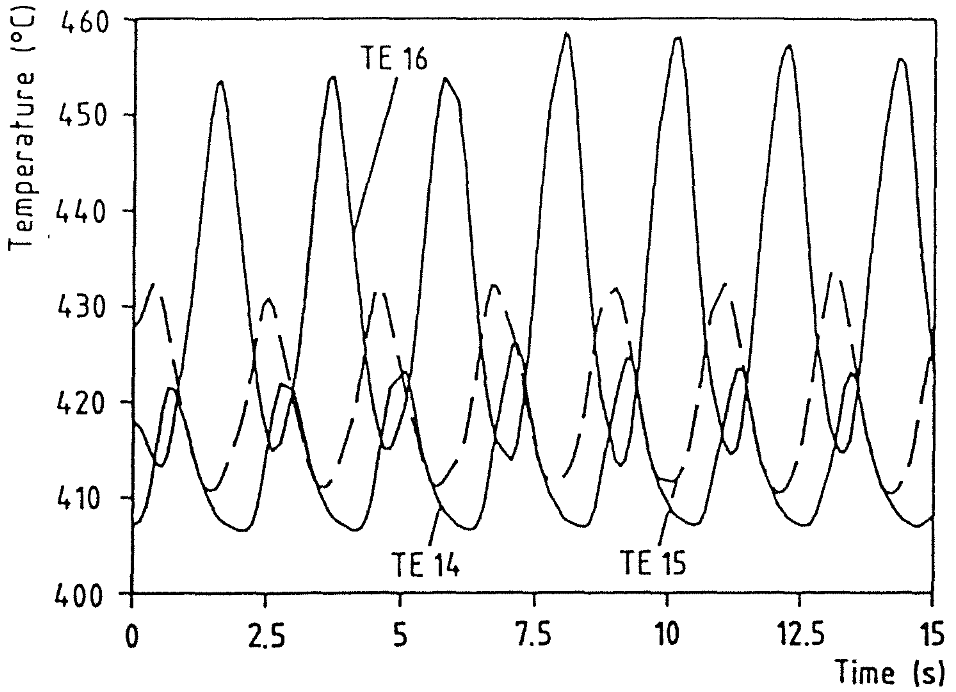

Fig. 12: Temperature curves at spacer 5 (rod clearance 8.2 mm/7.6 mm)
Test rod held at the bottom

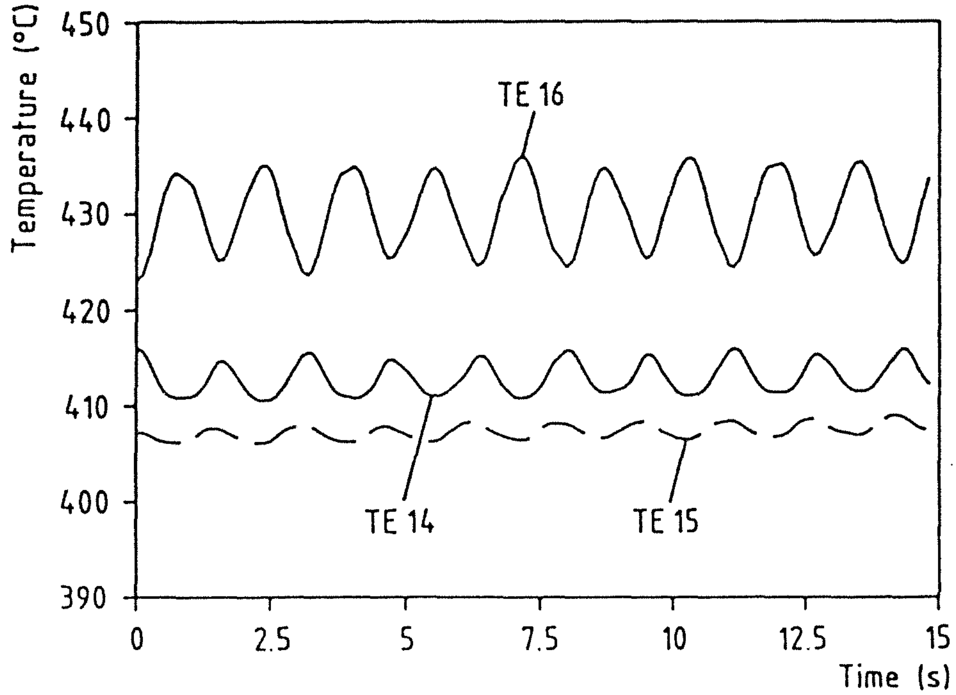

Fig. 13: Temperature curves at spacer 5 (rod clearance 7.9 mm/7.6 mm)
Test rod held at the bottom

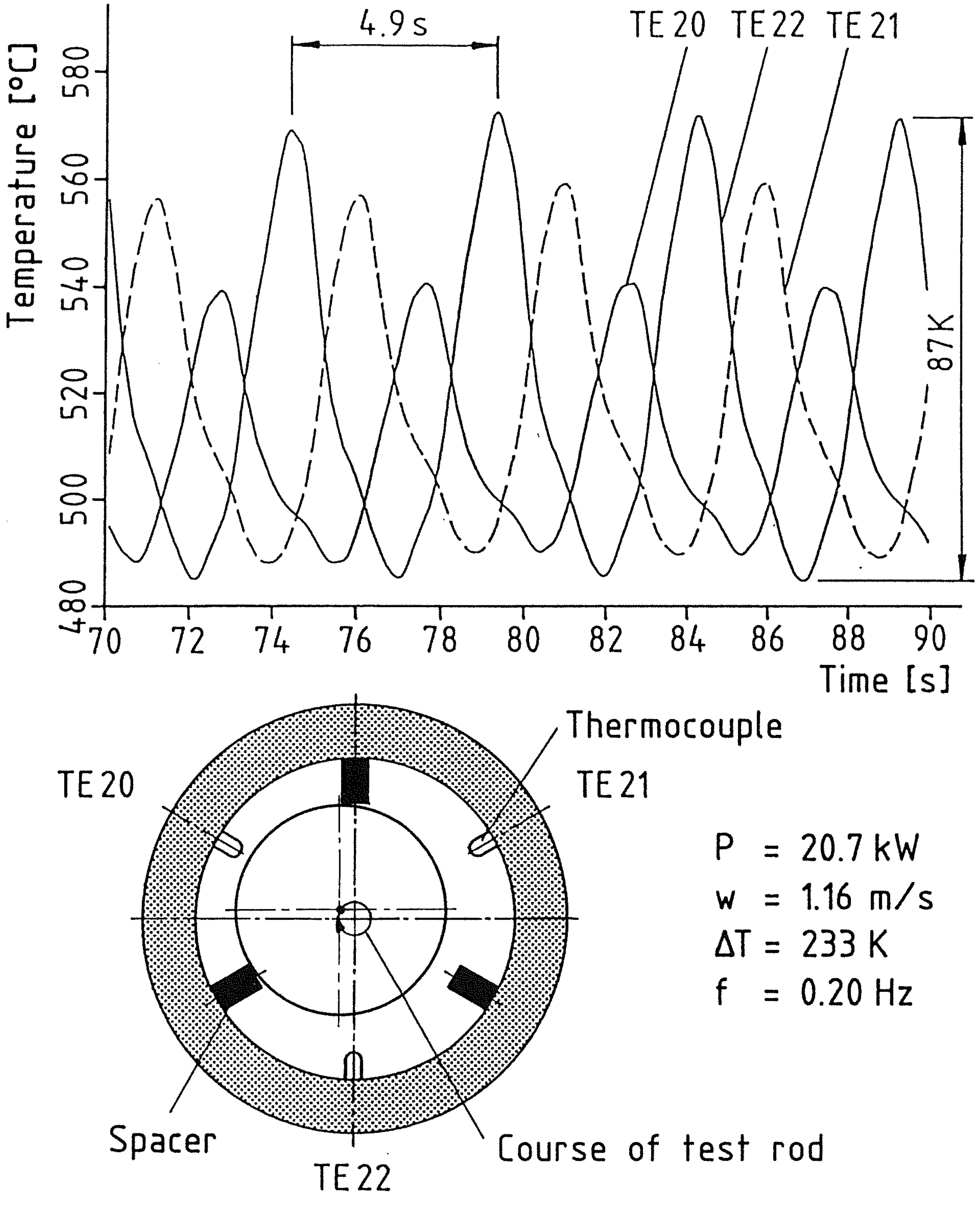

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Fig. 14: THIBO I test
Temperature oscillations and rod movements at spacer 6

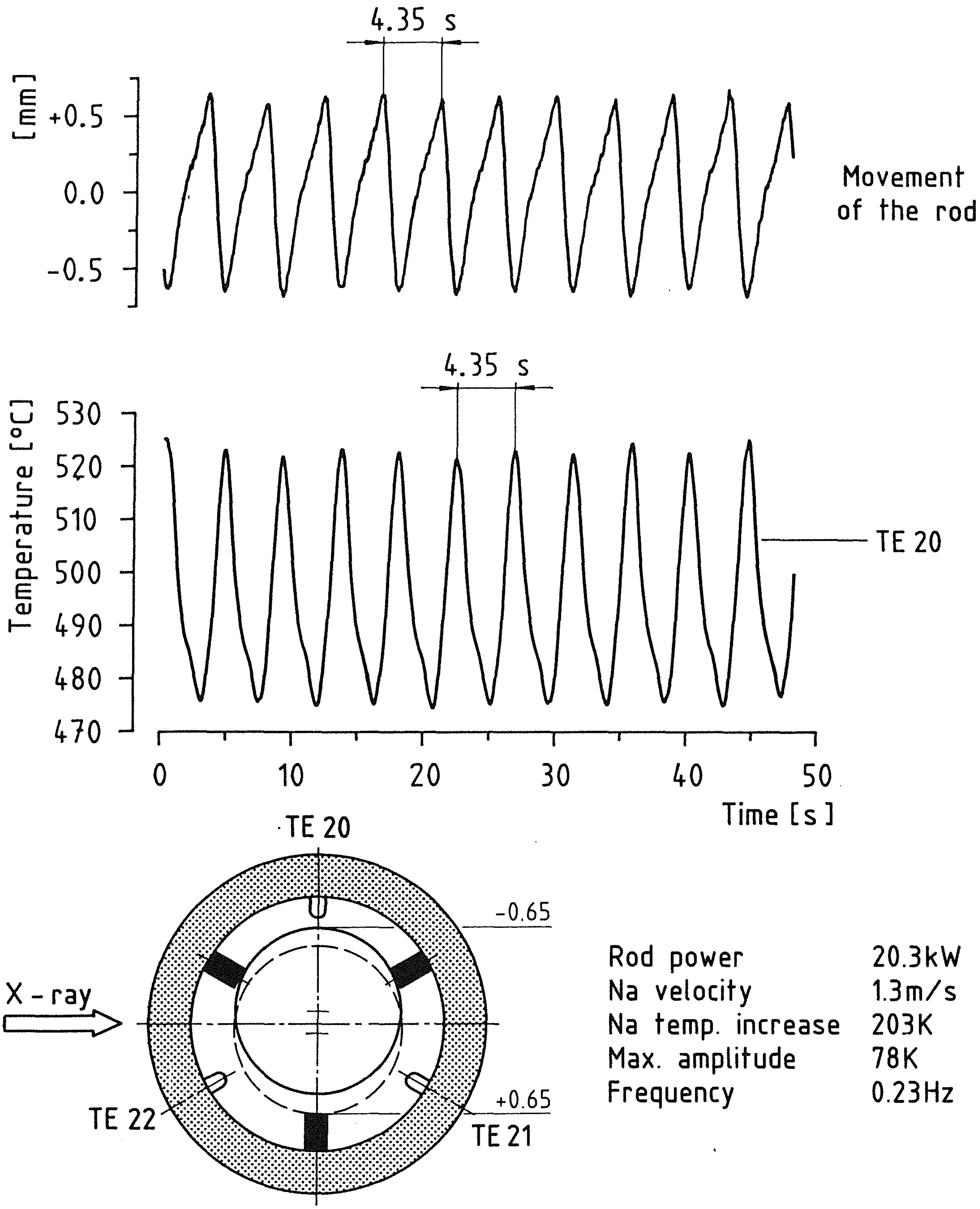

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Fig. 15: THIBO I test
Measured rod movement and temperature oscillation at spacer 6

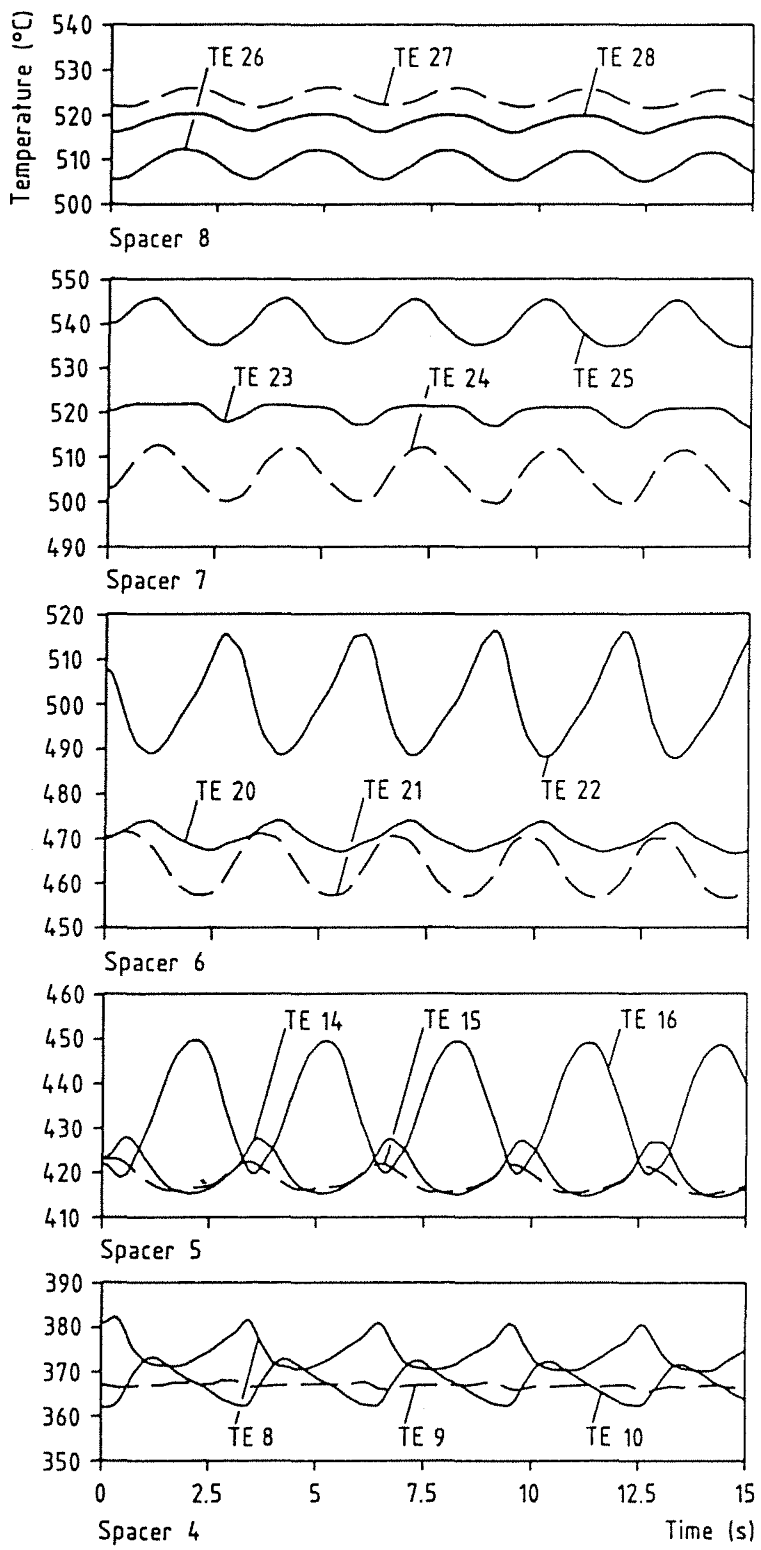

Fig. 16: Temperature curves at spacer planes 4 to 8

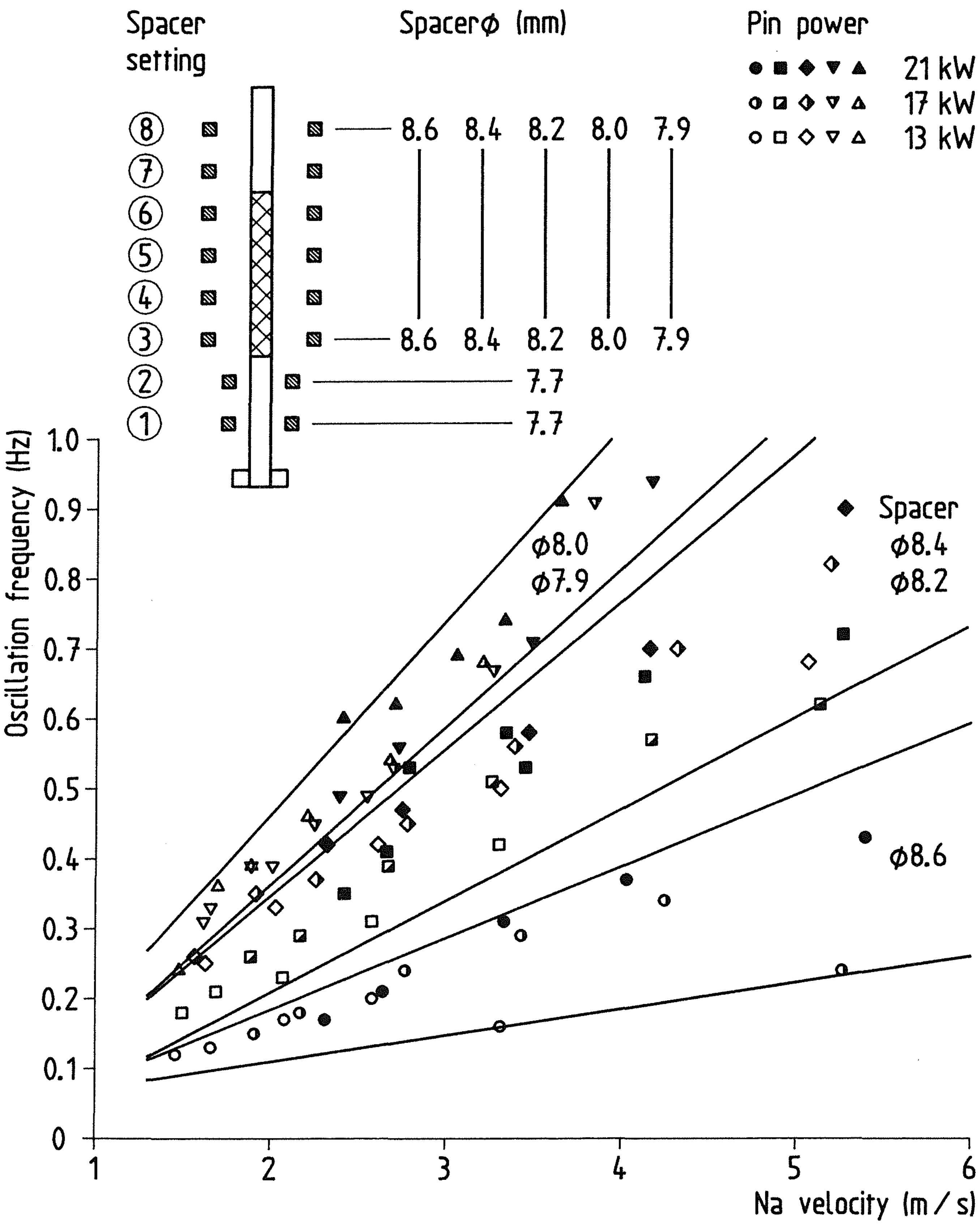

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Fig. 17: Frequency of temperature oscillations as a function of sodium flow rate and rod clearance

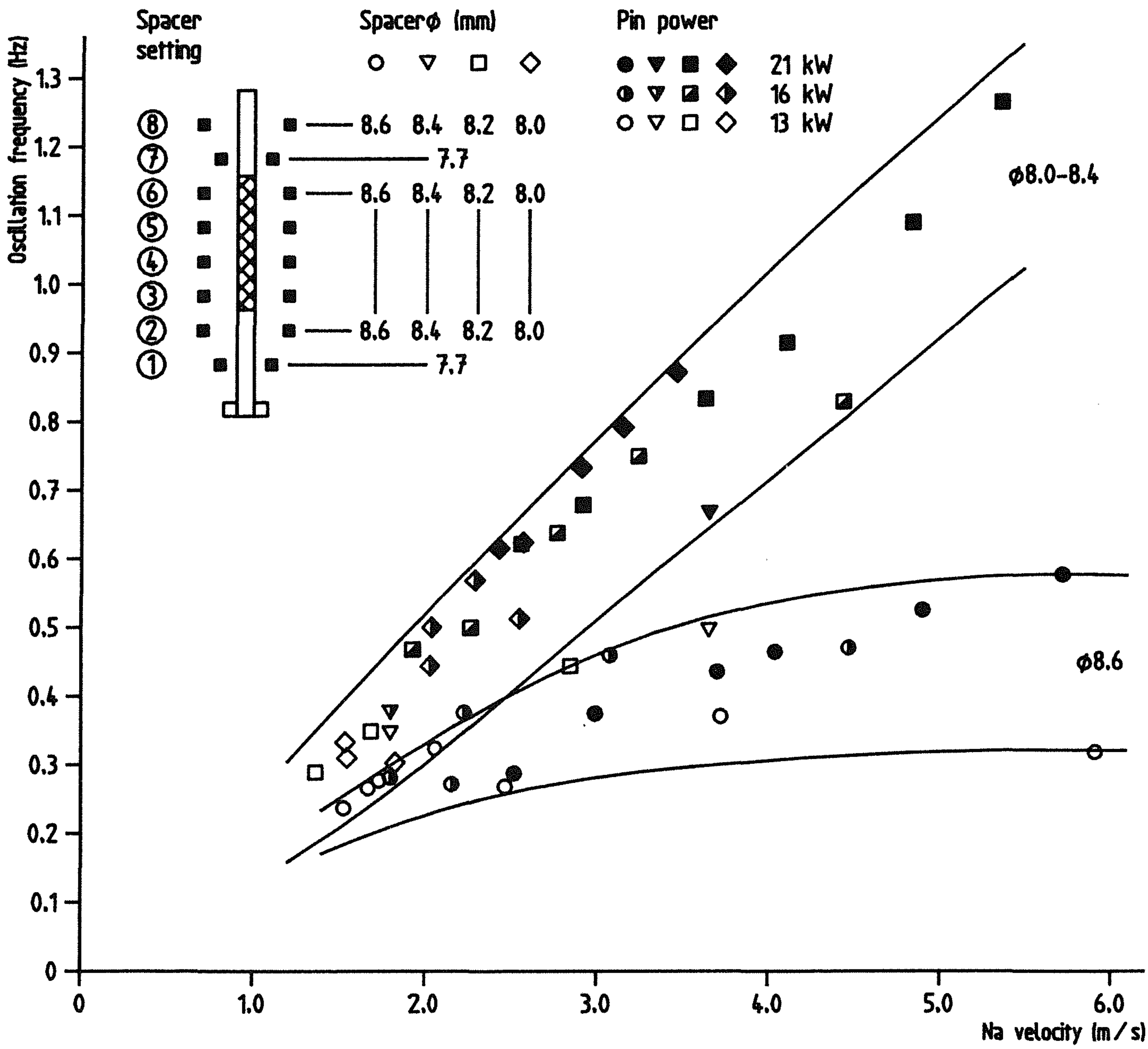

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Fig. 18: Frequency of temperature oscillations as a function of sodium flow rate and rod clearance

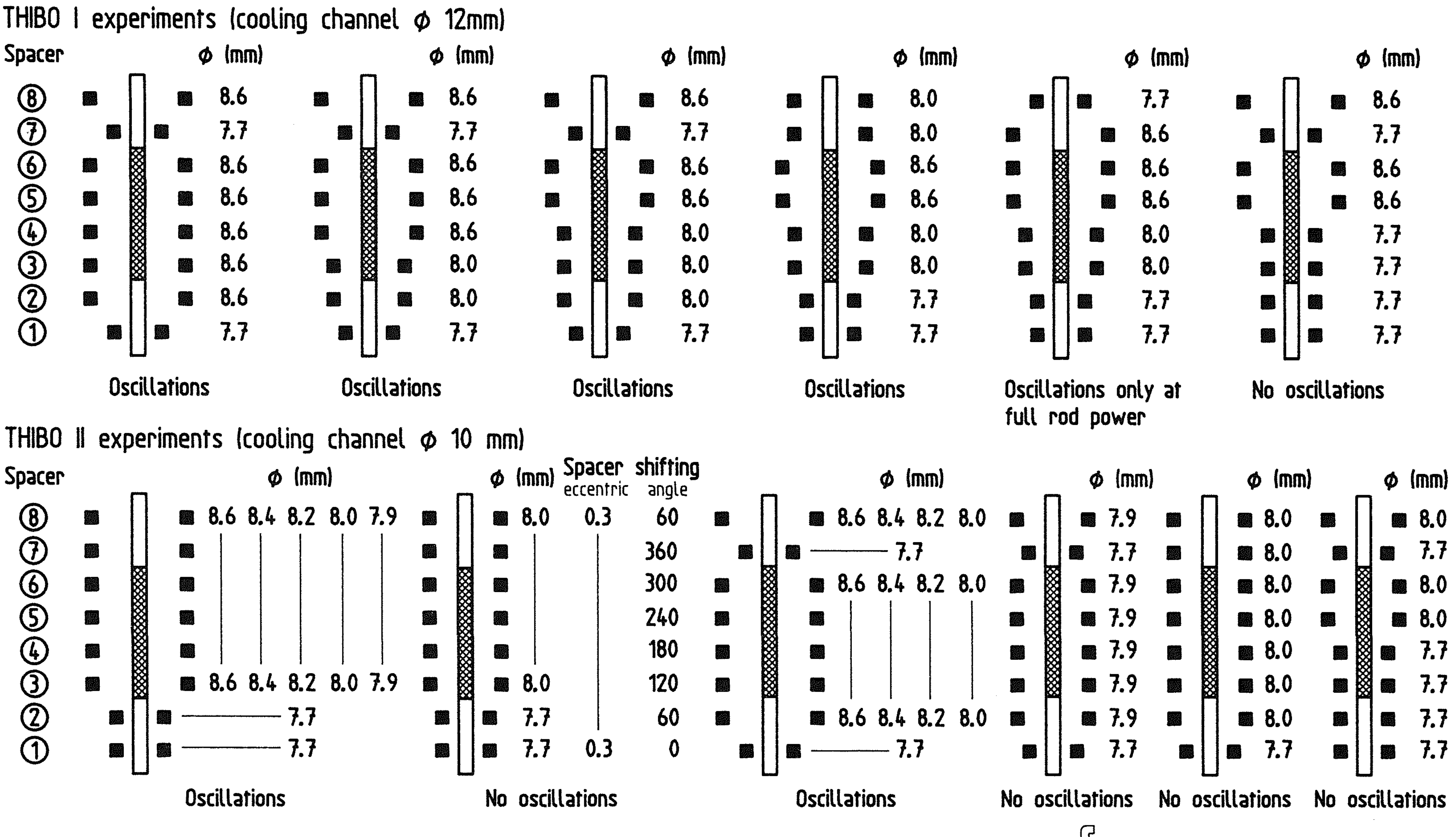

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Fig. 19: THIBO experiments - Influence of spacer setting on the rod oscillations

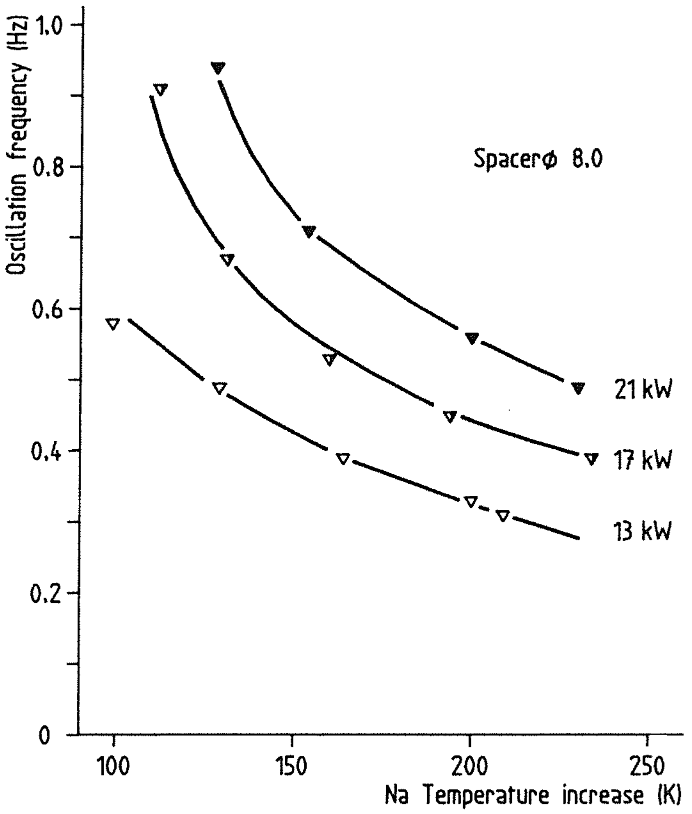

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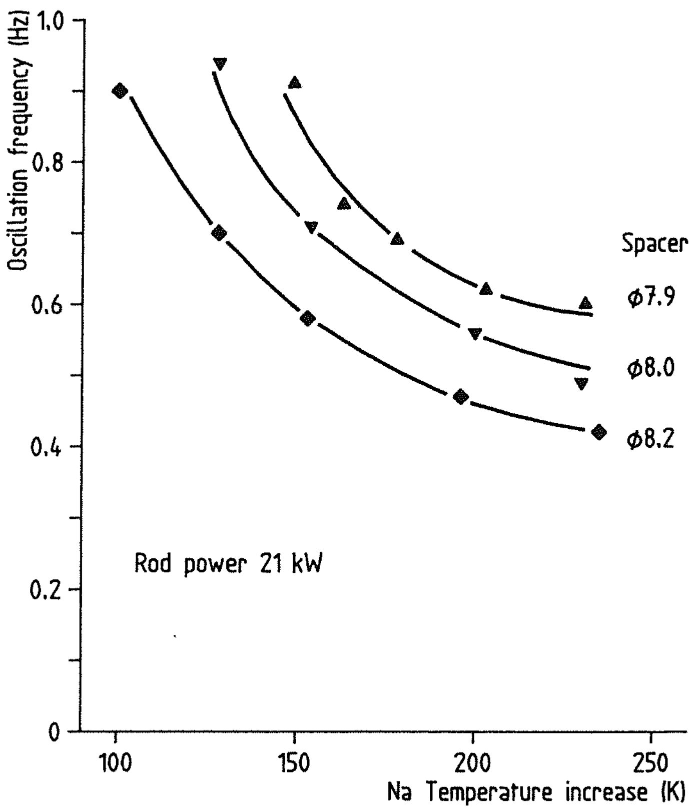
Fig 20: Frequency of temperature oscillations as a function of sodium temperature increase and rod power



IMF III / BST. 10 / 90

Fig. 21: Frequency of temperature oscillations as a function of sodium temperature increase and rod clearance

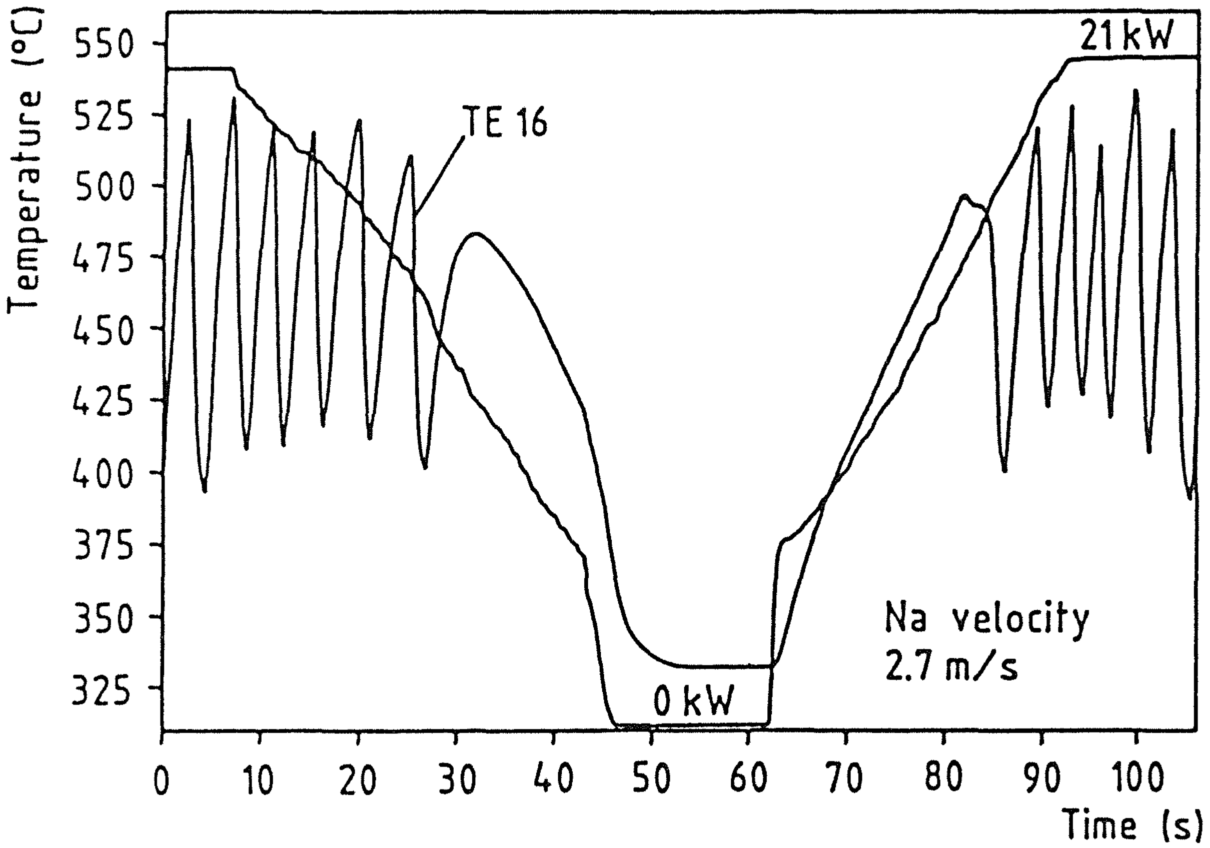


Fig. 22: Change in temperature oscillations as a result of turning the rod power off and on while keeping the sodium flow rate constant