LONG - TERM COOLABILITY OF A PARTIALLY BLOCKED CORE
- EXPERIMENTAL AND THEORETICAL RESULTS -

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Introduction

Under accidential conditions in a PWR high cladding temperatures may result in coolant channel blockages of some extent. The most severe blockage credible seems to be a 90% reduction of the coolant channels in a large number of neighboring channels located in the central region of the core with the blockage extending over approximately the distance between two spacer grids. There are good reasons why this is an excessive assumption, however this blockage geometry was chosen as a limiting condition for experiments designed to investigate the effects of an extreme blockage and to determine if the rods are sufficiently cooled under long term heat removal conditions.

The question to be answered was, if under steady state conditions after reflood of the surrounding core, the blockage would be an unacceptably hot island where the remaining coolant channels would be filled with superheated steam in the upper part of the blockage and therefore result in high steady-state clad and fuel temperatures in this region. Assuming no cross flow over the blocked length the question reduces to the investigation of two parallel channels of different cross section communicating at bottom and top of the blockage and having the same linear power input (Fig. 2). Fluid quality is expected to be higher in the narrow channel with reduced mass flow which may eventually lead to dryout and superheating in the upper part of the channel and may result in strong pulsations, when accumulated steam bubbles escape from the small diameter channel.

Experiment

A 4x4 full length rod bundle containing a 90% blockage was placed in a corner of a flow shroud large enough for a 5x5 bundle with the open cross section acting as bypass around the blockage (Fig. 3). The body of the blockage consisted of machined stainless steel slices clamped together with axial gaps to reduce axial heat conduction and enclosed by a radial gap to reduce heat losses to the outer block surface (Fig. 4). The massive block is a suitable blockage simulator to measure channel wall temperatures at steady state conditions uneffected by radial heat conduction and heat capacity.

Five slices were instrumented with 8 corresponding fluid- and wall-TC's each (Fig. 5). More TC-instrumentation was distributed expecially along the heater rods (Fig. 6). The test section was part of a watercircuit (Fig. 7) operating at up to 5 bar. The test parameters are listed in Fig. 8 with the fluid quality α around the blockage being a function of several other parameters.

Steady state conditions could be approached (Fig. 9) either from the wet cool condition (boiling test) or from the dry superheated condition (flooding test); both test modes resulted in the same steady state temperature distribution.

Experimental Results

A linear rod power of 15 W/cm seems to be the maximum to be considered since 500 W/cm operating power and 3% decay heat for times later than 300 seconds after shutdown are maximum values. Figures 10 through 12 show temperature distributions in the blockage for decreasing injection rates at 3 bar; even for the very low injection rate of 1.5 l/min (corresponding to a water velocity of 1.4 cm/s in a nominal channel) only one wall-thermocouple in the upper right corner of the blocked area indicates more than saturation temperature. This right channel turned out to always be the hottest channel; the reason is that heater rods and fluid channels are unsymmetrically distributed over the cross section of the blockage and this results in a diagonal profile of the power to the individual channels, thereby delivering more than the average power to the right channel. For injection rates low enough to be boiled off, for a given bundle power, water does not reach the upper end of the rods and overheating starts at this point while the blockage stays near saturation temperature. Fig. 13 shows this for the two hottest points in the blockage and near the upper end of the rods, respectively. Average water content in three sections of the bundle was measured (Fig. 14) and the data show why at 15 W/cm dryout occurs first near the upper end of the bundle.

These results show that low blockage temperatures can be expected, for realistic power levels, wherever the upper end of the rod is sufficiently cooled.

To investigate the safety margin, tests were done at unrealistically high power levels. In the test matrix (Fig. 15 and 16) is marked if and at which bundle position temperatures above 600°C were measured. It was possible to reach dryout in the upper part of the blockage channels (Fig. 17) only if unrealistically high power levels were applied (Fig. 18). Under these circumstances a rather stable dryout-front is established with saturation conditions below and increasingly superheated steam above this front. High blockage temperatures were measured only when small injection rates result in high steam quality in the bypass and therefore in low pressure head for the coolant flow through the blocked channels. Even then the steam flow was able to keep temperatures in the blockage channel below 800°C for a power level of 20 W/cm and very small injection rates (Fig. 19).

Models

Calculations based on estimates for the flow behavior wihtin partially blocked channels showed that single phase flow is not possible under the conditions given here. Therefore a steady state thermohydraulic two-phase code was used for the first step. The wall temperatures calculated by this code, however, were about 600 K higher than the experimental results.

The same discrepancy occurred when an attempt was made to adapt the dynamic two-phase code BLOW3A to this problem. BLOW3A has been successfully applied to LMFBR calculations for a few years and is based on a multiple-bubble model providing liquid slugs, annular film and superheated flow.

The alternating temperature distributions (Fig. 20) calculated by BLOW3A correspond to the unsteady flow behavior which was already observed in pilot tests, the frequency of the calculated oscillations being of the same order as the experimental ones. Realistic wall temperatures, however, could be only obtained by excessively increasing the heat transfer conditions within the range of dryout. The pilot experiment showed clearly that, under the given conditions, dryout is prevented by intensive flashing and rewetting phenomena, which could not be modelled properly with the code.

It can be stated that calculated data do not sufficiently agree to the experimental results, and further investigations or application of other codes are necessary.

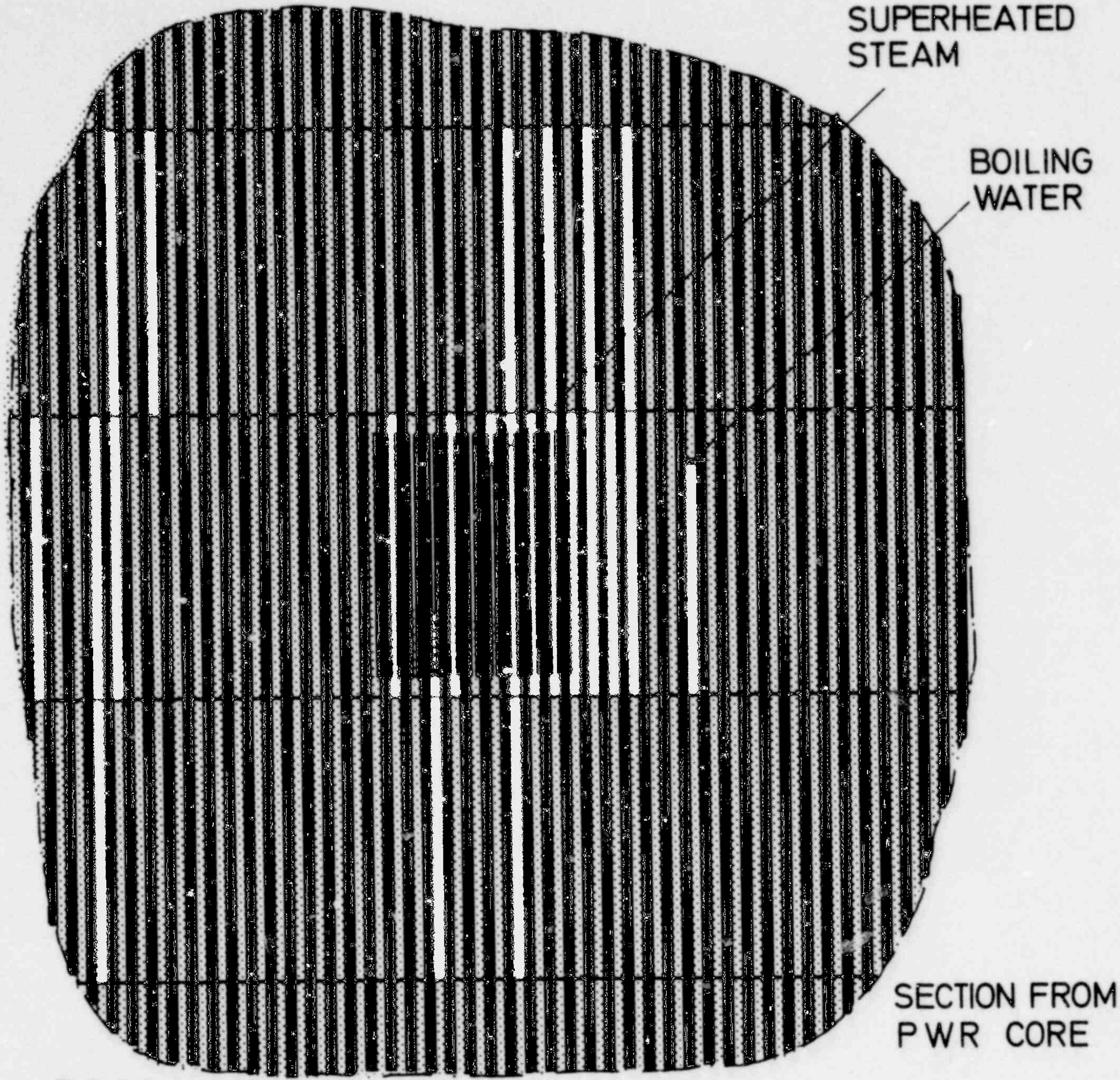
Conclusions

For realistic power levels and flow conditions an extreme 90% blockage in the center of a PWR core does not overheat during long-term heat removal.

Wall temperatures of the blockage channels are near saturation temperature.

With decreasing injection rates dryout starts at the upper end of the bundle rather than in the blocked area.

It seems to be sufficient to keep the core covered with water even if heavy blockages are present.



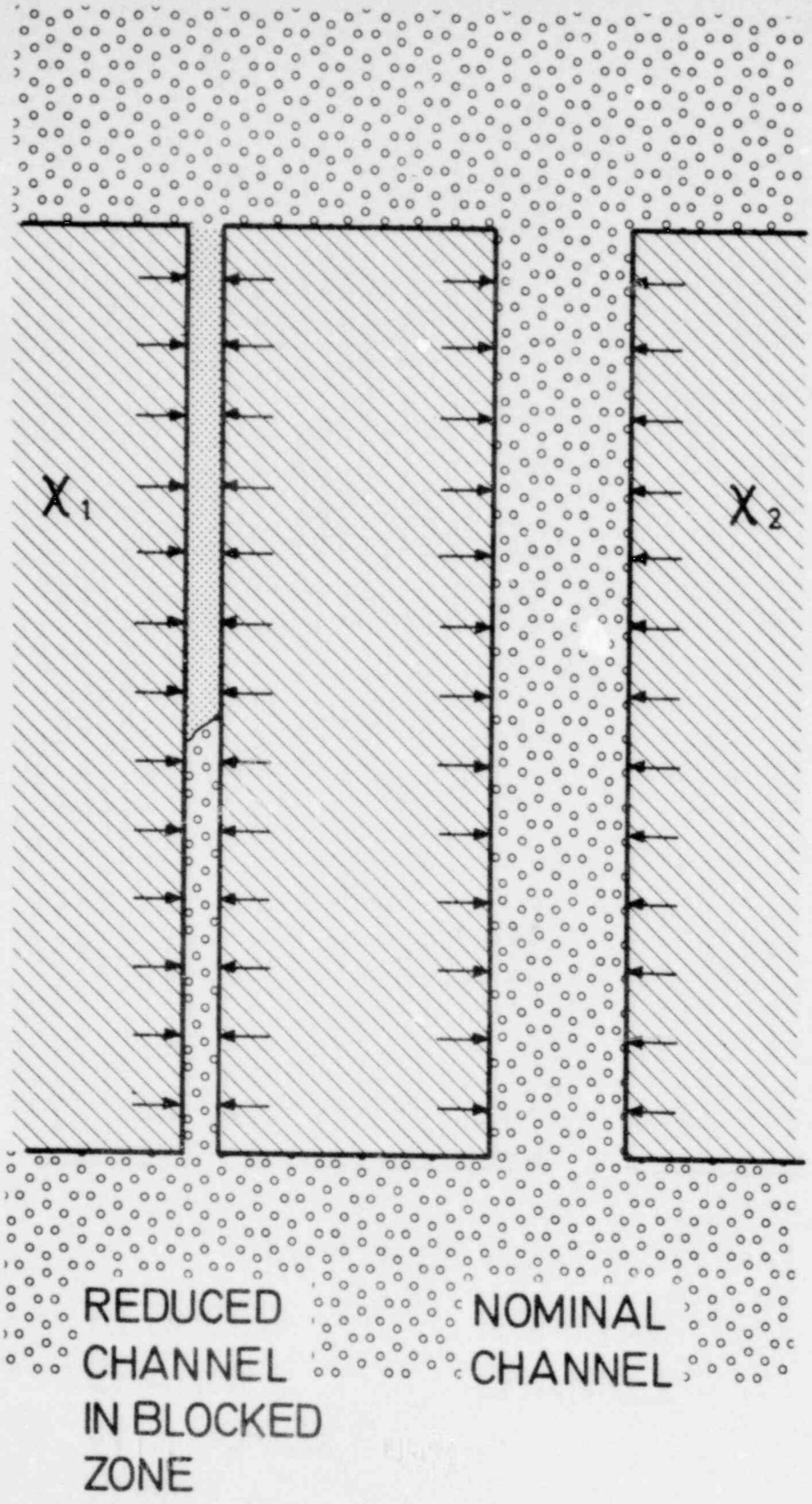
POOR ORIGINAL

KfK IRB

QUESTIONS:

- IS THIS A THERMOHYDRAULICALLY POSSIBLE SITUATION ?
- IF YES, WHICH ARE THE EQUILIBRIUM CLAD TEMPERATURES ?

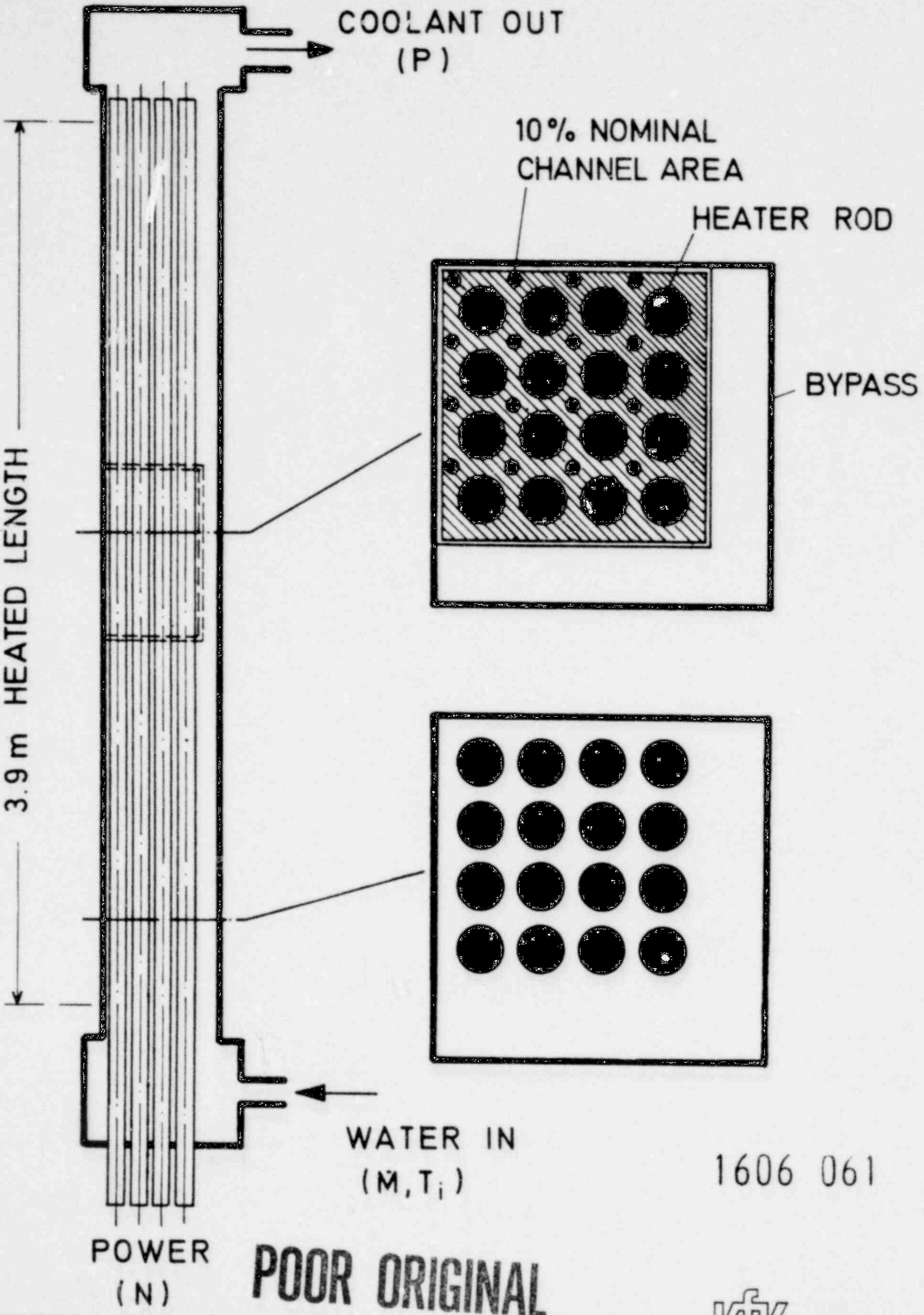
FIG. 1



KfK IRB

MODEL OF FLOW IN PARALLEL CHANNELS OF DIFFERENT SIZE

FIG. 2



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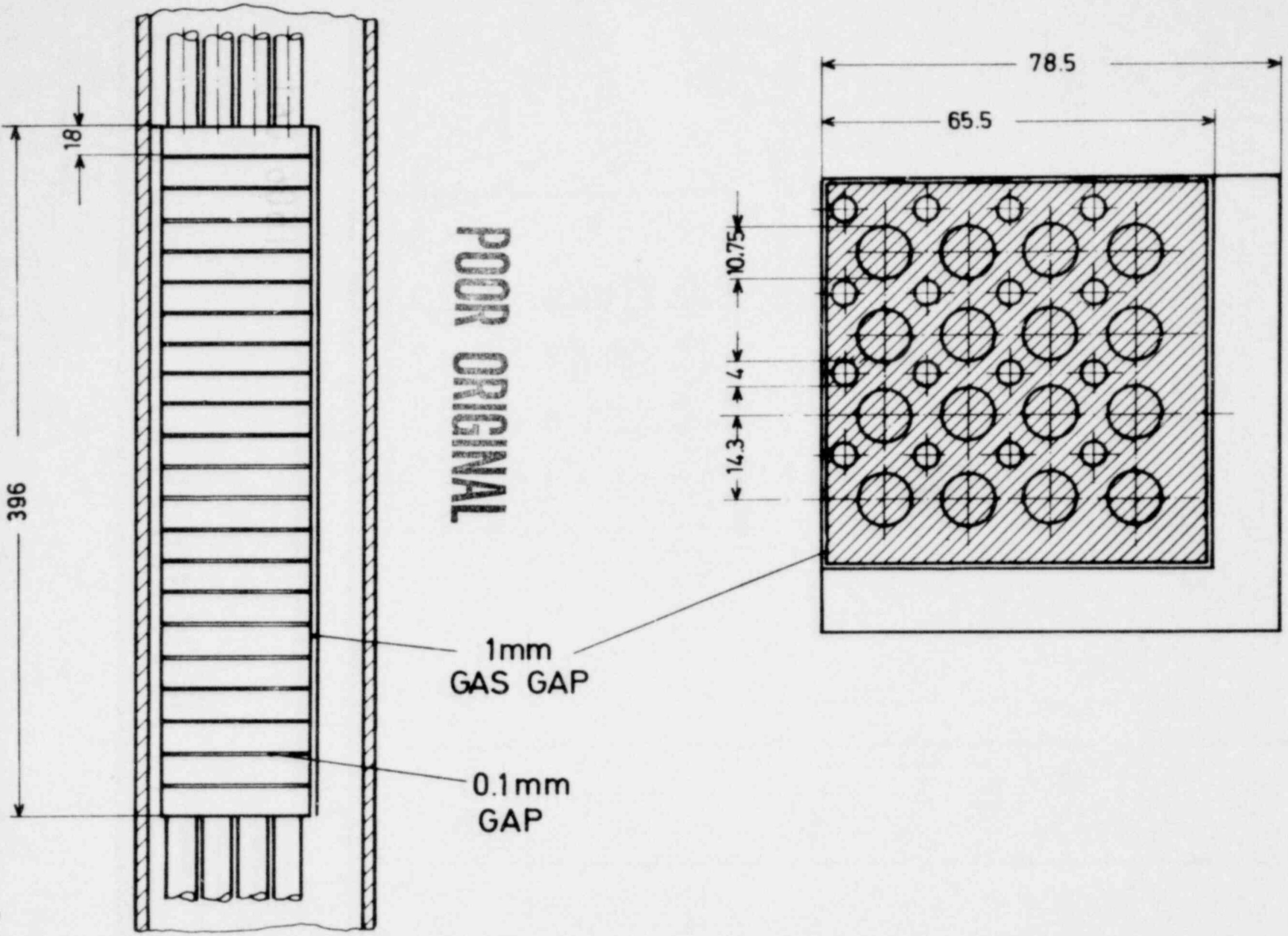
POOR ORIGINAL

KfK IRB

TEST SECTION - SCHEMATIC

FIG. 3



POOR ORIGINAL

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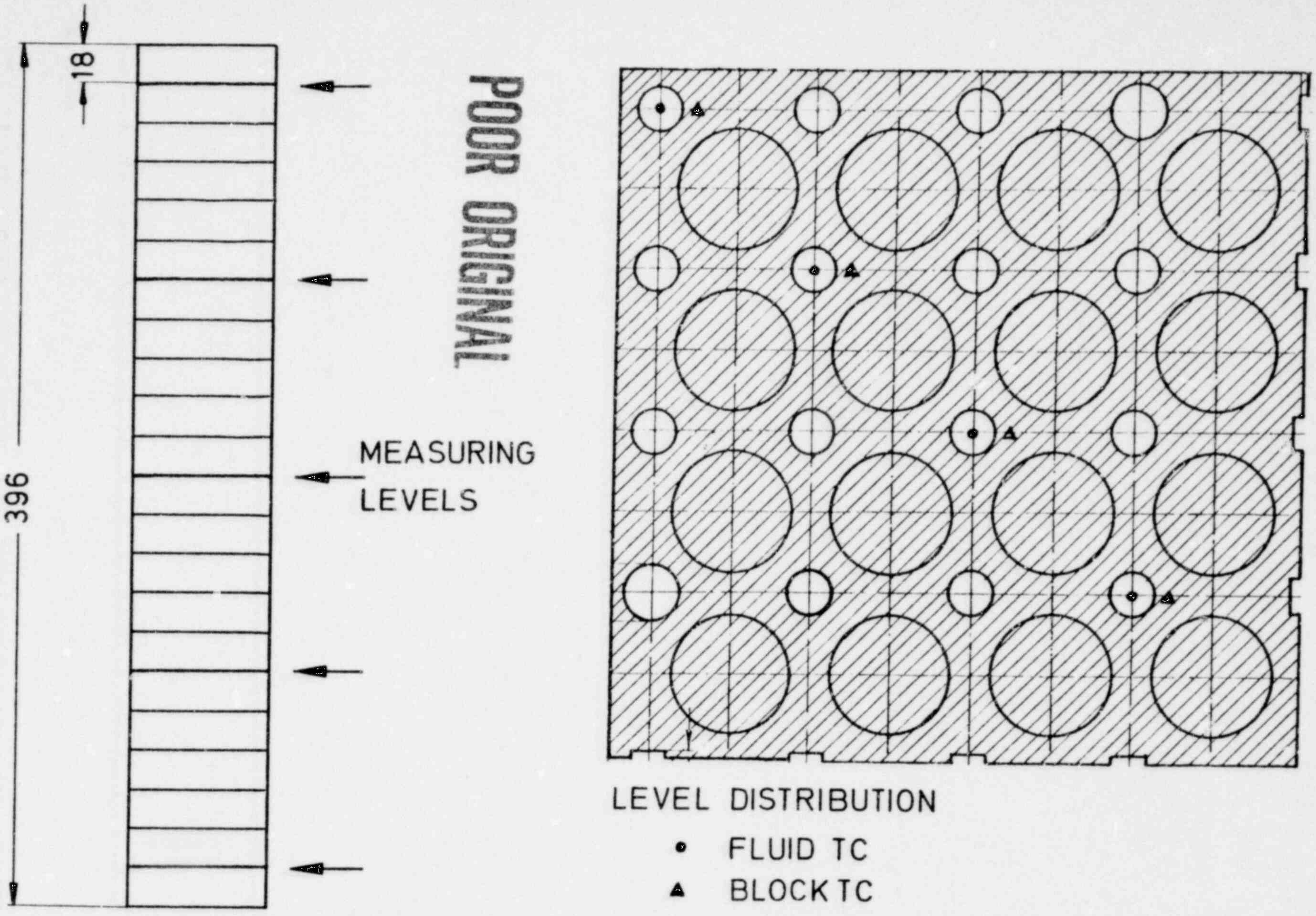
BLOCKAGE DETAILS

FIG. 4

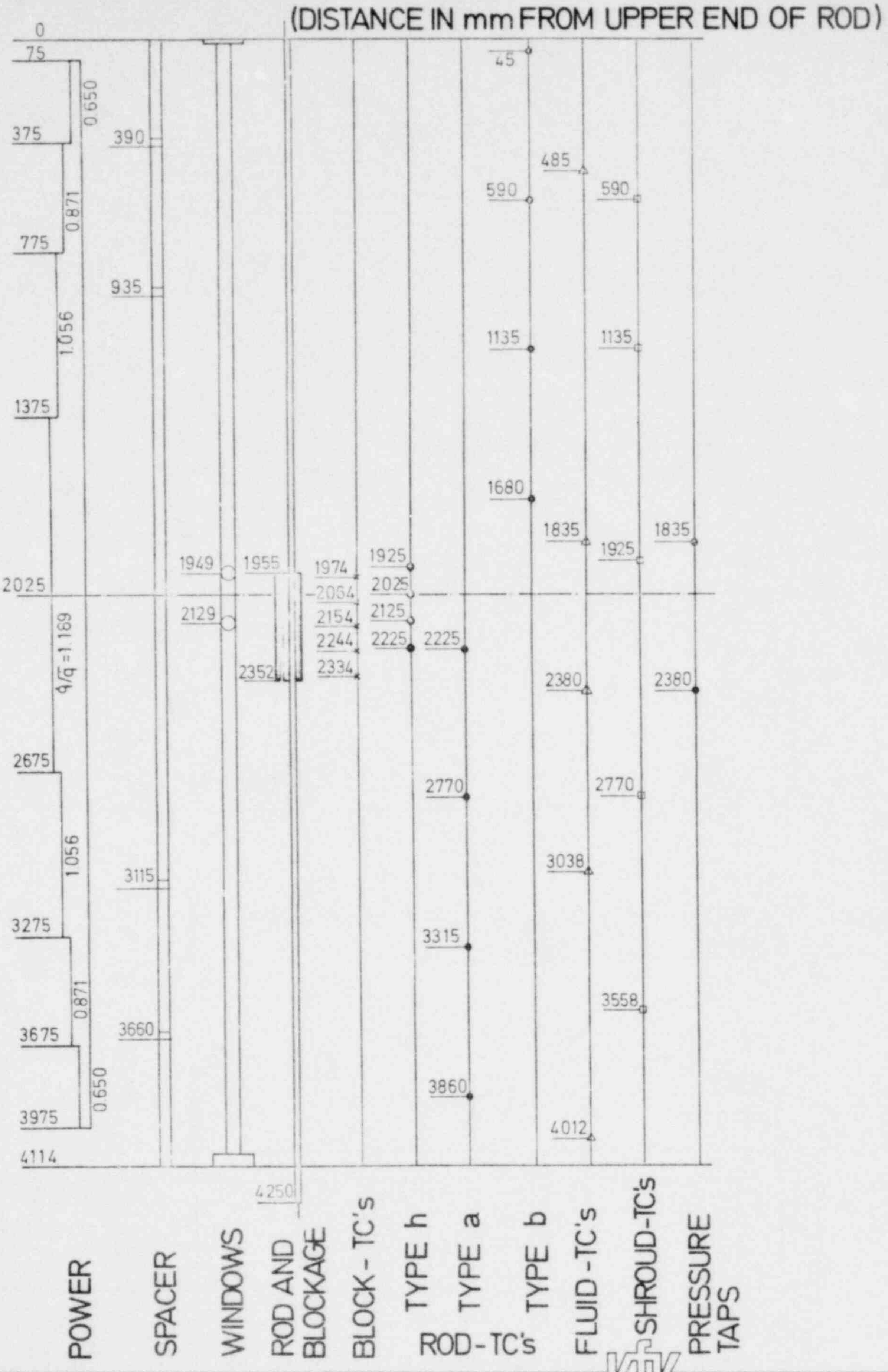


POOR ORIGINAL

KfK IRB

TC-INSTRUMENTATION OF THE BLOCKAGE

FIG. 5



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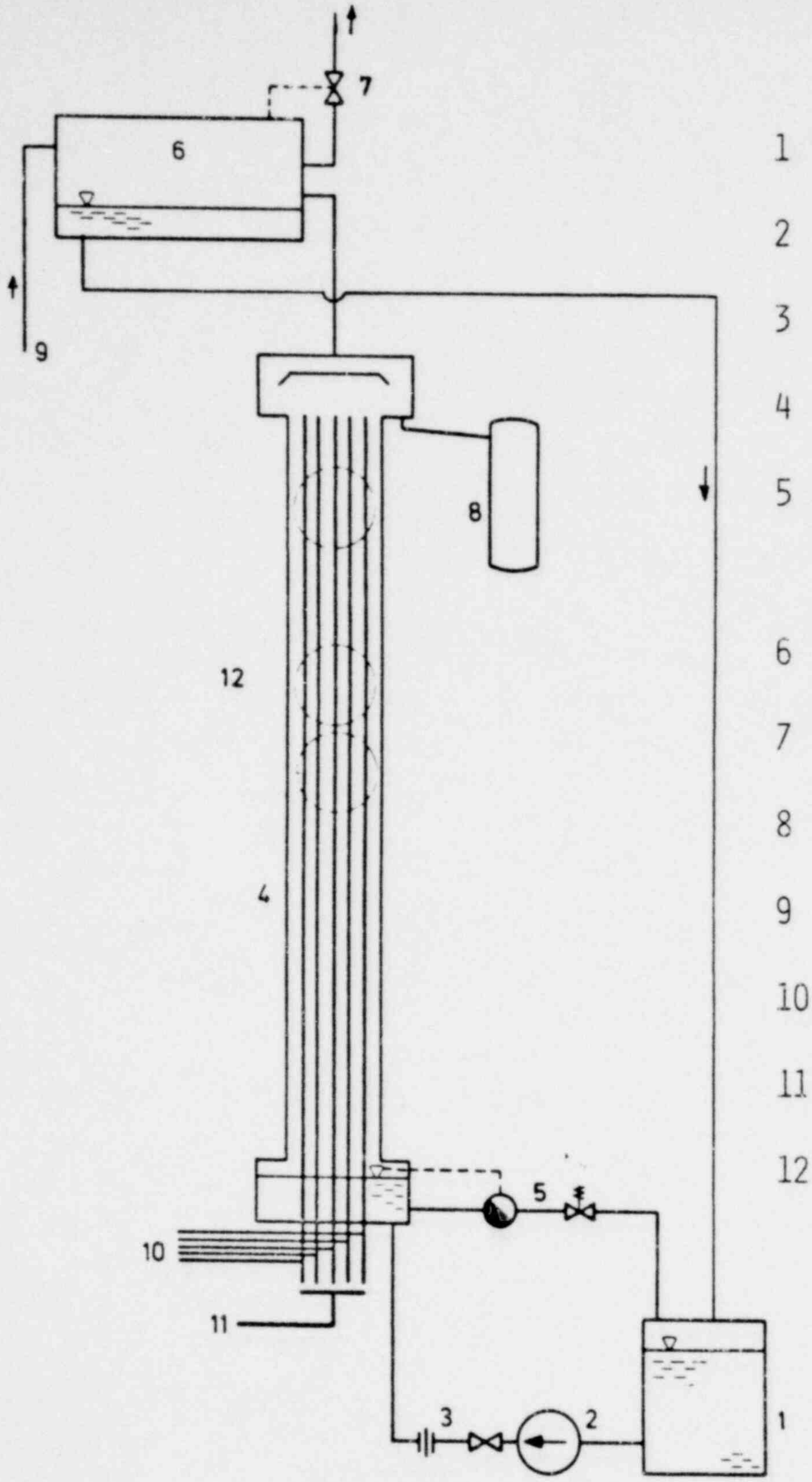
AXIAL POSITIONS IN THE TEST SECTION

FIG. 6



1	WATER TANK
2	PUMP + THROTTLE VALVE
3	FLOW METER
4	TEST SECTION
5	LEVEL-REGULATION + FLOODING VALVE
6	BUFFER
7	PRESSURE REGULATOR
8	WATER COLLECTING TANK
9	STEAM SUPPLY
10	ROD INSTRUMENTATION
11	ROD POWER SUPPLY
12	WINDOWS

IRB

FEBA TEST RIG-SCHEMATIC

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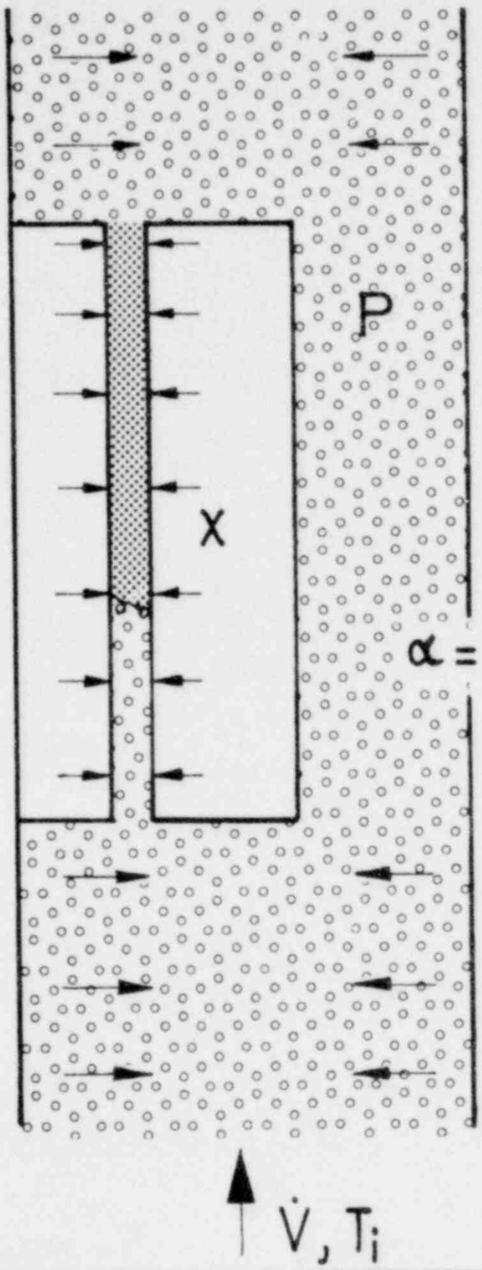
FIG. 7



Rod Power X	15 (10-26) W/cm
Injection Rate $\dot{V}$ Power Related Injection Velocity	1,5 - 6,0 l /min. 1,4 - 5,5 cm / s
Water Inlet Temperature T_i	30 (60) °C
System Pressure P	3 and 5 bar

KfK IRB

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TEST PARAMETERS

FIG. 8

	BOILING TEST	FLOODING TEST
BUNDLE STARTS AT :	SATURATION TEMPERATURE	APPR. 700°C
IS FILLED WITH:	WATER	STEAM
APPROACH TO STEADY STATE CONDITIONS FROM:	WET COOLANT CHANNELS AT LOW TEMPERATURE	DRY SUPERHEATED COOLANT CHANNELS
STEADY STATE TEMPERATURE DISTRIBUTION:	SAME RESULTS FOR BOTH TEST MODES	

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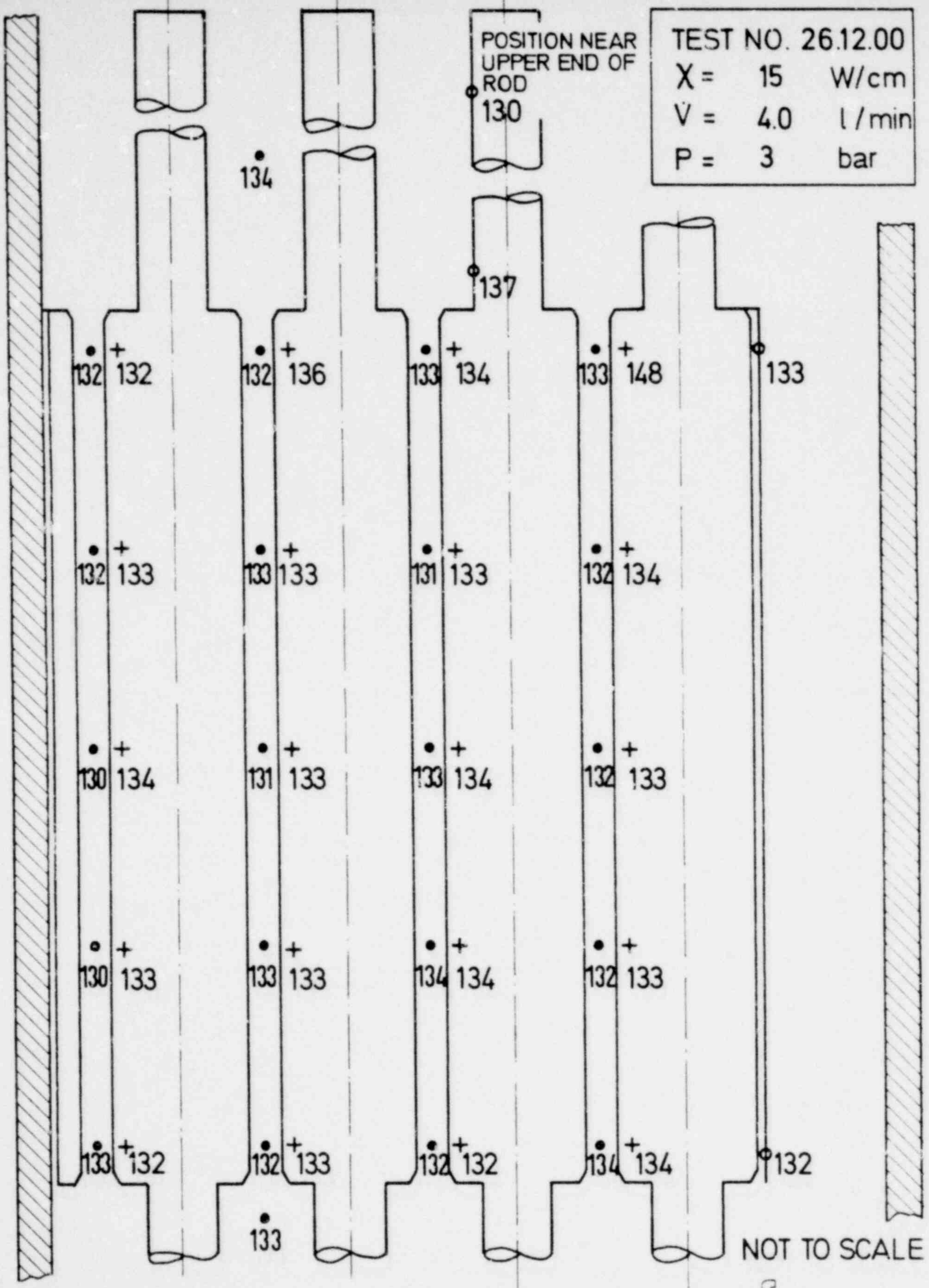
TEST MODES

FIG. 9



TEMPERATURE DISTRIBUTION, DEG. C
(DIAGONAL SECTION THROUGH BLOCKAGE)

FIG. 10

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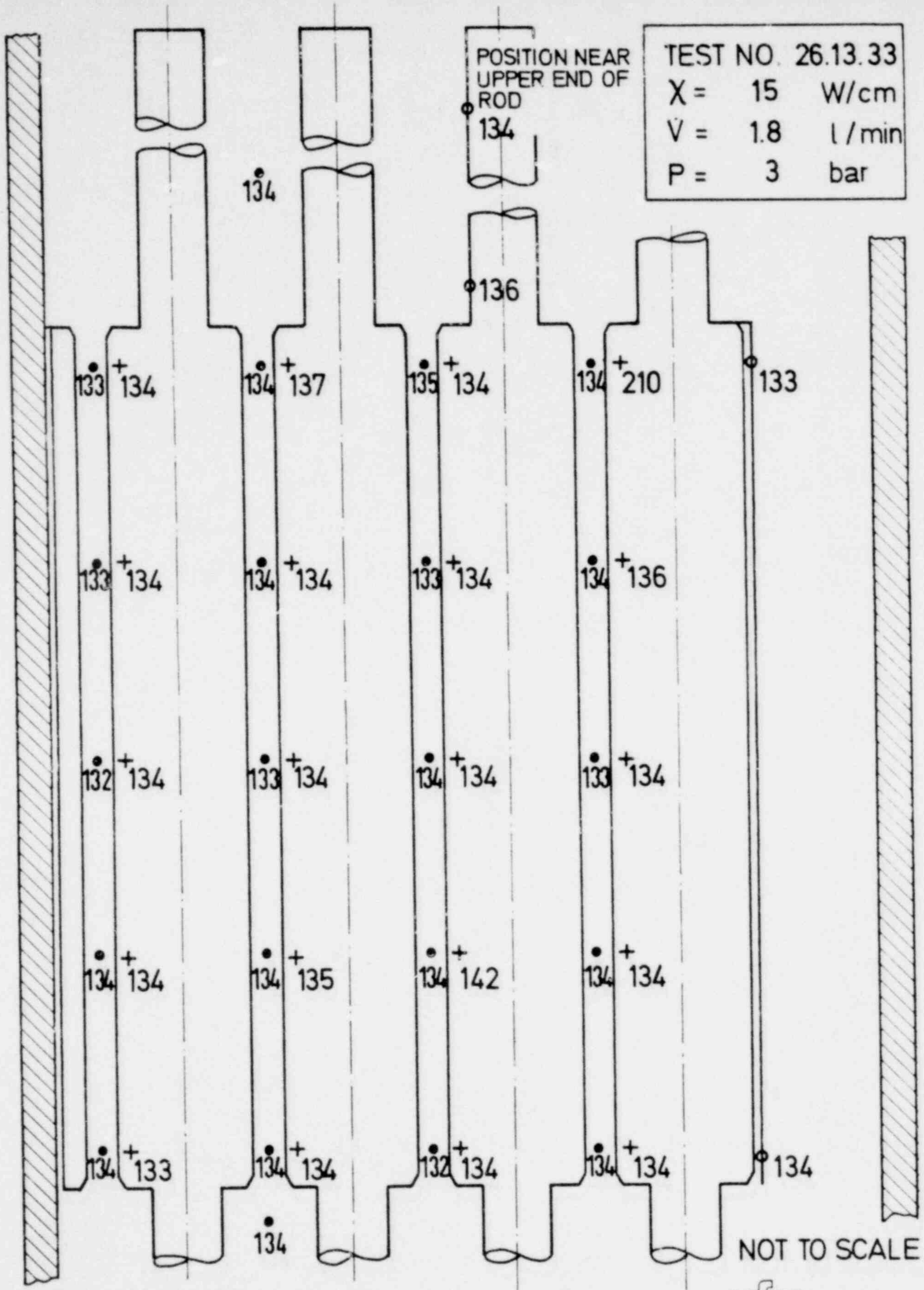

TEMPERATURE DISTRIBUTION, DEG. C
(DIAGONAL SECTION THROUGH BLOCKAGE)

FIG. 11

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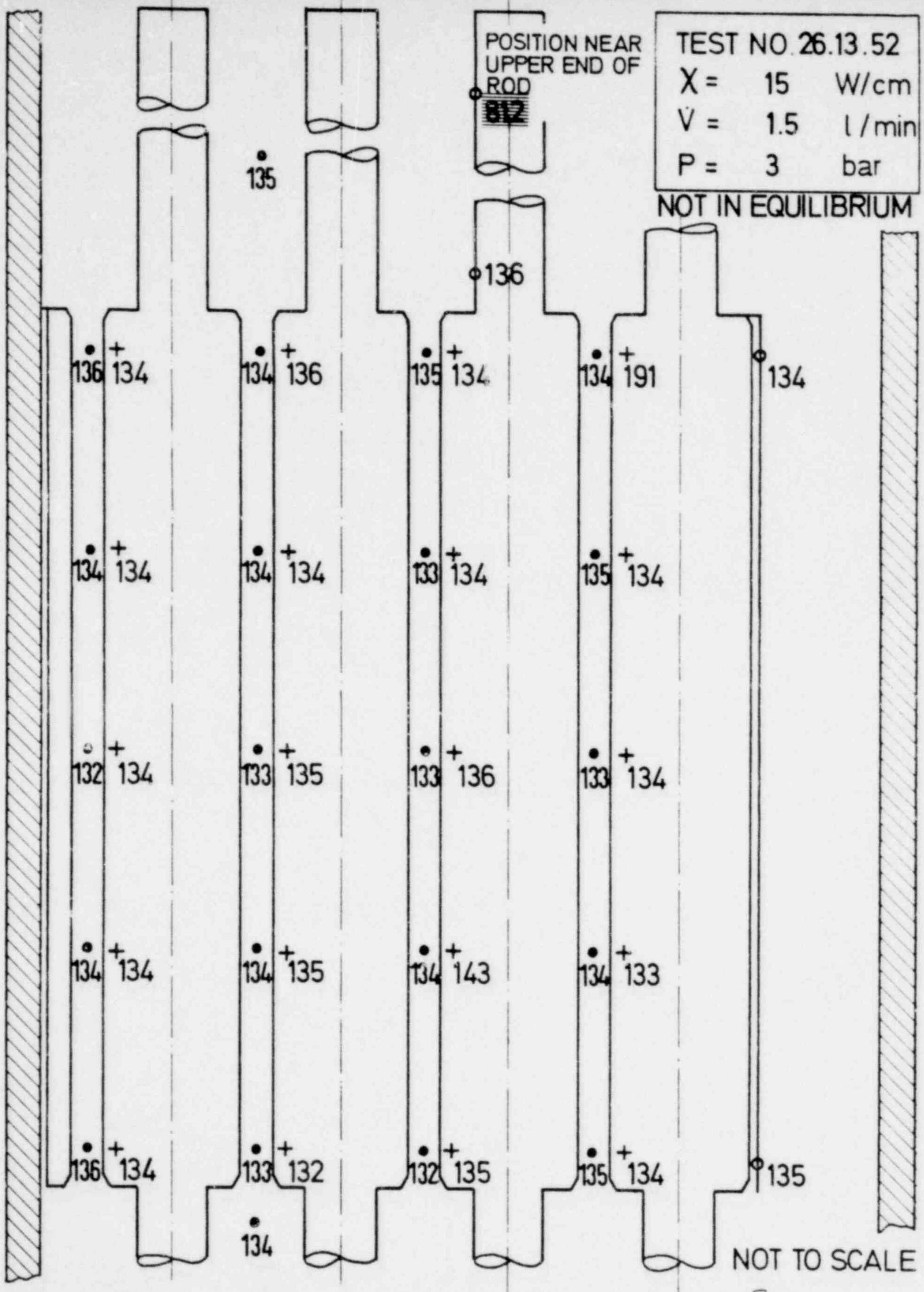

TEMPERATURE DISTRIBUTION, DEG. C

(DIAGONAL SECTION THROUGH BLOCKAGE)

FIG. 12

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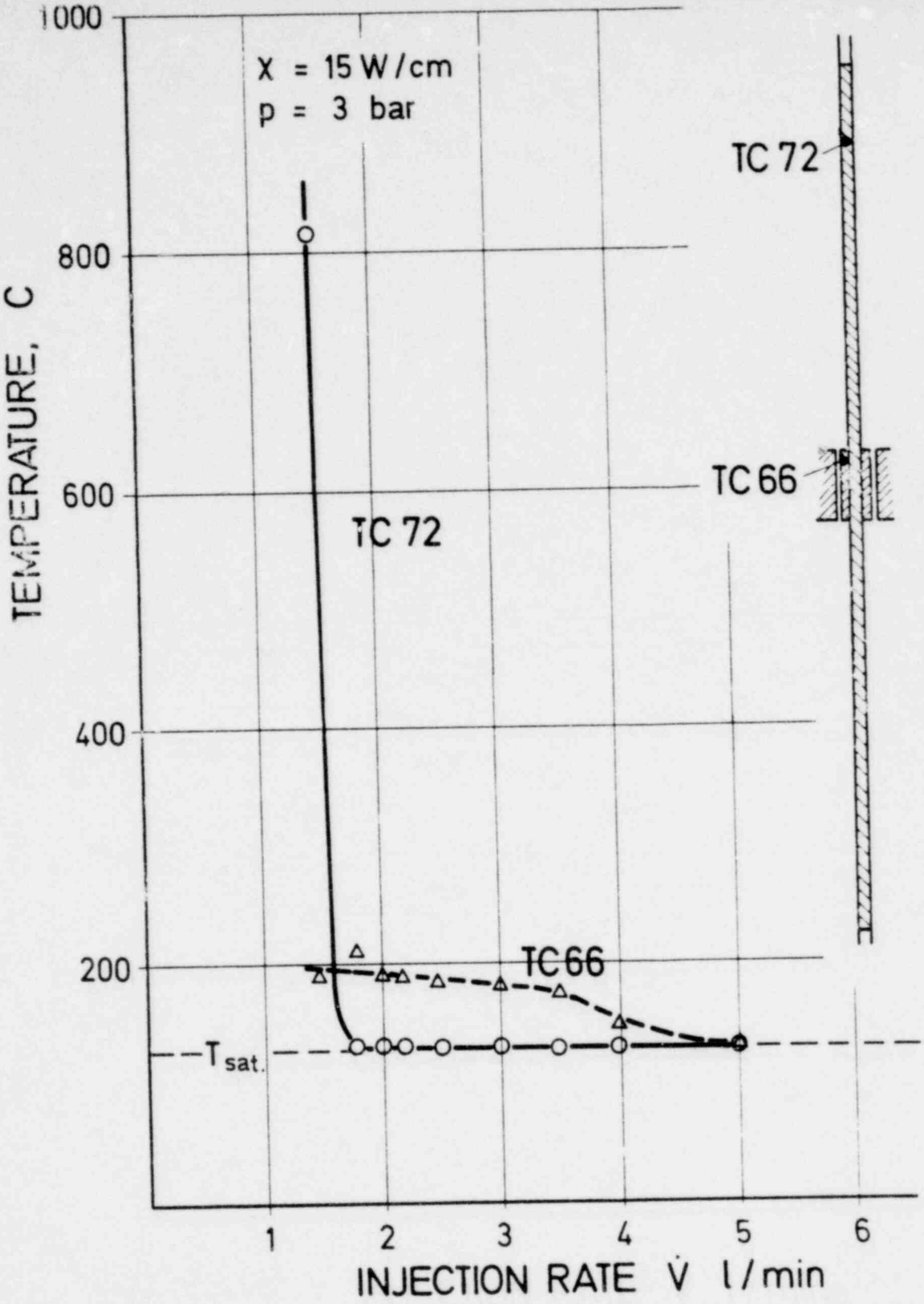
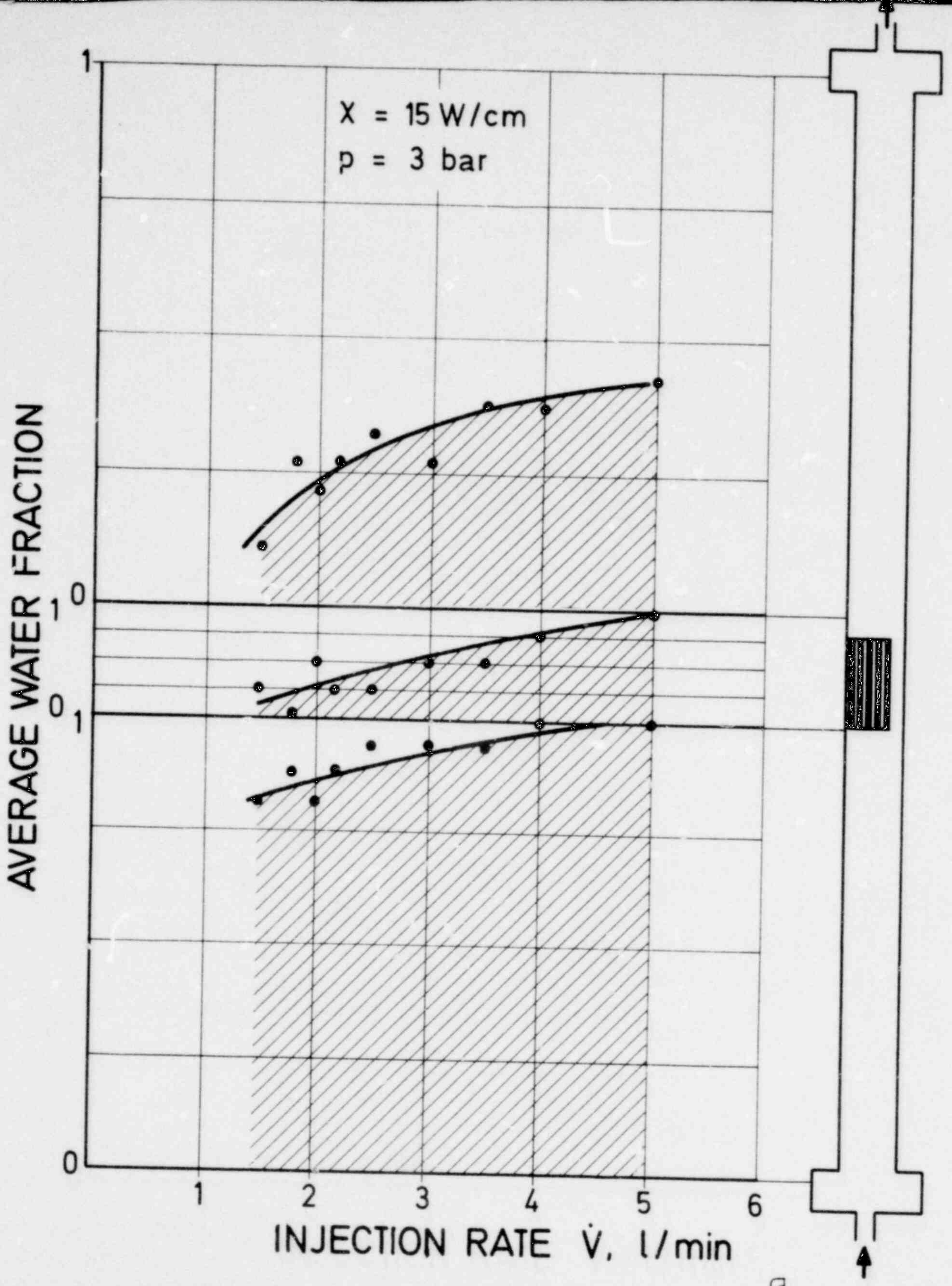


KfK IRB

MAXIMUM STEADY STATE TEMPERATURE

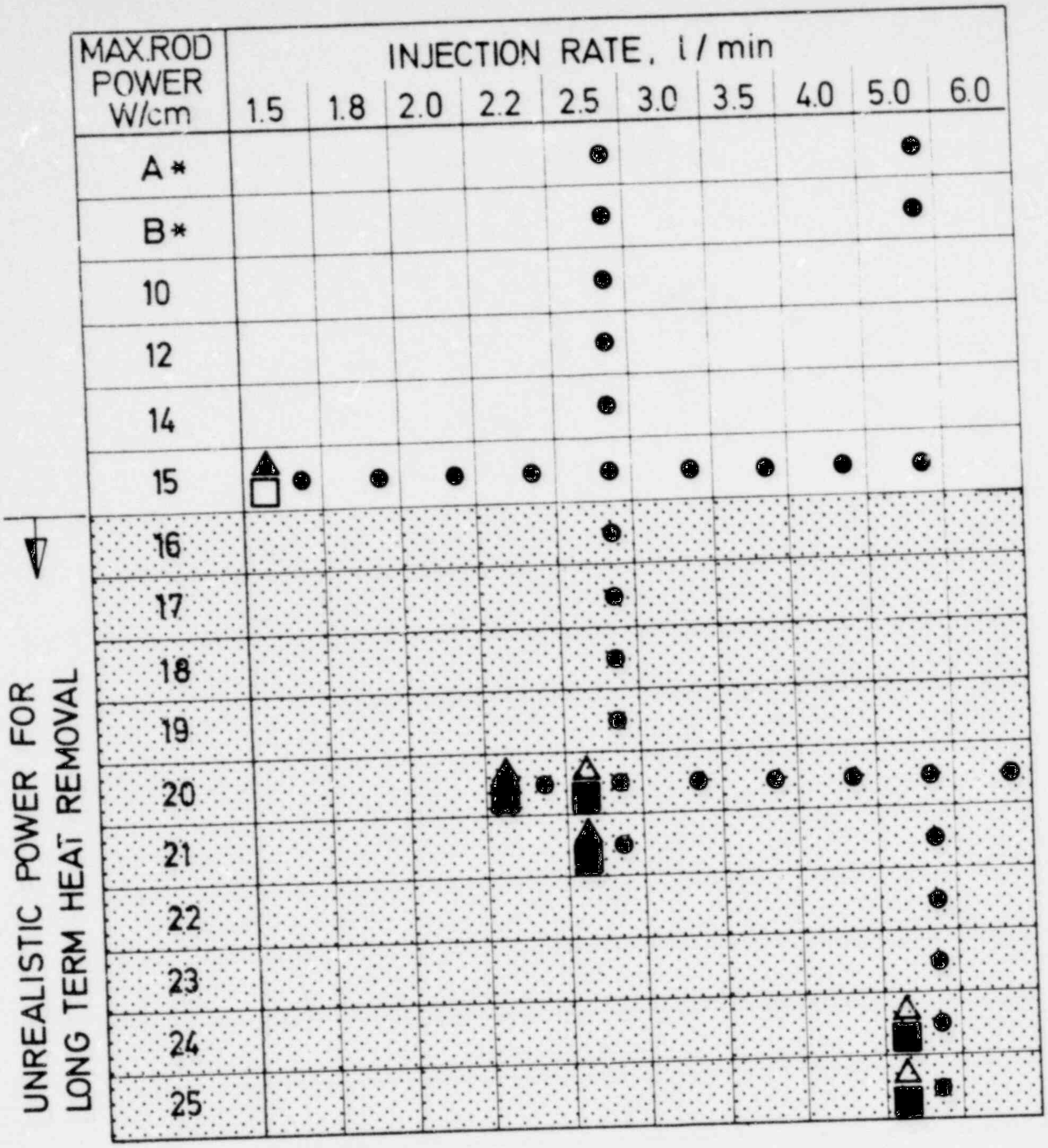
TC 66 WALL OF BLOCKAGE CHANNEL
TC 72 NEAR UPPER END OF ROD

FIG. 13



AVERAGE VOL. FRACTION OF WATER IN THREE SECTIONS OF THE CHANNEL
(FROM ΔP-MEASUREMENT)

FIG. 14



* SATURATED WATER AT
A UPPER END
B LOWER END
OF BLOCKAGE CHANNEL

<600°C	>600°C	
△	▲	NEAR UPPER END OF ROD
□	■	AT WALL OF BLOCKAGE CHANNEL

KfK IRB

TEST MATRIX

SYSTEM PRESSURE 3 bar
INLET TEMPERATURE 30 °C

FIG. 15

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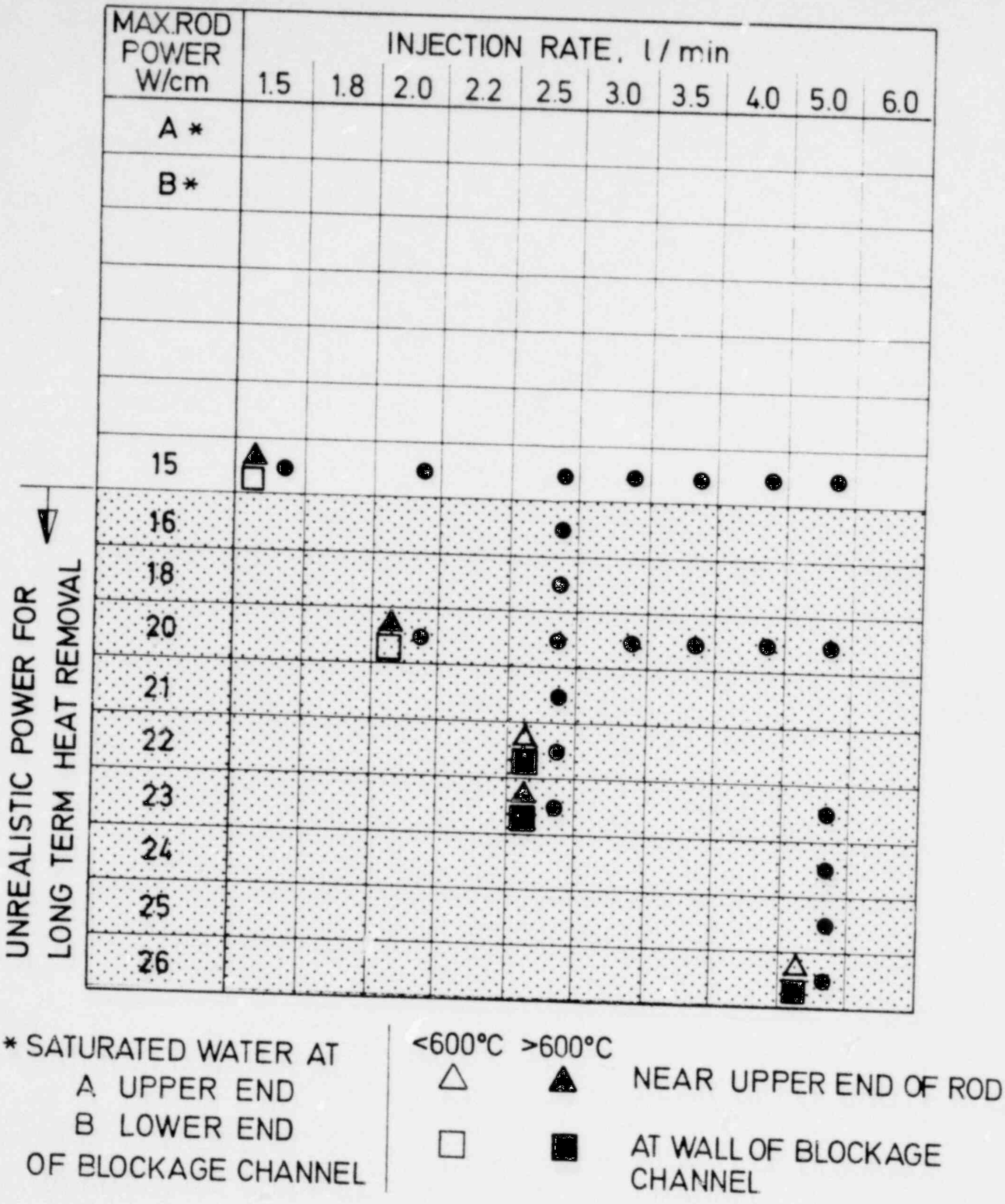
POOR ORIGINAL



MAX.ROD POWER W/cm	1.5	1.8	2.0	2.2	2.5	3.0	3.5	4.0	5.0	6.0
A *										
B *										
15	▲ □ ●		●		●	●	●	●	●	
16					●					
18					●					
20			▲ □ ●		●	●	●	●	●	
21					●					
22					△ ■ ●					
23					△ ■ ●				●	
24									●	
25									●	
26									△ ■ ●	

* SATURATED WATER AT
A UPPER END
B LOWER END
OF BLOCKAGE CHANNEL

<600°C	>600°C	
△	▲	NEAR UPPER END OF ROD
□	■	AT WALL OF BLOCKAGE CHANNEL

TEST MATRIX

SYSTEM PRESSURE 5 bar
INLET TEMPERATURE 30 °C

FIG. 16

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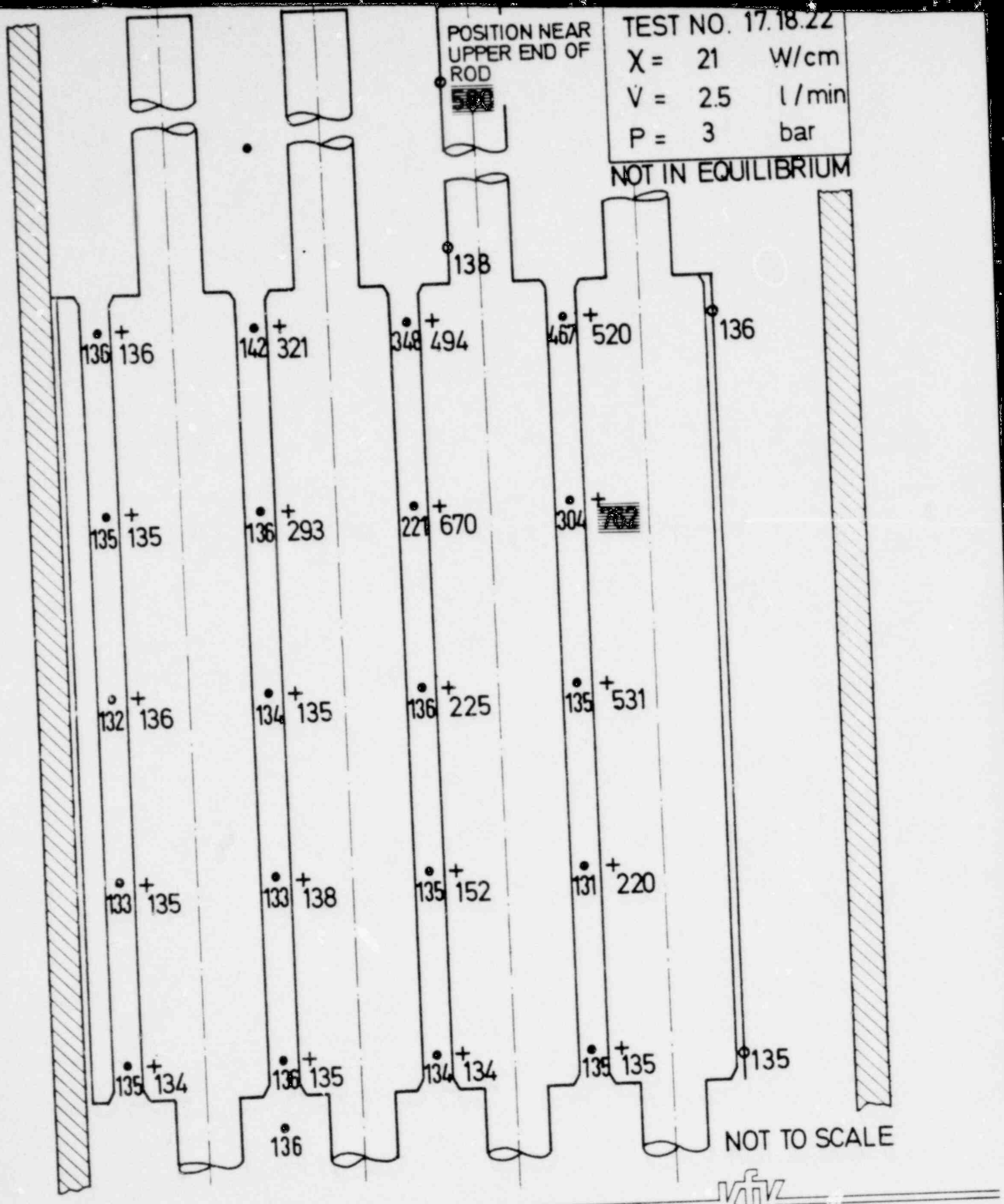

TEMPERATURE DISTRIBUTION, DEG. C
(DIAGONAL SECTION THROUGH BLOCKAGE)

FIG. 17

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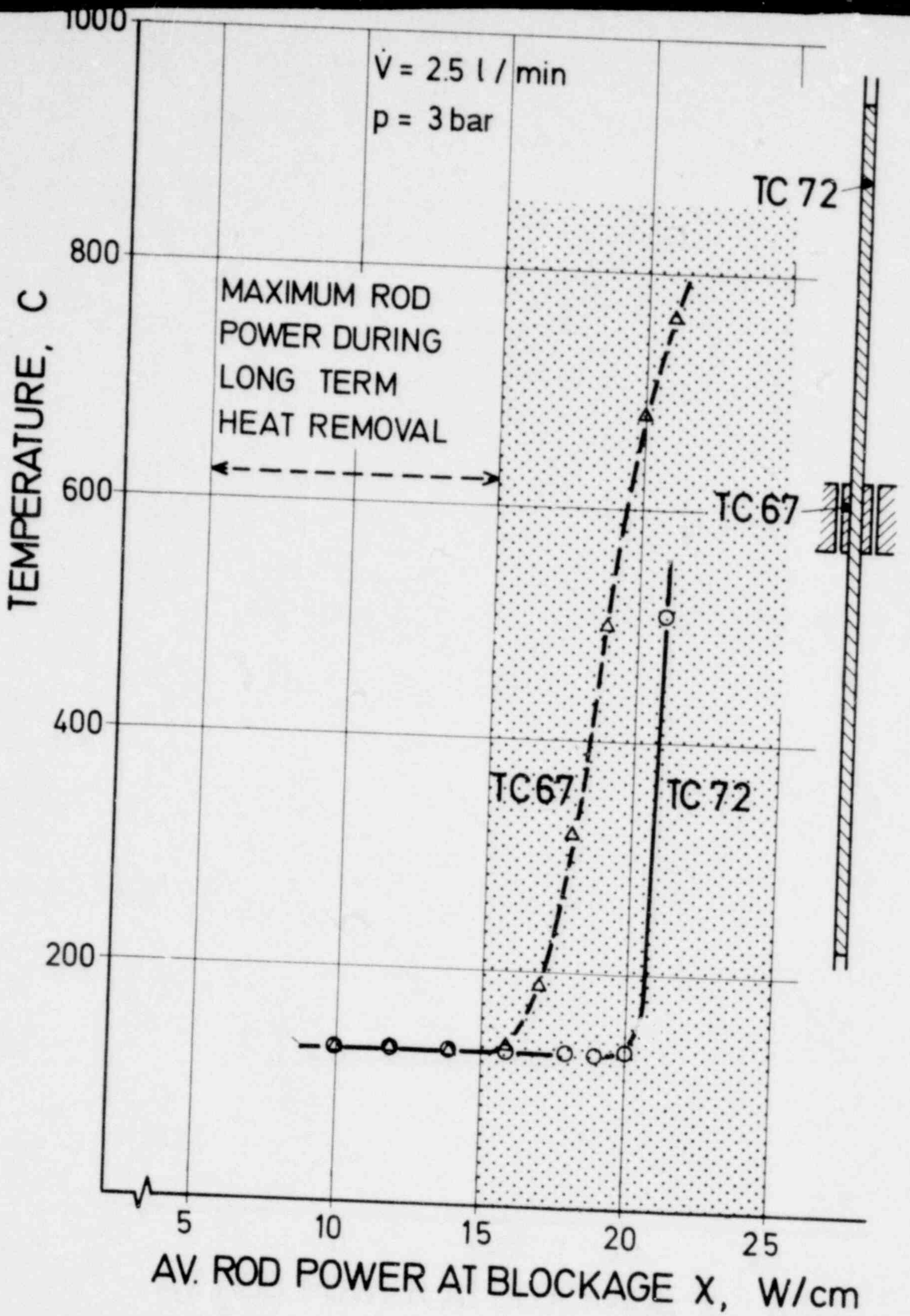

KfK IRB

MAXIMUM STEADY STATE TEMPERATURE

TC 67 WALL OF BLOCKAGE CHANNEL
TC 72 NEAR UPPER END OF ROD

FIG. 18

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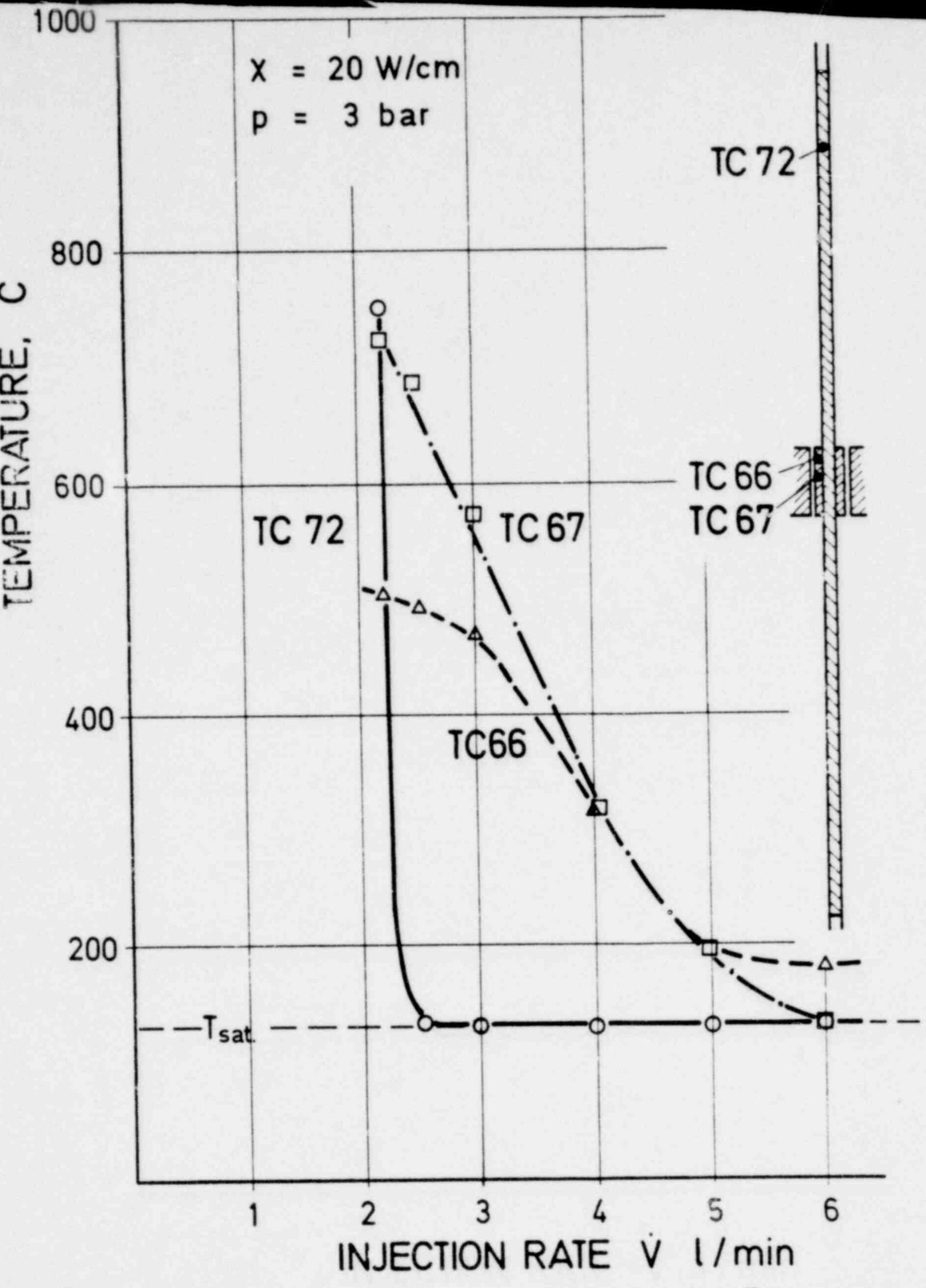

KfK IRB

MAXIMUM STEADY STATE TEMPERATURE

TC 66 WALL OF BLOCKAGE CHANNEL

TC 72 NEAR UPPER END OF ROD

FIG. 19

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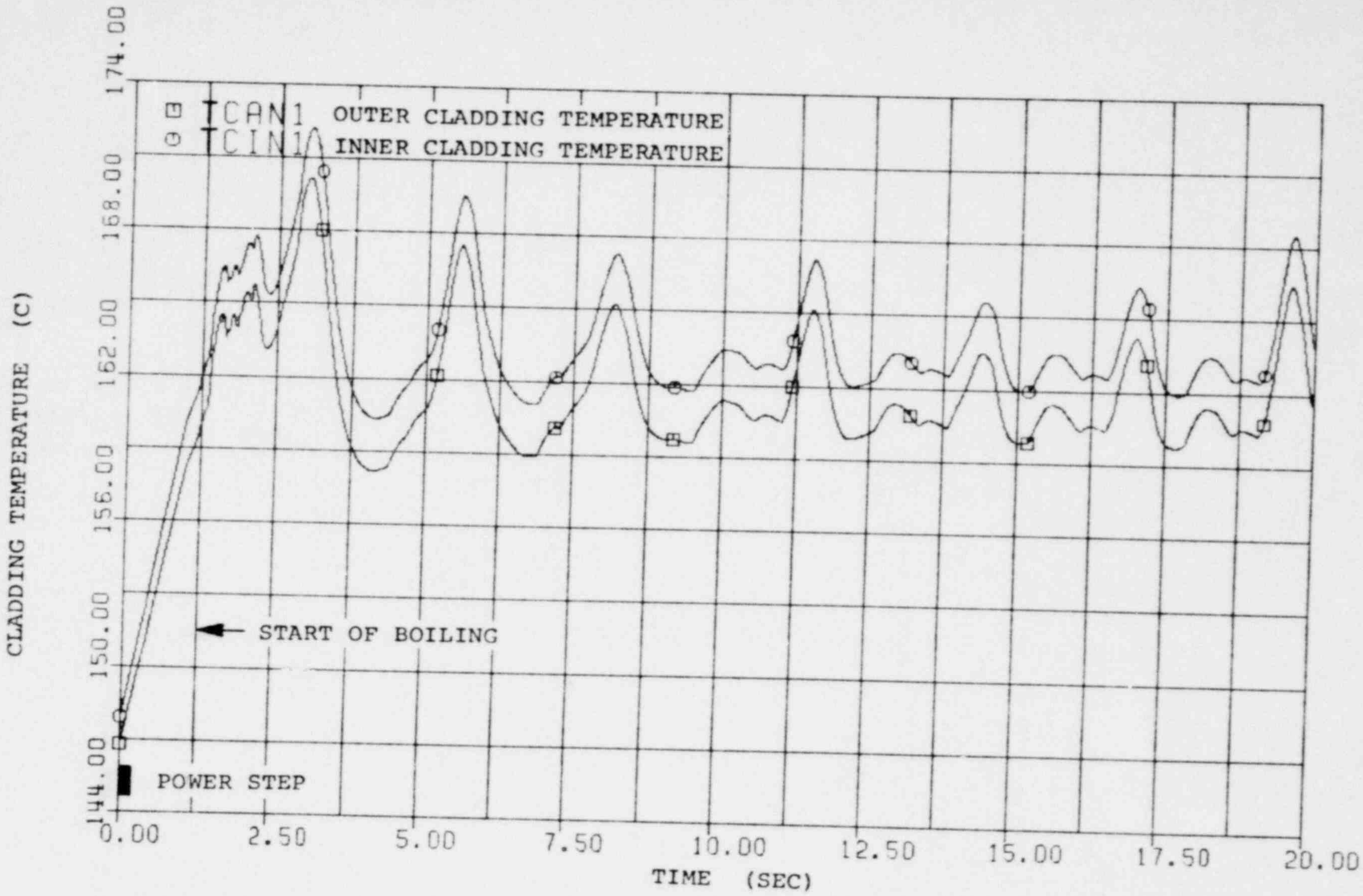

CLADDING TEMPERATURE AT THE END OF THE HEATED ZONE
CALCULATED BY BLOW3A

KfK INR

FIG. 20