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OUT-OF-PILE EXPERIMENTS ON THE HIGH TEMPERATURE BEHAVIOR OF ZRY-4 CLAD FUEL RODS.+)

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Abstract

Out-of-pile experiments have been performed to investigate the escalation in temperature of zircaloy clad fuel rods during heatup in steam due to the exothermal zircaloy steam reaction. In these tests single zircaloy/UO_2 fuel rod simulators surrounded with a zircaloy shroud - simulating the zircaloy of neighbouring rods - were heated inside a fiber ceramic insulation. The initial heating rates were varied from 0.3 to 2.5 K/s.

In every test an escalation of the temperature rise rate was observed. The maximum measured surface temperature was about 2200 ^{o}C The temperature decreased after the maximum had been reached without decreasing the input electric power. The temperature decreases were due to inherent processes including the runoff of molten zircaloy. The escalation process was influenced by the temperature behaviour of the shroud, which was itself affected by the insulation and steam cooling.

Damage to the fuel rods increased with increasing heatup rate. For slow heat up rates nearly no interaction between the oxidized cladding and UO_2 was observed, while for fast heatup rates the entire annular pellet was dissolved by molten zircaloy.

Out-of-pile Experimente zum Verhalten von Zry-4 umhüllten Brennstäben bei hohen Temperaturen.

Kurzfassung

Dieser Bericht beschreibt Out-of-pile Experimente zur Untersuchung der Temperatureskalation von zirkaloyumhüllten Brennstäben. Die Eskalation hat ihre Ursache in der exponentiell mit der Temperatur ansteigenden exothermen Zirkon-Wasserdampf-Reaktion. In diesen Versuchen wird der UO_2-Zirkaloy Brennstabsimulator von einem Zirkaloy-Rohr und einer dicken Keramikfaserisolation umgeben. Das Zirkaloy-Rohr soll den exothermen Einfluß der Nachbarstäbe simulieren. Die anfängliche Temperaturanstiegsrate wurde zwischen 0,3 und 2,5 ^{o}C/sec variiert.

In jedem Test wurde eine Temperatur-Eskalation beobachtet. Die maximale gemessene Temperatur der Brennstaboberfläche betrug ca. 2200 ^{o}C. Die Temperatur nahm nach Erreichen des Maximums ab, ohne daß die elektrische Leistung verringert wurde. Die Temperaturabnahme ist auf eine Abnahme der Reaktionsenergie zurückzuführen. Eine wesentliche Rolle spielte hierbei für schnelle anfängliche Anstiegsraten das Ablaufen des geschmolzenen Zirkaloys aus der Reaktionszone. Der Eskalationsprozeß wurde durch das Temperaturverhalten des Dampfführungsrohres beeinflußt. Dieses wiederum wurde durch die Isolation und die Dampfkühlung beeinträchtigt.

Der Schaden am Brennstab nahm mit ansteigender Aufheizrate zu. Für langsame Aufheizraten wurde nahezu keine Wechselwirkung zwischen der oxidierten Hülle und dem UO_2 beobachtet. Für schnelle Aufheizraten wurde praktisch das ganze UO_2-Ringpellet vom geschmolzenen Zirkaloy aufgelöst.

Contents

Introduction

Within the framework of the Project Nuclear Safety (PNS) at the Kernforschungszentrum Karlsruhe (KF) out-of-pile experiments /1/ have been performed for the understanding of the meltdown phenomena of UO_2/Zry-4 fuel rods. Experiments are on the way to investigate the Severe Fuel Damage behaviour.

The oxidation of zirconium in steam is an exothermal reaction, which may be written as

(1) $Zr + 2H_2O \rightarrow ZrO_2 + 2H_2 + 140$ Kcal/mole

In the energy balance 255 Kcal/mole are gained by the uptake of oxygen and 115 Kcal/mole are lost by the dissociation of two moles H_2O.

The energy potential of this reaction corresponds to almost a minute of full power of a 1000 MWe reactor. This energy is sufficient to heat the fuel rod (zircaloy and UO_2) to about 3700 ^oC including melting of both materials and neglecting any heat loss. However the rate and amount of this energy release depends strongly on the external boundary conditions.

The zirconium oxide layer formed acts as barrier to further oxidation. The oxide layer thickness thus has a parabolic time dependency.

This may be expressed by

(2) $W^2 = Kt$ or $\frac{dW}{dt} = \frac{K}{2} \frac{1}{W}$

$K = A \exp(-B/RT)$; W = weight of metal reacted; t = time;

A,B = Constants; T = temperature of cladding.

The reaction rate thus increases exponentially with temperature and decreases with the reciprocal of the oxide layer thickness.

The increase of the reaction rate with temperature means that an increasing amount of energy is produced. This heat increases the temperature of the zircaloy. The temperature increase will, in return, further increase the rate of reaction. In other words, the cladding temperature will escalate. Up to what temperature this process will proceed is a question of the overall balance of energy gain and energy losses.

The energy gain depends basically on temperature and thickness of the oxide layer. Limitations on the energy gain include consumption of the zircaloy, runoff of the zircaloy to cooler regions, steam starvation and hydrogen blanketing. The energy losses depend primarily on the temperature of the surroundings and the method of energy transportation. Heat is transported by radiation, convection and conduction. Which of these produces the greatest loss is strongly influenced by geometry and atmosphere.

Objectives

Previous meltdown experiments have shown that the damage behaviour of the fuel rod is determined by the degree of oxidation. The oxidation when reaching a specific temperature is dependent on the temperature rise rate. Thus the degree of temperature escalation will significantly effect the final rod character. Therefore the understanding of the temperature escalation is necessary for the investigation of Severe Fuel Damage Behaviour.

To investigate the temperature escalation and, in particular, possible inherent temperature limiting mechanisms, we have planned single rod and bundle out-of-pile experiments. Here is reported about the current series of single rod tests. This series is called ESSI as an abbreviation of escalation and single.

Experiment Configuration

The experiment configuration for the ESSI series of tests is shown in figure 1. The tests were conducted in the NIELS-facility /2/. The fuel rod simulators had lengths of 25 cm (ESSI-1 to ESSI-3) and 37 cm (ESSI-4 to ESSI-11). The central tungsten heater had a diameter of 6 mm and the annular UO_2 pellet an inner diameter of 6.1 mm and an outer diameter of 9.2 mm. The zircaloy cladding had the original PWR dimensions of 9.29 mm innner and 10.75 mm outer diameter.

To better simulate the effect of surrounding rods, which would also follow the escalating temperature, a zircaloy shroud was placed around the fuel rod simulator. The shroud had an inner diameter of 26.5 mm and wall thickness of 0.5 mm (ESSI-1 to ESSI-3) and 1 mm (ESSI-4 to ESSI-11).

The arrangement was surrounded by 4 inches of fiber ceramic material. For tests ESSI 1-8 the inner most inch consisted of ZrO_2 (ZYFB 3) and the remaining outer 3 inches of an Al_2O_3/SIO_2(ASH) mixture. Only the inner layer makes use of the more expensive ZrO_2. Due to a porosity of 92% the fiber ceramic is a very effective insulation. (ZYFB: 0.24 Watts/m ^{o}K for 1650 ^{o}C; ASH: 0.2 Watts/m ^{o}K for 1100 ^{o}C). For tests ESSI-10 and 11 a quarter inch of ZrO_2 fiber ceramic was wrapped directly on the zircaloy shroud with no gap between shroud and insulation (fig. 1c).

Steam is brought into the shroud by the double tube system shown in the lower right corner of figure 1. The four holes in this system assure a uniform supply of steam to the surface of the rod.

Temperature measurement was accomplished by two-color pyrometers. The surface temperature of the rod was measured at 140 mm from the upper end of the shroud, and the shroud temperature was read at 140 mm and 190 mm. Holes for the measurement were cut into the shroud and into the insulation. For some tests the temperature on the upper and lower end of the rod and in the insulation was measured by NiCrNi thermocouples with Inconel sheaths. The details of these measurements will be given in a later KfK-report.

Test Conduct

ESSI-1 was intended to have conditions for escalation as favorable as possible, that is, with an oxide layer as small as possible. Therefore the rod and shroud were heated in argon. The voltage was raised stepwise until a temperature of about 1700 ^{o}C was reached. Afterwards the voltage input was held constant. The shroud reached a temperature of about 1200 ^{o}C by radiation heating from the rod. Then a steam flow of 35 g/min was suddenly introduced to start the escalation.

In all other tests steam was introduced right from the start into the vessel which had an initial argon pressure of 1 bar. In this way the oxide layer developed from the beginning according to the temperature rise. In these experiments the voltage was raised continously in a nearly linear fashion and then held constant. Due to the strong increase in resistance of the tungsten heater with temperature the current increase was sufficiently reduced, so that the resulting power increase was nearly linear (figures 4, 6 and 8). The electric power input shown is the product of measured voltage and current. The voltage rise rate from test to test was increased by a factor 2 for tests ESSI-4 to ESSI-7. This gave an initial temperature rise rate of the rod surface temperature between 0.3 ^{o}C/sec and 2.5 ^{o}C/sec.

To investigate the influence of the insulation thickness tests ESSI-5 and 6 were repeated with similar rods and shrouds but with an insulation of 0.25 inches fiber ceramic wrapped directly on the shroud. This arrangement is similar to the insulation in the PBF Severe Fuel Damage inpile tests /5/. Theses tests were designated ESSI-10 and ESSI-11. Test ESSI-10 has the same power rise rate as ESSI-6 and ESSI-11 the same as ESSI-5.

General Results

In every test the exothermal energy led to a temperature escalation. The escalation developed faster, and began at a lower temperature, the shorter the time spent in the temperature region below 1200 ^{o}C. That is, the escalation was greatest for the thinnest previously formed oxide layers. Accordingly, the steepest temperature rise was for test ESSI-1 with heatup in argon and a sudden steam input. However in no case was the measured maximum surface temperature much greater than 2200 ^{o}C. The following sections describe specific aspects of the individual tests.

Results and Discussion of Heat up in Argon with Sudden Steam Input

Figure 2 shows the temperature behavior of test ESSI-1. With an electric power of barely 1200 Watts the rod reached a surface temperature of almost 1700 ^{o}C. When the steam (32 g/min) was added, the temperature increased to around 2200 ^{o}C. However, in less than a minute the temperature decreased to below the initial 1700 ^{o}C and fell below the measuring limit of the two color pyrometer. The shroud showed nearly the same behavior. The maximum temperature of the shroud was around 100 ^{o}C lower, but the temperature increase in comparison to the initial 1200 ^{o}C was higher and the decay at the end some what slower.

The steep temperature rise was caused by the sudden onset of the exothermal zircaloy-steam reaction as the steam was introduced. The reaction energy was only able to overcome the heat losses up to around 2200 ^{o}C. Then the temperature decreased very quickly to a temperature much below the initial temperature in argon. This illustrates the strong contribution of steam cooling.

To estimate the energy contribution of the zircaloy-steam reaction calculations with the MOP program /3/ have been performed. MOP is a modification of the SIMTRAN program. It calculates the oxygen uptake and distribution in zircaloy by solving the diffusion equations according to the oxidation kinetics of Cathcart. Using the measured surface temperature as input, the absorbed oxygen was calculated.

With the known heat of reaction (140 Kcal/mole Zr) and the surface area for rod and shroud the reaction power was determined. In figure 12 the reaction rate per cm of rod and shroud is given for test ESSI-1 and ESSI-4. For a short period ESSI-1 had a calculated zircaloy-steam reaction energy, which was 10 times higher in the shroud and 3 times higher in the rod than the electric power input. Such calculations help explain the steep temperature rise in ESSI-1. The quantitative values must, however, be considered with care, since the Cathcart data are verified only up to 1550^{o}C and the calculations are valid only for the solid state.

In addition to the reciprocal dependency of the oxidation process on the growing oxide layer thickness, the reaction rate can be limited by the consumption of zircaloy, runoff of molten zircaloy, or limitation of the necessary oxygen, which can be caused by steam starvation or hydrogen blanketing. In the case of ESSI-1 only a small portion of the zircaloy was consumed by oxidation when the melting temperature of zircaloy was reached. A large amount of the molten zircaloy ran off and refroze at the lower end of the rod and shroud as seen in figure 3. Therefore, ESSI-1 runoff of the molten zircaloy from the reaction zone was a major limiting mechanism.

The demand for steam was estimated as follows. Using the measured temperature-time history, the maximum oxygen absorption was determined to be 2 mg/cm^2 in the rod and 3 mg/cm^2 sec in the shroud. Due to the influence of steam cooling the axial temperature profile has a maximum in the upper region of the rod. Assuming, therefore, a reaction length of 10 cm, the rod had an oxygen consumption of 5 g H_2O/min and 15 g H_2O/min for the shroud. For the shroud oxidation from both sides has been taken into account. This compares to a steam input of 32 g/min. Thus, in the maximum temperature region a high percentage of the steam may have been converted into hydrogen. The experiments of H. Chung /4/ from Argonne National Laboratories have shown that, for these concentration ratios, oxidation will be diminished by the presence of hydrogen.

Figure 3 shows two different views each of the ESSI-1 rod and shroud. The pictures demonstrate the strong axial temperature gradient caused by steam cooling. The lower 6 cm still appear metallic, while the upper 8 cm show the strongest change in surface appearance. The opening from which the molten material came is 13 cm above the lower end of the rod. The molten material is distributed over a length of 9 cm. Some of the molten material has also dropped down on the steam distribution system connected to the lower electrode. The molten material came from the upper part of the rod.

As shown by pieces broken off during dismantling of the test, the thickness of the oxide layer was between 0.1 and 0.2 mm. The fully oxidized cladding would have had a thickness of around 1 mm. A gap existed between the oxide layer and the remaining pellets. The shroud of ESSI-1 also formed a thin oxide layer with a thickness between 0.1 and 0.2 mm, which stayed intact during the experiment, but broke during dismantling.

Heat up in Steam

With the exception of ESSI-1, the rest of the experiments were conducted in an atmosphere of flowing steam. The major test parameters were the electric power input and the arrangement of the insulation. In the following examples from the test series will be used to illustrate the discussion.

Figures 4 and 5 show the fuel rod simulator and shroud surface temperatures for tests ESSI-4 to 7. These tests and test ESSI-4/5 were done with the same insulation arrangement as shown on the left side of figure 1. They differed only in the gradient of the electric power input. The power inputs are shown as dotted lines in figure 4.

The power was raised linearly to ca. 5 KW (7.5 KW for ESSI-4) and then kept constant. Test ESSI-4/5 was a multiple heatup of a single rod and will be discussed later.

In all tests an escalation peak was observed. The temperature at which the escalation began increased from ESSI-7 (below 1200 °C) to ESSI-4 (around 1600 °C). Depending upon the initial temperature rise, caused by the different electric power ramps different oxide layer thicknesses were formed by the time specific temperatures were reached. Thus higher temperatures were necessary to get the same reaction rate for slower initial heatup rates. The maximum temperature in all tests stayed below 2100 °C, and the highest temperature was reached in test ESSI-6. The observed temperature escalations were much lower than the temperature escalation predicted for PBF inpile tests /5/. In those calculations for 6 x 6 bundles temperatures of 3300 and 2600 °C were found for fast (4 °C/sec) and slow (0.5 °C/sec) heat up rates respectively.

The much lower temperatures observed here suggest that there are inherent processes which limit extremely high escalations. Examining the pictures of the fuel rod simulators and shrouds shown in figures 10 and 11, it can be seen that molten zircaloy moved into lower regions for tests ESSI-6 and 7. That means the heatup process was reduced by the runoff of zircaloy into the cooler region where the reaction energy was reduced. The much larger amount of zircaloy which moved down into a cooler region during test ESSI-7 compared to ESSI-6 may be the reason for the lower ESSI-7 temperature maximum which had the same maximum electric power input but a slower heatup rate.

Another possibility for limiting the escalation could be reduced oxygen availability. Calculations of the oxygen consumption with the MOP program indicate that in ESSI-7 the maximum oxygen was clearly less than 1 mg/cm^2 for rod and shroud. Assuming a simultaneous escalating length of 10 cm, the oxygen consumption of rod and shroud was less than 7 g H_2O/min compared to a steam input of 20 g/min. The consumption is even less for the tests with slower initial rise than ESSI-7. Therefore, on an integrated basis there was decidedly more steam available than was consumed.

On the other hand hydrogen was produced on the surface of the zircaloy. Therefore, the ratio of steam to hydrogen in the neighbourhood of the zircaloy surface was not the mean value. This effect is known as hydrogen blanketing. The much thinner oxide layer which can be recognized in broken parts of the can in the upper region of rods E7 and E6 point out that hydrogen blanketing seems to have had some influence in these tests. Again the influence of the hydrogen blanketing is stronger the faster the escalation because a higher reaction energy is connected with higher hydrogen production. So hydrogen blanketing appear to be an inherent mechanism which reduces the escalation possibility.

The final maximum heatup rate is nearly the same for all tests (around 6 ^{o}C/sec). Also, the gradient of the temperature decrease is similar for the different tests (around 1.2 ^{o}C/sec). These tests had the same geometrical arrangement and insulation. Therefore the cooldown with the decrease of the exothermal energy input is determined by the similar heat losses.

For test ESSI-4 the reaction energy for rod and shroud, calculated with the MOP program, is shown in figure 12. For this test, which had the slowest heatup, the reaction energy of rod and shroud together is of the order of the electric power input. The reaction energy was effective over a much longer time than in ESSI-1, which had a much higher energy for a much shorter time. In ESSI-4 there was no runoff of molten zircaloy from the reacting zone.

Temperature of the Shroud

Essential for the temperature escalation of the rod is the temperature behaviour of its surroundings. To simulate the behaviour of neighbouring rods, the fuel rod simulator was surrounded by a zircaloy shroud. The temperature on this shroud at the same height as measured on the rod (dashed line) and 50 mm lower (dotted line) are given in Fig. 5 and Fig. 4a. The temperature on the shroud was very similar to that of the rod. This demonstrates that the simulation of the surrounding rods was quite reasonable.

The temperatures on the shroud 50 mm lower indicate that the escalation at this elevation began later. That means that the escalation begins in the upper part of the test section and moves down into the lower region. This movement is caused by the axial temperature gradient. The cold steam (120 °C) entering at the bottom and warming up while moving upward influenced the axial temperature distribution such that the highest temperatures were in the upper section.

Tests with 0.25 Inches Insulation

The 4 inch fiber ceramic insulation was intended to keep radiation losses as small as possible. To investigate the influence of the thickness of the radial insulation and its configuration, tests were done with the power input of ESSI-5 and 6, but with 1/4 inch insulation wrapped directly on the shroud instead of the 4 inches insulation with a gap between shroud and insulation.

The results are plotted in Fig. 6 to 9. In both cases the escalation started earlier at a lower temperature and with a steeper temperature rise, than in the tests with 4 inch insulation. The maximum temperature of the peaks were nearly the same as in the corresponding tests with 4 inch insulation although the electric power input at the time of escalation was smaller. The results show that with 0.25 inch insulation the shroud is able to more quickly follow the temperature rise of the rod.

The faster temperature rise of the shroud was strongly influenced by the lack of a gap between shroud and insulation. The low heat capacity and conductivity of the fiber ceramic wrapped on the shroud favor a steep temperature gradient through the shroud insulation and thus a quick temperature rise. In contrast, the slower temperature increases observed in ESSI 5 and 6 indicated that significant cooling of the shroud outer surface by steam probably occurred. Thus, for the transient event, cooling by steam in the outer annulus exerted a greater influence on the temperature escalation than did the extra 4 inches of insulation.

Damage to the Fuel Rod Simulators

Photographs of the fuel rod simulators and shrouds of tests ESSI 4 to 7, 10 and 11 are given in figures 10 and 11. The pictures clearly demonstrate that the damage to the fuel rod increases with heatup rate. The heatup rate is directly connected to oxygen uptake. During heatup the oxygen has an stabilizing influence on the fuel rod behaviour. The thickness of the oxide layer decreases with the heatup rate. Preparation of cross sections from the fuel rod simulators is not yet finished. However, preliminary measurements of oxide layer pieces broken off during cool down give the following oxide layer thicknesses for the middle region of the rods.

Test	Measured thickness (mm)
4	0.75
5	0.55 - 0.6
6	0.35 - 0.4
7	0.15 - 0.2
10	0.25
11	0.3

In the test ESSI-4 only small pieces of the nearly fully oxidized can cladding were broken off in the middle region of the test. Below the oxide layer only very limited attack on the pellets can be recognized.

In test ESSI-5 the oxide layer enclosed the melt (zircaloy which has dissolved some UO_2). The break away of the oxide layer in the middle region happened after the refreezing of the melt, that is, during cool down, which can be seen from the smooth surface of the refrozen material.

In ESSI-6 the oxide layer in the upper region was swept down from the remaining molten zircaloy. The melt broke through the shroud as seen in figure 11. In the lower part the melt was enclosed inside the oxide layer.

In ESSI-7 in the upper part the complete annular pellets were dissolved by the molten zircaloy. The molten alloy ran down into the lower region region and refroze between rod and shroud.

A comparison of ESSI-4 and ESSI-7 demonstrates the stabilizing influence of the oxygen. Although ESSI-4 had a power input higher by the factor of 1.5 and a higher temperature by about 150 °C, there is nearly no attack of the UO_2 in contrast to the complete dissolution in ESSI-7.

As discussed in /6/ in detail the dissolution of UO_2 by liquid zircaloy is a chemical process in which the UO_2 disintegrates by giving its oxygen to the zircaloy. The amount of UO_2 which can be dissolved by zircaloy depends on the oxygen concentration in the zircaloy. The fast temperature rise in ESSI-7 keeps the oxygen concentration in the zircaloy low. A calculation with the MOP program showed that more than half of the zircaloy cladding was still in the bèta state when the melting temperature of zircaloy was reached.

The volume ratio of the UO_2 annular pellets to the zircaloy cladding was 1.62. According to the ternary phase diagramm at 2000 °C /6/ in oxygen-free zircaloy a volume ratio of about 2 is possible for the dissolved UO_2. How much UO_2 actually was dissolved shall be detemined by an analysis of the composition of the refrozen melt. For ESSI-4 the oxygen concentration in the zircaloy was so high (0.75 mm oxide layer thickness at the end of the test) that notable dissolution of UO_2 by zircaloy was avoided. The metallurgical investigations of these tests are under way and will be reported in a future KfK report.

Conclusions

- In all tests a temperature escalation due to zircaloy steam reaction was observed.
- The maximum measured surface temperature was only about 2200°C.
- The temperature at which the escalation begins increases with decreasing initial heatup rate.
- For fast initial heatup run off of molten zircaloy is a limiting process for the escalation. There are indications that hydrogen blanketing may also have a limiting influence on the escalation.
- For slow heatup the formation of a protective oxide layer is a mechanism which reduces the reaction energy.
- In these tests, with 120 °C steam entering at the lower end, the escalation started in the upper region and moved towards the lower end.
- The damage to the fuel rods increases with the heatup rate. For slow heatup rates nearly no interaction between the oxidized cladding and the UO_2 was observed. For fast heatup rates the entire annular pellet was dissolved by the molten zircaloy.

Acknowledgements

I would like to thank Mr. H. Malauschek and Mr. K.P. Wallenfels for the performance of the tests, Mr. A. Grünhagen for the calculations with the MOP-program and Mr. S. Malang for the delivery of the MOP-program. Especially thanks are due to Mr. Scott Peck for critical review of the manuscript.

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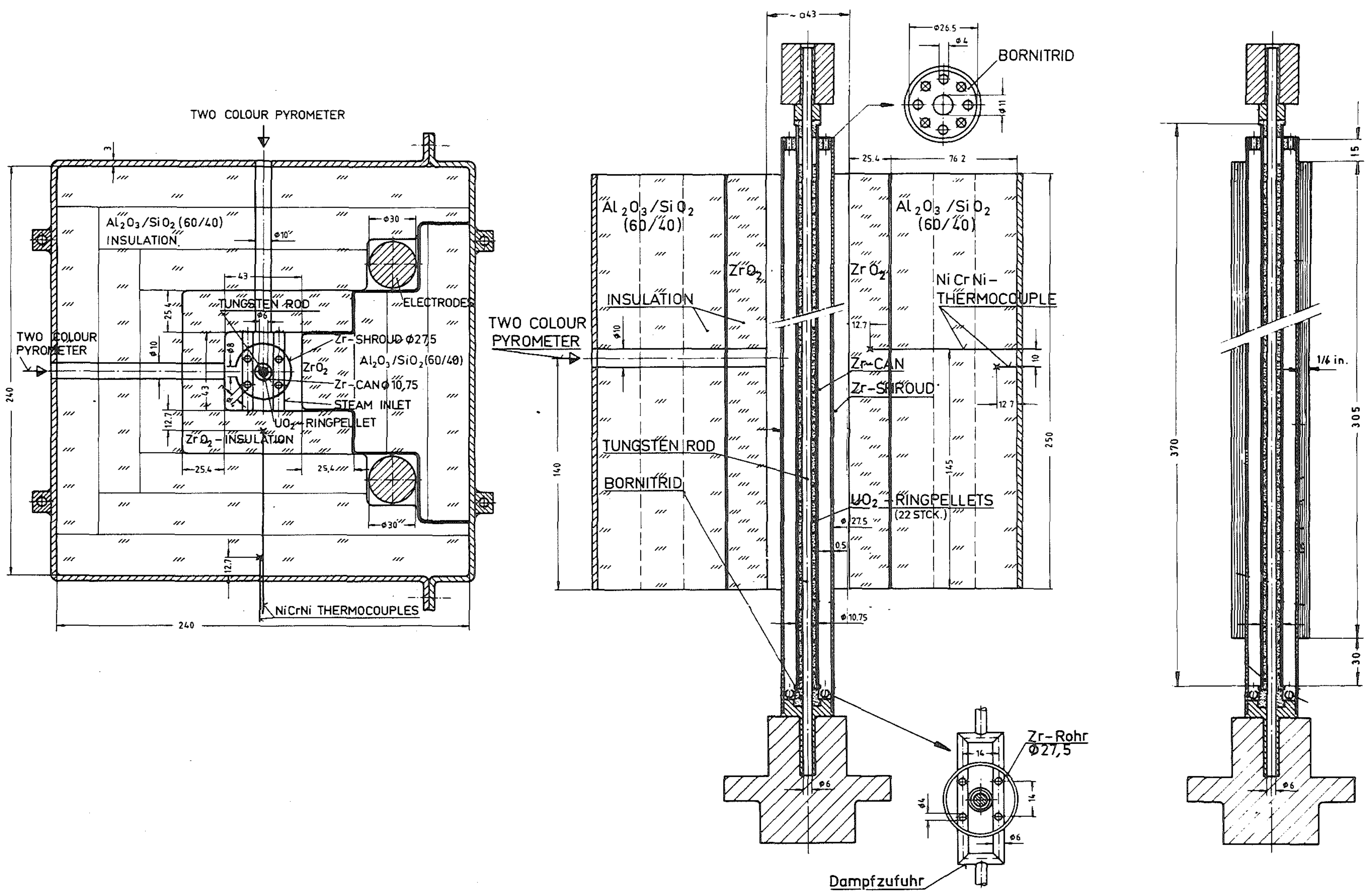

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Fig. 1: Experimental Arrangement for Tests ESSI 1-7 with 4 Inch Insulation and Tests ESSI 10-11 with 0,25 Inch Insulation.

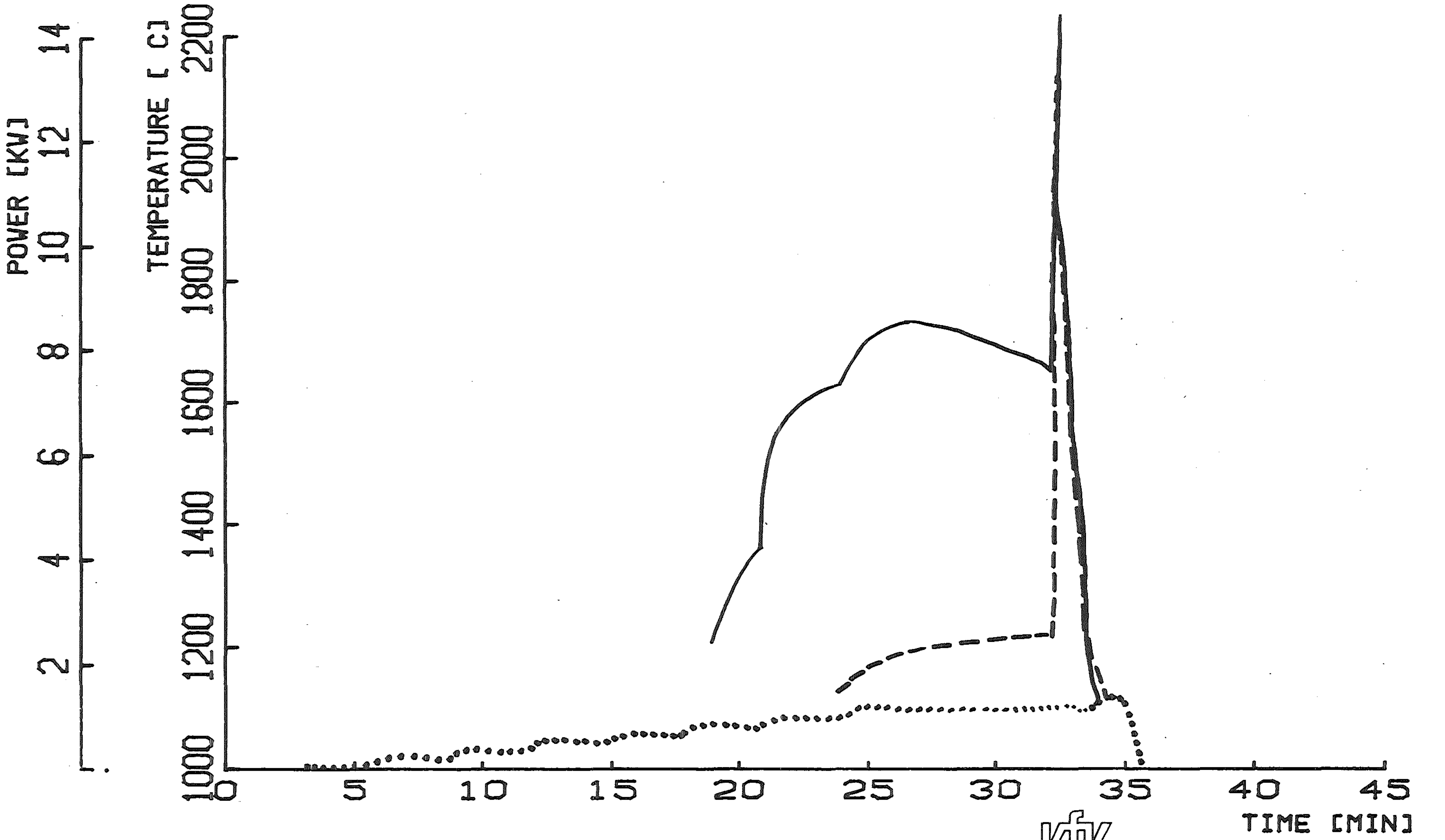

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FIG.2: TEMPERATURE ON ROD (——) AND SHROUD (- - - -) IN 140 MM FROM UPPER END COMPARED TO ELECTRIC POWER (·······) FOR TEST ESSI 1

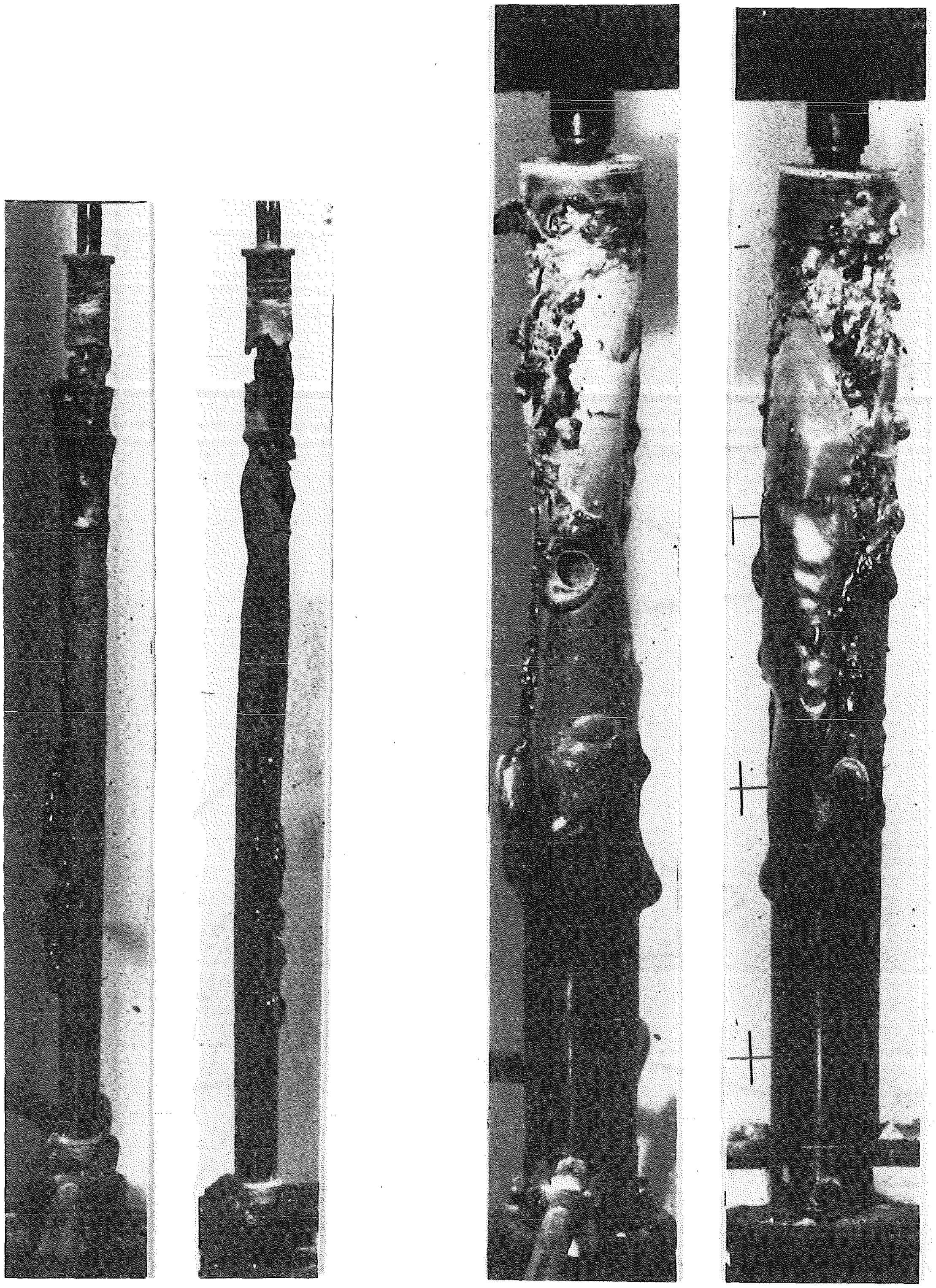

FIG.3: FUEL ROD SIMULATOR AND SHROUD FOR TEST WITH HEATUP IN ARGON AND SUDDEN STEAM INPUT: ESSI 1

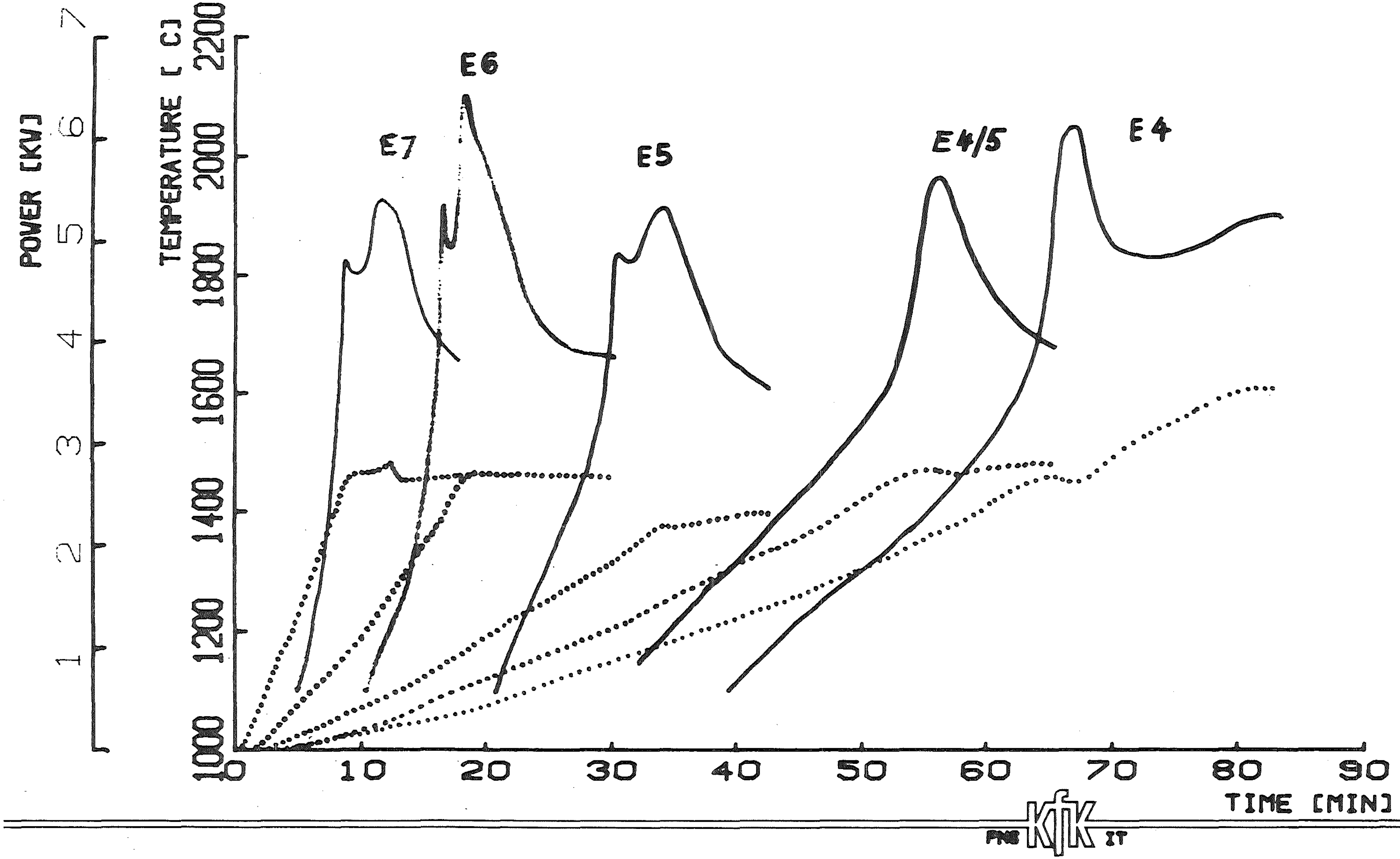

FIG.4: TEMPERATURE (———) ON ROD AND ELECTRIC POWER (··········)
FOR TESTS ESSI 4,5,6,7

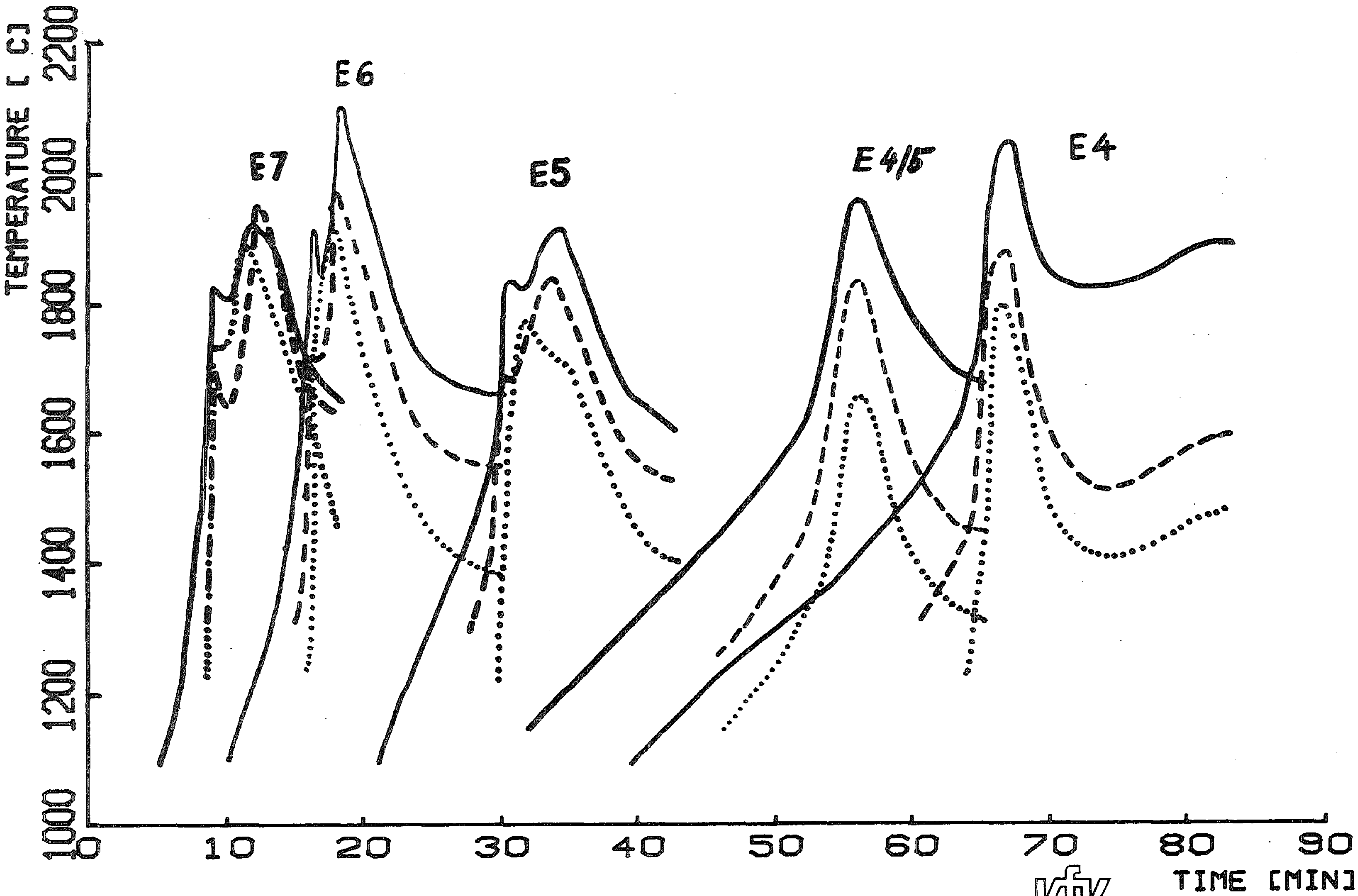

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FIG.5: TEMPERATURE ON ROD (———) IN 140 MM AND ON SHROUD IN 140 MM (- - - -) AND 190 MM (··········) FROM UPPER END OF SHROUD FOR ESSI 4.5.6.7

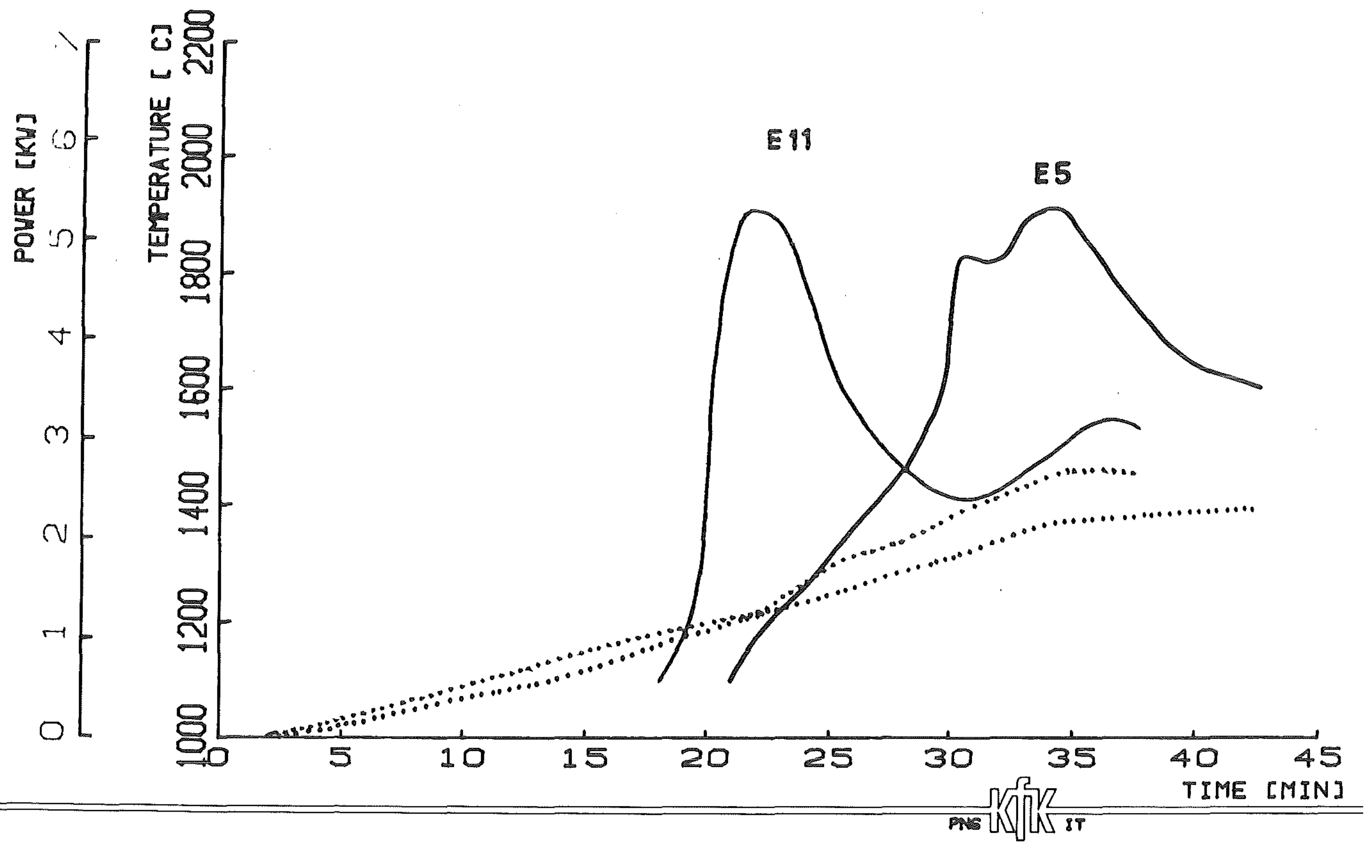


FIG.6: TEMPERATURE (———) ON ROD AND ELECTRIC POWER (·········) FOR ESSI 11 (0.25 INCH ISOLATION, NO GAP) AND ESSI 5 (4 INCH ISOLATION, GAP)

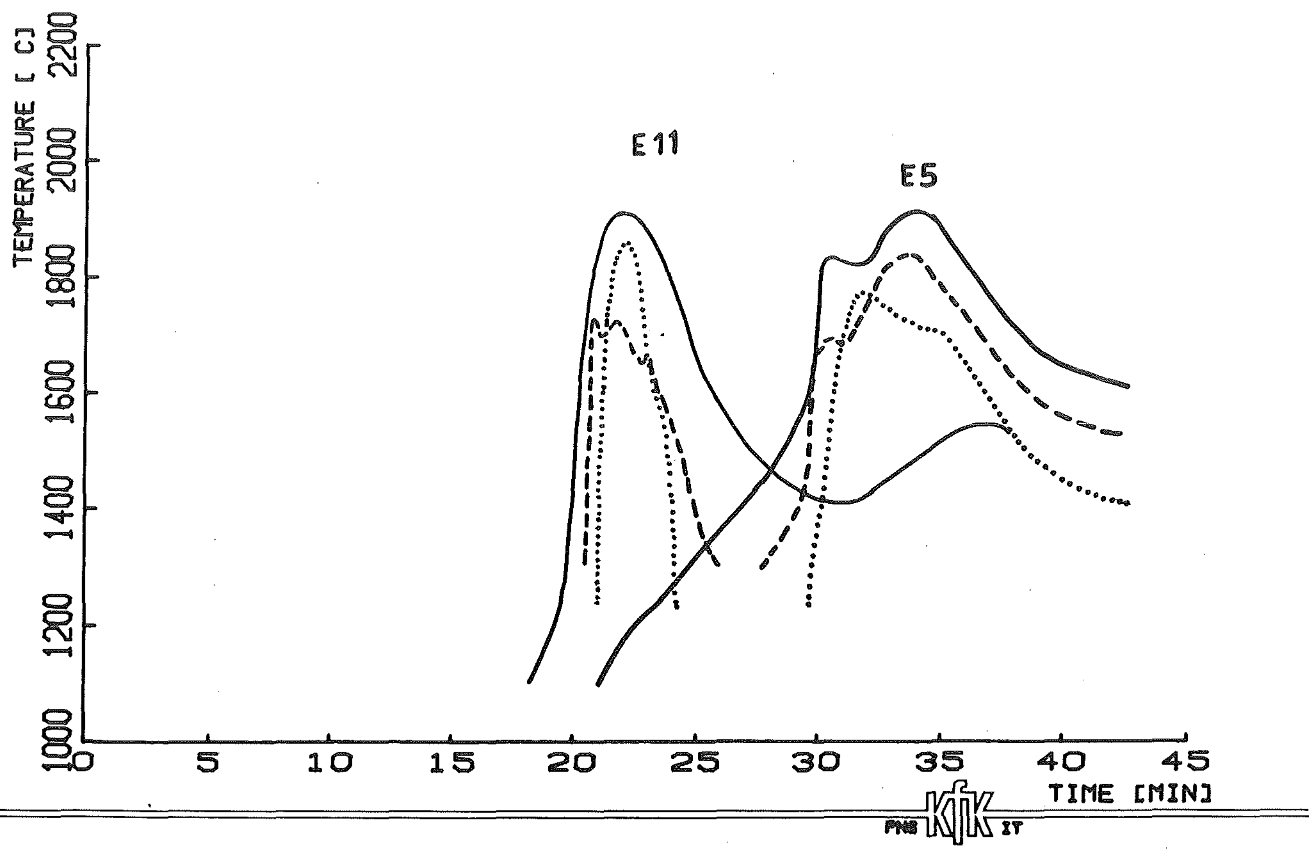


FIG.7: TEMPERATURE ON ROD (———) IN 140 MM AND ON SHROUD IN 140 MM (- - - -) AND 190 MM (·········) FROM UPPER END OF SHROUD FOR ESSI 5 AND 11

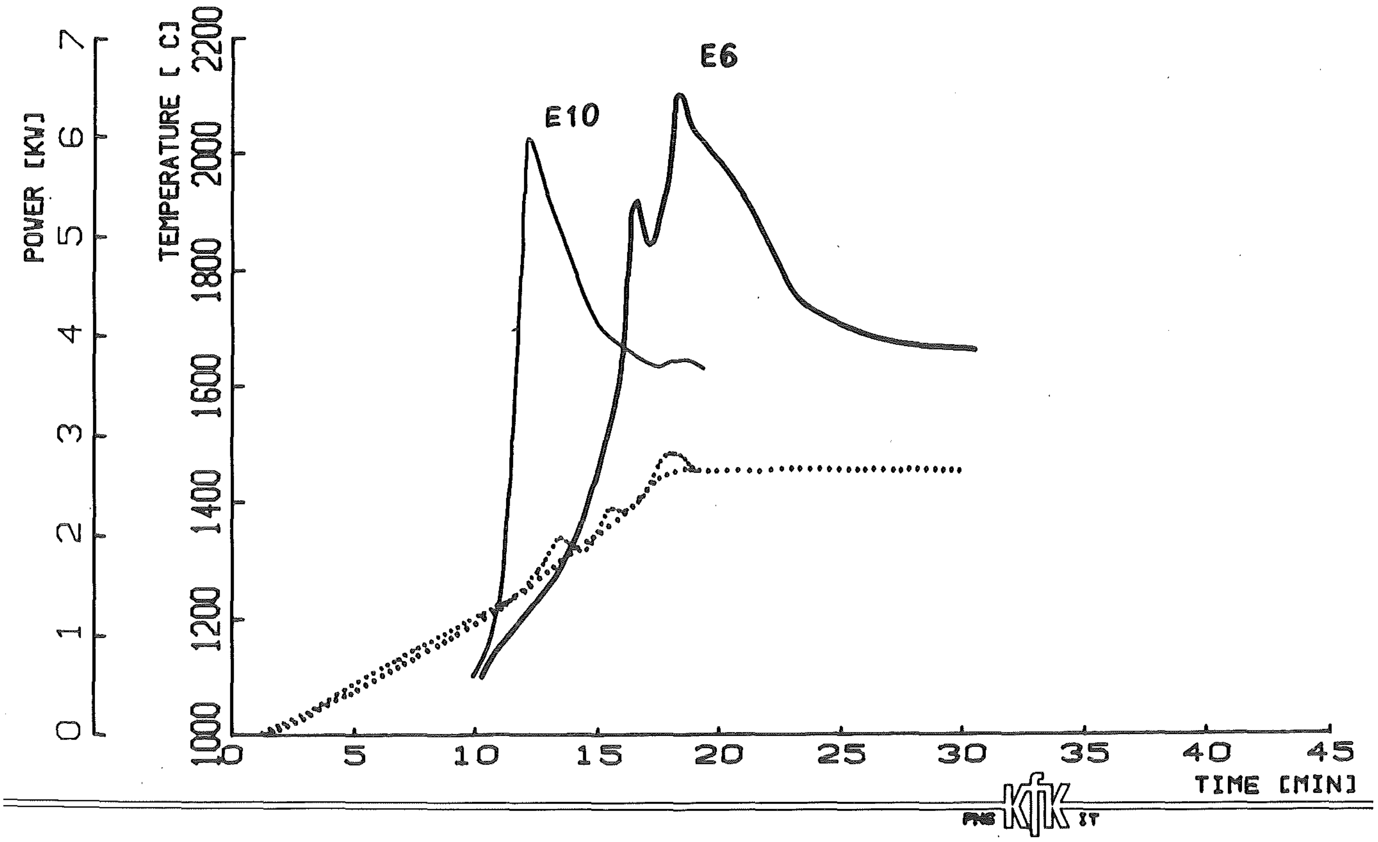


FIG.8: TEMPERATURE (———) ON ROD AND ELECTRIC POWER (·········) FOR ESSI 10 (0.25 INCH ISOLATION,NO GAP) AND ESSI 6 (4 INCH ISOLATION,GAP)

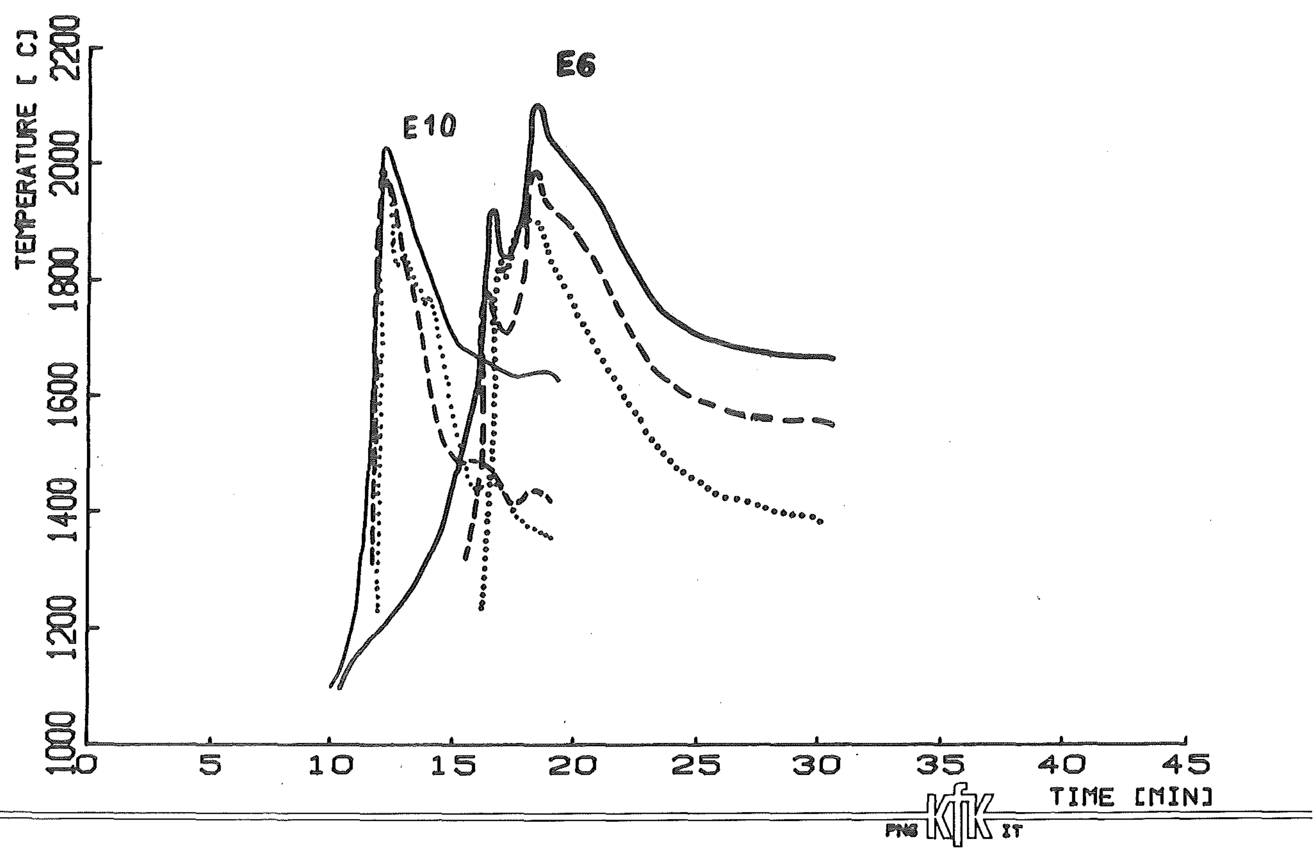
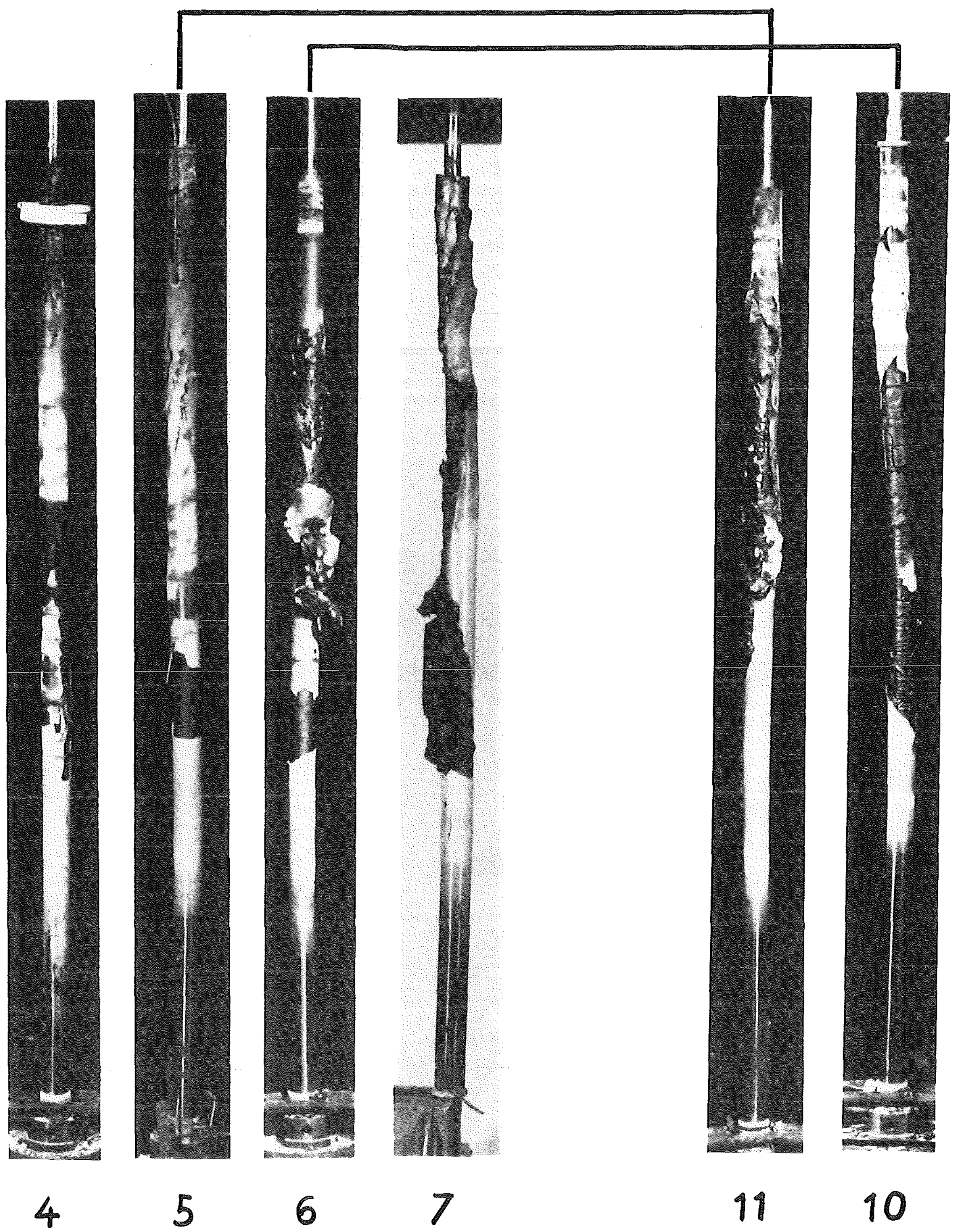
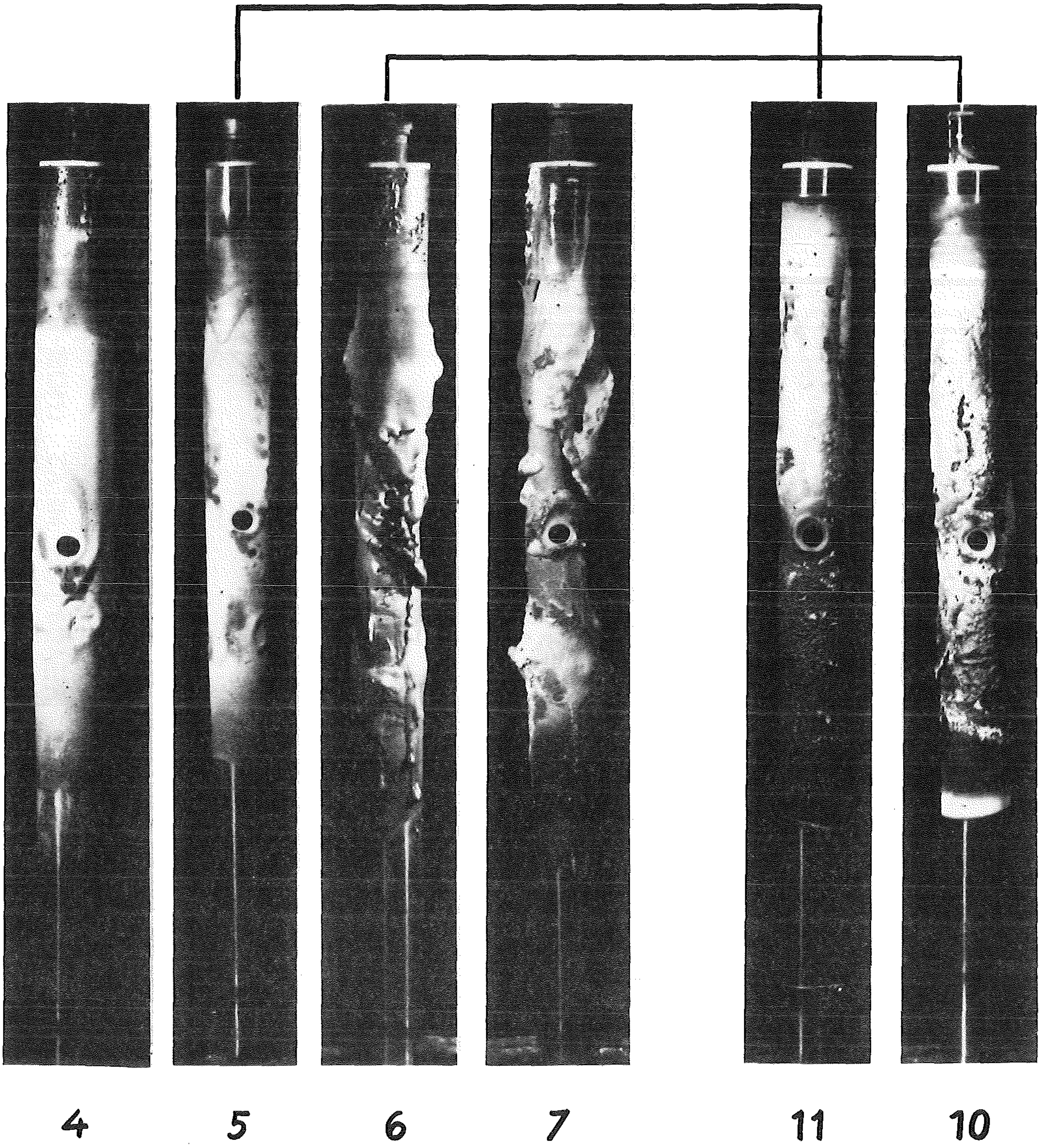


FIG.9: TEMPERATURE ON ROD (———) IN 140 MM AND ON SHROUD IN 140 MM (– – – –) AND 190 MM (·········) FROM UPPER END OF SHROUD FOR ESSI 6 AND 10



PNS KfK IT

FIG.10: FUEL ROD SIMULATORS FROM TESTS ESSI 4,5,6,7,11,10



PNS KfK IT

FIG.11: SHROUDS FROM TESTS ESSI 4,5,6,7,11,10
AFTER REMOVAL OF ISOLATION

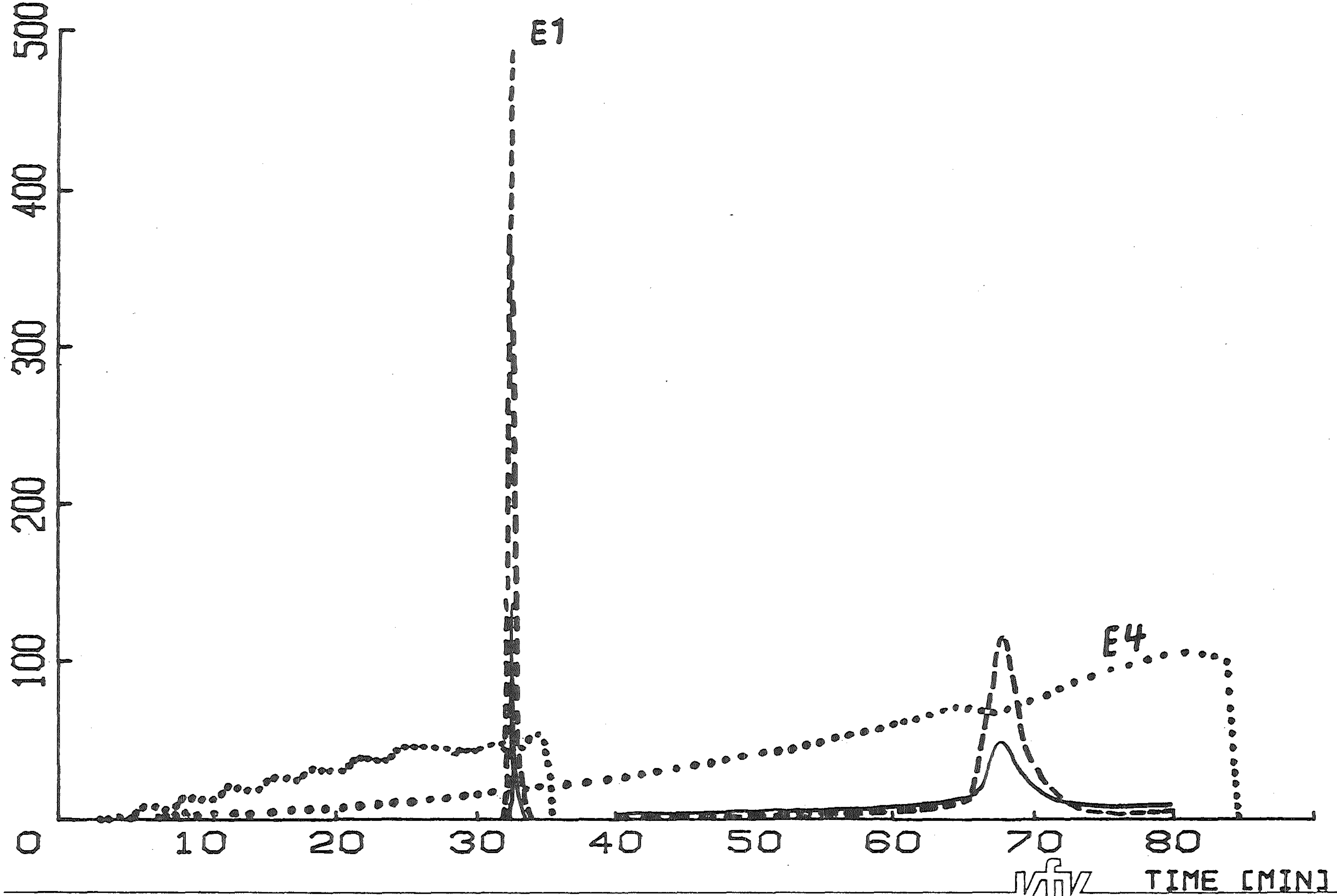


FIG. 12: COMPARISON OF EXOTHERMAL REACTION HEAT (MOB-PROGRAMM) FOR ROD (———) AND SHROUD (- - - -) WITH ELECTRIC POWER INPUT (••••••) FOR ESSI 1 AND ESSI 4

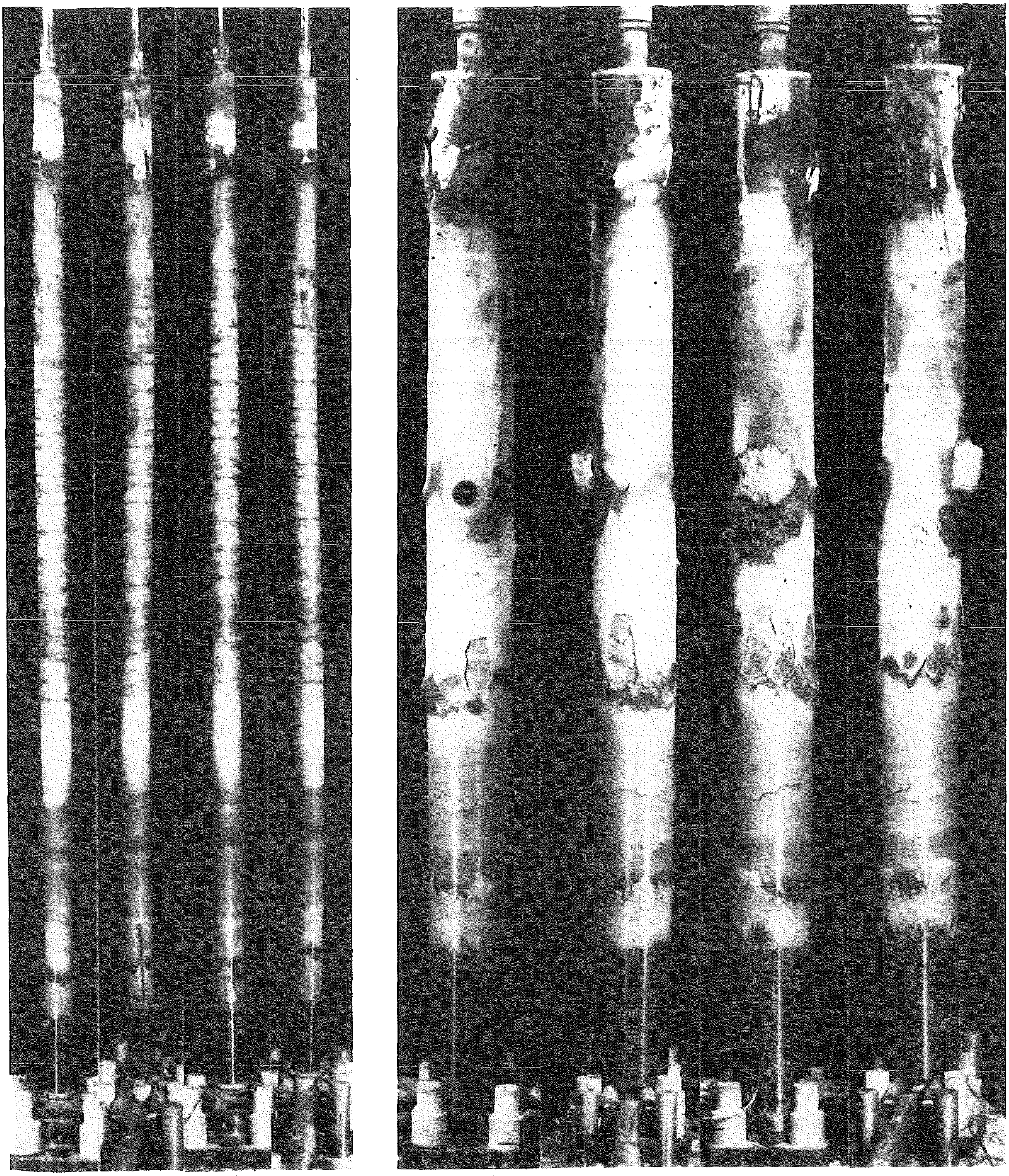


FIG. 13: ROD AND SHROUD FROM FOUR DIFFERENT DIRECTIONS FOR TEST ESSI-4/5