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M. Nishida
Institut für Reaktorbauelemente
Projekt Nukleare Sicherheit

Kernforschungszentrum Karlsruhe

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Single Rod Tests

M. Nishida*

* Delegated from Power Reactor and Nuclear Fuel Development Corporation (PNC), Japan, to Kernforschungszentrum Karlsruhe

Kernforschungszentrum Karlsruhe GmbH, Karlsruhe

Kernforschungszentrum Karlsruhe GmbH
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Abstract

The influence of a gas filled gap between cladding and pellet on the quenching behavior of a PWR fuel rod during the reflood phase of a LOCA has been investigated. Flooding experiments were conducted with a short length electrically heated single fuel rod simulator surrounded by glass housing. The gap of 0.05 mm width between the Zircaloy cladding and the internal Al_2O_3 pellets of the rod was filled either with helium or with argon to vary the radial heat resistance across the gap. This report presents some typical data and an evaluation of the reflood behavior of the fuel rod simulator used. The results show that the quench front propagates faster for increasing heat resistance in the gap between cladding and heat source of the rod.

Brennstabsimulatoreffekte in Flutexperimenten Einzelstabversuche

Zusammenfassung

Der Einfluß eines gasgefüllten Spaltes zwischen Hüllrohr und Pellet eines DWR Brennstabes auf das Benetzungsverhalten während der Flutphase eines Kühlmittelverluststörfalles wurde untersucht. Mit einem einzelnen elektrisch beheizten kurzen Brennstabsimulator in einem Glasrohr wurden Flutexperimente durchgeführt. Der Spalt von 0.05 mm Weite zwischen dem Zircaloy Hüllrohr und den inneren Al_2O_3 Pellets des Stabes war entweder mit Helium oder mit Argon gefüllt, um den radialen Wärmewiderstand durch den Spalt zu variieren. Dieser Bericht stellt typische Daten vor und eine Auswertung des Flutverhaltens des benutzten Brennstabsimulators. Die Ergebnisse zeigen, daß die Benetzungsfront bei zunehmendem Wärmewiderstand im Spalt zwischen Hüllrohr und Wärmequelle des Stabes schneller fortschreitet.

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1. Introduction

The reflood phase of a loss-of-coolant accident (LOCA) in a pressurized water reactor (PWR) is terminated when all fuel rods are quenched completely. Out-of-pile reflood experiments performed with electrically heated fuel rod simulators show different quench behavior depending on the design of the rods used. Fuel rod simulators without gap between cladding and heat source show higher reflood temperature transients and slower quench front progression than nuclear fuel rods or electrically heated simulators with a gap underneath the claddings /1,2,3,4,5/. For investigation of the Zircaloy cladding behavior during the refill and reflood phases of a LOCA in a PWR, the REBEKA fuel rod simulator /6/ has been developed. This rod is characterized by a gas filled gap between the Zircaloy cladding and Al_2O_3 pellets.

The influence of the rod design on the reflood behavior is being investigated in the SEFLEX program (Fuel Rod Simulator Effects in Flooding Experiments) /7/. Forced feed reflood tests are carried out with full length 5x5 rod bundles as well as with short single rods of REBEKA rod design.

Results of the single rod SEFLEX tests (SEFLEX-E) are presented in this report. Emphasis is placed on the quench behavior of a rod with Zircaloy cladding pressurized with either helium or argon. Helium filling leads to a relatively small heat resistance in the gap between cladding and pellets. The argon filling providing a rather high gap heat resistance simulates the conditions of high fission gas content and/or increased gap width.

2. Test Program

To investigate separate effects of the thermohydraulic behavior of PWR fuel rods during the reflood phase of a LOCA, a short length single rod test facility has been chosen. A glass housing surrounding the rod allows visual observation of the quench front progression and of the flow patterns during the tests.

A REBEKA-type fuel rod simulator with a gap between the Zircaloy cladding and the pellets has been installed to investigate its behavior under different reflood conditions. The heat resistance across the gap underneath the Zircaloy cladding has been varied by replacing the helium filling by an argon in some of the tests.

The quench behavior of the rod as well as the flow patterns in the annulus have been studied in the following range of parameters:

Rod Power	10 through 36 W/cm
Heated Length (uniformly heated)	1 m
Flooding velocity (in the cold test section)	2 through 5 cm/s
Inlet Water Temperature	20 ^{o}C
Maximum Initial Cladding Temperature	500 through 800 ^{o}C
Filling Gas	helium, argon
Filling Gas Pressure	2 bar

Complementary tests served for analyzing the repeatability of the tests and the data including the influence of the increasing oxidation of the Zircaloy cladding.

The main test parameters of the SEFLEX-E tests are listed in Table 1.

3. Test Facility Design

The test facility is designed mainly for investigation of the quench behavior of electrically heated fuel rod simulators under various reflood conditions on a comparative basis. Rod power, flooding velocity and characteristics of the single rod are the essential parameters chosen. Atmospheric pressure for all of the tests is maintained for easy assembling as well as the application of a glass tube surrounding the fuel rod simulator over the total length.

Visual observation of the rewetting of the rod and the flow patterns in the annulus between glass tube and rod provides additional information about the thermohydraulic phenomena and the rod behavior.

3.1 Test loop

The test loop is shown in Fig. 1 schematically. Coolant water is stored in a tank. During operation the coolant is pumped through a control valve and a flow meter into the lower plenum region of the test section. From the lower plenum the coolant flow is directed either upwards through the test section or through the bypass valve back into the water tank.

The coolant water rises in the test section, i.e. in the annular region between the test rod (fuel rod simulator) and the glass tube, to the hot zone of the rod after the reflooding is initiated by closing the bypass valve. Entrained water droplets are transported upwards by the rising steam and impinge on the steam water separator placed in the upper plenum. The liquid then drains back into the storage tank and the steam is flowing to the atmosphere. The rod instrumentation exists from the lower end as well as the upper end of the test rod, as do the electric power connections for the heating element.

The glass tube housing covers the test rod over the whole length. The filling gas, e.g. helium or argon, is conducted to the lower end of the test rod by a capillary tube connected with the space between the Zircaloy cladding and the internal heating element.

3.2 Fuel Rod Simulator

The fuel rod simulator consists of an electrically heated rod of 6 mm outer diameter placed in the center of annular Al_2O_3 pellets simulating UO_2 pellets. As for a nuclear fuel rod the pellets are encapsulated in a Zircaloy cladding tube. The space between the pellets and the Zircaloy cladding is filled with inert gas.

Figure 2 shows a longitudinal cross section of the SEFLEX-E fuel rod simulator with a heated length of 1 m for the single rod tests. The Al_2O_3 pellet stack is hold down by a spring to maintain the radial heat transfer from the heating element to the cladding across the pellets at all axial elevations. The gas filling enters at the lower end of the rod. Radial cross sections of the fuel rod simulator and of the test section are shown in Fig. 3. The heating element of the rod consists of an electrically heated tube of 3.5 mm outer diameter filled inside with MgO. This tube is insulated by boron nitride which is encapsulated by an Inconel sheath of 6 mm outer diameter. The heat generated in this heating element is transferred across the pellet and the gap of 0.05 mm nominal width between pellet and cladding. The behavior of a rod of this design has been compared to that of nuclear fuel rods by calculation /8/. For the single rod tests using a heated length of only 1.0 m uniform axial rod power is designed.

3.3 Instrumentation

The quench behavior of fuel rods or simulators may be influenced by instrumentation of the claddings with thermocouples. Therefore, information about the temperature transients including the quenching at individual axial elevations of the single rod is obtained from thermocouples embedded in the heating element inside the Al_2O_3 pellets. The Zircaloy cladding exposed to the two-phase flow cooling is not instrumented. Figure 4 shows the axial and radial locations of the thermocouple junctions embedded in the Inconel sheath of the internal heater rod. The Chromel-Alumel thermocouples of 0.36 mm outer sheath diameter are led out to the top as well to the bottom end of the rod.

The temperature of the coolant is measured in the inlet tube and the steam temperature in the upper plenum, after separation from the water carried out, by Chromel-Alumel thermocouples of 1 mm, and in the latter case of 0.25 mm outer sheath diameter.

The data are recorded digitally by a PDP 11 computer with a scan frequency of 10 cycles per second.

The flooding rate is measured with a rotor flow meter, without data recording by a computer.

The moments of initiation and termination of the reflooding are determined by visual observation. Corresponding manual pulses are recorded by the computer as electrical on/off signals.

4. Operational Procedure

With respect to the sequence of events during a LOCA the following procedure is made:

Prior to reflood, the fuel rod simulator is heated to the desired initial temperature of the heating element with constant rod power. The time span for heat up depends on the rod power as well as the initial temperature chosen.

During the heat up of the heater rod, water is flowing to the lower plenum conditioning its temperature and cooling the O-ring sealing at the lower end of the rod. This water flow is drained back to the water tank by the bypass valve which controls the water level at 10 cm below the lower end of the heating zone.

Reflooding is initiated by closing the bypass valve when the rod is heated to the desired temperature. The initial rod power is maintained constant during heat up as well as during the reflood phase. After the completion of a test, i.e. when the rod is quenched completely, the data recorded on disks during heat up and reflood are checked prior to be transfered on tapes for further evaluation.

5. Results and Discussions

The test program consisted of two major steps to investigate the influence of the heat resistance in the gap between cladding and pellets on the quench behavior of a fuel rod simulator in a simulated reflood phase of a LOCA.

In the first step helium was used as the filling gas of the rod and the gap, respectively. In the second step argon gas was filled in the identical rod. Argon has low thermal conductivity simulating high fission gas content and/or increased gap width of a nuclear fuel rod.

5.1 Reflood and Quench Behavior of a Fuel Rod Simulator with Helium Filled Gap

Figure 5 shows typical heater temperatures of the rod with helium filled gap as a function of time. The transients include the heat up and the reflood phase. The constant rod power of 2.7 kW is switched on at - 120 seconds. The heater temperatures increase to the desired constant temperature level of about 800 ^{o}C within about 120 s.

The temperatures at the lower part of the rod are somewhat lower than at the upper part of the rod. This is due to heat convection in the annulus during the heat up phase. The top part of the rod (T.C.8) is cooled slightly by thermal conduction to the unheated portion of the rod.

By closing the bypass valve at the exit of the lower plenum, the cooling water rises to the heating zone of the rod. The reflooding is initiated when the cooling water touches the lower end of the heating zone of the rod. This moment is defined as time t = 0 seconds. Entrained water droplets are transported upwards by the rising steam after the initiation of reflooding.

The heater temperatures of the rod decrease, after having reached their individual peak temperatures by the increasing cooling of the dispersed flow. The quenching begins to occur in the lower part of the rod, and the temperature of the rod at the corresponding elevation decreases rapidly when the cladding is rewetted.

While the quench front progresses upwards from the lower part of the rod, a second quench front is initiated at the top of the rod by cooling due to entrained water droplets and heat loss to the unheated end. The quenching times at 602 mm from top (T.C. 4) and at 52 mm from top (T.C. 8), caused by the two different quench fronts, are nearly the same under these test conditions.

The slopes of the temperature transients during quenching are different for these two levels. This is due to the different flow conditions at these two levels (see Section 5.1.4).

The reflooding is terminated when the whole rod is quenched completely as indicated in the figure at the time t ≈ 235 seconds.

Figure 6 shows additional data of the same test, already presented in Fig. 5 together with some temperatures repeated. The power is controlled by the power controller for steady level during the experiment. The temperatures measured in the upper plenum show that the steam is being highly superheated in the beginning of reflooding and decreases to the saturation temperature slowly.

The heater temperature decreases rapidly when the cladding starts to quench as indicated in the figure. The quenching time is determined by the knee of rapid decrease of the heater temperature in this experiment. This quenching time may have a few seconds difference compared with the real rewetting time of the cladding.

Figure 7 shows the axial quench front progression versus time, the quench front velocity and the quench temperature of the heater depending on the axial elevation for the same test presented in Figs. 5 and 6. Nine points are used to make the progression curve of the quench front. The time and the level of the final quench point are obtained by visual observation.

Though each point may have a few seconds error, it does not affect the general tendency of the quench front progression curve. The lower quench front velocity decreases as the quench front progresses upwards while the upper quench front velocity increases as the quench front moves downwards.

In the early stage of reflood the cooling water is cold and the steam generation is small. The cooling water cools mainly the lower part of the rod. With progressing of the lower quench front upwards, the steam and the water droplets entrained gradually are cooling the upper part of the rod. Flow pattern and cooling pattern above the lower quench front are changing and the velocity of the quench front is decreasing. Dispersed flow cooling in the upper portion of the rod leads to increased velocity of the upper quench front.

The level of the heater temperature at quenching indicates the magnitude of the heat transfer from the rod to the water before quenching. Low heater temperature level prior to quenching indicates high preceeding heat transfer while high heater temperature shows low heat transfer generally. The latter finding is evident for the upper portions of the rod.

5.1.1 Influence of the Rod Power

The heater temperatures obtained from tests performed with different rod power are shown in Fig. 8. The times of quenching are long and the temperatures of the heater before quenching are high in the case of the high rod power.

Figure 9 shows quench front progressions for four different rod power levels and three different flooding velocities. The quenching times are delayed at every point as the rod power increases.

The axial levels of the final quench points are nearly the same for the four different rod powers applied. The low rod power leads to high quench front velocities while the high rod power causes low quench front velocities at both lower and upper quenching fronts.

Figure 10 shows the final quench times at the rod as a function of the rod power for three different initial rod temperatures. In the case of flooding velocities of 2 cm/s and 3 cm/s, the final quench times are delayed immensely as the rod power increases.

The change of the flow pattern leading to poor cooling delays the quench times at low flooding velocity and high rod power. Figure 11 shows the quench times obtained in the midplane and at the top level of the rod. The tendency remains the same as shown in Fig. 10.

5.1.2 Influence of the Flooding Velocity

Figure 12 shows heater temperatures from tests performed with two different flooding velocities. The times of quenching are long and the heater temperatures decrease slowly before quenching in the case of low flooding velocity. Figures 13 and 14 show the quench front progression for four different rod power levels and for three different flooding velocities.

The quench times become long as the flooding velocity decreases. The axial level of the final quench point is placed at a higher axial level with increasing flooding velocity and for the same rod power. The differences of the quench front velocities for the three different flooding conditions are small for the upper quench front and large for the lower quench front, maintaining the same rod power.

The dispersed flow conditions at the top of the rod may not be largely different for the three flooding velocities mentioned and the same rod power.

5.1.3 Influence of the Initial Rod Temperature

The transient heater rod temperatures measured in tests performed with two different initial rod temperatures are shown in Fig. 15. For high initial rod temperature the heater temperature decreases rapidly in the beginning of reflooding. This effect may be supported by increased heat loss from the hot rod to the atmosphere through the glass tube.

Figure 16 shows quench front progressions for three different rod power levels with the initial rod temperature as parameter. The differences of the quench front progressions are small for the different initial rod temperatures mentioned.

5.1.4 Flow Pattern

The flow patterns are observed during reflooding. Figure 17 shows the three typical flow patterns which affect the quench front progression. The quench front velocity is high in the case of pattern A observed for low rod power or high flooding velocity conditions. The rewetting region of the rod is surrounded by small bubbles of nucleate boiling. From the instantaneous level of the quench front at the rod the steam flows upwards entraining small water droplets in the annular region of swelling water.

In the case of pattern C observed for high rod power or low flooding velocity conditions, the quench front velocity is low. The lower part of the rewetting region at the lower end of the rod is surrounded by large bubbles of nucleate boiling. The upper part of the rewetting region at the lower portion of the rod is surrounded by a liquid film. The same is observed in the upper rewetting region at the top and of the heated zone of the rod. From the rising water level the liquid phase dispersed in the steam flows upwards to the top end of the rod under unstable flow conditions (oscillating). Pattern B is the transient flow pattern from A to C. These three patterns are indicated in the quench front progression curves in Fig. 18.

Under the conditions of high flooding velocity and low rod power, the quench front velocity is high and roughly constant. The flow pattern A exists from the start to the end of the reflooding. For decreasing flooding velocity or increasing rod power, the quench front velocity is decreasing accordingly to the change of the flow pattern from A to B or C.

5.2 Reflood and Quench Behavior of a Fuel Rod Simulator with Argon Filled Gap

For the test series 6, mentioned in Table 1, the argon gas was filled in the identical rod to evaluate the influence of different heat resistance of the gap between the cladding and the pellets on the reflood behavior of the fuel rod simulator. In Fig. 19 typical heater temperature transients are shown from tests performed with the same reflood conditions. However, different gases are filled in the rod and the gap, respectively. The heater temperatures with argon gas filled in the fuel rod simulator rise faster during the heat up phase.

The peak temperatures are high and the heater temperatures decrease slowly compared with the temperature transients of the case with helium gas in the rod. In Fig. 20 the quench front progression in the tests with argon gas and that of helium gas in the gap are compared for three different rod power levels and three different flooding velocities.

The quench times in the cases of argon gas filling are short under all conditions investigated and compared with the corresponding tests performed with helium gas filling. The influence of the rod power and the reflooding velocity on the tendency of the quench front progression remains the same for helium as well as argon filling of the rod, qualitatively. However, the quantitative difference is significant. In Fig. 21 the quench front progressions and velocities are compared for argon and helium gas filling. The comparison is made for two different rod power levels.

The difference of the quench front velocity of fuel rod simulators with different gap heat resistance decreases as quench front moves upwards. It shows that the influence of the heat resistance in the gap on the quench front progression is large in the annular flow region (pattern A in Fig. 17) rather than in the dispersed flow region (pattern B or C in Fig. 17).

6. Conclusions

The influence of a gas filled gap between cladding and heat source of a fuel rod simulator on the quenching behavior during the reflood phase of a LOCA has been investigated with a short length electrically heated single fuel rod simulator with a gas filled gap between the Zircaloy claddings and the pellets. The most important parameters as rod power, flooding velocity and heat conduction of the filling gas have been varied in a significant range. From the results can be concluded:

- The quench front propagates faster for a rod with increasing heat resistance in the gap between cladding and heat source.
- The influence of the heat resistance in the gap on the quench front progression is large in the annular flow region rather than in the dispersed flow region.
- The quench front velocity decreases with increasing rod power or decreasing flooding velocity according to the change of the flow pattern. This finding is consistent with the behavior of fuel rod simulators without gap, usually used for thermohydraulic reflood experiments.

7. Acknowledgment

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In addition, I would also like to thank the members of IRB for helpful advice, encouragement and discussions. The work of the following colleagues is particulary acknowledged hereby: Mr. F. Erbacher, Mr. P. Ihle, Mr. K. Rust, Mr. H. Schneider, Mr. P. Schäffner, Mr. E.T. Palmieri (NUCLEBRAS).

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/8/ Casal, V.; Malang, S.; Rust, K.:
"Thermal and Mechanical Behavior of PWR Fuel Rod Simulators for LOCA Experiments" KfK 3331, May 1982

Series No.	Run No.	Power kW	Flooding Velocity (cold) cm/s	Cladding Temperature[1] at Start °C	Gap Gas
1	1 - 30	1.0, 1.5, 1.8	2	500, 700	Helium
2	31 - 49	1.0, 1.5, 2.5	2, 3, 5	500, 600, 700, 800	Helium
3	50 - 54	1.0, 1.5	2, 3, 5	500, 600	Helium
4	55 - 67	1.0, 3.5	2, 3, 5	500, 600, 700, 800	Helium
5	1 - 22	1.3, 2.1, 3.1	2, 3, 5	500, 600, 700, 800	Helium
6	23 - 40	1.3, 2.1, 3.1	2, 3, 5	600, 700, 800	Argon
7	41 - 55	2.7, 3.1, 3.6	2, 3	700, 800	Helium
8	56 - 67	2.7	2, 3, 5	700, 800	Helium
9	69 - 80	1.4, 2.7, 3.6	2, 5	700, 800	Helium

1) Temperature of thermocouple No. 5 (502 mm from top end) at reflood start

Feedwater temperature: 20 - 30 °C
Gap gas pressure: 2 bar
System pressure: 1 bar

Series 1, 2, 3, 4: Base line tests
Series 5, 6: Investigation of the effects of gap gas
Series 7, 8, 9: Complementary tests

Table 1 Main Test Parameters of SEFLEX-E Experiments

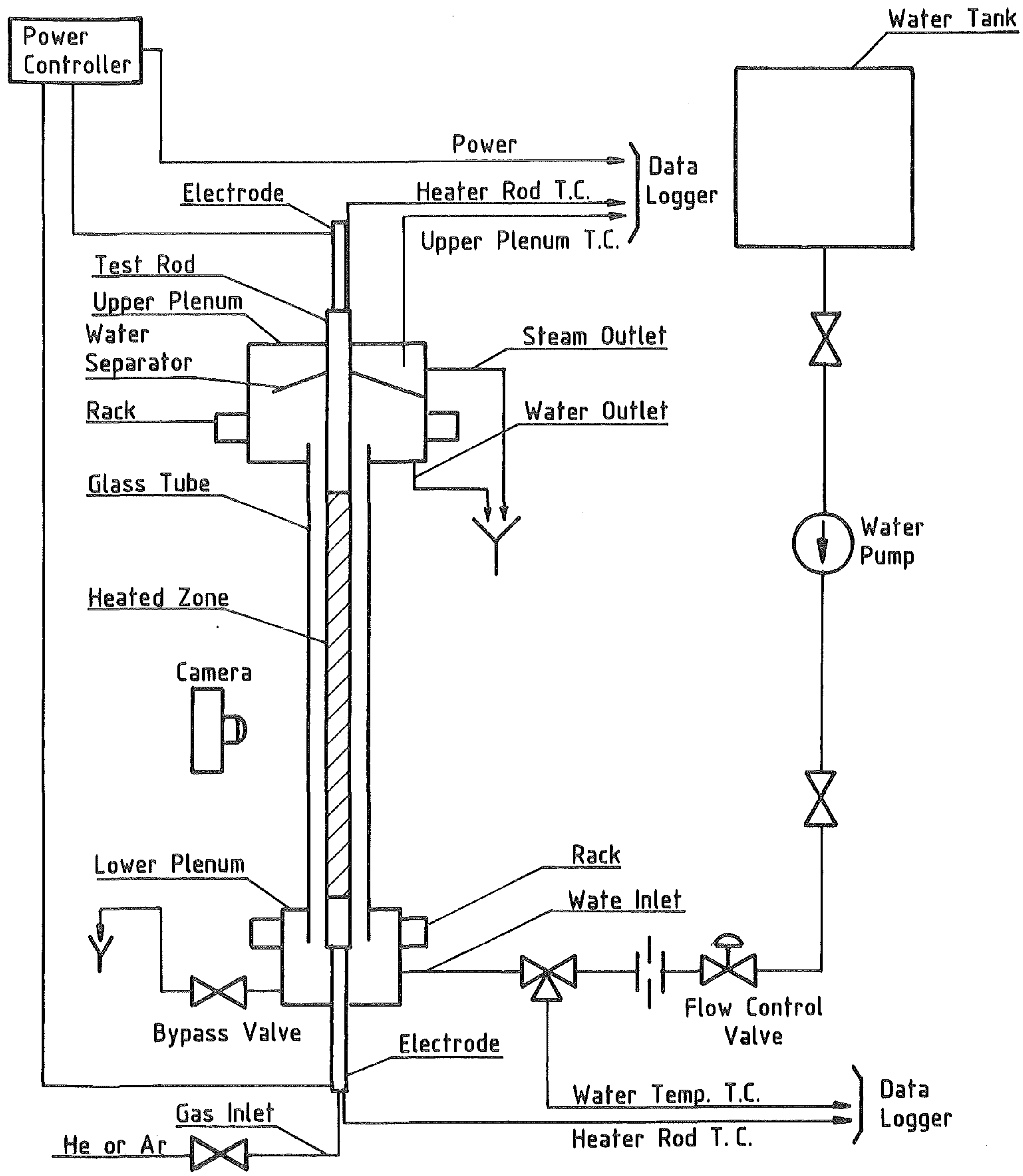


Fig. 1 SEFLEX-E Test Loop

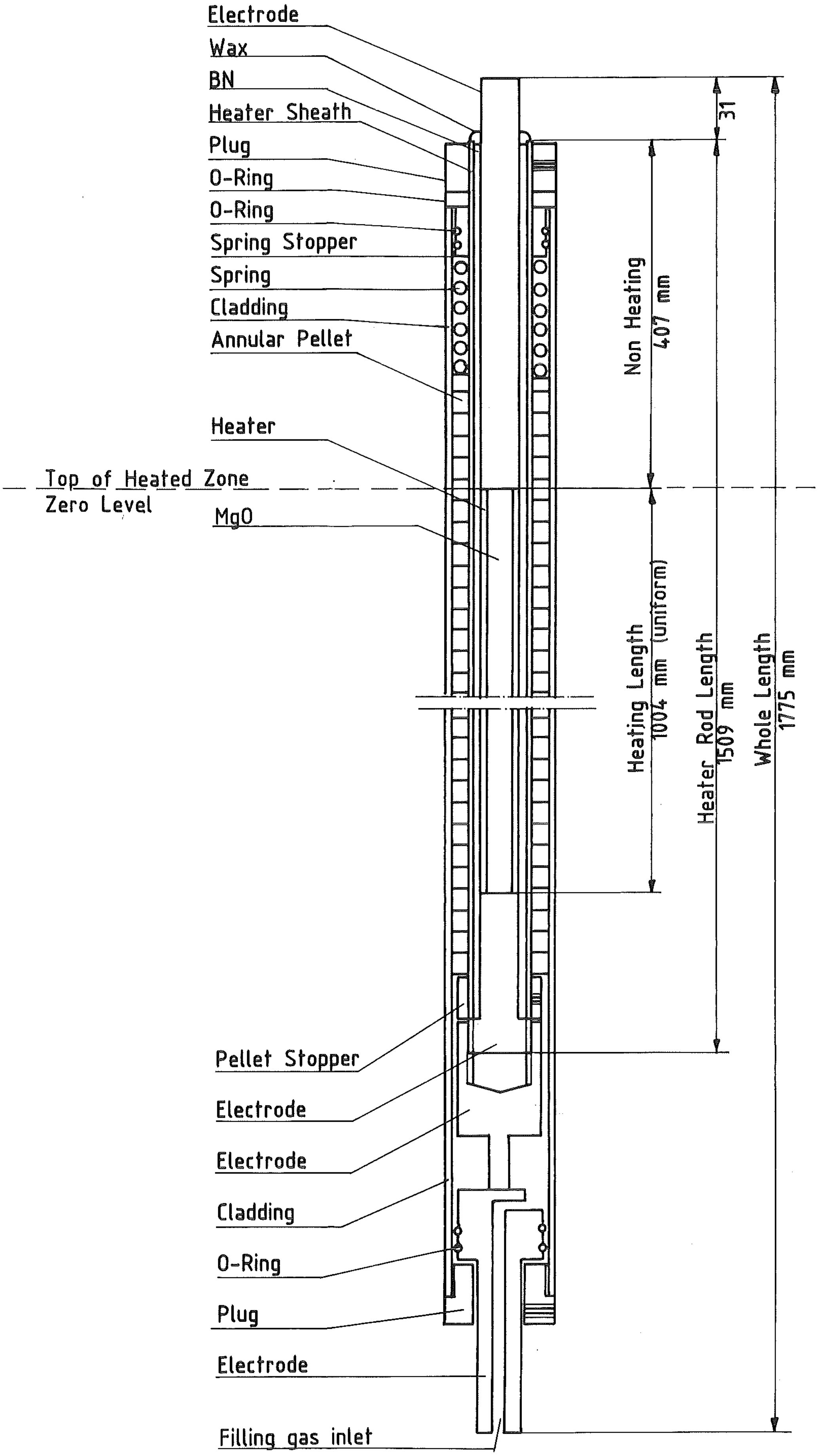


Fig. 2 Longitudinal Cross Section of SEFLEX-E Fuel Rod Simulator

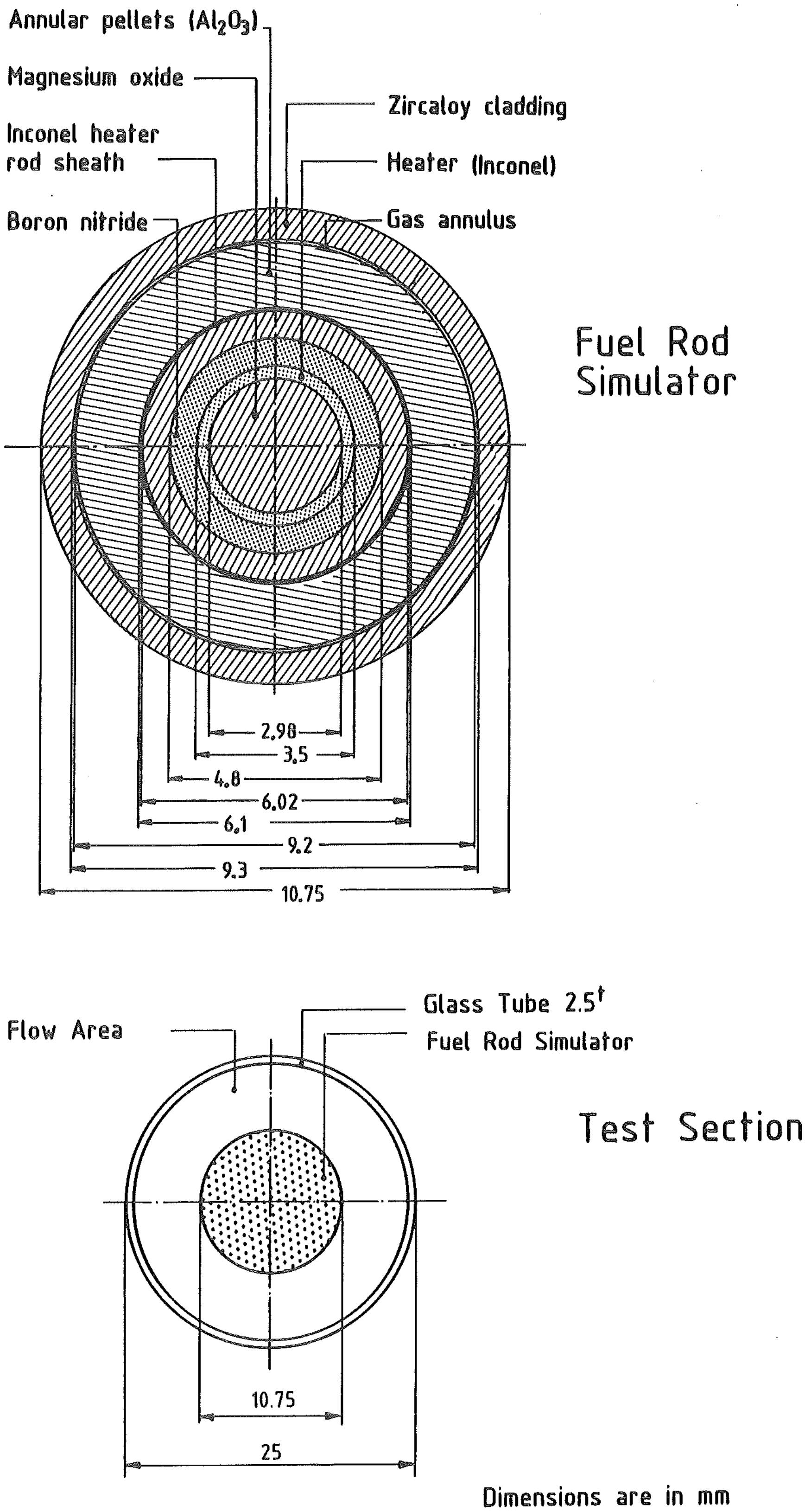


Fig. 3 Cross Section of Heater Rod and Test Section

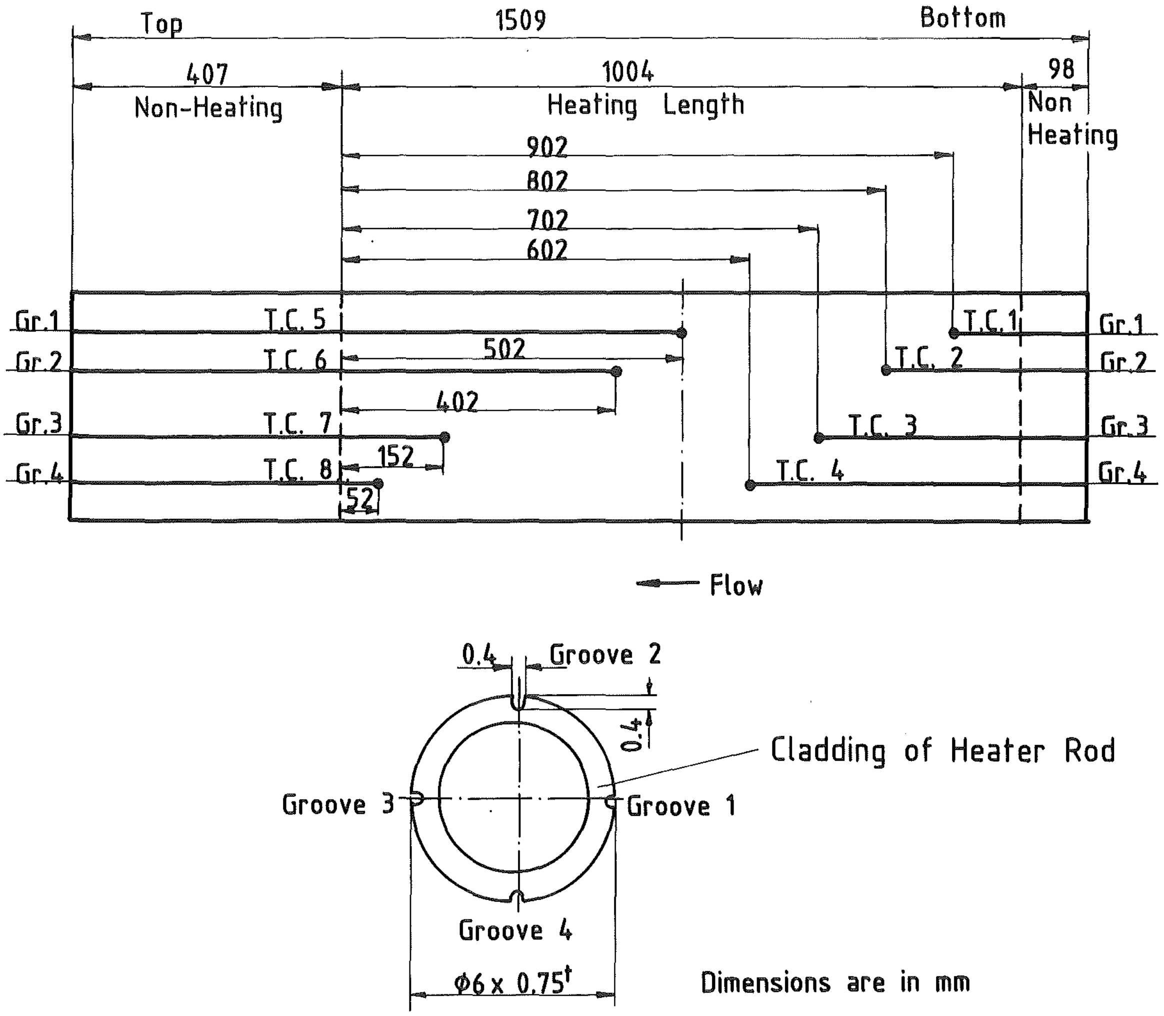


Fig. 4 Positions of Thermocouples of the internal SEFLEX-E Heater Rod

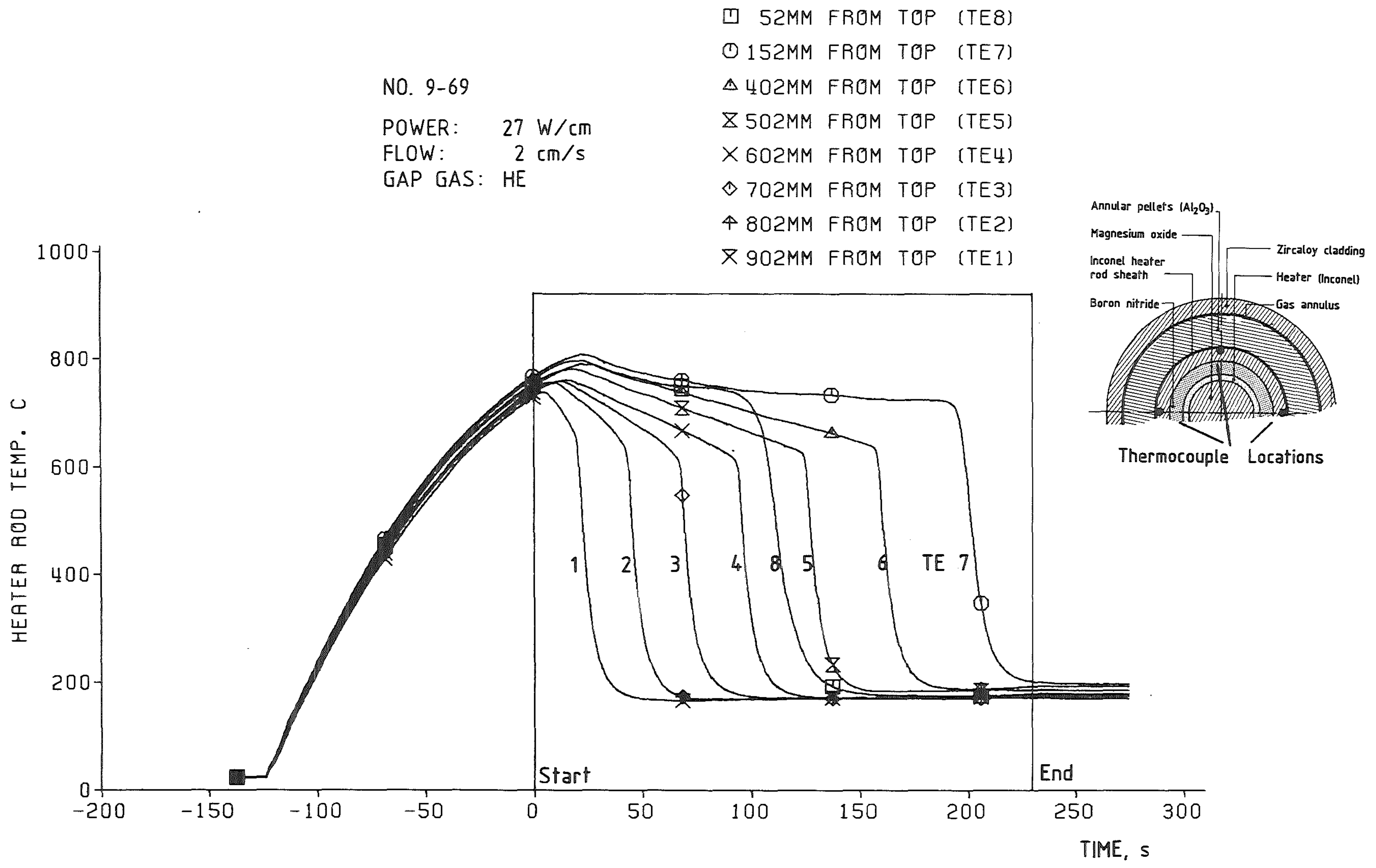


Fig. 5 Heater Rod Temperatures

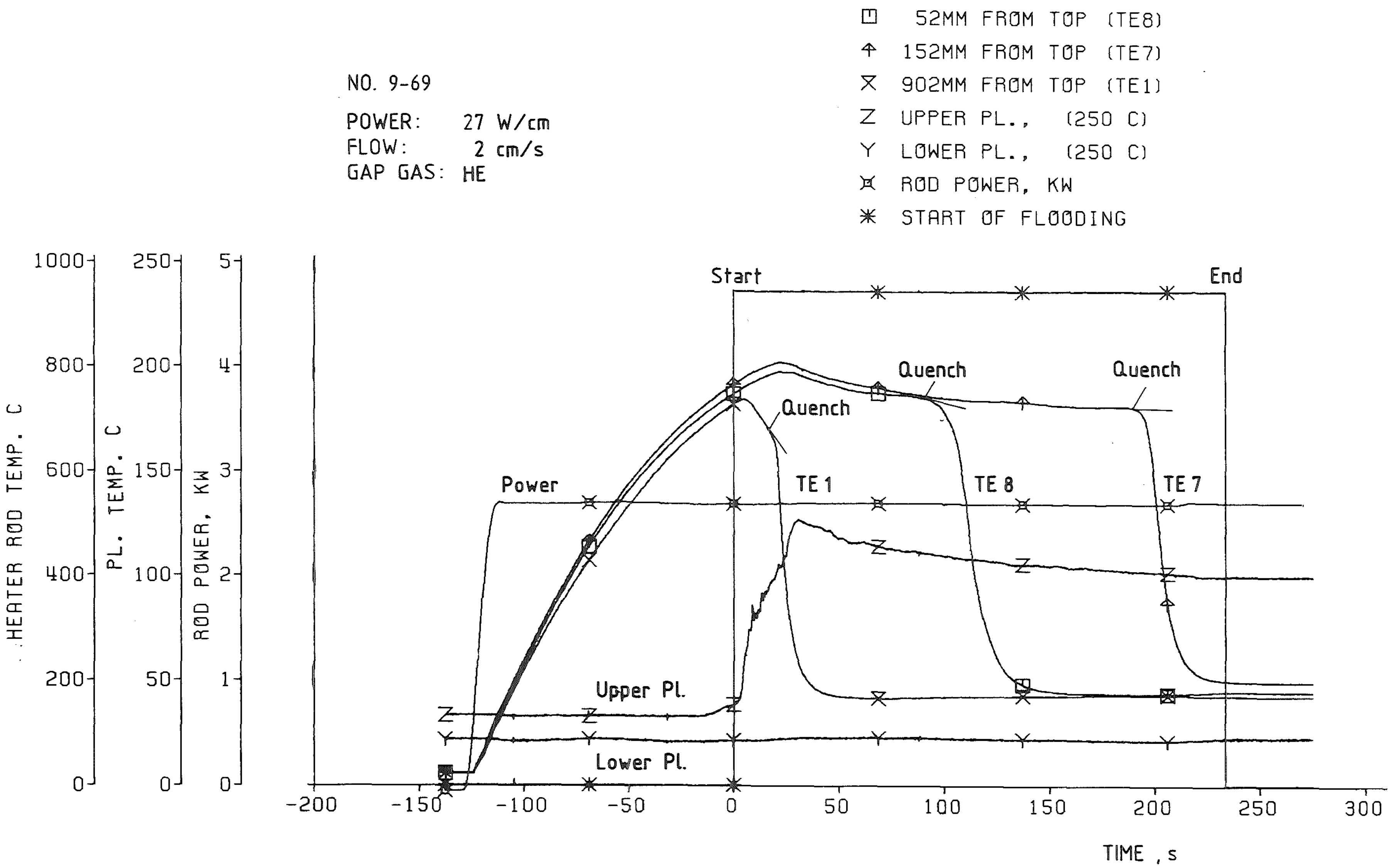


Fig. 6 Heater Rod , Plenum Temperatures and Power

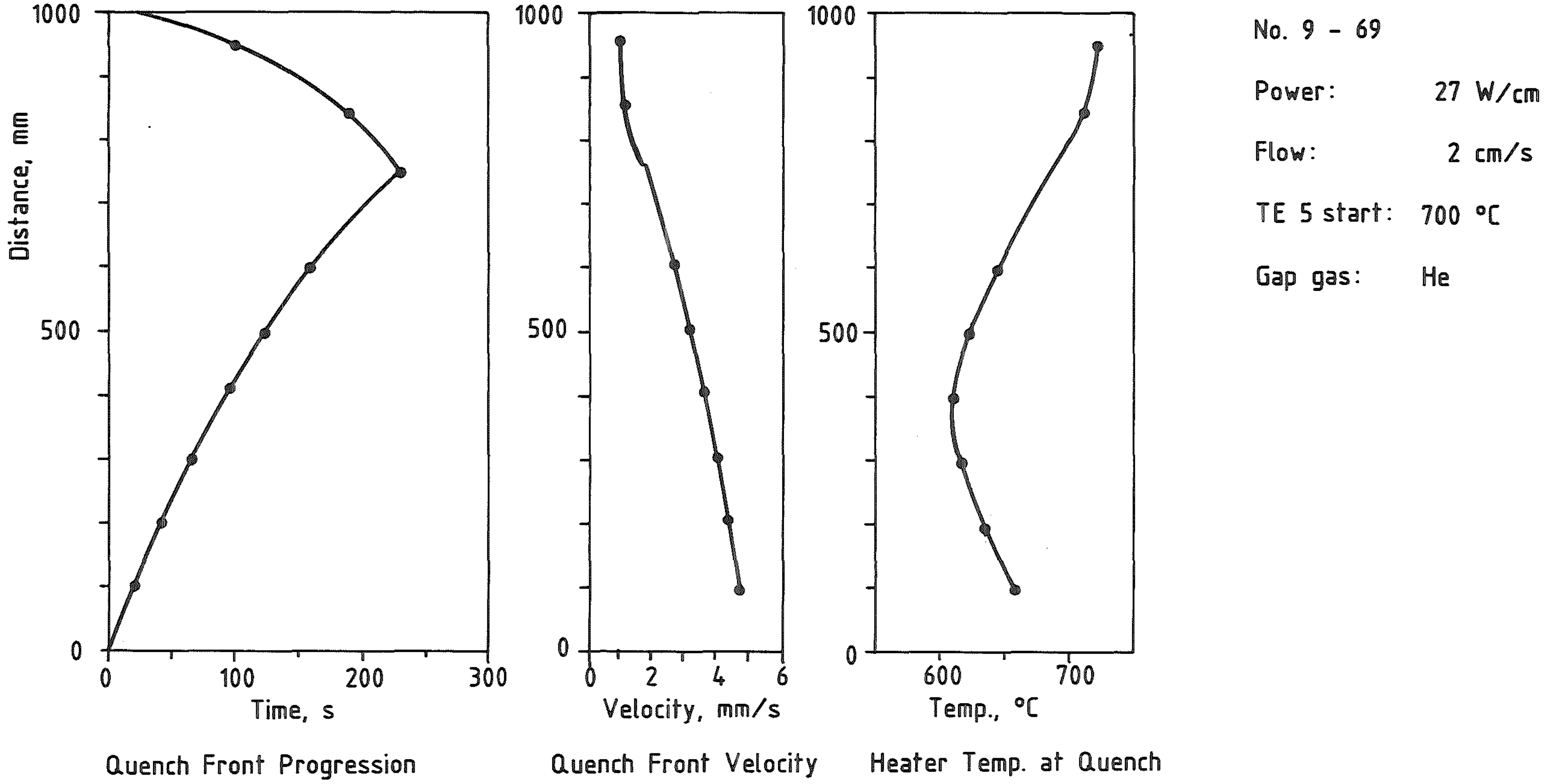


Fig. 7 Quench Front Progression

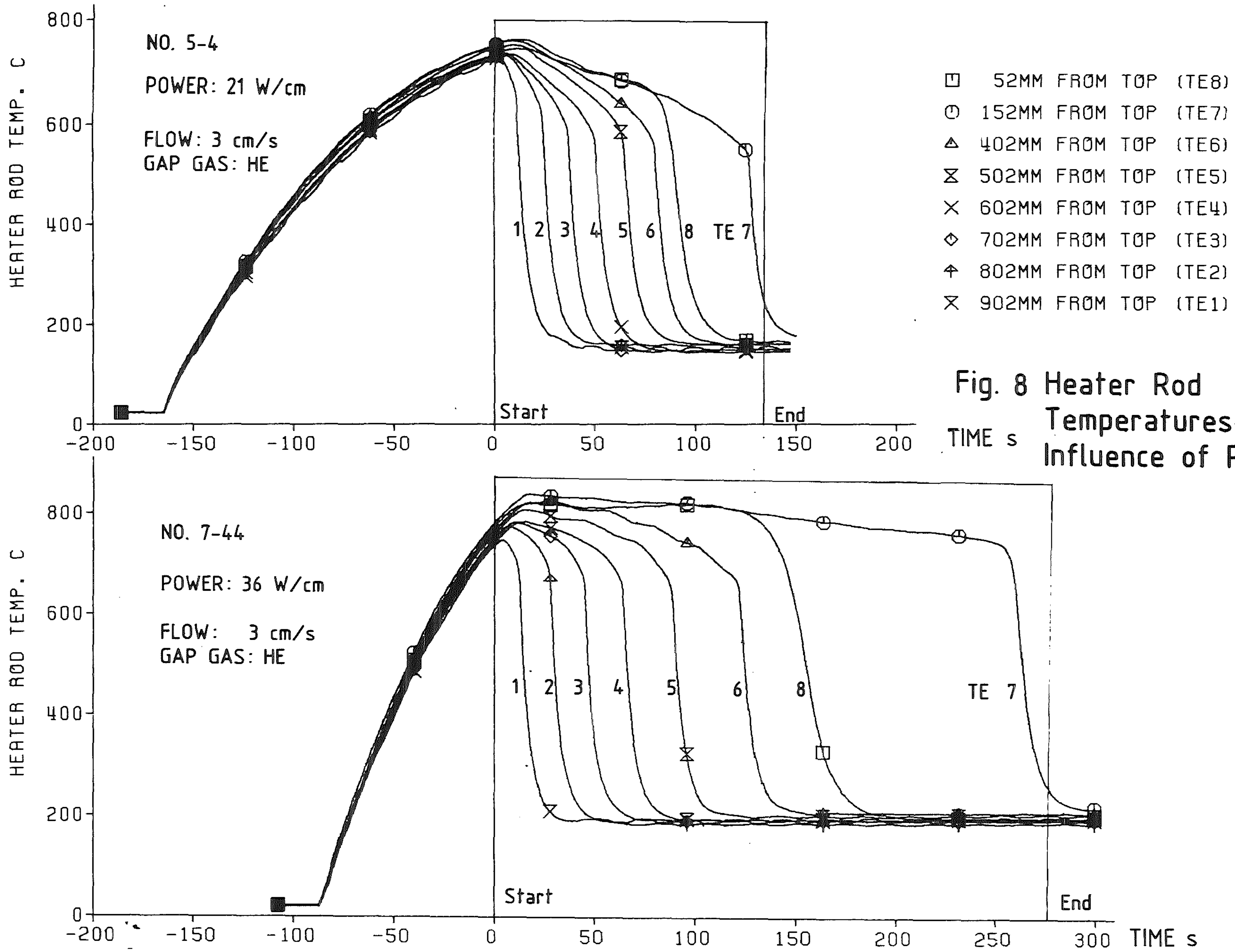


Fig. 8 Heater Rod Temperatures- Influence of Power

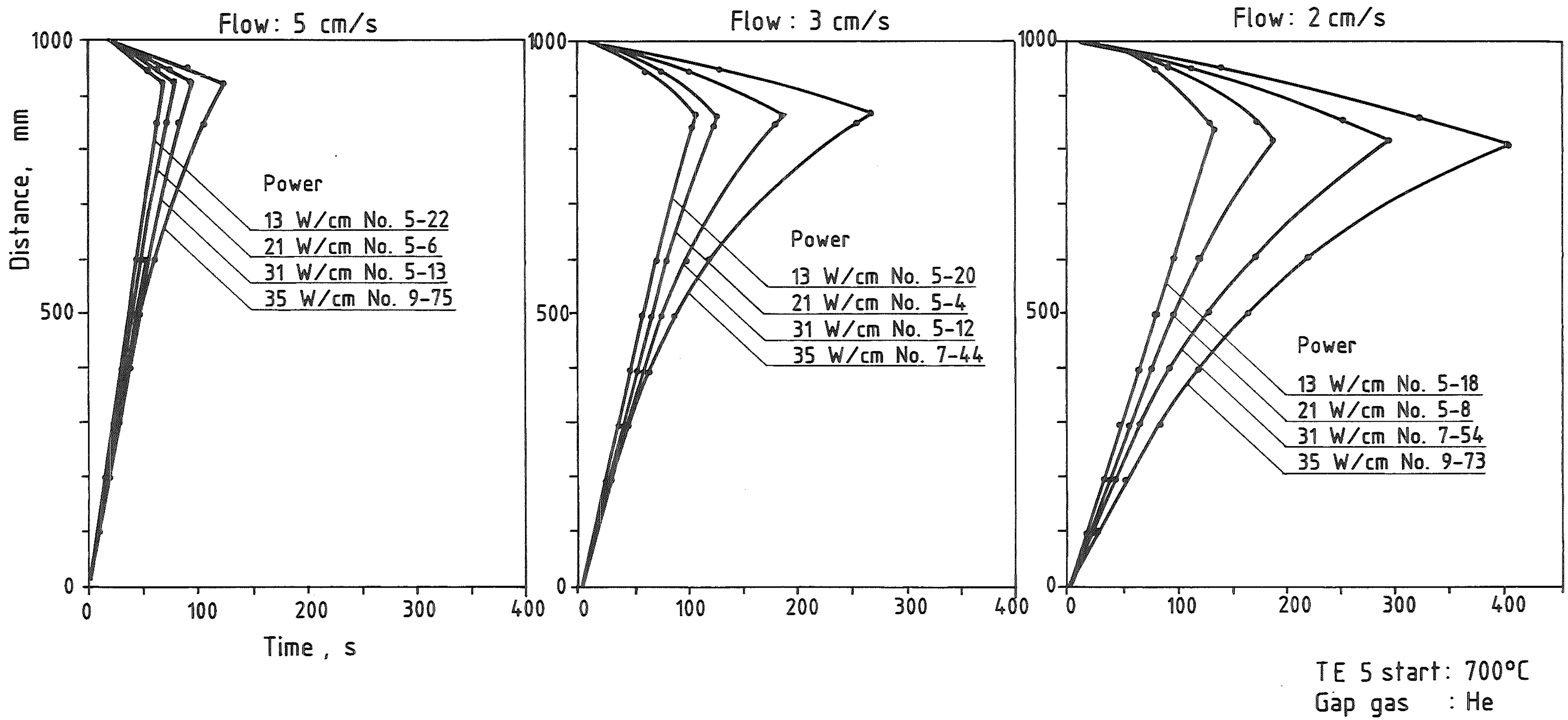


Fig. 9 Influence of flooding velocity and rod power on quench front progression

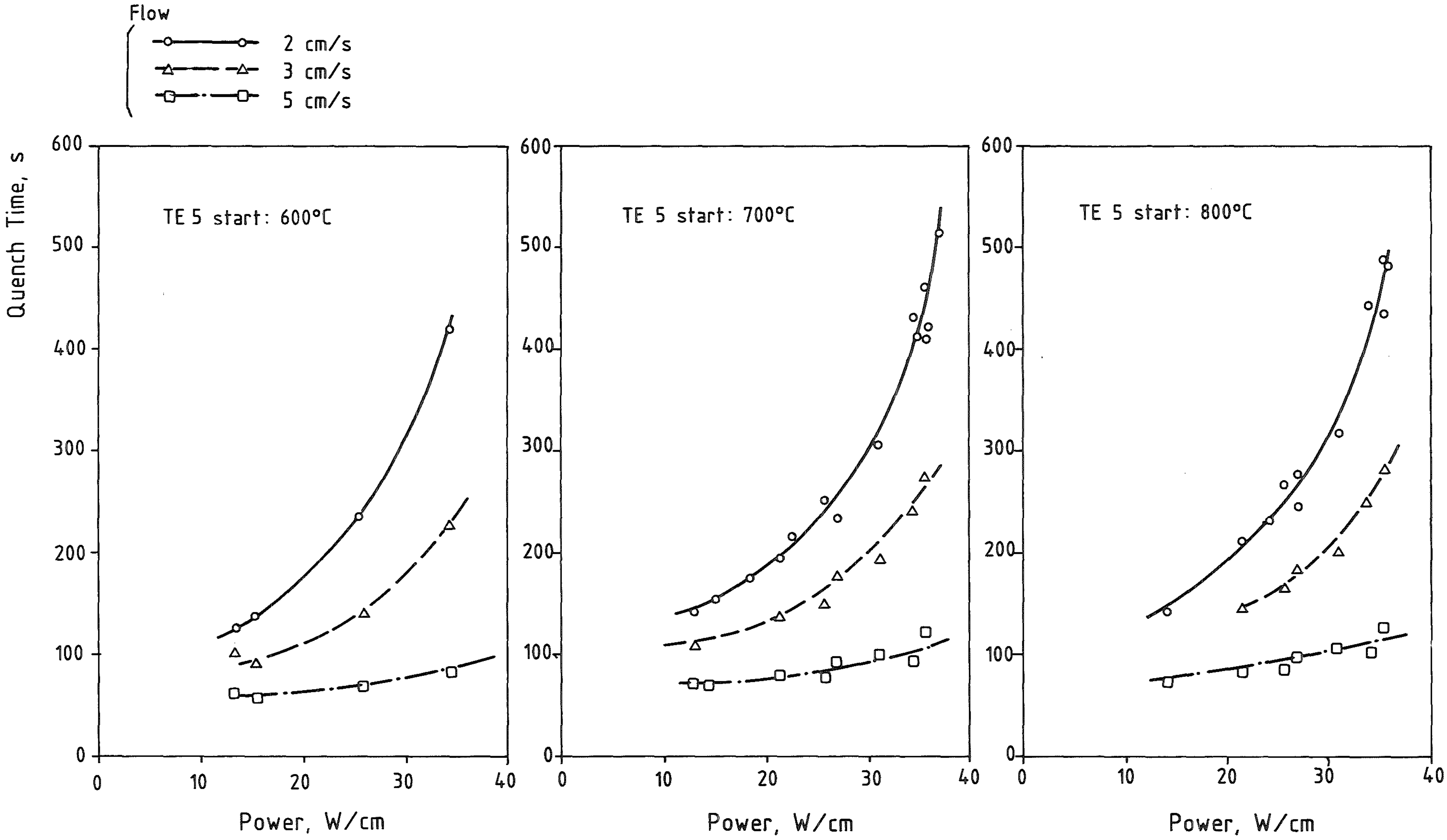
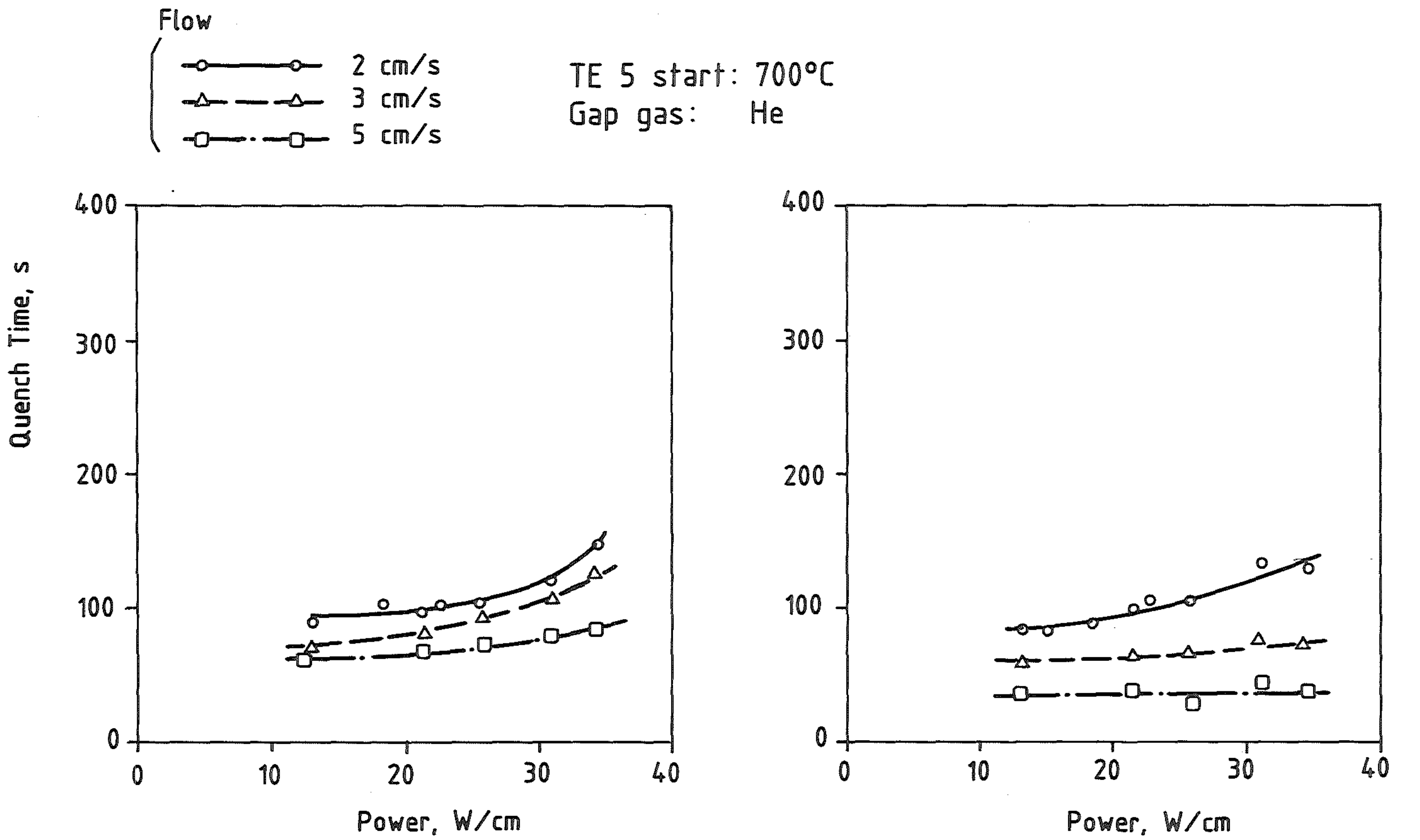


Fig. 10 Quench Times of Whole Rod, Influence of flooding velocity and rod power



Quench Time at 502 mm from Top (TE 5)

Quench Time at 52 mm from Top (TE 5)

Fig. 11 Quench Times at 502mm, 52mm from Top, Influence of flooding velocity and rod power

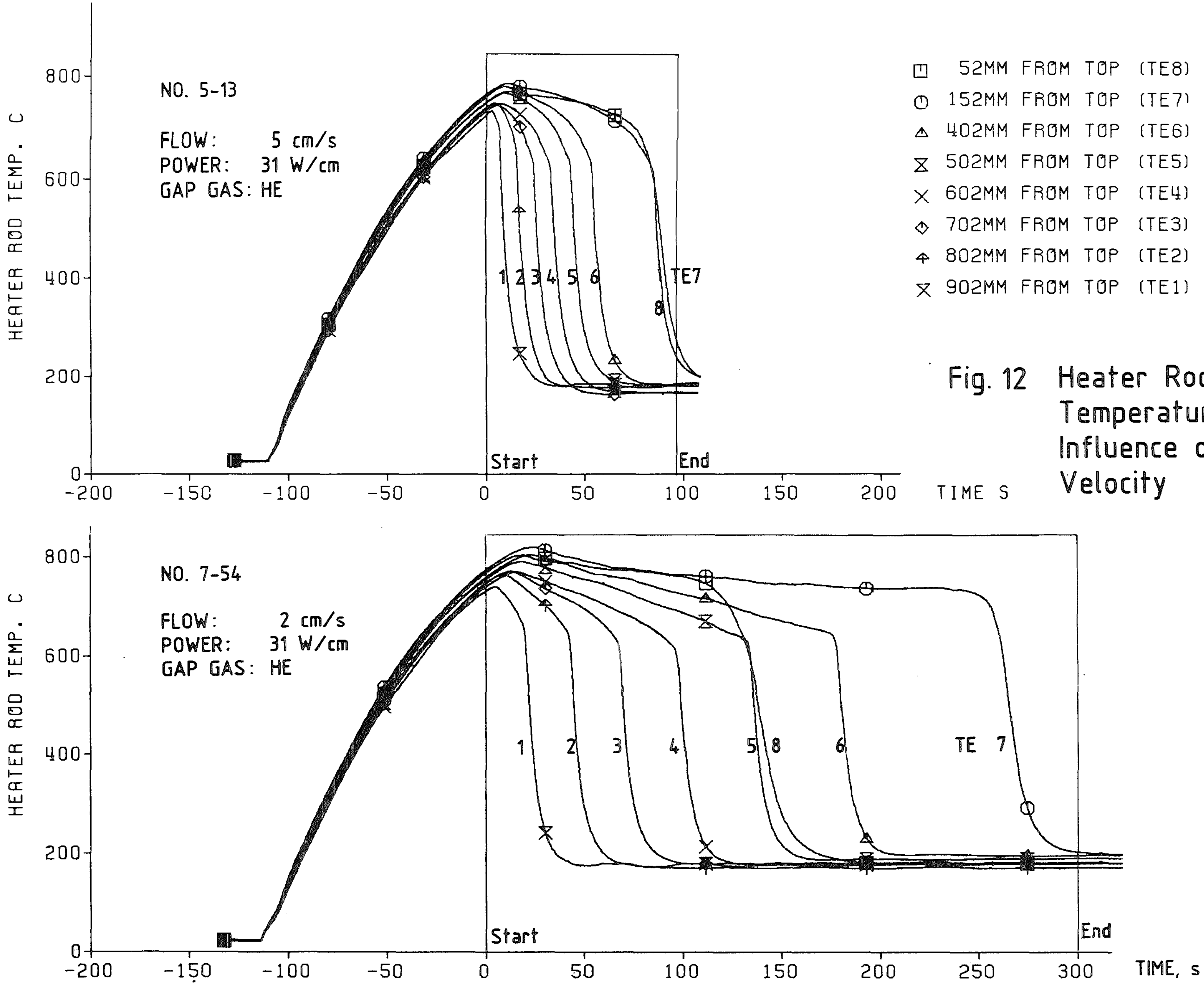


Fig. 12 Heater Rod Temperatures- Influence of Flooding Velocity

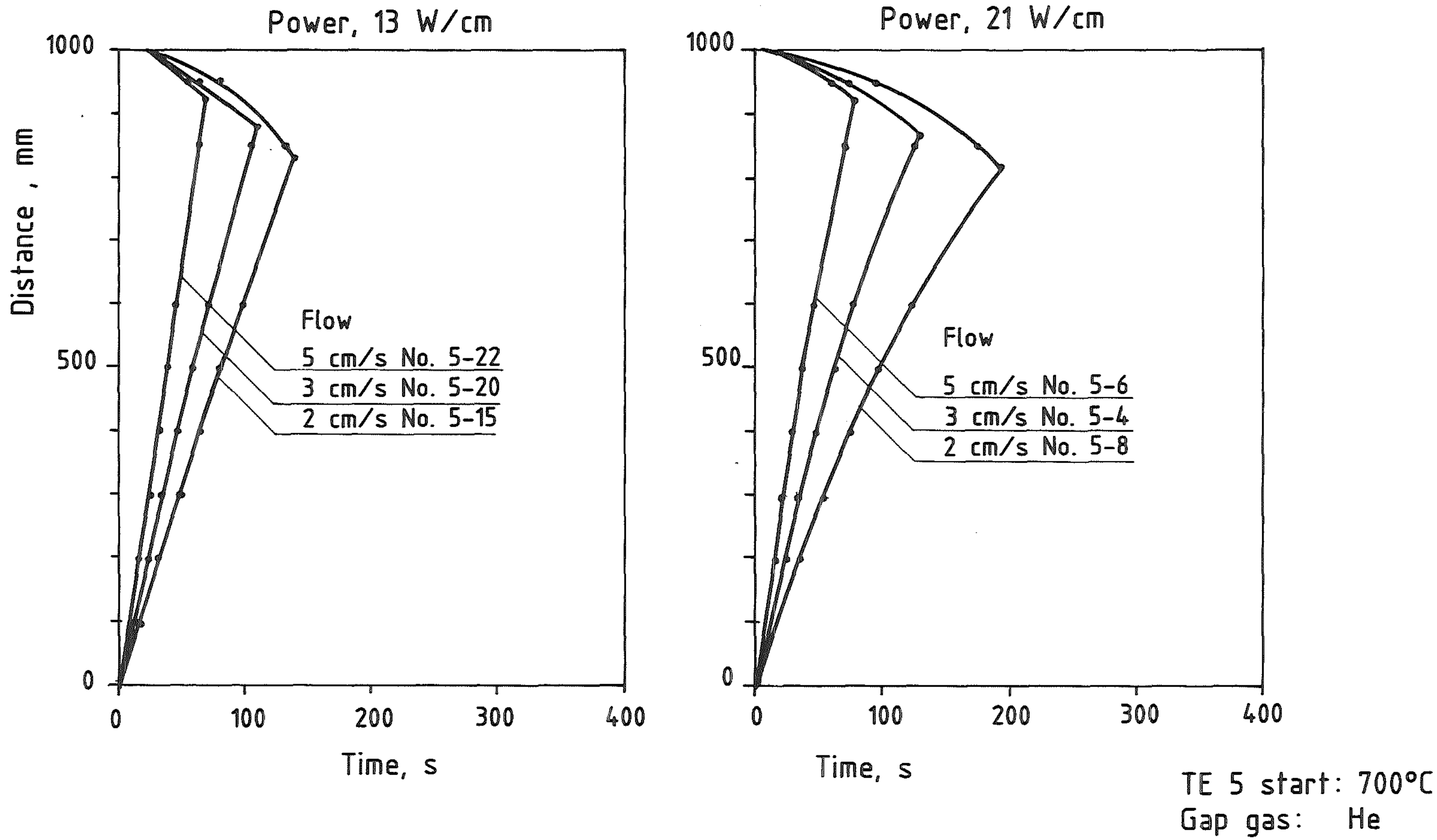


Fig. 13 Quench Front Progressions–Influence of Flooding Velocity

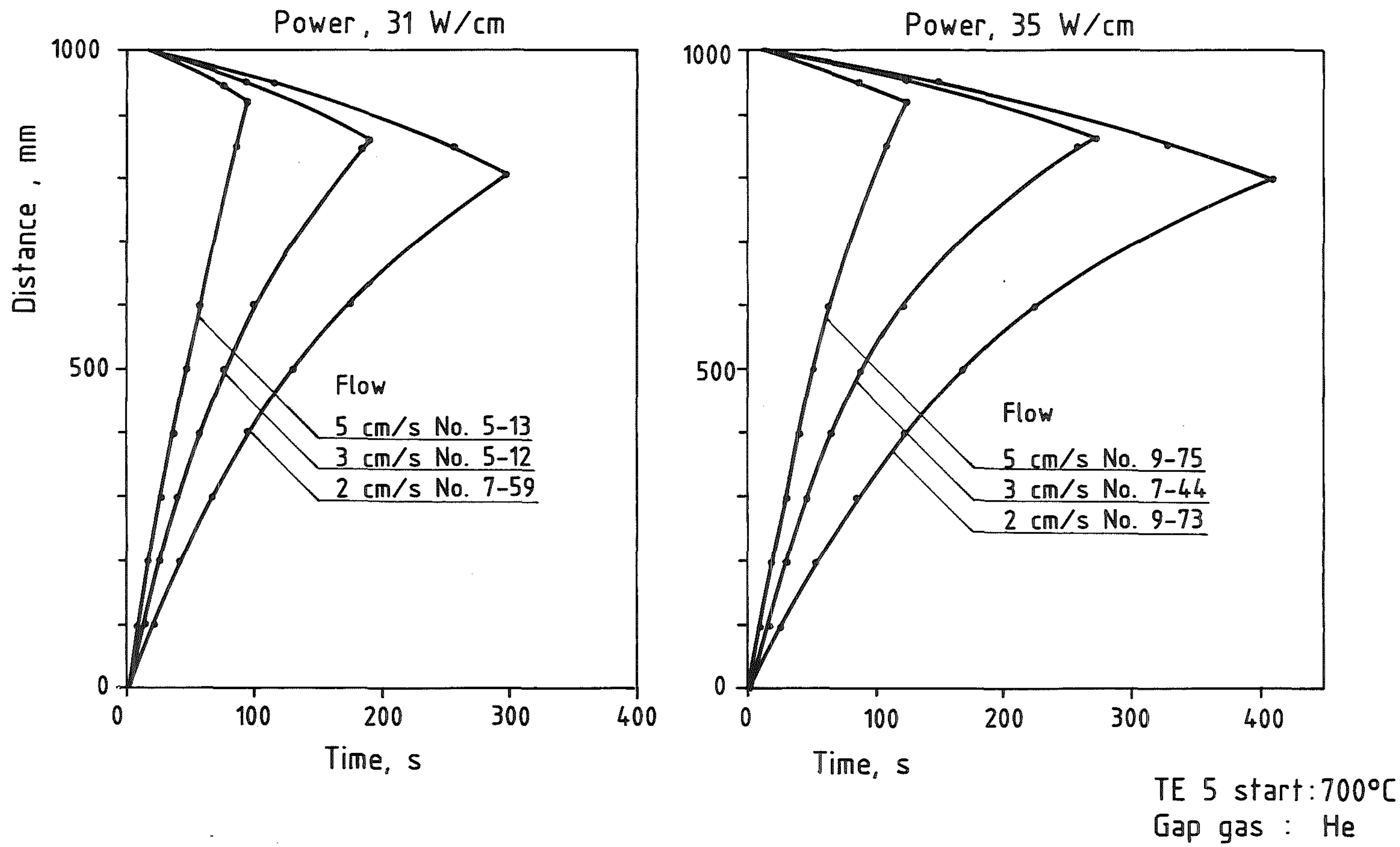


Fig. 14 Quench Front Progressions-Influence of Flooding Velocity

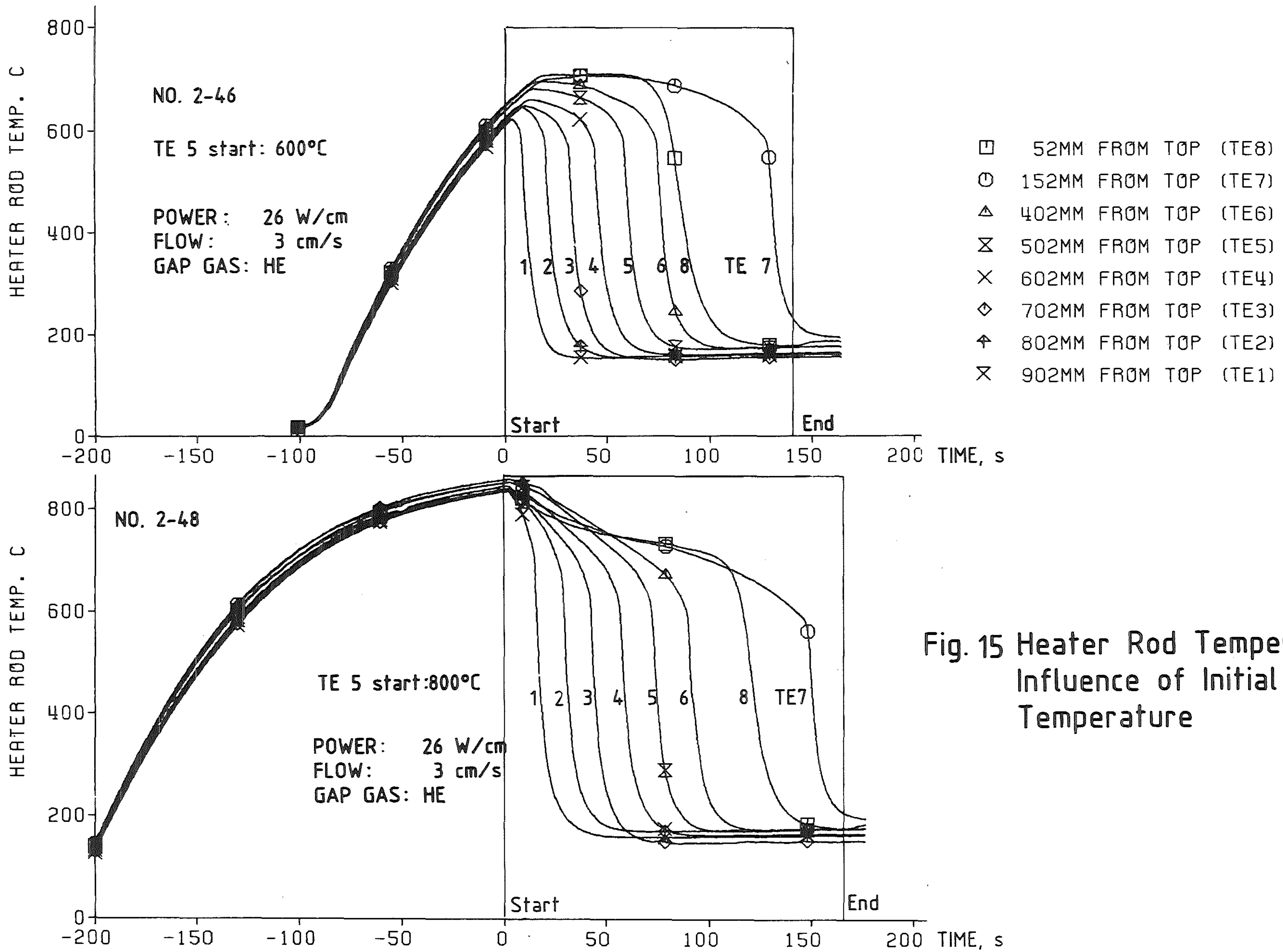


Fig. 15 Heater Rod Temperatures- Influence of Initial Rod Temperature

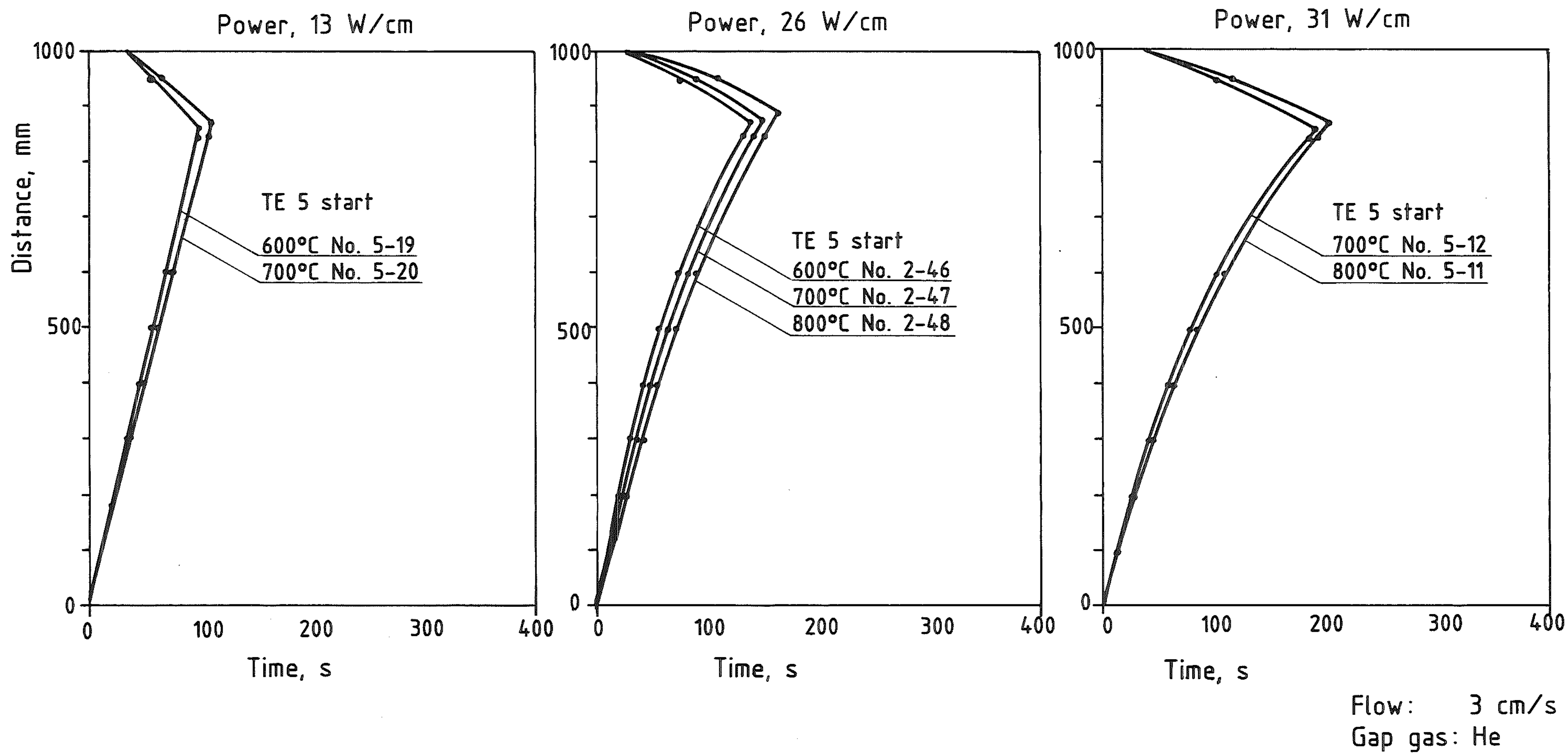


Fig. 16 Quench Front Progressions-Influence of Initial Rod Temperature

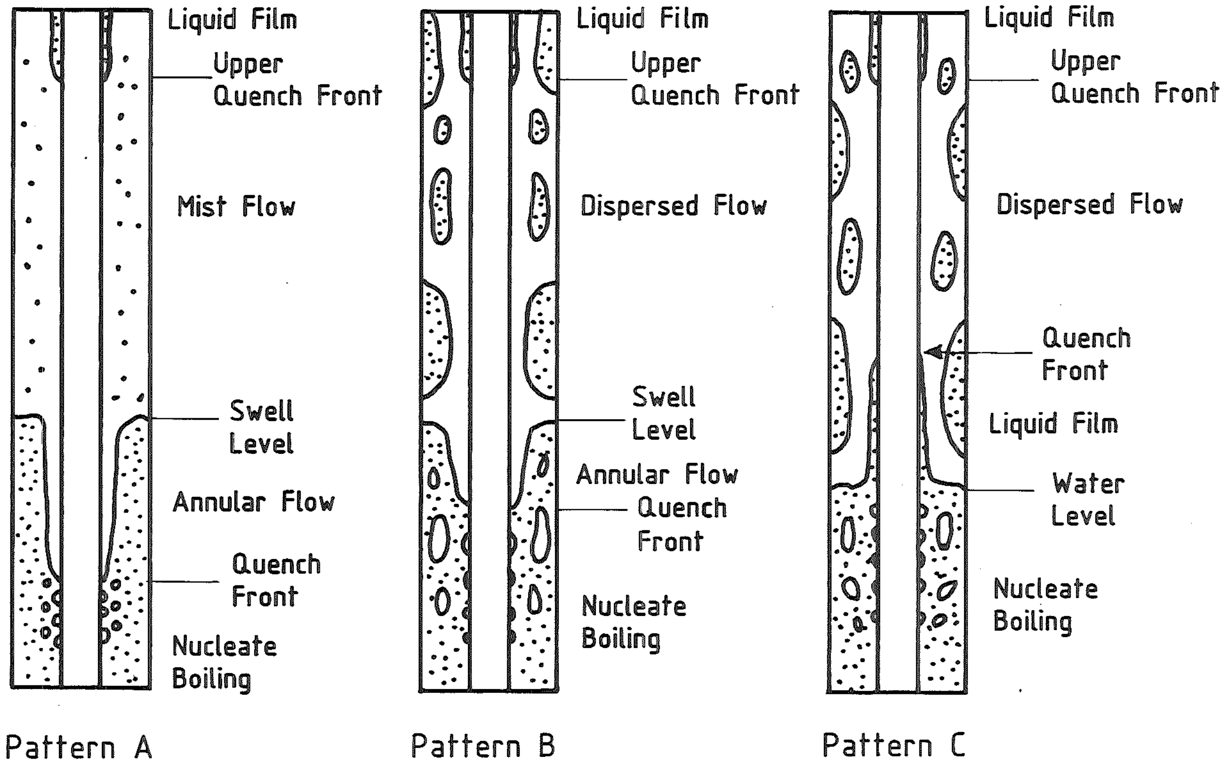


Fig. 17 Comparison of Quench Patterns

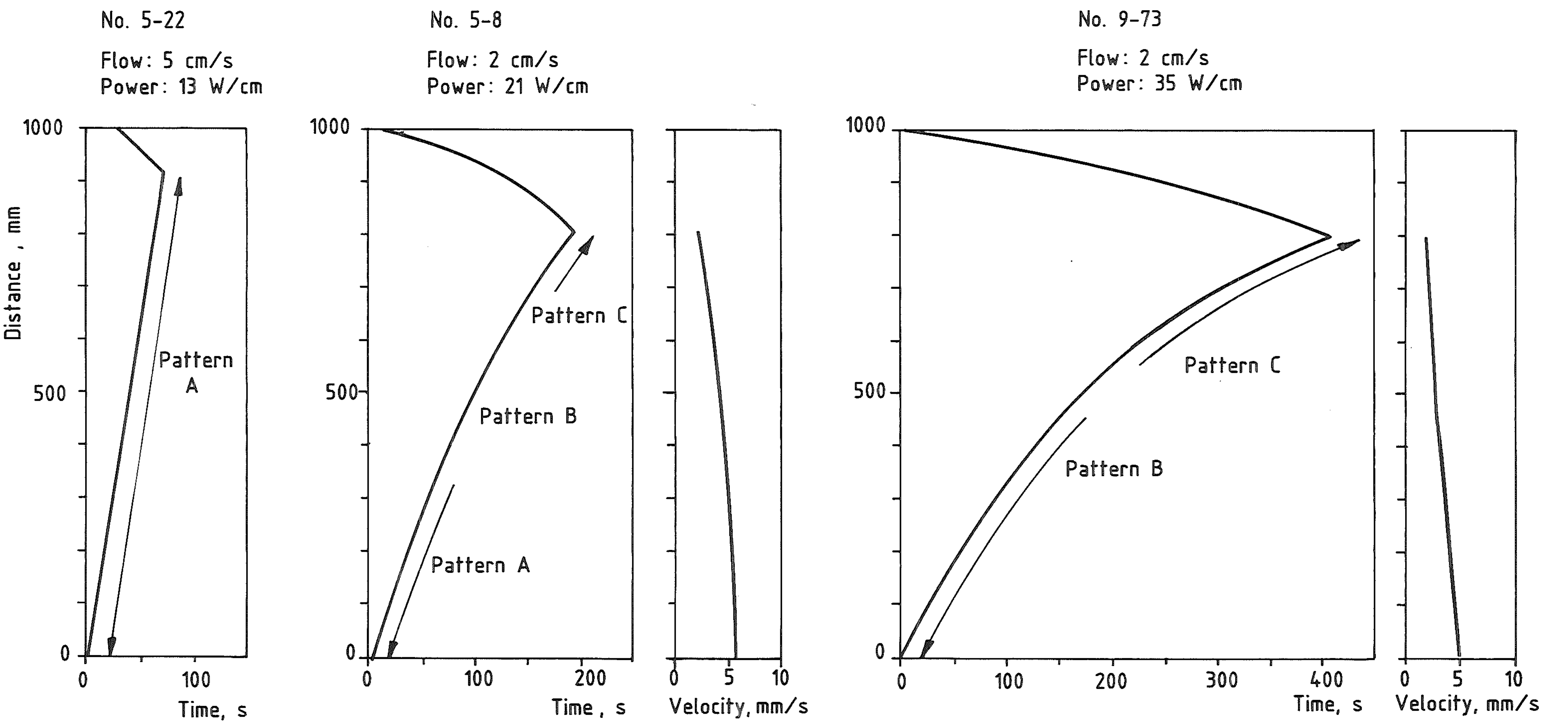
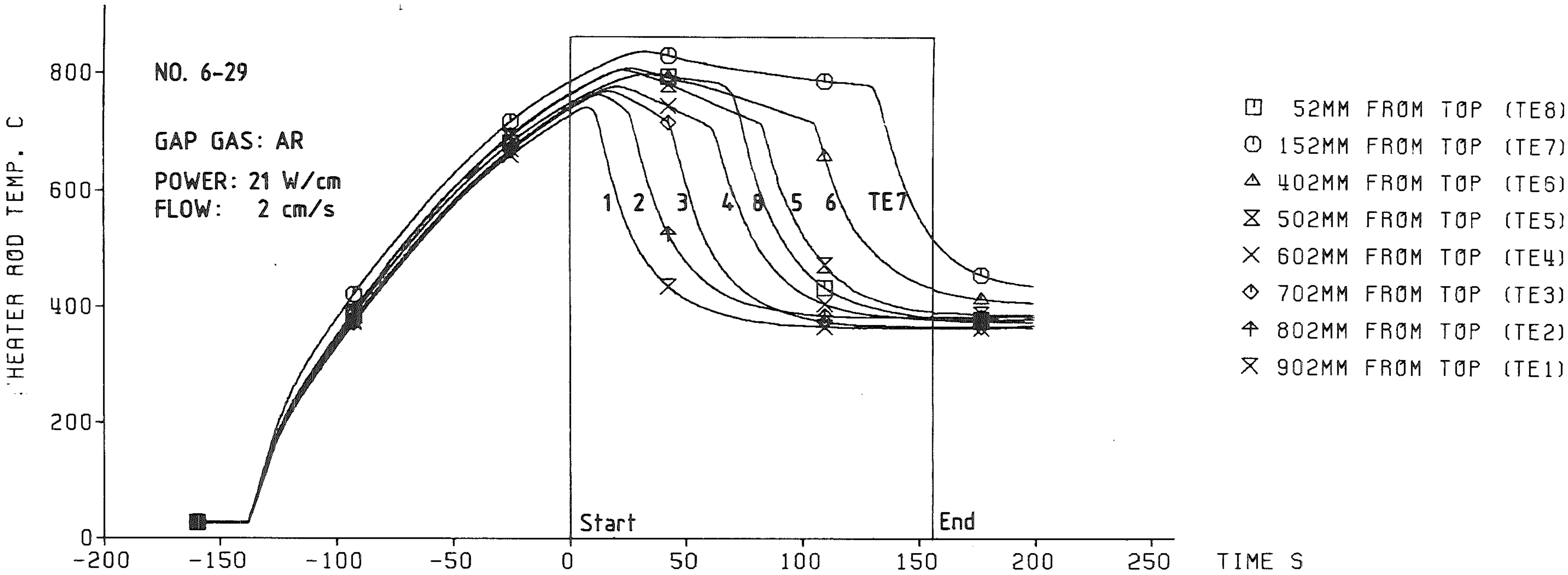


Fig. 18 Quench Front Progressions and Quench Front Velocities - Comparison of Qench Pattern



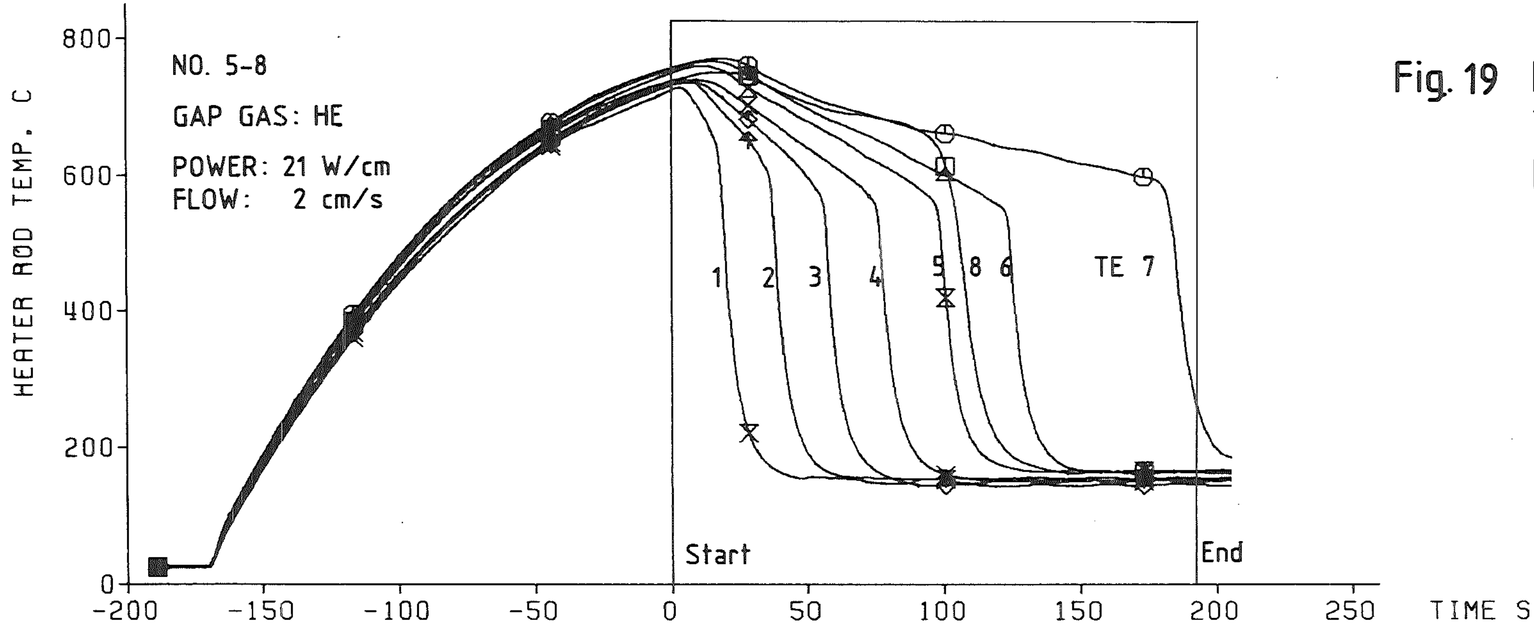


Fig. 19 Heater Rod Temperatures- Influence of Gap gas

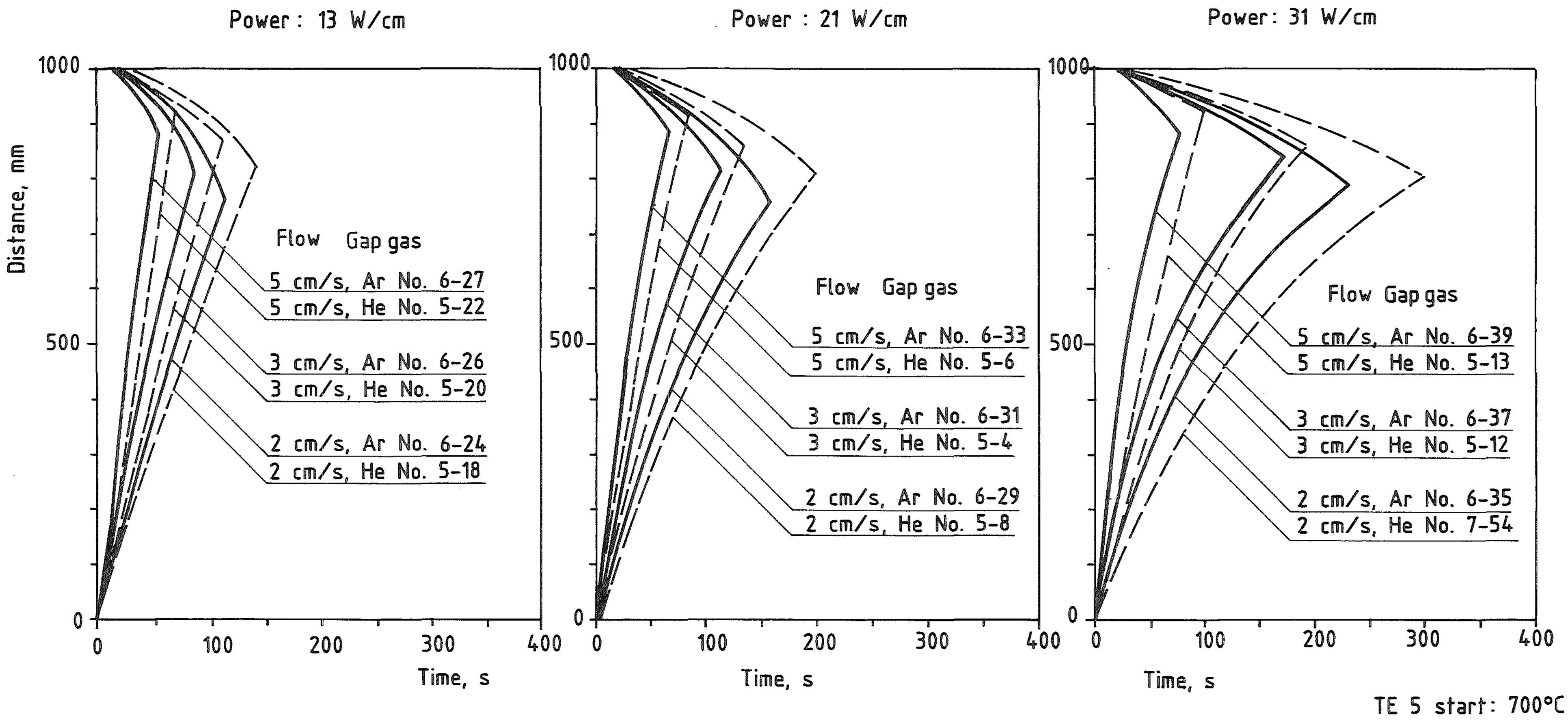


Fig. 20 Quench Front Progressions - Influence of Gap gas

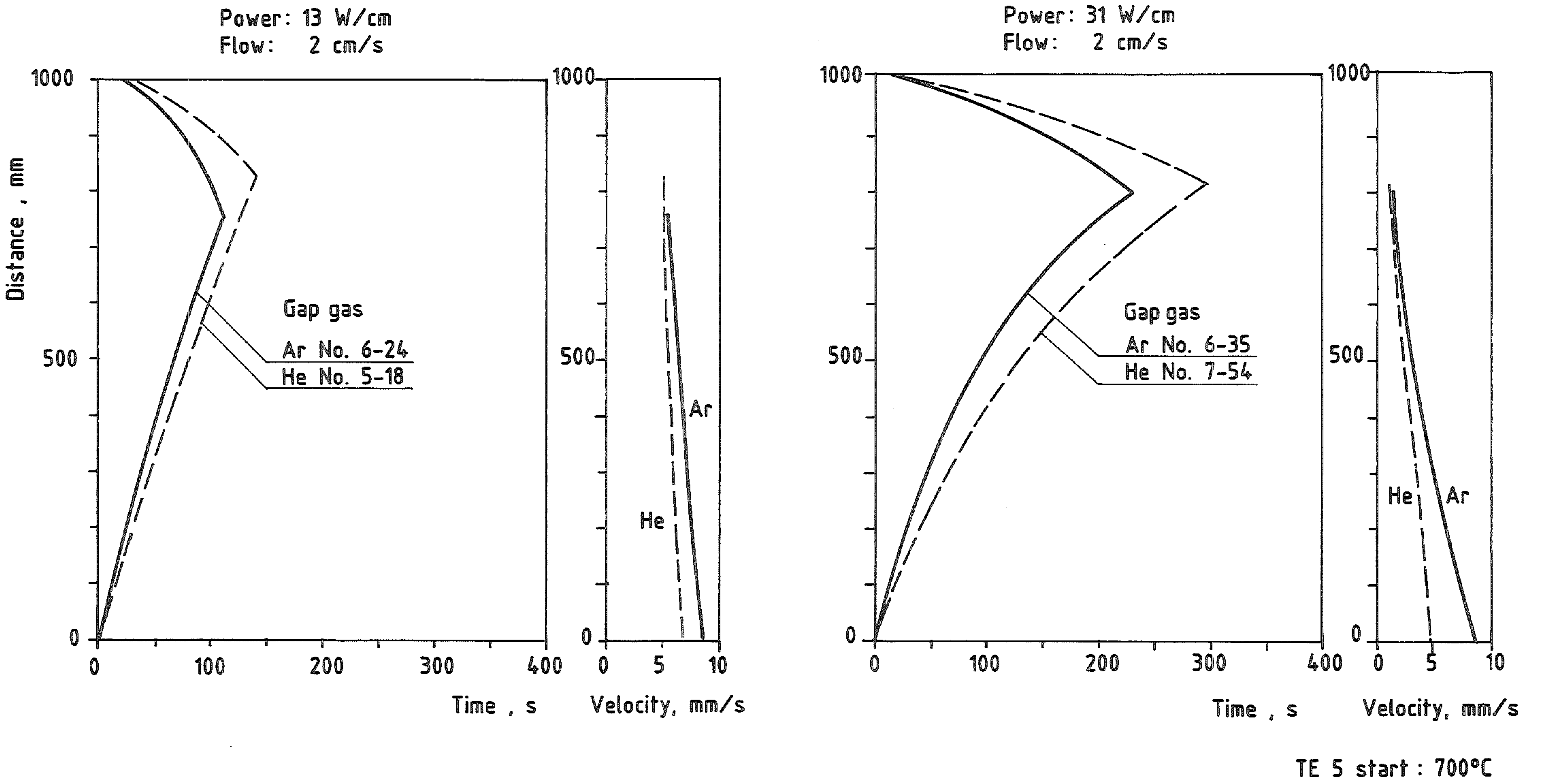


Fig. 21 Quench Front Progressions and Quench Front Velocities - Influence of Gap gas