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ABSTRACT

The CWL-3 loop is used to study the mass transfer of corrosion products in water at 270°C for pressures up to 6.9 MPa. Two parallel Zircaloy-2 test sections are heated directly by a low voltage a.c. electrical current to give a heat flux up to 500 W cm^{-2} and a heat rating up to 1500 W cm^{-1}. Coolant flow rates can be varied up to 0.4 kg cm^{-2} s^{-1} with or without boiling.

A tracer technique has been developed to monitor continuously the deposition of corrosion products in the test sections during operation of the loop. Magnetite deposits 2.6 nm thick can be readily detected.

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COOLANT LOOPS; CORROSION PRODUCTS; DEPOSITION; FLUID FLOW; MASS TRANSFER; PRIMARY COOLANT CIRCUITS; WATER COOLED REACTORS

CONTENTS

CONTENTS(Continued)

1. INTRODUCTION

In water-cooled nuclear reactors, the movement of crud (solid corrosion products) from one point to another in the primary coolant circuit has several harmful consequences:

(i) Crud, after being activated in the core of the reactor, is entrained by the coolant and deposited on out-of-core surfaces causing high radiation fields around the circuit.

(ii) Crud deposited on fuel element surfaces can restrict heat transfer, increase cladding temperatures and cause fuel failures.

(iii) Excessive quantities of crud deposited in regions of high coolant flowrates can choke coolant flow.

While the problems of fuel element failure and flow blockage attributable to crud have receded with improved chemical control and materials selection, the problem of high radiation fields has proved to be particularly intractable.

The effects of crud vary for different types of reactors. In pressurised water reactors (PWRs), the coolant is in a closed circuit enabling chemically reducing conditions and low crud concentrations to be maintained. While this decreases the problem, the accumulation of crud, especially in steam generators to which access is required from time to time, still produces unacceptably high radiation fields [*e.g.* Montford 1973]. In PWRs using light water as coolant, the primary circuit can be decontaminated, although this is a costly process and not without risk to the life of reactor components. On the other hand, in pressurised heavy water-cooled reactors (PHWRs), the presence of heavy water makes normal chemical decontamination impracticable; it is in these reactors that crud movement is most troublesome. In direct cycle reactors, *e.g.* boiling water-cooled reactors, the primary circuit acts as a concentrating boiler for the small concentrations of crud in the feedwater. Relatively high concentrations of crud result, and the subsequent deposition on fuel is probably the major problem.

It was these considerations which prompted the concept of the CWL-3 loop in which the factors governing the transfer, especially the entrainment and deposition of corrosion products, could be studied. In the original concept, evaluation of the influence of deposited crud on heat transfer and burnout was a prime objective, but the emphasis later switched to the mechanism, chemistry and, especially, the dynamics of crud entrainment and deposition. The utility of the loop regarding heat transfer and burnout is unimpaired despite the change of emphasis.

The operating conditions for the loop were selected, subject to some experimental requirements, to be as close as practicable to those of coolant circuits of water-cooled nuclear reactors. The design of the loop was readily achieved, for boiling as well as pressurised conditions, although the pressure limitations of the circulator precluded full PWR pressures.

One of the difficulties inherent in the study of crud movement concerns the small quantities of crud which are important in practice. This, together with the long periods necessary for the accumulation of significant quantities of crud in full-size equipment, made it apparent that the loop should be designed to ensure the very highest rates of mass transfer. Because crud deposition is well known to be a function of the heat flux squared (or, at least, some high power of the heat flux [Charlesworth 1970]), the loop was designed to ensure high heat fluxes. In the loop a flux of 500 W cm^{-2}, equivalent to a heat rating of 1500 W cm^{-1}, can be obtained.

Thermal, hydraulic and chemical shocks can cause rapid re-entrainment of deposited crud, a phenomenon known as a 'crud burst'. It is, therefore, desirable to be able to observe crud deposition during operation of the loop before a shutdown induces a crud burst and alters the pattern of deposition. A radioactive tracer technique and the gamma-counting system described in Section 5 were developed for this purpose.

Although the two test sections operating in parallel made the loop more complex, this proved experimentally beneficial in the long term [Evans & Nicholson 1975].

2. THE CWL-3 LOOP

The loop is designed for the following requirements:

- a working pressure of 10.34 MPa gauge at 288°C (but the operating pressure is limited by the design pressure of the pump, 6.89 MPa at 260°C);
- a total flow, through the two test sections, of 600 cm^3 s^{-1}; and
- a total power input of 225 kW.

2.1 Layout

The general layout of the loop is shown in Figure 1 and an equipment flowsheet in Figure 2. The loop is enclosed in four mild steel walls, 2.5 mm thick. To shorten bus bars and for economy of floor space, some electrical power components associated with the loop are situated on top of the enclosure.

2.2 Pipework

The piping is made from AISI-316 stainless steel tube or pipe as follows:

Description	o.d. (mm)	i.d. (mm)	Wall thickness (mm)
Most of the main loop and preheater	19.0	15.8	1.6
Downstream from the test sections to the tee of the rupture disc	31.7	27.7	2.0
Chemical loop	9.5	7.7	0.91
Instrumentation	6.3	3.1	1.6
Pressuriser	60.0	55.0	2.8

Most pipe joints are Ermeto connections. Where electrical isolation is required, bolted welding-neck-flanges are used, fabricated to ASA B16.5, with electrically insulating gaskets. The loop is insulated to reduce heat loss.

Pipe and tubing stresses and bolted flange design are in accordance with SAA Boiler Code (AS No. CB1 Part 5-1951) Appendix W; AS CM 18.1-1967; and ASME Boiler and Pressure Vessel Code, Section 8, 1965.

The test sections are 914 mm long x 9.5 mm i.d. and fabricated from Zircaloy-2 tubing (1.6 mm wall).

2.3 Heating

The loop contains three portions of heated pipework, two test sections and a preheater, in which the a.c. heating current flows through the pipework itself. Appendix A summarises the design of the power supply system.

2.3.1 Test sections

Two parallel test sections allow different operating conditions for flow, inlet subcooling, exit quality and heat flux (although these variables are not completely independent). Figure 3 shows the burnout power and outlet quality conditions of either test section for various inlet temperatures at an inlet pressure of 6.9 MPa (abs). Similarly, Figure 4 shows 70 per cent of burnout power, which represents near maximum operating conditions for this inlet pressure. The calculations for Figures 3 and 4 were based on the correlation of Thompson & Macbeth [1964].

At an early stage in the design, consideration was given to using indirect electric heaters in annular passages. The simpler, directly-heated test section was chosen because the cross-sectional area of flow necessary for an indirectly heated test section would have necessitated too large a pump. In addition, high heat flux, indirect heaters performed poorly, as did those of other workers [Quarrington & Wilkhammer 1966; Teytu 1971].

2.3.2 Preheater

Each of the three heated sections, which are connected in series for fluid flow, is 660 mm long; the arrangement is shown in Figure 5a. The burnout power is given in Figure 5b; this figure shows that the margin to burnout is very large, except at low flow, and operation of the preheater is satisfactory.

The method of operation is to raise the power on the upstream section to 25 kW (power is supplied from a voltage regulator *via* a transformer). This section is then switched off and the same power is applied immediately to one of the other two sections. The power on the upstream section is again raised to 25 kW to give a total of 50 kW. The process is repeated to raise the power to 75 kW.

The large preheater and cooling coil make it possible to run the pump without danger of cavitation at the operating conditions of the loop.

2.4 Cooling

2.4.1 Cooling coil

Heat is removed from the loop by pool boiling from a coil of the pipework in a drum of water at atmospheric pressure. The cooling water supply is larger than that required for evaporation; excess cooling water flows to waste, thus limiting the concentration of scale-forming salts and chlorides. The latter might cause cracking of the coil due to stress corrosion. The coil, 430 mm in diameter, consists of 15 turns of the main loop tubing, having an outer surface area of 1.23 m^2. The maximum heat input to the loop (225 kW) can be dissipated assuming that the overall heat transfer coefficient is 1.3 $kW\ m^{-2}\ {}^{\circ}C^{-1}$ and the log mean temperature difference is 140°C. The outer surface of the coil is reasonably accessible for mechanical cleaning.

2.4.2 Spray condenser

Inside the loop, condensation takes place in and downstream of the spray condenser (Figure 6) and is probably completed before the fluid enters the cooler. However, by providing a large pressure drop across the test section control valves and also by reducing the bypass flow, it is possible to ensure that some condensation takes place in the cooling coil.

2.5 Pump

A stainless steel, 3-stage, centrifugal, glandless pump (J & S Pumps Ltd) is used with ratings shown in Table 1.

TABLE 1

J & S PUMP RATINGS

Flow		Head		Pressure		Temperature		Remarks
m^3h^{-1}	gallon/min	m	ft	MPa(abs)	psia	°C	°F	
2.3	8.3	129	425	6.89	1000	260	500	Measured at rated flow
6.8	25	100	320	6.89	1000	260	500	Measured at rated motor power
2.7	10	76	250	6.89	1000	260	500	Design specification*

The continuous rating of the motor is 6.7 kW (9 BHP). The net positive suction head requirement of the pump is 5 m at 254°C. The unit requires a secondary coolant water flow of 120 cm^3 s^{-1} at a temperature not exceeding 30°C. The pump, which is equipped with its own heat exchanger, was static cold-pressure tested to 8.27 MPa. The motor and pump cases were tested to 10.34 MPa.

2.6 Crud Release Vessel

Immediately downstream of the preheaters, in the common inlet to the test sections, is the crud release vessel shown in Figure 7. The crud release vessel consists of an enlarged section of the main loop pipework with a bolted welding-neck-flange in the middle. Inside the section, a holder supports a number of 12.7 x 2.5 cm metal plates in, and parallel with the water flow.

The plates may incorporate radioactive nuclides, either from irradiation of the plate itself or from electrodeposition onto the plate, which are slowly released to the flowing coolant. Alternatively, the plates may be of different metals, perhaps with different surface finishes, on which deposits may be observed.

With the aid of two valves upstream and two downstream, the crud release vessel can be isolated and removed from the loop. The main coolant flow from the preheaters can be bypassed around the crud release vessel.

3. CONTROL AND OPERATION

3.1 Control

The control and instrumentation of the loop has been described by Witt

---

* Loop regain

[1973]. Figure 8 is a schematic diagram of the instrumentation and control system. Operation of the preheater was outlined in Section 2.3.2.

3.1.1 Flow

Water flowrates are controlled by Ermeto or Swagelok needle or shut-off valves. Flowrates in the test sections, the main bypass and the chemical loop are measured with calibrated orifice plates (see Figure 9) and Barton differential pressure gauges. Modifications are being made so that the flowrates in the two test sections can be recorded.

3.1.2 Temperature

Temperatures at various points in the loop are measured with chromel/alumel thermocouples fixed to the outside of the loop pipework, and electrically insulated where necessary by mica films. A Honeywell-Brown instrument records eight of the more significant temperatures, including those at the inlets and outlets of the test sections.

The temperature of the water entering the main circulator is controlled automatically by the main loop cooler via a Mack solenoid normally-open valve and a Ether 'Transitrol' 12-91B controller. This unit has the option of ON/OFF control or proportional band ON/OFF control. In the latter mode, a resistor/capacitor circuit is brought into action when the temperature enters the proportional band. This circuit automatically adjusts the TIME ON/TIME OFF ratio to maintain the temperature at the required setting. The controller is used in the proportional band mode. The rate of coolant supply to the outside of the cooling coil, and of drainage from it, can be set to increase the sensitivity of temperature control.

Overtemperature trips on the preheater, test sections, circulator windings and circulator inlet water close down the circulator and all heaters.

3.1.3 Pressure

Four Bourdon tube gauges (0-11 MPa) indicate coolant pressures in the primary loop. Pressure is automatically maintained above a lower limit, which may be adjusted, by a diaphragm valve on a high-pressure nitrogen supply to the pressuriser. A strip chart recorder is being installed to record the loop pressure.

A Microvar differential pressure gauge indicates the water level in the pressuriser. High and low levels are detected by a differential pressure transmitter which stops and starts a makeup pump. Excessively low levels trip the circulator and all heaters.

3.2 Stability

The presence of three parallel paths, with two of them being heated, introduces the real danger of parallel channel instability. Either parallel channel or loop instability or a combination of them might result in burnout leading to bursting of the test sections. Hydrodynamic stability is achieved as follows:

- Valves are located at the inlets to the three parallel paths to control flow and provide a large pressure drop - the standard method of avoiding boiling instability in parallel channels.
- The effectiveness of the spray condenser and its location (immediately downstream of the test sections) ensure a small steam volume. Because the small steam volume is contained by large bore tubing, the two-phase pressure drop is small - low two-phase pressure drop is a feature usually considered to promote loop stability.
- Because of the large inlet pressure drop and low loop two-phase pressure drop, the flow is steady and, since heat input is steady (during unattended operation), the steam volume does not vary.
- The temperature controller (described in Section 3.1.2) is used in the proportional band ON/OFF control mode.
- The pressuriser with its large gas volume prevents small changes in fluid volume (resulting from variation in steam volume) from significantly altering pressure. Consequently, the temperature remains constant (saturation conditions) and little action is required of the temperature controller, except when manual adjustments are made.
- The location of the pressuriser downstream of the test sections (rather than upstream of them, and downstream of the pump) avoids the type of instability known as 'inlet softness', although flashing in the test section inlet valves could produce it on a small scale.

It was anticipated that improved means of pressure control might be required for unattended operation under suppressed boiling conditions; however, no instabilities have been observed that prevented such operation. Violent level fluctuations in the pressuriser, which were sufficient to trip the loop, have been observed. They could usually, but not always, be explained by a too-rapid removal of water *via* the sample valve.

If the loop were used for burnout experiments, the stability would be tested more severely than it has been because the power required for burnout is very sensitive to slight instabilities, especially at low exit qualities.

3.3 Protection

The protection system is designed to protect the loop during unattended operation and to render the loop safe in the event of a power failure. Overpressure conditions are relieved by a safety relief valve or a rupture disc. The safety valve with an orifice of 39 mm^2 is set to lift at 7.2 MPa, and the 12.5 mm diameter Inconel rupture disc is designed to burst at 10.3 MPa and 25°C.

Test section and preheater temperatures in excess of preset values cause the power to the circulator and all heaters to be turned off. Once the setting is reached, the power is shut off in less than 0.2 seconds. A transient temperature rise may occur in the wall of one of the heated sections. If the trip system does not operate in time, weakening of the tube wall and consequent bursting of the tube are possible. It is partly to cope with this contingency that the loop is enclosed. The entry of personnel into the enclosure is prohibited when the loop is pressurised and the heaters are in operation.

Other features of the protection system include the following:

- Power cannot be applied to any heaters unless the pump is turned on.
- Loss of cooling water to the pump, excessive pump winding temperature, and loss of power to the control console all cause the pump and heaters to trip.

4. CHEMICAL CONTROL

A bypass loop for chemical control of the loop water operates in parallel with the main loop as shown in Figure 2. A flow of up to 0.3 $\ell\ s^{-1}$ is cooled in two heat exchangers, usually to 25°C.

In the bypass loop are the following devices:

- A stainless steel probe (cell constant 1.01 m^{-1}) and a Beckman conductivity meter to measure the conductivity of the water.
- A Beckman high-pressure oxygen meter to monitor the oxygen concentration of the water by measuring the change in the conductivity of the water that results from the production of thallous hydroxide by the thallium/oxygen reaction.
- A mixed-bed ion-exchange column and a Cuno 5 µm cellulose filter to purify the water.
- A vessel (Figure 2) for injecting chemicals, gases or crud

into the loop.

Degassed, demineralised makeup water is pumped into the loop by a Yarway diaphragm metering pump with a capacity up to 1.3 $cm^3\ s^{-1}$. The pump is started and stopped, either manually or automatically, on low and high signals from the pressuriser. A second Yarway metering pump of 4 $cm^3\ s^{-1}$ capacity can also be used as a makeup pump.

5. MEASUREMENT OF DEPOSITS

The deposition of iron in the two test sections is continuously monitored with the aid of a radioactive iron tracer. The isotope used is iron-59 which disintegrates with a half-life of 45 days emitting either 1.099 MeV (56%) or 1.242 MeV (44%) photons. The deposition of any other element can be measured if a suitable gamma-emitting tracer is available.

A sodium iodide (thallium activated) crystal (1.75 cm diameter x 2.5 cm long) and an EMI 6097B photomultiplier tube in a Jefferson head measure the radioactivity in each test section (Figure 1). Up to 13 cm of lead shield each photomultiplier tube from the high magnetic field originating with the alternating current in the test sections. Collimators restrict the view of the counters to an 8 cm length of the test sections. The counting heads can be driven up and down to scan the heated portion of the test sections and a few centimetres beyond. Output from the two counters is obtained *via* a typewriter and a paper punch.

Before each experiment or series of experiments, the counters were calibrated by circulating in the loop a solution of radioactive iron of known concentration. A typical calibration, shown in Figure 10, was carried out with a 13.5 $\mu g\ g^{-1}$ solution of radioactive iron simulating a deposit of 32 $mg\ m^{-2}$. The specific activity of the iron was 4.7 $mCi\ g^{-1}$ which was readily achieved by irradiating natural iron in the AAEC Research Reactor HIFAR. Allowance was made in the calibration and during experiments for the general background and also for the background radioactivity caused by traces of iron in the loop.

Figure 10 shows that a 32 $mg\ m^{-2}$ deposit can be measured with precision; in fact, smaller deposits down to 10 $mg\ m^{-2}$, equivalent to a magnetite layer 2.6 nm thick, can be readily measured.

The radioactivity in samples removed from the loop is measured in lead-shielded equipment consisting of a 2.5 cm diameter sodium iodide crystal in a Jefferson head and an IME type IIB scaler. Sampling can be done either directly with an isokinetic sampling device or with a 0.45 μm Millipore filter. With this counting equipment, iron concentrations in the water down to 10 ng g^{-1} can be measured.

6. CONCLUSION

The loop has operated satisfactorily in every respect. The radioactive tracer technique for following deposition has proved to be very sensitive, measuring deposits as thin as 2.6 nm.

7. ACKNOWLEDGEMENTS

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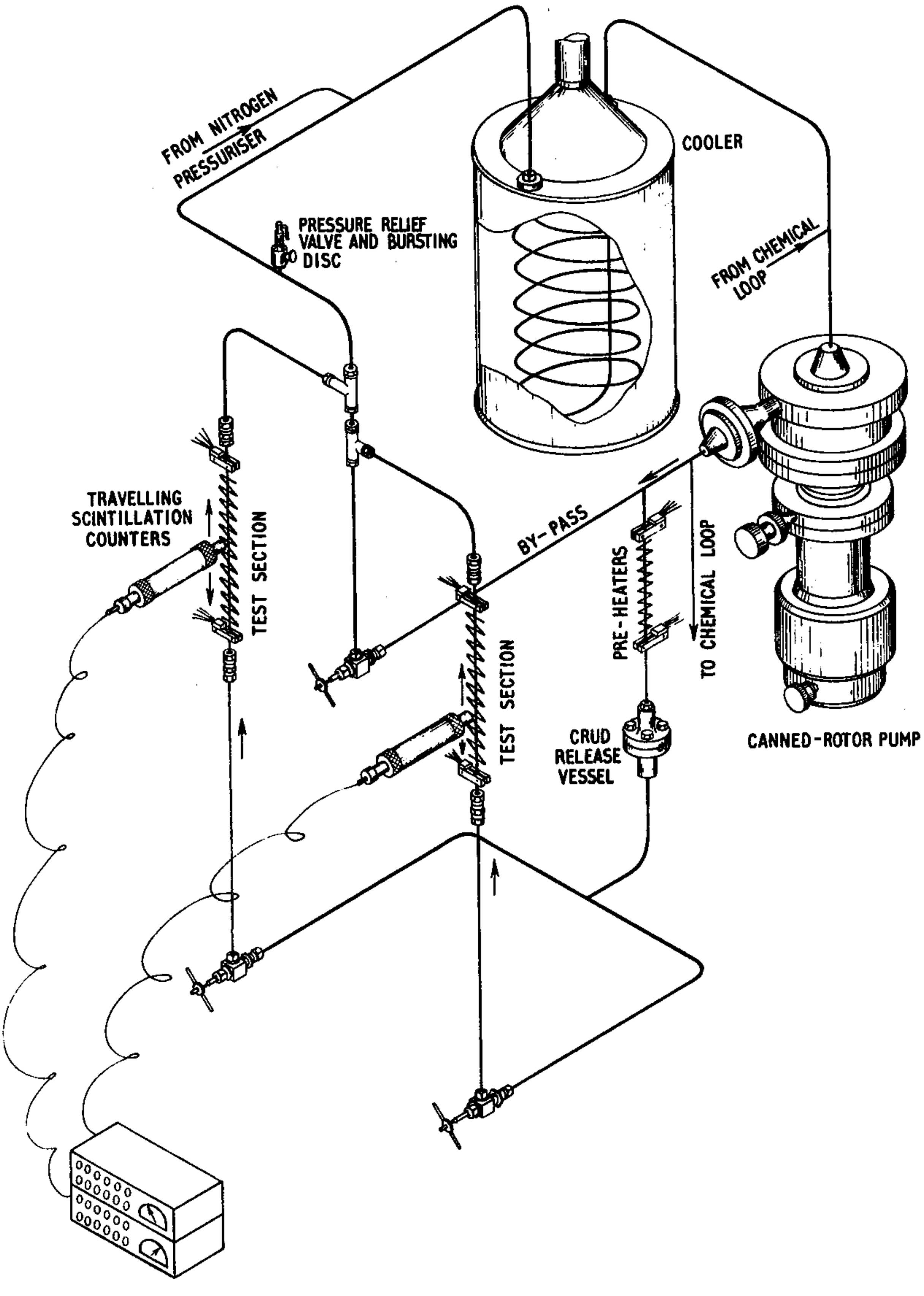


FIGURE 1. CWL-3 MASS TRANSFER LOOP

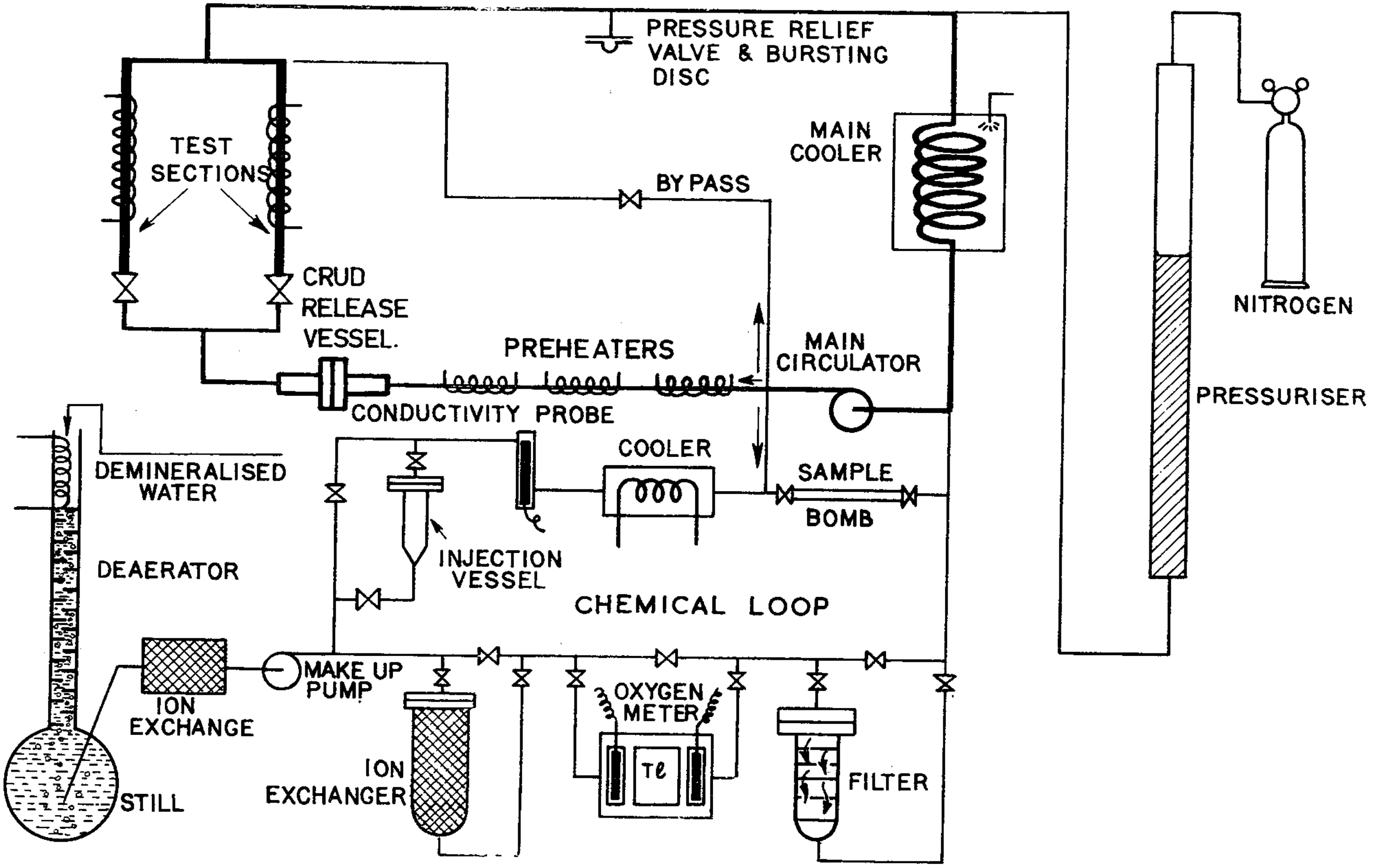


FIGURE 2. EQUIPMENT FLOWSHEET FOR THE CWL-3 MASS TRANSFER LOOP

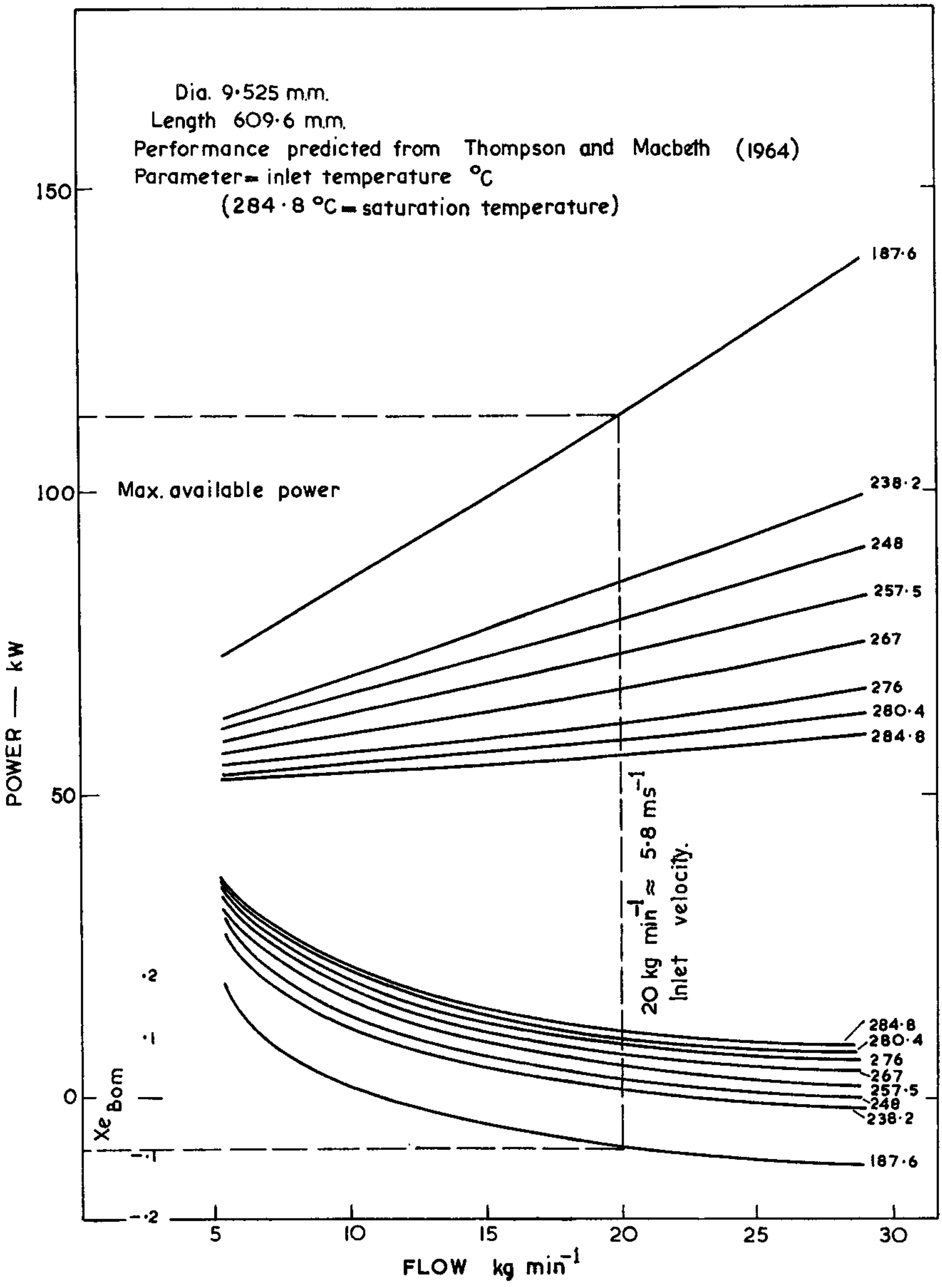


FIGURE 3. CALCULATED BURNOUT POWER AND QUALITY AT 6.9 MPa (abs)

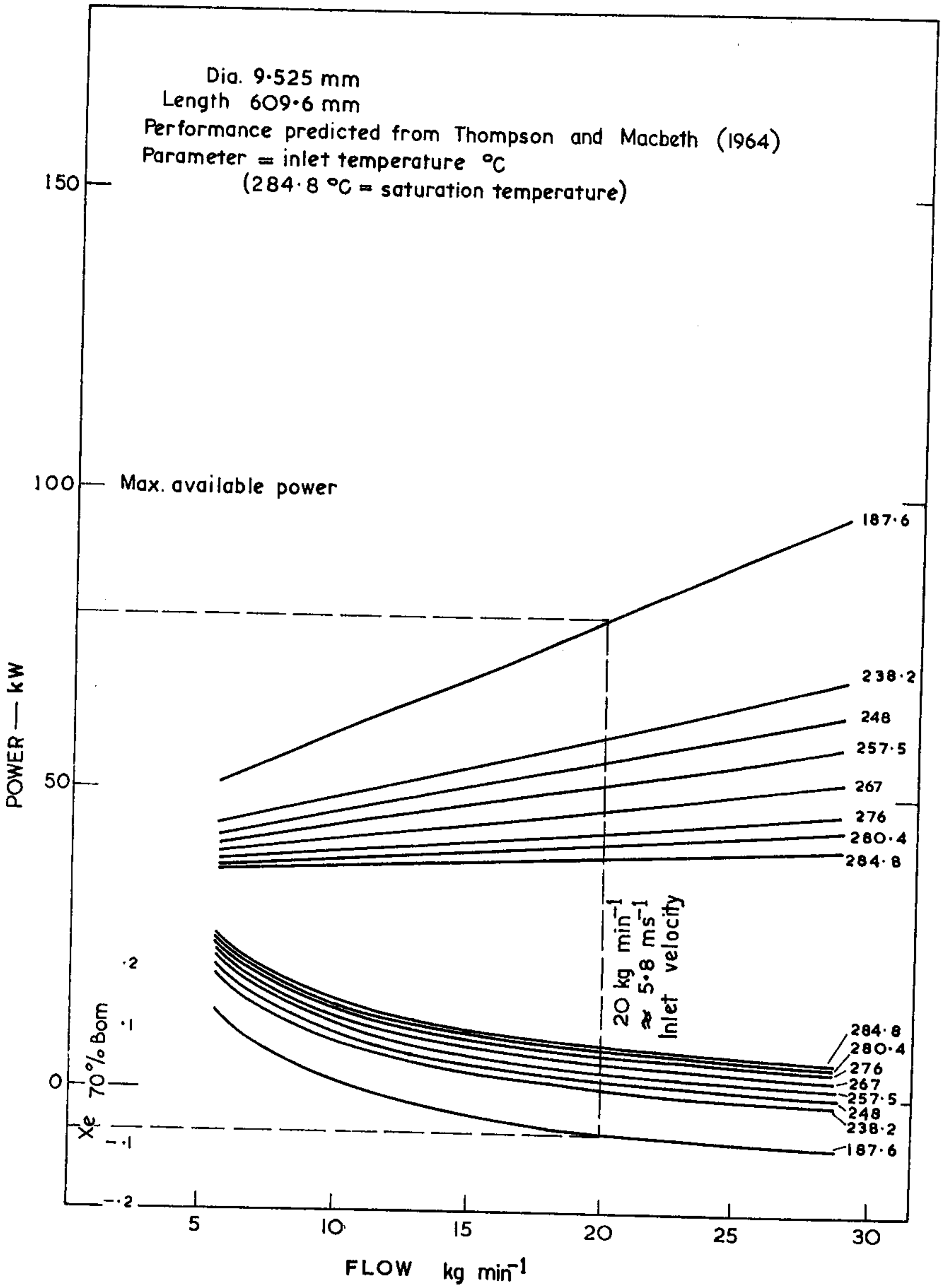
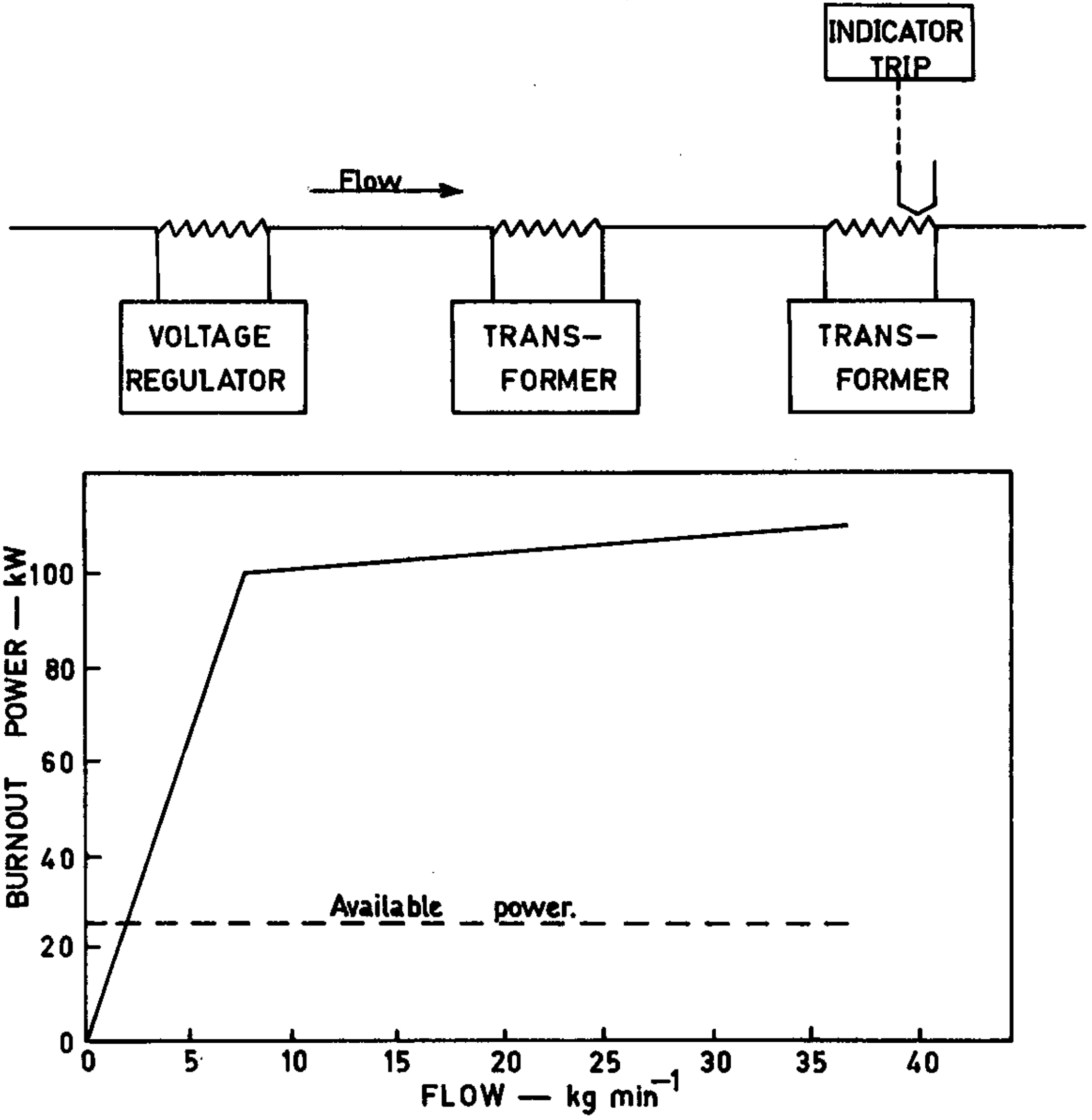


FIGURE 4. 70% OF BURNOUT POWER AND CORRESPONDING QUALITY AT 6.9 MPa (abs)

(a) PREHEATER



(b) BURNOUT FOR DOWN-STREAM THIRD OF PREHEATER WITH INLET SUB-COOLING 66·29 kJkg^{-1} TO THAT PORTION. 6·9 MPa

FIGURE 5. PREHEATER (After Thompson & Macbeth 1964)

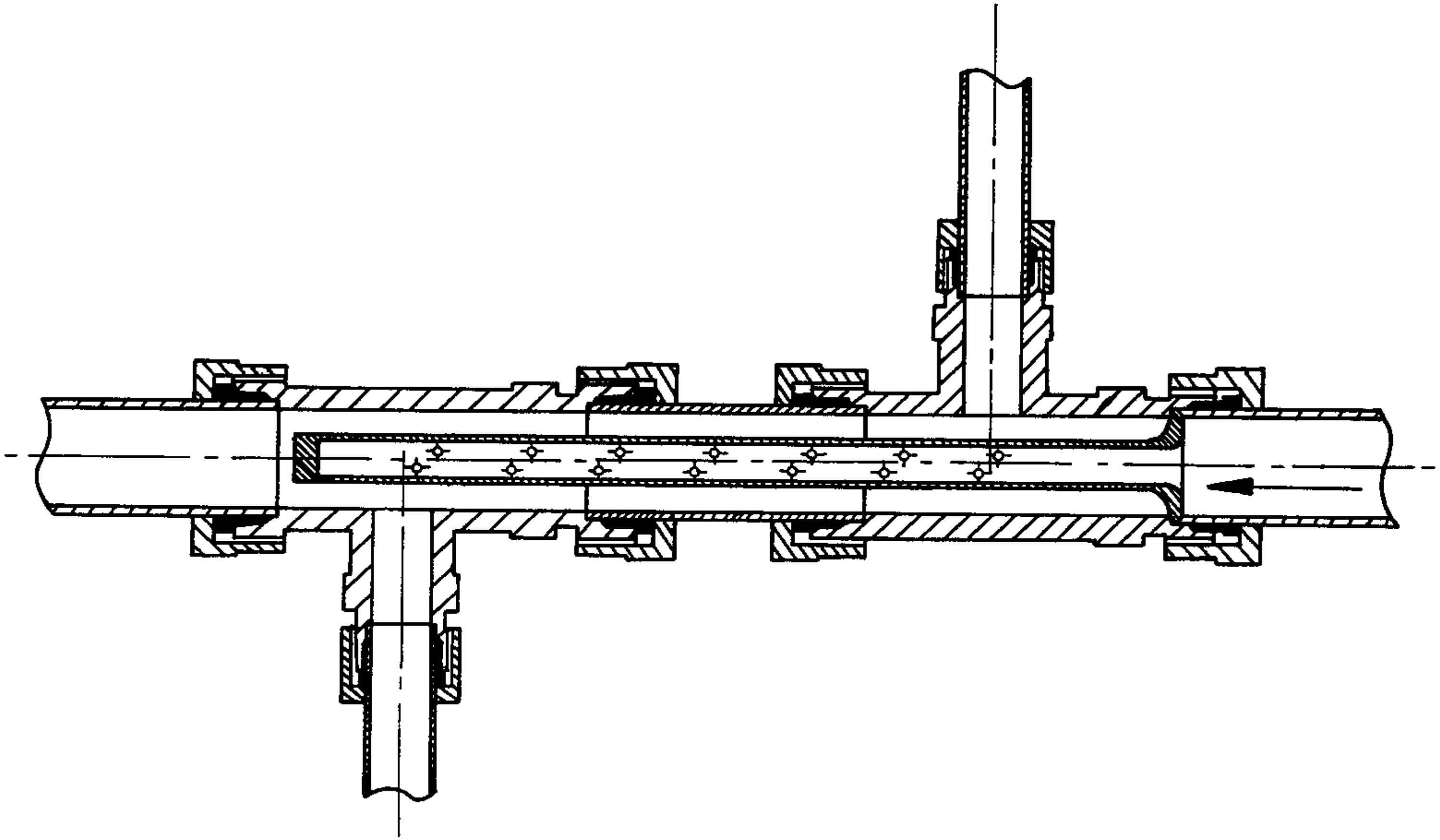


FIGURE 6. SPRAY CONDENSER

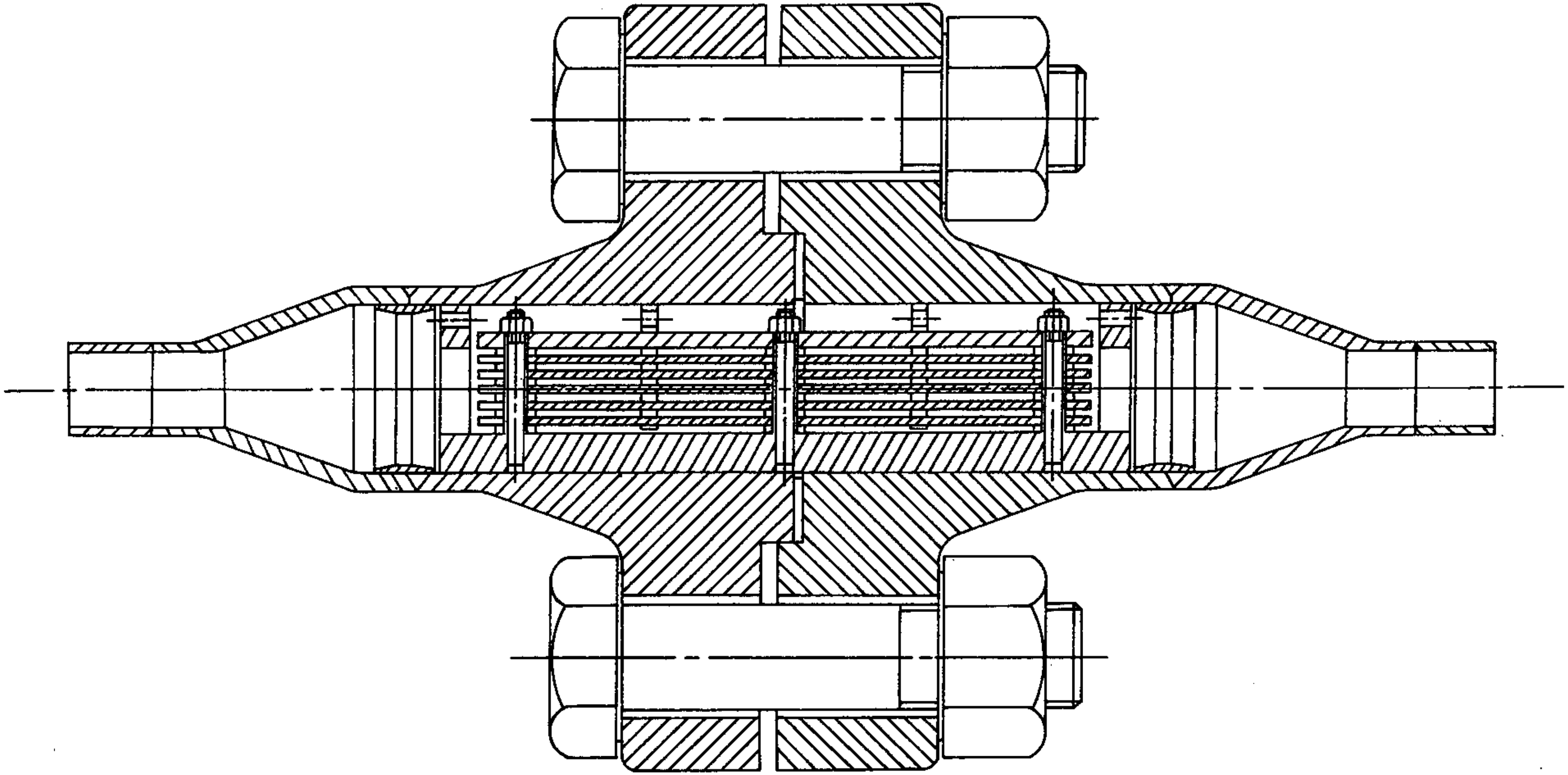


FIGURE 7. CRUD RELEASE VESSEL

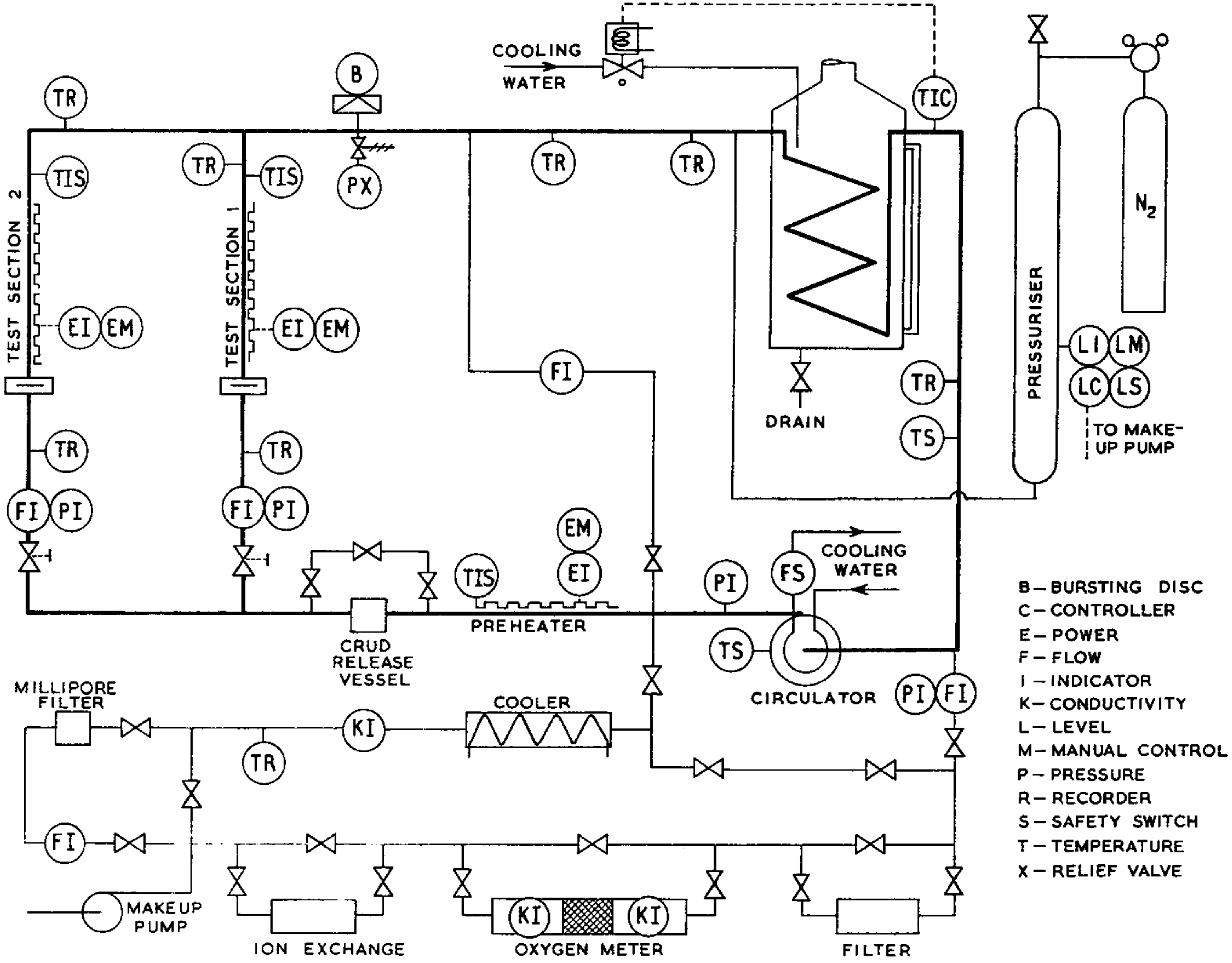


FIGURE 8. INSTRUMENTATION FLOW DIAGRAM

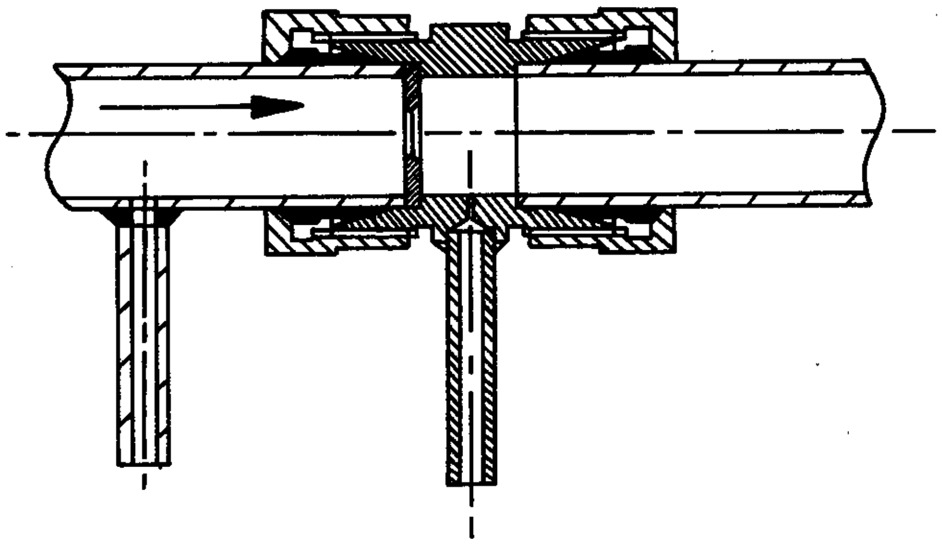


FIGURE 9. ORIFICE PLATE ASSEMBLY

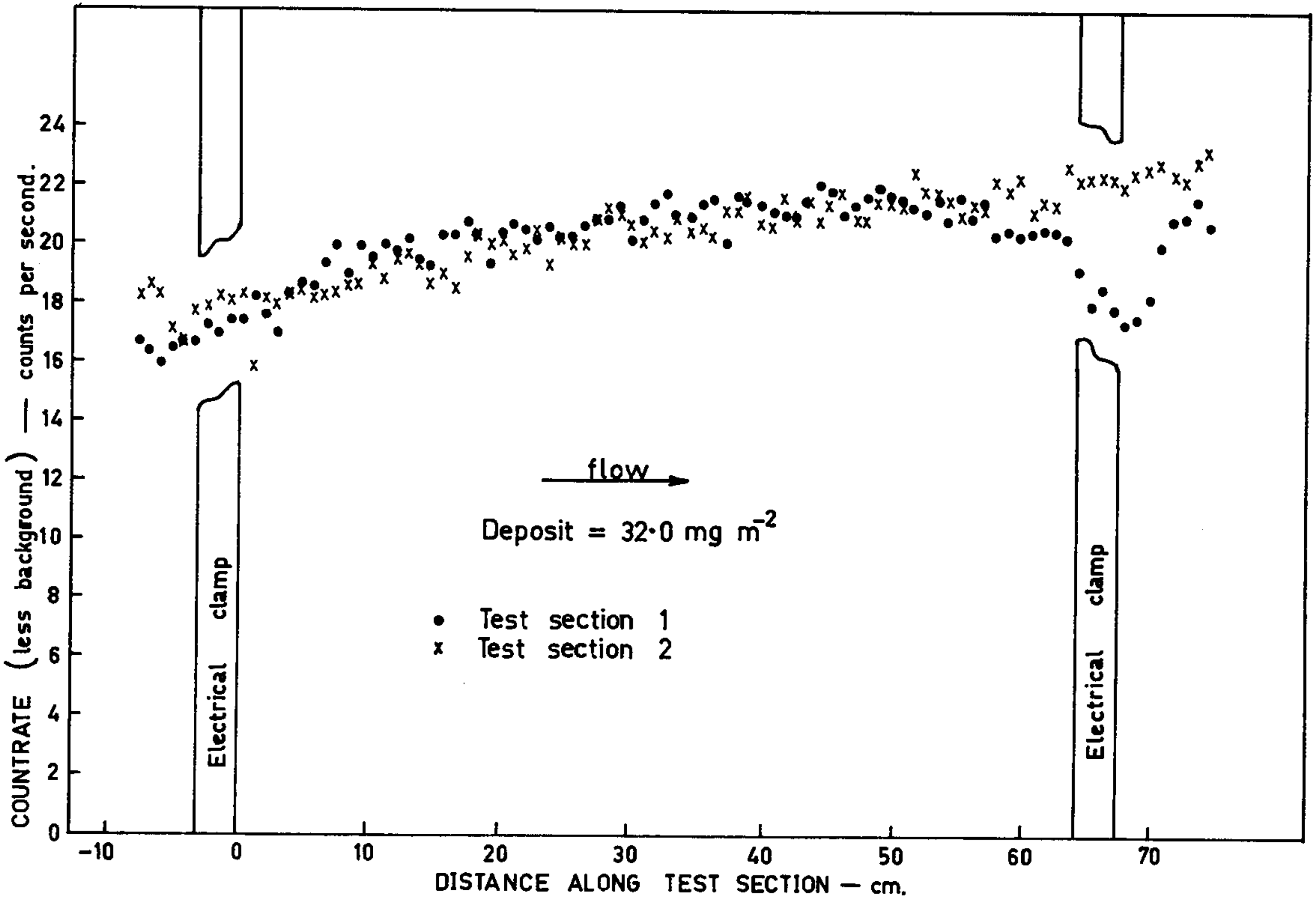


FIGURE 10. TYPICAL CALIBRATION OF TEST SECTION COUNTERS. THE COUNTRATE IS PRODUCED BY A SIMULATED DEPOSIT OF 32 mg m^{-2} IN EACH TEST SECTION

APPENDIX A

ELECTRICAL POWER

Circuit No.	Phases connected	Circuit breaker rating (A)	Voltage regulator rating	Contactor rating, O/L (A)	Transformer rating	Comments
1	Red/Yellow	300	100 kVA, 415 V	250	100 kVA, 415 V/33 V	Test section, 32 volts under load. Two x 152 mm x 12.7 mm aluminium busbars are used for connection.
2	Yellow/Blue	65	25 kVA, 415 V	60	25 kVA, 415 V/13 V	Secondaries of these transformers are connected in series to supply about 25 volts under load to the test section. Two x 102 mm x 6.4 mm aluminium busbars are used for connection
3	Yellow/Blue	65	25 kVA, 415 V	60	25 kVA, 415 V/13 V	
4	Red/Blue	65	30 kVA, 415 V	60	25 kVA, 415 V/13 V	Each of these transformers is connected by two x 102 mm x 6.4 mm aluminium busbars to an independent section of the preheater. Voltage of any section above earth potential does not exceed 13 volts.
5	Blue/Red	65	-	60	25 kVA, 415 V/13 V	
6	Red/Blue	65	-	60	25 kVA, 415 V/13 V	