INVESTIGATIONS INTO THE CRITICAL HEAT FLUX (BURN-OUT) IN BOILING

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1. Test Programme

The object of the work carried out under a contract between USAEC/EURATOM and M.A.N. is the study of the influence of the flow conditions prevailing at the inlet of a channel on the critical heat flux in boiling. The measurements are being carried out on internally cooled, round tubes with diameters ranging from 5 - 15 mm. Points of special interest are the influence on the transition between nucleate and film boiling of the length/diameter ratio of the test channel and the influence of the history of the flow. Flow history in this context is defined as the influence of the type of flow prevailing at the inlet of the test channel, in other words, the influence of, say, a long or short heated section preceding the heated length of the test channel or an orifice or nozzle located in the close vicinity of the inlet to the heated test channel.

The programme provides for the length/diameter ratio to be varied between 20 and 100. Efforts are also made to extend this range for lower values by suitable design measures because interesting results are anticipated for smaller l/d ratios. In order to ensure continuity with research efforts elsewhere the tests were started in the range between 100 and 140 atms., the emphasis being on the upper pressure range up to about 210 atms.

In short, the test programme covers the following parameters:

pressure	100 - 210 atms.
temperature at channel inlet	270 - 370 deg. C.
steam quality at channel inlet (mass ratio)	0 - 10%
sub-cooling below saturation temperature at channel inlet	to 40 deg. C.
mass velocity	500 - 2000 kgs./hr. sq.cm.
l/d ratio	100 - 20 (and smaller)
hydraulic diameter	5 - 15 mm.

2. Description of Test Rig

The test loop with which these measurements were made is schematically shown in Figure 1. Demineralized and deaerated water is delivered by the circulating pump 6 through 3 flow metering sections arranged for alternate operation into the preheater 7 in which the water is heated to saturation temperature and, depending on the test conditions, partly evaporated by an electric resistance heating system. From the preheater 7 the medium flows into the test section 1 which embodies the 5 - 15 mm. inside diameter tube intended for the burn-out investigations. This tube is electrically heated by direct current with the tube wall itself serving as ohmic resistance. The steam water mixture produced is separated in the steam separator 2 and the dry saturated steam is condensed in the condenser 4 whereas the water removed is cooled in the cooler 3 to slightly below saturation temperature. The condensate flow is determined in 2 parallel flow metering sections and 3 parallel flow metering sections are provided for the water flow. Downstream of these metering sections the two flows are led together and flow back to the pump 6 to complete the circuit via the cooler 5.

A pressurizer 8 is provided in order to be able to adjust the pressure in the loop in tests with steam-free water. Furthermore, there is a mixed-bed filter connected in a by-pass to provide continuous purification of the circulating water from impurities that are liable to cause corrosion.

The installed electrical heating capacity is 350 kW. in the test section and 250 kW. in the preheater. Figure 2 shows the test loop in the course of erection before the insulation was applied. The circulating pump can be clearly seen, the pressurizer is in the background and the condenser at the left in the foreground. Figure 3 shows another view of the plant before insulation in which the steam separator and the test section can be seen. A part view of the completed insulated test rig is given in Figure 4.

The test channel in which the measurements are made is surrounded by a pressure-tight autoclave as shown in Figure 5. This autoclave consists essentially of a thick-walled tube, about 70 mm. diameter, in which the test channel is centrally mounted. Welded to this main tube there are two further tubes at right angles which serve to admit the power leads, thermocouples as well as various instrument leads. The test channel is carried by the two power leads via supports, some of which are conical and others cylindrical. The positive power lead is introduced, electrically insulated, into the pressure tube. The space between the channel and the pressure tube is subdivided by concentrically arranged radiation shields with the spacing so proportioned that the critical Raleigh number of 1700 is not exceeded, in other words, that no free convection can occur. As a result, a well-insulating steam cushion will develop in this space under steady-state conditions. Between the power leads there are also the tappings for measuring the static pressure drop in the heated length of the test channel.

3. Measuring Equipment

Measurements of the surface temperature at the cooled side of the heated channel are obtained by three different types of thermocouples: Coated Chromel-Alumel thermocouples, mica-insulated thermocouples and so-called three-wire thermocouples.

It appears appropriate at this juncture to give some explanations of this three-wire thermocouple. As can be seen from Figure 6 the two outer wires consist of thermo-electrically homologous material whereas the inner wire is thermo-electrically dissimilar. The material used in the thermocouple shown in Figure 6 is nickel and nickel chrome. The three wires are welded directly to the current carrying surface and spaced 0.5 mm. apart. The thermocouple is so connected with a potentiometer and a galvanometer that a Wheatstone bridge is formed which can be compensated for the heating potential drops between the welds of the 3 wires. Basically, this layout was adopted by Buchberg and his co-workers (1) for boiling heat transfer studies.

When the bridge is balanced there is only the thermo e.m.f. across the detector circuit of the bridge. Unbalance of the bridge is liable to arise in operation due to variations in the resistances of both the thermocouple wires and in the tube metal between the welds of the wires. Unbalance due to resistance variations in the wires can be eliminated by suitable proportioning the potentiometer resistance $R_1 + R_2$ which has to be chosen so that the parasitic e.m.f. will be below the class accuracy of the measuring instrument used. The calculation of this resistance is described in detail in (2).

Unbalance of the bridge due to resistance variations in the tube metal between the welds of the wires is liable to arise in nucleate boiling when, for instance, a bubble forms between wire 1 and wire 2 causing a temporary decrease in the local metal temperature while there is a non-boiling liquid boundary layer between the wire 2 and wire 3. The resulting unbalance does not produce an error except in very thin-walled test channels. In order to determine and eliminate this parasitic e.m.f., d.c. pulses of extremely short duration are superimposed on the steady-state heating current. If the direction and magnitude of these pulses is chosen so that, on attaining their peak value, the heating d.c. is just balanced, the envelope curve of the current pulses which are recorded by means of an oscillograph represents the actual thermo e.m.f. The procedure is for the integrated value of this impulse current to be kept so small that the power measurements are not influenced by it.

A simple method of superimposing this pulse is by intermittently short-circuiting the heating channel by means of a silicon thyratron. The purpose of this short-circuiting is to exactly balance the heating d.c. on the peak value being reached. Preparations are being made for a detailed study of this method, the idea being primarily to find out up to what time constant such an arrangement will work and whether these very short current pulses will influence the boiling behaviour of the water.

In order to justify the relatively great complexity of the three-wire thermocouple it is important to obtain a definite assurance that the gain in speed of response is worthwhile over alternative thermocouple arrangements. Tests have been made for this purpose, and the differences in the speed of response between the three-wire thermocouple and a mica-insulated thermocouple have been investigated. The set-up chosen for these tests is shown schematically in Figure 7. It consists essentially of a 0.5 mm. thick chrome-nickel steel band, 6 mm. wide and 120 mm. long. On this steel band were attached a normal mica-insulated thermocouple with 0.1 mm. wire thickness and a three-wire thermocouple also with a wire thickness of 0.1 mm. The thickness of the mica was 0.1 mm. The steel band was connected in the circuit directly as an ohmic resistance and short current pulses of 3000 to 4000 amps. were produced for a mean duration of 0.5 millisec.

As shown in Figure 7 the necessary power pulse in this set-up was produced in the steel band H by having a capacitor battery C discharged by closing a switch S. By suitably selecting the ohmic resistance as well as the capacitance and inductance of the discharge circuit, it was ensured that the heating output was largely approximated to the aperiodic border case. This ensures that energy stored by the capacitor is converted into heat energy in an optimally short period and the gradient of the temperature rise approximates closely the ideal curve shown in Figure 7.

As can be seen from Figure 8 the three-wire thermocouples have a speed of response about 40 times that of the equally thick mica-insulated thermocouples. Furthermore, these illustrations show a method of visualizing this by means of a Lissajous figure. The Lissajous figure is generated by the two thermo e.m.fs. to be compared. The input of the x-amplifier of the oscillograph was fed with the thermo e.m.f. of the mica-insulated thermocouple and the y-amplifier of the oscillograph with that of the three-wire thermocouple. Had both thermocouples had the same speed of response at any time during the heating-up process, the screen of the oscillograph would have shown a straight line starting from zero and inclined at 45 degrees provided that both hot junctions tend to attain the same final value. With different response characteristics the ratio of the two speeds at any time can be quickly appreciated by placing a tangent to the curve in these illustrations.

Safety equipment takes the form of a burn-out detector which relies on the change in specific electrical resistance of the tube for determining an excessive temperature rise liable to cause a burn-out. Basically the connection of the burn-out detector is arranged so that the potential drop along a shunt is compared with the potential drop in the burn-out section that is proportional to the wall temperature of the tube at this point. The comparison is effected by two coils wound on a common core with the current flowing in opposite directions. The resulting magnetic flux of both coils is proportional to the difference of the above mentioned potential drops. If this difference reaches a pre-determined value a relay is energized and a contact is closed in a control circuit. This closing operation is used to actuate the tripping circuit of a rapid-action circuit breaker. In this circuit arrangement the amperage of the burn-out section produces an error which is compensated by means of a resistance based on prior calculations and calibration measurements.

The density of the steam/water flow immediately upstream of the burn-out zone is measured by means of the change in the pulse rate of a gamma radiation. In order to ensure an adequate sensitivity with this method it is necessary to weaken the wall thickness of the autoclave as far as necessary structural strength permits. This was done by drilling a radial hole into the copper gasket in the upper part of the test section which at the same time serves as power supply lead, sealing element and support for the test channel. The test channel being seal-welded into this copper gasket, the channel wall is directly exposed to atmosphere at the location of this hole and a collimated gamma ray transmitted through this hole has to pass through a steel wall of only 0.2 to 0.7 mm. thickness.

4. Present Status of the Work

The test loop described here was first put into commission in November 1962 after the first test channel had been installed. During the first 3 or 4 months various difficulties were encountered which were due in particular to the high pressure in the test loop and instabilities arising under certain conditions. An unstable flow with low-frequency fluctuations caused errors in our initial measurements. It was possible by suitable operational changes to improve flow conditions in the loop. Shortly after this improvement the test channel was destroyed by a burn-out when in spite of the burn-out detector tripping the rapid-action circuit breaker failed to open.

A second test channel was fitted with instruments at once and installed in the test section. Subsequent insulation work and wiring of the measuring circuits was completed at the beginning of February 1964 when the test loop was put back into operation.

After a short period of operation a leak developed in the gasket in the cover of the steam separator downstream of the test section. It was not possible to remedy the leak with simple measures and therefore the cover of the steam separator had to be dismantled and the gasket re-worked.

As this repair work required quite some time this opportunity was used to improve the performance of the coolers and condensers at the same time. It had been found during operation that these two heat exchangers could not be run below a certain minimum load which was still too high for certain tests proposed to be carried out. Improvements were therefore studied that are likely to give a better part load performance. The proposal is for a Diphyl (a mixture of diphenyl and diphenyl oxide) circuit to be provided as an intermediate circuit between the H.P. primary circuit and the cooling water system. This will make it possible to vary the velocities at the secondary side of the condensers and coolers as well as the temperature level in the intermediate circuit and so to obtain effective control of secondary side heat transfer.

The theoretical work undertaken included the preparation of a system of equations for the prediction of the void fraction. This system is described in detail in (3) and is based on a derivation given by Levy (4) for the forces prevailing in a water/vapour system flowing through a channel. Similar, but separate, equations were established for the forces acting separately in the liquid and gaseous phases. By adding these two equations an expression was obtained for the pressure drop in the two-phase flow as a function of steam quality, void fraction, shear stresses in the gaseous and liquid phases and the densities of the water and the steam at any time. In a similar manner, the two equations were subtracted whereby a second equation was obtained that is dependent on the above mentioned variables. In these equations the steam quality, the void fraction and the shear stresses are functions both of the channel radius and the channel length, so that it appears at first sight that for the integration of these equations a description of the radial distribution of these variables was necessary. If, however, in contrast to the previous approach the volume that exists in a differential length of the channel is taken as a basis, instead of a differential volume in the channel, in other words, if the mean is derived across the channel radius, two similar equations are obtained which now include values of the steam quality and the void fraction.

Further correlations were established for the energy balance within the test channel as well as for the entropy change along the channel.

This system of differential equations is at present being tested in the M.A.N. computer centre with a view to finding a time-saving numerical solution of the differential equations. It is proposed to compare the results with experimental data given in previous literature.

5. Further Research Work in the Field of Two-Phase Flow

In addition to these burn-out tests further work is in hand in the research laboratory of M.A.N.'s reactor department in the field of two-phase flow. However, this work is outside the EURATOM contract and mentioned here only for completeness' sake. These tests are primarily concerned with the study of the burn-out safety of horizontal fuel element bundles and provide for uniform and non-uniform heating of individual rods in this bundle, i.e. the influence of a hot channel on the burn-out behaviour of the bundle is also studied. These tests are being carried out in the region of sub-cooled boiling at pressures of 100 - 140 atms. Apart from that, it is proposed to study the transient behaviour of horizontal fuel element bundles, the main aspects being the conditions arising in the event of pump failure and fluctuating loads. The test loop employed for these tests is shown in Figure 9.

Bibliography

(1) H. Buchberg and co-workers

"Studies in Boiling Heat Transfer," Final Report Coo-24, March 1951, USAEC Department of Engineering, Los Angeles, California

(2) D. Henkel

"Measurement of Surface Temperature of D.C. Heated Channels by Thermocouples," M.A.N. Report No. 09.32.01 (M.A.N./EURATOM Research Contract No. 057-61-RDD)

(3) J. O. Bradfute

"Theoretical Pressure and Phase Distributions in Two-Phase Flow," M.A.N. Report No. 09.07.01 (M.A.N./EURATOM Research Contract No. 057-61-RDD)

(4) S. Levy

"Steam Slip - Theoretical Prediction from Momentum Model," Trans. ASME, Journal of Heat Transfer, May 1960, PP. 113 - 122

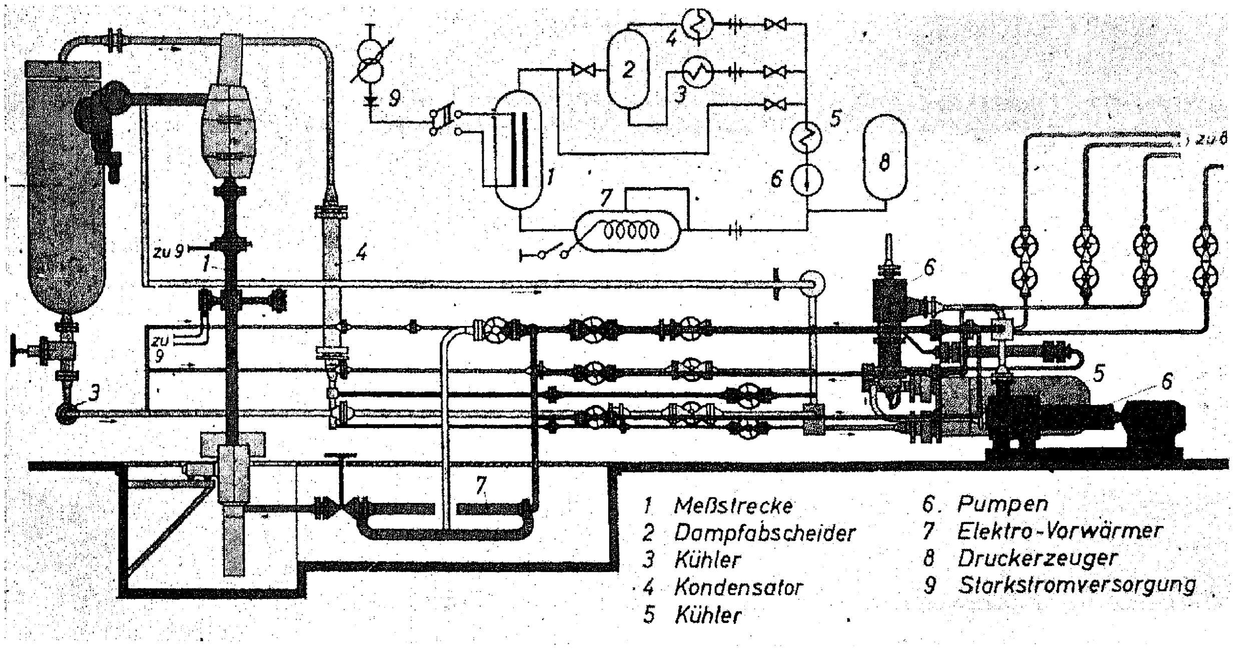

Figure 1 Schematic layout of test loop

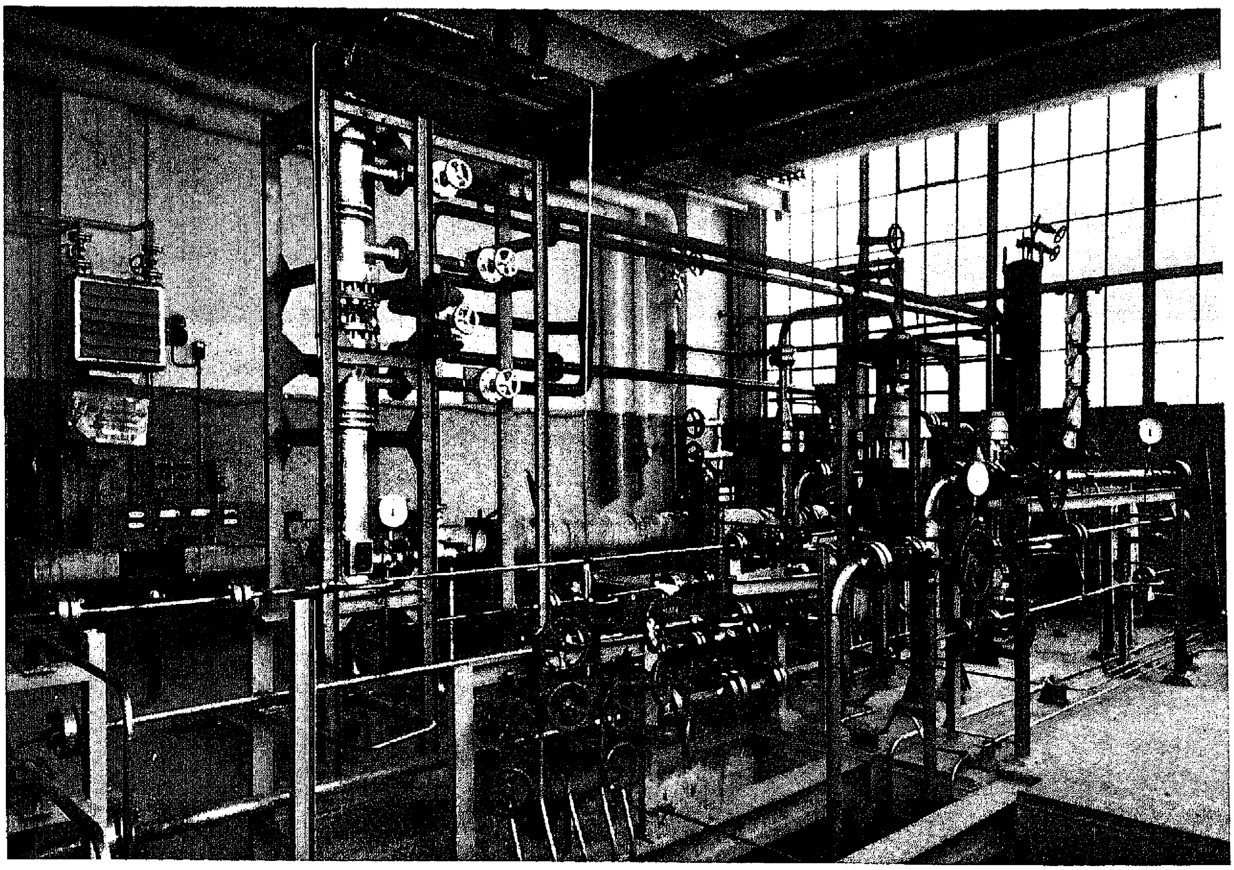

Figure 2 Boiling water test rig (before insulation)

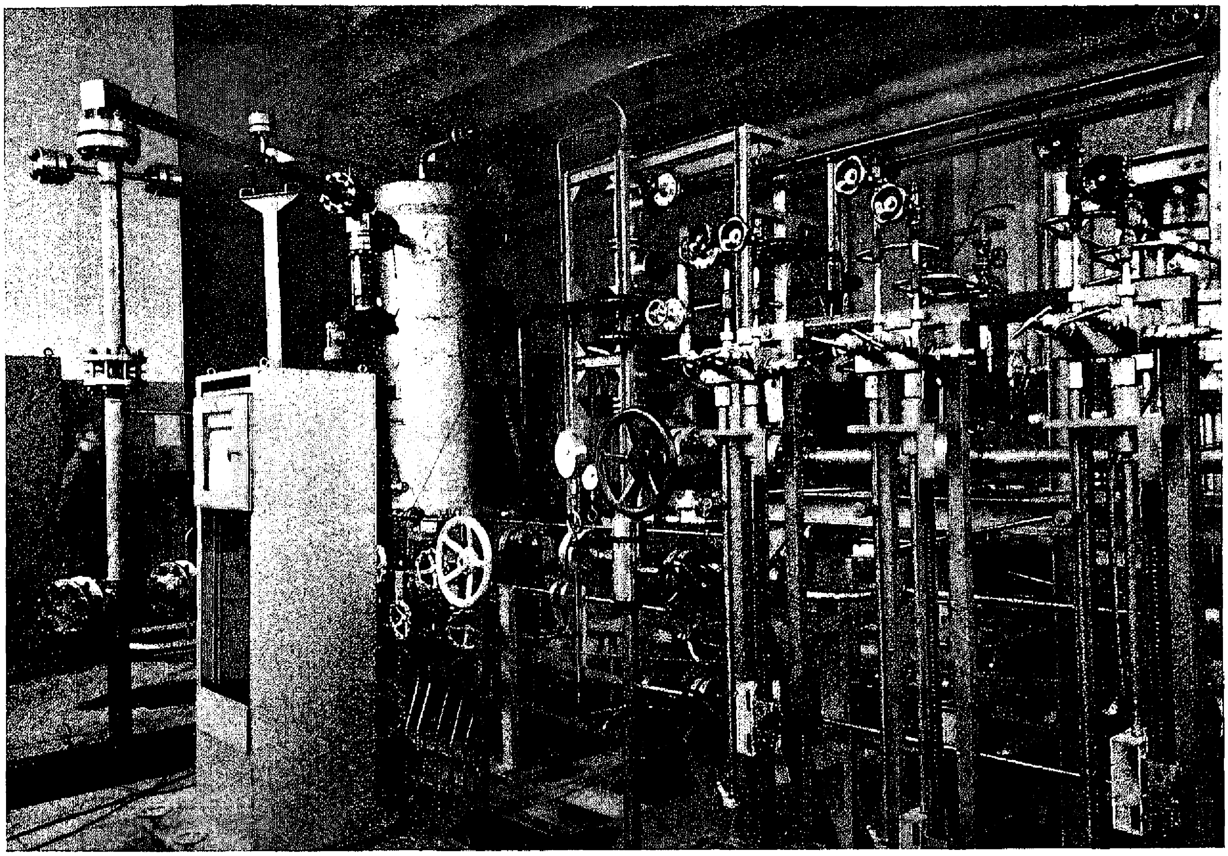

Figure 3 Boiling water test rig (before insulation)

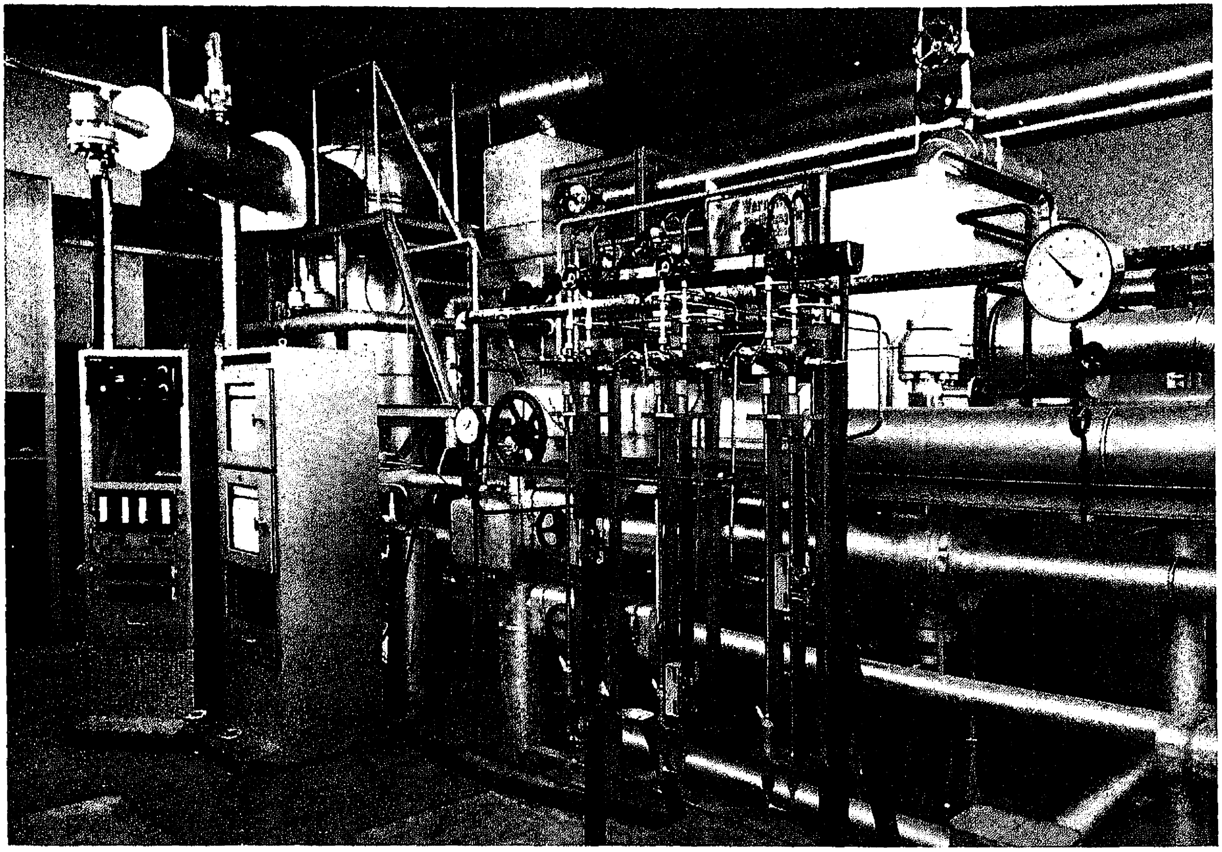

Figure 4 Boiling water test rig part view

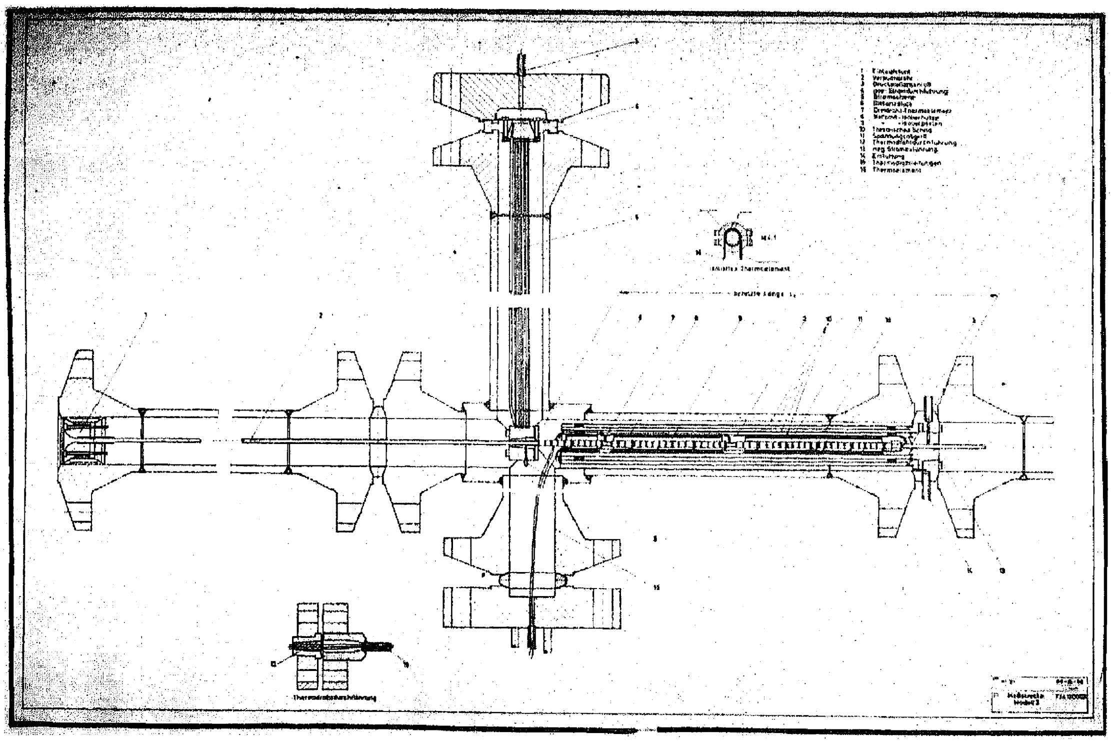

Figure 5 Test section

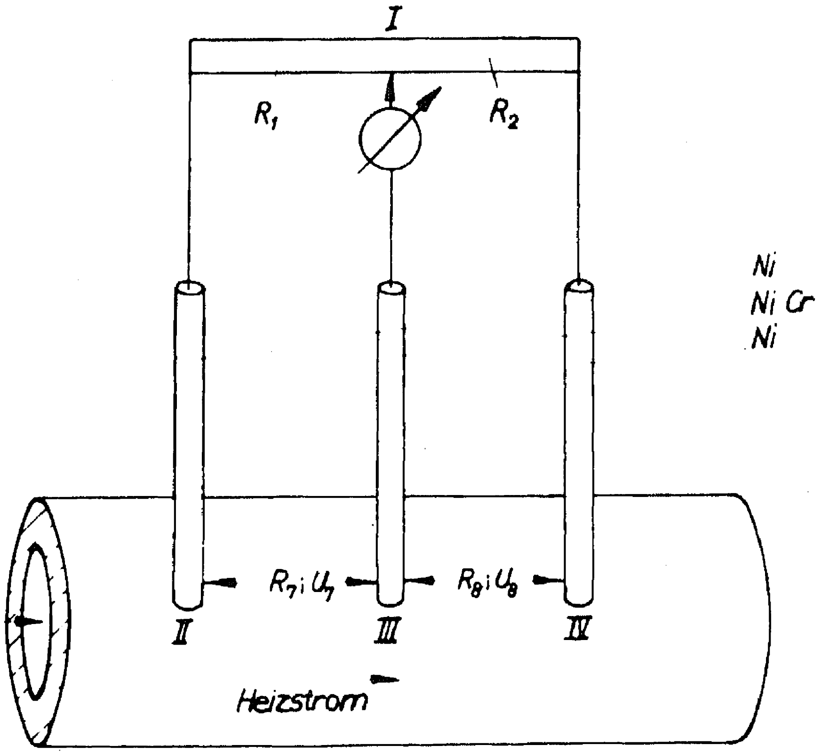

Figure 6 Three-wire thermocouple layout

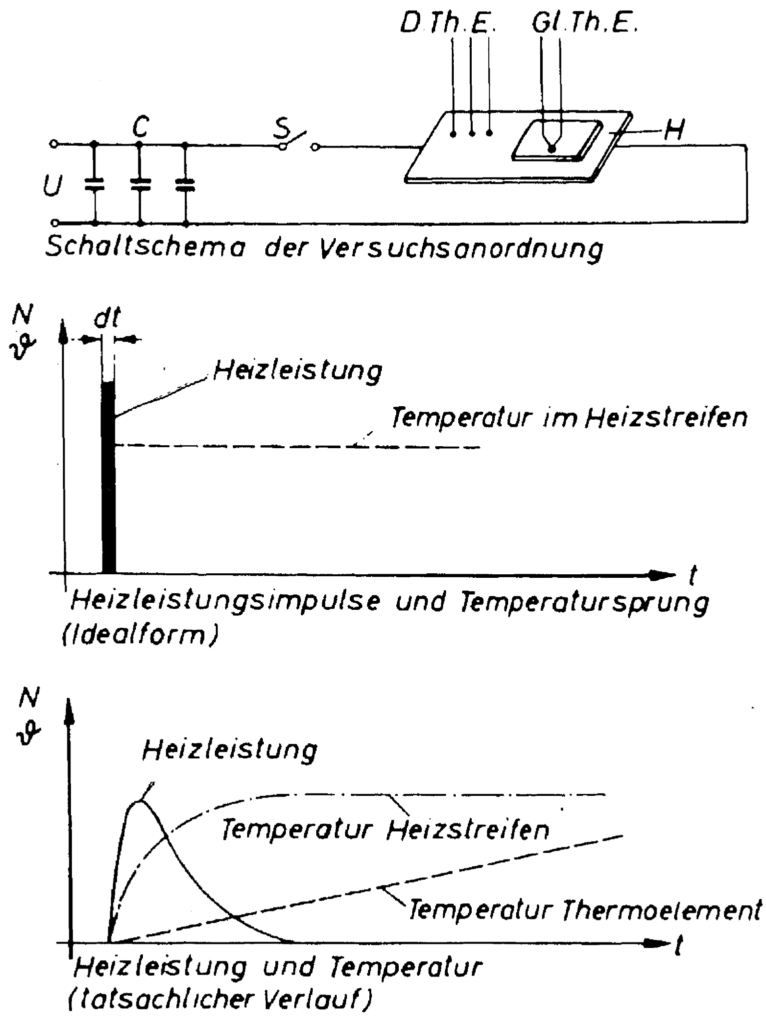

Figure 7 Set-up to measure response speed

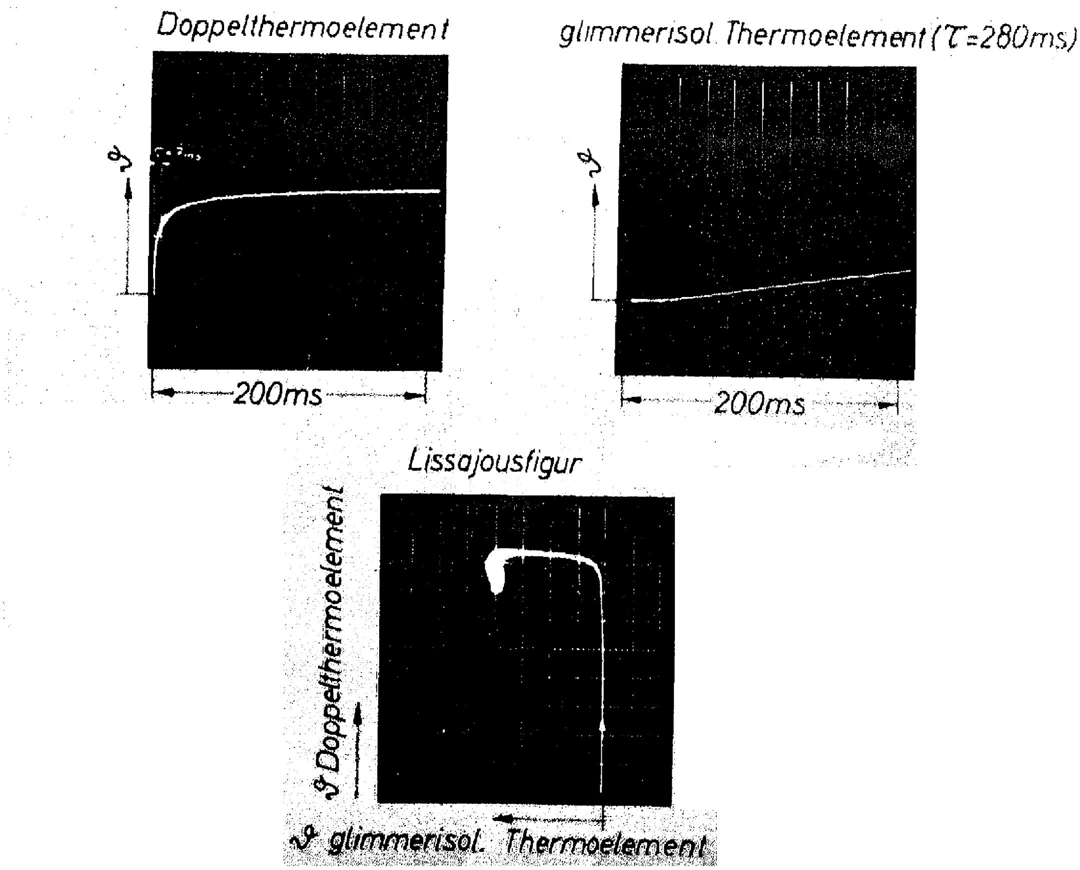

Figure 8 Comparison of thermocouple response (0.1 mm. wire diameter)

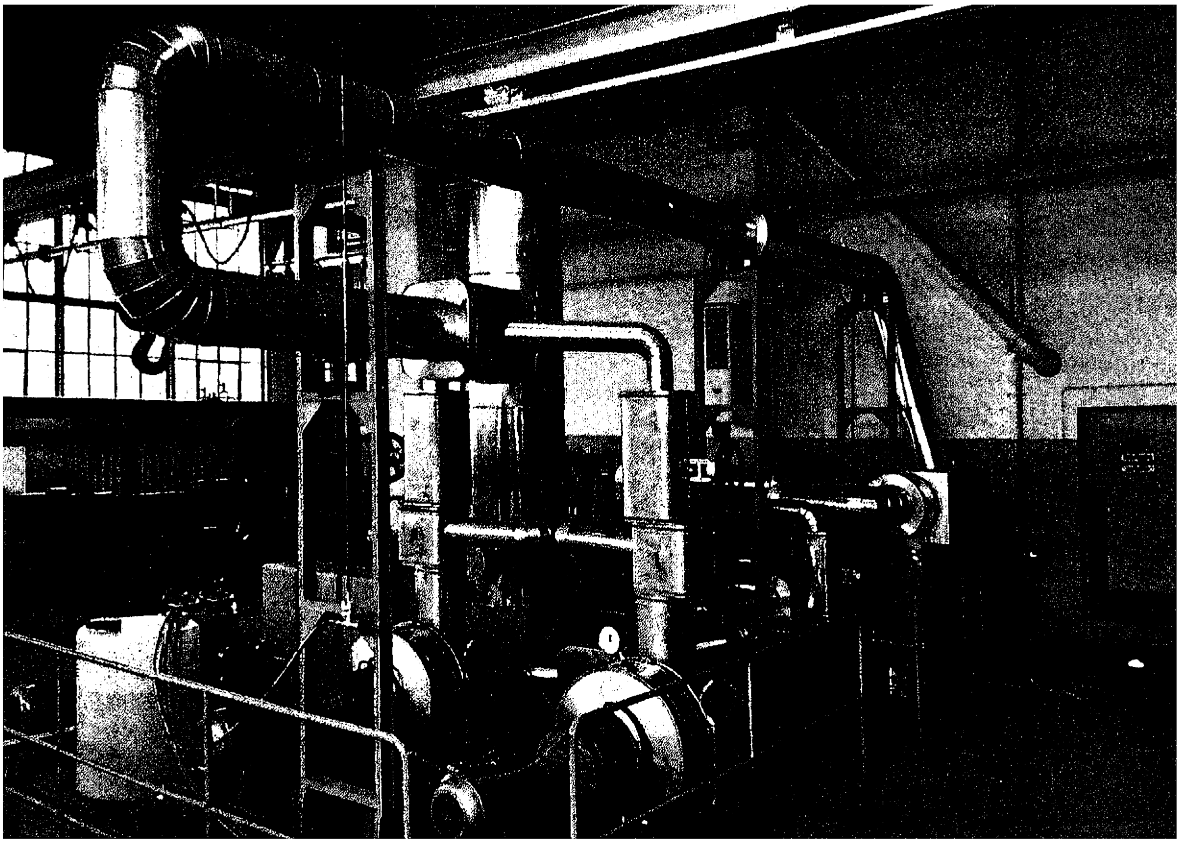

Figure 9 Pressurized water test rig