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Experimental Study of the RBMK Fuel Channel Pressure Tube Behaviour under Accident Conditions

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ABSTRACT. The Fuel Channel Pressure Tube in RBMK reactor is the important pressure boundary that contains the fuel inside and it is surrounded by the graphite components. A series of the six small-scale experiments has been carried out to study the behaviour and failure of a single pressure tube under LOCA conditions. These data are utilised for verification of the available and developed computational codes, as well as for refinement of mathematical and physical models used in these codes. The experimental results obtained at EREC in 1994-1998 are discussed in this paper.

1. INTRODUCTION

The challenges of the existing RBMK reactors operational safety and creation of channel-type reactors of a new generation are closely related to the problem of integrity of the fuel channels (FC) operating under emergency conditions. In order to make an adequate prediction of the RBMK FCs behaviour in the course of an accident condition it is essential to utilize comprehensive computational codes that would take account of the specific features of the governing processes going on in the FC components. It is a matter of general experience that the creep of the RBMK PT at such accidents as LOCA is the basic cause of the tube integrity failure. In an effort to verify the comprehensive codes which are being developed or currently applied for simulating the PT creep and its failure under diverse accident conditions in the RBMK-type reactor, and to check and refine the mathematical and physical models used in these codes, it will be a good job to perform the pertinent experimental studies. The present paper deals with the results of the accomplished experimental program pertaining to investigation of the single PT behaviour and failure and conducted in the EREC (Electrogorsk Research Engineering Centre, Electrogorsk town, Russia) on the K-6 test facility within a period of 1994-1998.

2. EXPERIMENTAL TESTS AND RESULTS

2.1. K-6 Test Facility. Brief Description

The K-6 small-size test facility has been designed to carry out investigations into behaviour of a fragment of the single RBMK FC in the conditions associated with diverse accident situations taking place in the RBMK-type reactor and followed by disturbance of the standard heat exchange process in the FC (LOCA-type accidents, transient conditions and etc.). The schematic diagram of the K-6 test facility is illustrated in Fig. 1. Used as experimental specimens in the tests conducted within a period of 1994-1998 were the straight sections of the RBMK PT made of alloy Zr+2.5%Nb. These fragments were cut out from the standard non-irradiated tube of the RBMK FC and featured a length of 1100 to 1400 mm with their interior diameter and wall thickness being equal to 80 mm and 4 mm, respectively. The tube is heated by passing alternating current directly through the tube. In the experiment performed in 1994 and designated as K-6-94 a steam-water mixture was selected for the use as an operating medium, whereas in the subsequent experiments carried out on the K-6 test facility the function of the operating medium was fulfilled hy nitrogen. The temperature of the tested tube is measured throughout the experimental process with the aid of the Chromel-alumel thermocouples installed on the external surface of the model under test. The radial displacement of the tube due to its creep was registered by means of three displacement gauges (D1-D3) that were installed in the most heated tube section that was inferred from the results of previously adjustment test procedures. The basic dimensions of the test tubes, as well as the arrangement of thermocouples (Ti) and displacement gauges are presented in Figs 2-6. The patterns showing temperature variations and the values of internal pressure in the tube observed in the course of the experiment are presented in Figs 7-12.

2.2. Tests and results

The K-6-94 Experiment. The objective of the experiment implied the simulation of an emergency situation in the RBMK-type reactor as a consequence of an abrupt cessation of the coolant circulation through the FC. The experiment scenario included a premise that the tube model should be heated from 573 to 873 K at a heating rate of up to 10 K/s with a constant pressure of 7.5 MPa maintained in the tuhe. It was anticipated that, after attaining these parameters, the tested tube would be exposed to the above temperature and pressure until it undergoes a breakdown. At the first stage of the experiment the tube under test was filled with water at a pressure of 7.0 MPa, then it was heated to a water saturation temperature at a pressure of 7.5 MPa. After exposure of the tube model to a temperature of 670 K and a pressure of 7.3 MPa within 30 minutes, the tube was subjected to quick heating. During experiment the tube heating to a temperature of up to 873 K and its holding time at this temperature was controlled with the aid of thermocouple T7 (Ref. Fig. 2). As might be seen from the curves in Fig. 7, the tested tube sustained a rapture at a lapse time of about 120 seconds since the beginning of the process of its quick heating. The most considerable radial deformations of the tube as a result of its creep turned out to occur in the section area that accommodated thermocouples T3-T8 (Ref. Fig. 2). The maximum radial deformation of the tube in this area was as high as 0.60. The data pertaining to the tube radial deformation at various tube sections are provided in the same Fig. The tube temperature parameters in the section incorporating thermocouples T6-T8 and the pressure values obtained prior to the tube failure were equal to 930 K and 7.7 MPa, respectively (Ref. Fig. 7). The pattern of destruction of the investigated tube fragment is depicted in Fig. 13.

The K-6-95 Experiment. The objective of the test consisted in investigation of the RBMK PT behaviour in a situation of an accident caused by an abrupt cessation of the coolant circulation through the FC. The experiment scenario included a premise that the test tube model should be quickly and continuously heated from the original temperature of 620 K at a heating rate of 10 K/s to the instant of its rapture. It was anticipated that, in the course of the experiment, the pressure in the tube would be maintained at a constant level of 7.5 MPa.

The first stage of the experiment involved the tube model testing by building up an internal pressure of about 7.0 MPa and heating this tube slowly to a temperature of up to 620 K. The next stage of the experiment included fast heating of the tube with a heating rate of 8 K/s. During the progress of heating the pressure inside the tube was kept constant at a level of

7.3 MPa through relief of the operating medium (nitrogen) pressure. The data obtained during the experimental work and relevant to the temperature variations throughout the height of the tube under test and to the tube pressure are presented in Fig. 8. The tube rapture took place after a lapse of the 36-th second from the moment of the initiation of the tube fast heating. The temperature in the area of rapture (T17) and the pressure magnitude in the tube at the instant of its rapture were as high as 1035 K and 6.6 MPa, respectively (Ref. Fig. 8). The post-experiment examinations of the tube revealed that the maximum radial tube deformation turned out to be equal to 0.4 in the tube section located 180 mm lower than the tube central area. The external condition of the post-experiment tube fragment is depicted in Fig. 14.

The K-6-96 Experiment. There were two objectives to be pursued by the experiment: (i) to obtain experimental results suitable for verification of comprehensive computational codes; (ii) to investigate into the behaviour of the RBMK PT under emergency conditions consistent with an accident of partial rapture of the circulatory circuit components without operation of the emergency protection system. The above accident conditions are attended with the creation of an excessive pressure of about 4.0 MPa and the PT heating at a heating rate of up to 6 K/s. Taking into consideration the experience gained from the previous experiments, a decision was made to locally apply thermal insulation to the external surface of the tube in the areas intended for installation of the radial displacement gauges. The pressure built up in the test tube model at the initial stage of the experiment constituted 2.5 MPa with the tube wall temperature being equal to 573 K. Measurement point T10 was used for monitoring the temperature. The second stage of the experiment consisted in uninterrupted heating of the tube at a heating rate of about 7 K/s until the instant of its rapture. In the course of heating the pressure in the tube kept on growing up. After a lapse of time of approximately 129 seconds since the beginning of the rapid heating process the tube sustained a rapture. The tube temperature in the heating area and the pressure built up prior to its rapture were found to be about 1080 K and 3.4 MPa, respectively. The inspection and examination of the test fragment on completion of the experiment have shown that the magnitude of the relative radial deformation of the tube and the length of the rapture area accounted for 0.67 and 150 mm, respectively. The external condition in which the FC test tube was found after the experiment is depicted in Fig. 15.

The K-6-97 and K-6-98(1) Experiments. The tests performed were mainly focussed on the experimental data to be achieved for verification of the thermomechanical codes in accident situation when the thermal and mechanical load undergoes changes both in magnitude and in sign. The specific feature of the above experiments consisted in the utilization of the tube model that had already exhibited a residual creep deformation after K-6-97 Experiment and had been tested during the K-6-98(1) Experiment. The tube fragment selected for testing was essentially a tube that had been used in K-6-97 experiment and subsequently repaired. The repair procedure involved welding of a new lower reducer to the tube as the breakdown of the model under test, performed in the course of the K-6-97 experiment, occurred in the area of the lower weld joining the main tube with the «steel-zirconium» reducer. The pressure built up in the test tube model at the initial stage of the K-6-97 experiment rated at 2.5 MPa with the tube wall temperature being equal to 573 K. The temperature measurements were taken at point T5. In the course of the second stage of the experiment the pressure in the test tube fragment and its temperature were changing in conformity with the curves shown in Fig. 10. The termination of the K-6-97 experiment took place after a time lapse of 9400 seconds as a result of the lower reducer rapture. The weld rapture occurred due to its local overheating. By that time the tube diameter in its central section appeared to be 117.4 mm (Ref. Fig. 16) which corresponded approximately to a relative deformation magnitude of 0.32.

K-6-98(1) Experiment. As has been mentioned above, the subject of investigation was represented by the tube fragment that had been already tested during the K-6-97 experiment and subsequently repaired. At the first stage of the K-6-98(1) experiment the test tube was subjected to heating to a temperature of 600 K and the specimen test extended over two hours. The next phase of the experiment involved the uninterrupted heating of the tube until its rapture. The breakdown of the tube under test occurred at the 150-th second as counted from the onset of the rapid heating process. By the time of the tube rapture the pressure in the tube was as high as 1.58 MPa (Ref. Fig. 11). The maximum radial tube deformation rated at about 0.642 with the tube rupture area located in the tube central part. (See Figs 5, 17).

The K-6-98(2) Experiment. The principal goal of the experiment was to derive experimental data associated with the conduct of a single RBMK PT under the conditions in which the Zr+2.5% Nb alloy exhibited its superplastic properties. One of the problems to he solved by the experiment consisted in deriving specific data on the heat exchange processes going on in the «PT – graphite components» system of the RBMK. Such data are important to carry on further investigations into the behaviour of the RBMK FC fragments that accommodate PT and graphite components (graphite split rings and blocks). The scenario of the experiment concerned was based on the assumption that the test tube should be held under a temperature of 1000 K and a pressure of 0.9 MPa as long as it withstands destruction. It was anticipated that such parameters of the test process would bring about rather sizable creep deformations. During the first stage of the experiment the tube was slowly heated to a temperature of 573 K and was exposed to the effects of this temperature for two hours. The second stage of the experiment included the tube model heating procedure to 1000 K at a heating rate of 3 K/s and subsequent holding of the tube under attained conditions until the time of its destruction. The pressure maintained at this stage of the experiment rated at a level of 0.9 MPa (Ref. Fig. 12). As evident from the curves in the Fig. 12 the damage to the tube integrity was caused in its central part after a lapse of 6100 seconds since the beginning of the test process. The tube rapture appeared as a hole of 0.5 mm in diameter located on the central part of the test tube. The tube maximum deformation reached the magnitude of 1.171 in its central part. Two deformed zones were formed on the lower part of the tube model (Ref. Fig. 18) in the area where graphite components had been installed on the tube. The values of radial deformation in these zones were as large as 0.875 and 0.955 (Ref. Fig. 6). As it was expected, the tube deformation in this experiment happened to be in the area where the material, from which the tube had been manufactured, exhibited its superplastic properties.

3. CONCLUSION

A number of experiments carried out on the K-6 test facility furnished an opportunity to obtain experimental data related to the behaviour and failure of a single PT in the conditions of varying in time temperature and load factors. These data are utilized for verification of the available and developed computational codes, as well as for refinement of mathematical and physical models used in these codes. The information obtained through experimentation will make it possible to supplement and perfect the well-known criteria of the RBMK FC failure, and also to appreciate in a more understandable way the regularities of the RBMK PT deformation and rapture in the accident conditions taking place in the RBMK-type reactor. The data provided by the experiments are supplementary to the results of studies performed earlier in the RDIPE (Russia) with the view of investigating creep and rapture of the FC tubes manufactured from the Zr+2.5% Nb alloy. The next stage of experimental studies is supposed to be accomplished on the RBMK FC fragments incorporating FC tubes in a set with graphite components (split rings and blocks).

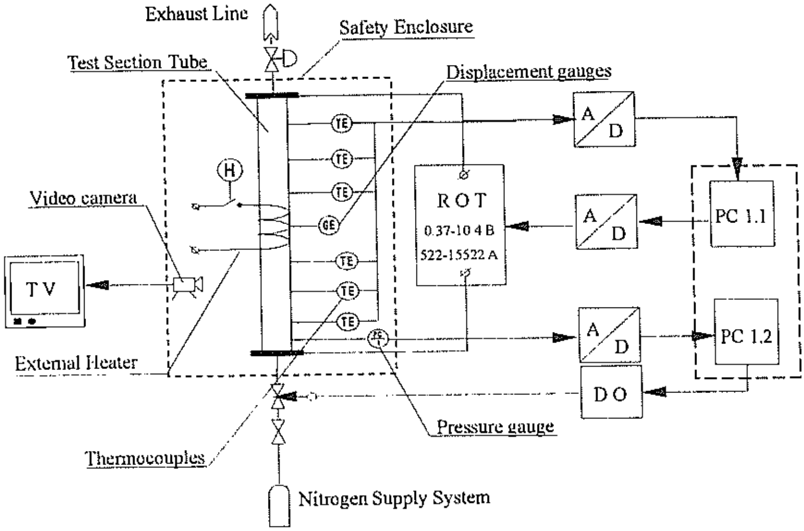

Fig. 1. Schematic of the K-6 Test Facility

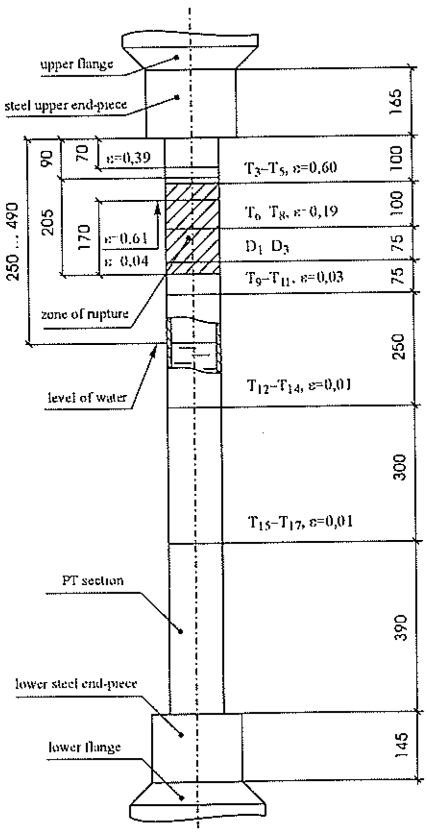

Fig. 2. K-6-94 Experiment. Test tube

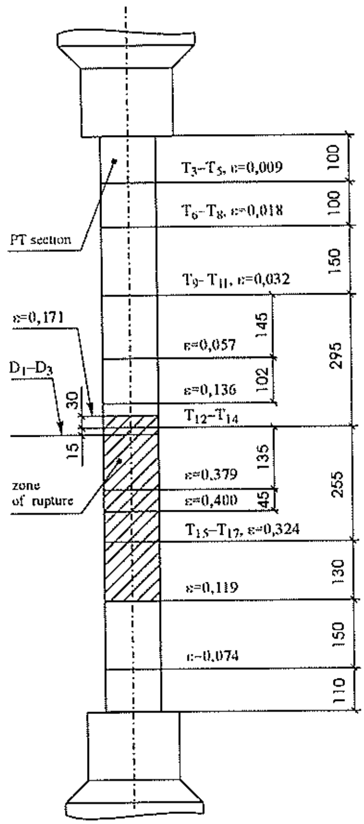

Fig. 3. K-6-95 Experiment. Test tube

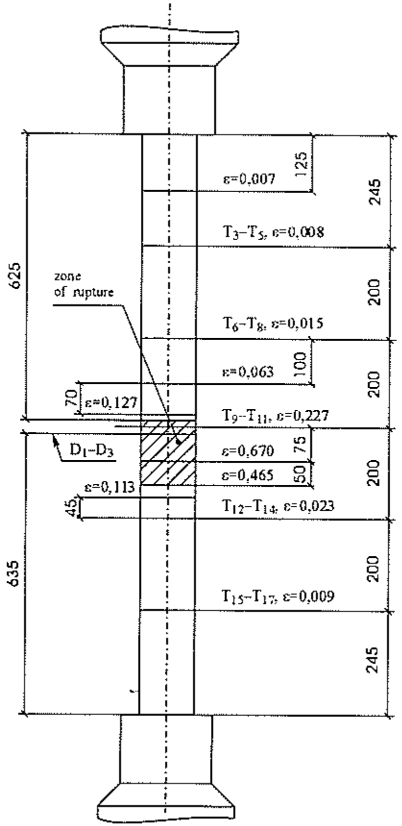

Fig. 4. K-6-96 Experiment

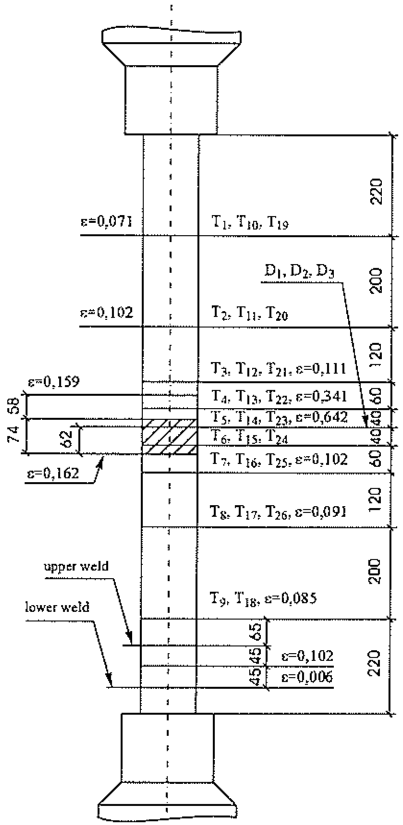

Fig. 5. K-6-97 and K-6-98(1) Experiments

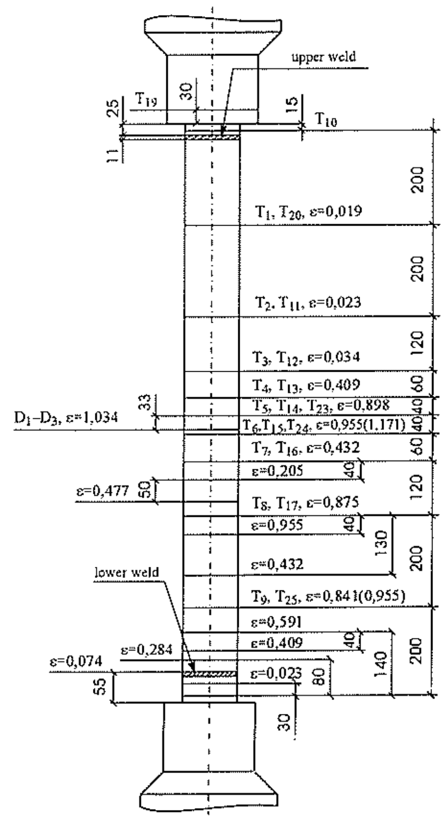

Fig. 6. K-6-98(2) Experiment

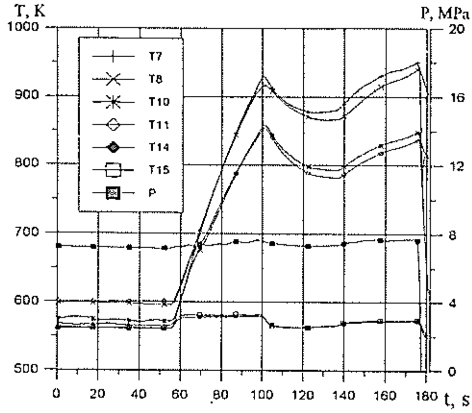

Fig. 7. K-6-94 Experiment

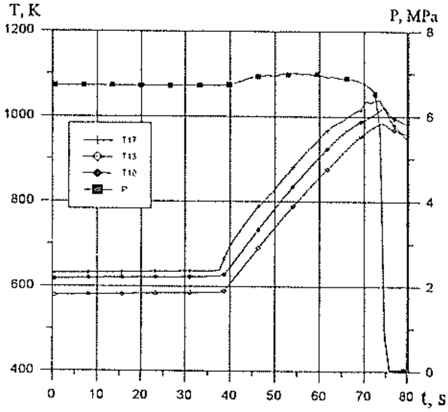

Fig. 8. K-6-95 Experiment

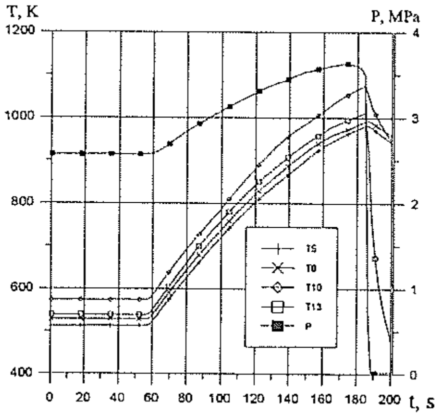

Fig. 9. K-6-96 Experiment

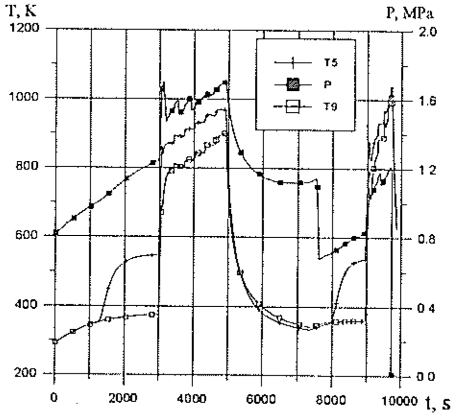

Fig. 10. K-6-97 Experiment

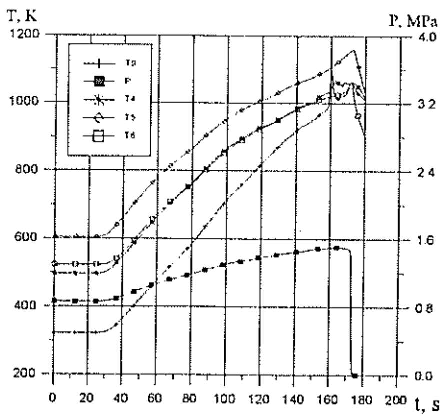

Fig. 11. K-6-98 (1) Experiment

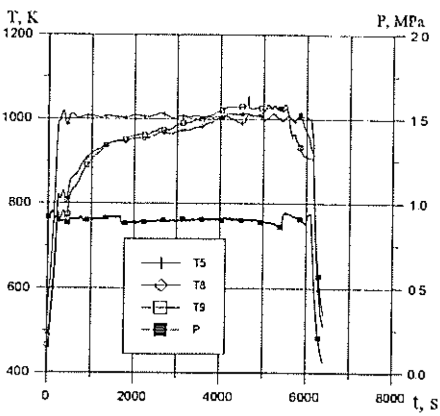

Fig. 12. K-6-98 (2) Experiment

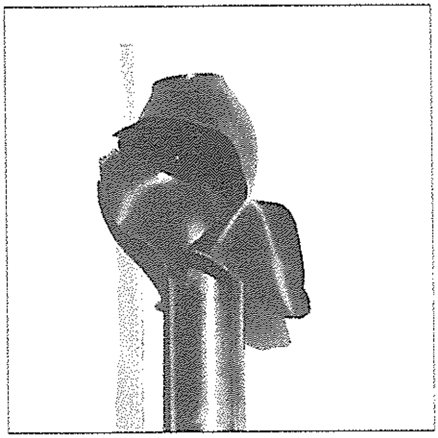

Fig. 13 K-6-94 Experiment

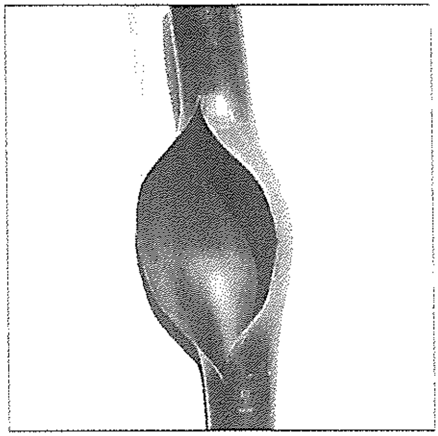

Fig. 14 K-6-95 Experiment

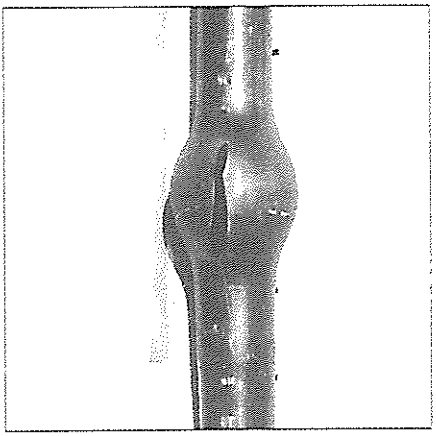

Fig. 15 K-6-96 Experiment

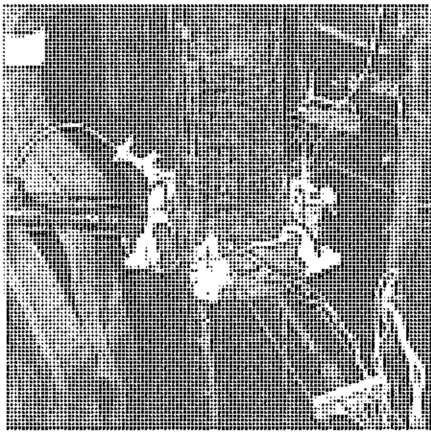

Fig. 16 K-6-97 Experiment

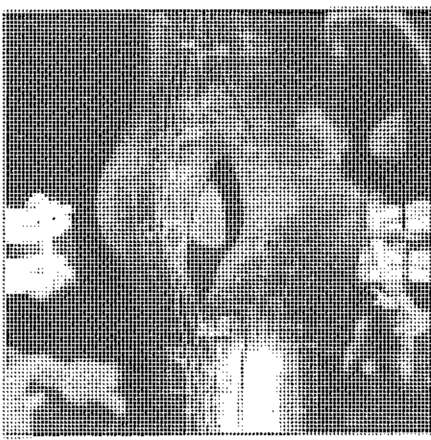

Fig. 17 K-6-98 (1) Experiment

Fig. 18 K-6-98 (2) Experiment