DESIGN CONSTRUCTION AND TESTING OF A HEAT LOOP FOR STUDY OF FOULING AND ITS INTERRELATIONSHIP TO CORROSION IN HEAT EXCHANGER TUBES

by

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ABSTRACT

A heat loop suitable for the study of thermal fouling and its relationship to corrosion processes was designed, constructed and tested. The design adopted was an improvement over those used by such investigators as Hopkins and the Heat Transfer Research Institute in that very low levels of fouling could be detected accurately, the heat transfer surface could be readily removed for examination and the chemistry of the environment could be carefully monitored and controlled. In addition, an indirect method of electrical heating of the heat transfer surface was employed to eliminate magnetic and electric effects which result when direct resistance heating is employed to a test section.

The testing of the loop was done using a 316 stainless steel test section and a suspension of ferric oxide and water in an attempt to duplicate the results obtained by Hopkins. Two types of thermal fouling resistance versus time curves were obtained.

(i) Asymptotic type fouling curve, similar to the fouling behaviour described by Kern and Seaton and other investigators, was the most frequent type of fouling curve obtained. Thermal fouling occurred at a steadily decreasing rate before reaching a final asymptotic value.

(ii) If an asymptotically fouled tube was cooled with rapid circulation for periods up to eight hours at zero heat flux, and heating restarted, fouling recommenced at a high linear rate.

The fouling results obtained were observed to be similar and in agreement with the fouling behaviour reported previously by Hopkins and it was possible to duplicate quite closely the previous results. This supports the contention of Hopkins that the fouling results obtained were due to a crevice corrosion process and not an artifact of that heat loop which might have caused electrical and magnetic effects influencing the fouling.

The effects of Reynolds number and heat flux on the asymptotic fouling resistance have been determined. A single experiment to study the effect of oxygen concentration has been carried out.

The ferric oxide concentration for most of the fouling trials was standardized at 2400 ppM and the range of Reynolds number and heat flux for the study was 11000-29500 and 89-121 KW/M^2, respectively.

TABLE OF CONTENTS

Chapter | Page

LIST OF FIGURES

Figure Page

Figure		Page

LIST OF TABLES

Table		Page

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CHAPTER 1

INTRODUCTION

1.1. The Fouling Problem

It is a well observed phenomena that after a certain period of operation the heat transfer surfaces of heat exchangers are usually coated with various extraneous materials present in the flow system, or the surfaces are corroded as a result of interaction between the fluid and the material of construction of the exchanger. In either case, this coating manifests itself as an additional resistance to heat transmittal, and results in decreased overall heat transfer coefficients, reduced performance of the exchanger and increased pressure drops. This phenomenon is commonly referred to as 'fouling'.

Fouling is costly as exchangers must be overdesigned to provide the extra surface and must periodically be cleaned. Extra fuel to make up for poor heat transfer may be required to maintain temperatures or expensive surfactants may have to be used to keep the fouling material dispersed. Operating efficiencies are reduced while maintenance costs increase due to fouling.

The primary variables, generally recognized as affecting the fouling build-up are those pertaining to temperature (both surface and bulk), fluid velocity, surface material, flow geometry and the fouling fluid chemistry [1].

The effect of fouling in the design of heat exchangers can be better appreciated if one considers the equation

$$U_d = \frac{1}{\frac{1}{h_o} + \frac{X_o}{k_o} + \frac{X_w}{k_w} + \frac{X_i}{k_i} + \frac{A_o}{h_i}} \qquad (1.1)$$

It is clear from the above equation that the higher the film coefficients the greater will be the effect of the fouling resistance on the overall coefficient and thereby on the exchanger size. Also as the fouling builds up its conductance $\frac{kA}{X}$ would decrease and the total resistance to the transfer of heat would be increased.

The usual practice in design is to counteract the effect of fouling by providing additional heat transfer area based upon empirical fouling factors such as those recommended by TEMA [2]. However, as pointed out by a number of workers [3,4] these are only very approximate and frequently unreliable. At best they are only an estimate based on experience and fail to take into account the unsteady state nature of the fouling process [5].

Although a number of studies [5-10] have appeared in the literature identifying some of the fundamental types of fouling mechanisms, systematic research on fouling is limited and still in the developing stage. State of the Art (Review) papers by Taborek et al., [10] Suitor et al., [11] Bott [12] and more recently by Epstein [13] summarize the present status of research on fouling. It is obvious from these, that there still exists an urgent need for more information and data on fouling in order to improve upon more reliable design methods, and to reduce or eliminate it. Taborek et al. [10] stress the need for large experimental data sets obtained under systematically varied conditions before any further progress in this field can be made.

1.2. Literature Survey

1.2.1. Experimental Apparatus for Study and Monitoring of Fouling

Fouling is known to exhibit several quite different basic forms and to be affected by a large number of variables pertaining to mode of operation and equipment construction [10]. Consequently, research on fouling has been confined to studies with well defined and narrow objectives which have tended to aim only at eliminating or minimizing specific problems. A wide variety of experimental equipment has been used according to the individual requirements of each study. Although some work has been done with process size equipment or nearly full scale apparatus [1,14] in plant conditions, the major portion has come from laboratory scale apparatus. The general idea has been to pass the fouling fluid over or through a test section in which all the parameters suspected of affecting the fouling process are controlled. Evidence of the growth of fouling deposit with time is noted for a desired set of conditions typical of those occurring in process equipment.

The design of any research equipment for thermal fouling studies depends primarily upon whether local or overall values of fouling resistance are desired, the flow geometry, the type of heating employed, and the need for supplementary data [1]. Test section design, flow control, method of heating, mode of operation, fouling measurement techniques, method of analyzing the fouling deposit, etc., shall be reviewed here.

Test section configurations are commonly based on double pipe heat exchangers [11]. The fouling fluid may be either tube side or annular and when fluid heating is used may be parallel or counterflow. Special flow patterns have been studied by Watkinson et al. [15] using tubes of finned and spiral indented, and recently by Cooper et al. [16] in Plate heat exchangers. Among the more unusual designs is that of Banchero and Gordon [17] who developed a helical flow channel in a copper cylinder to approximate conditions in evaporators producing potable water. Kerst [18] used a 6 mm hairpin shaped tube for insertion in process pipelines to study deposition and corrosion. Freedman et al. [19] have developed an improved method for laboratory testing of recirculating cooling water treatments which allows visual and gravimetric determinations of corrosion and heat transfer surfaces under typical field conditions. A shell side fouling research unit consisting of small tubular exchanger bundle has been designed by HTRI for measuring shell side fouling [1,20]. OTEC [21] have recently developed an unsteady-cooling test unit. Epstein [13] lists other apparatus and methods employed for specific fouling studies.

Heating of test sections has been accomplished using electrical resistance heating, indirect electrical heating, vapor condensation and sensible fluid heating [11]. The merits and demerits of each have been discussed by Fischer et al. [1]. Electrical resistance heating has the advantage of providing a uniformly distributed heat flux and the ease by which heat flux or input can be controlled and measured. Its limitations, however, are high current requirements limiting the materials of construction of test section to those of high electrical resistance, and the possibility of current leakage which can create instrumentation problems in measurements. Cartridge type electric heaters in annular flows have been the most common [11], however another often used approach combines tubeside flow with direct resistance heating of the tube wall [3,22]. Direct heating of the tube wall has an added disadvantage in that the AC frequency could give rise to a magnetic field around the heat transfer metal which could influence particle deposition on the wall. Indirect electrical heating, on the other hand, has the advantage of being convenient to apply although its use is limited to simple geometries [1,11]. Use of sensible heating fluids gives good control, but usually is only suitable for low heat fluxes and low temperature applications.

Numerous methods for monitoring deposits have been reported in the literature [13], but the most common has been to employ thermal sensors imbedded below the fouling surface to monitor the temperature differentials between the clean and fouled situations to provide a measure of the fouling thermal resistance. This has a definite advantage over other methods as it directly provides information on R_f and $\frac{dR_f}{d\theta}$ which can be used to determine the extent of fouling [13].

Two methods can be used to compute fouling resistances from thermal data. Local fouling measurements are used to compute fouling resistances at single localized positions on the fouling surface. These resistances are evaluated from temperature measurements of the fouled and initial clean condition by

$$R_f = \left(\frac{T_w - T_b}{Q/A}\right)_{\text{fouled}} - \left(\frac{T_w - T_b}{Q/A}\right)_{\text{initial clean}} \tag{1.2}$$

For constant heat flux and constant bulk temperature

$$R_f = \frac{T_{w(f)} - T_{w(i)}}{Q/A} \tag{1.3}$$

or simply the rise in temperature from clean to fouled condition divided by the heat flux.

The second method calculates the degradation of the overall heat transfer coefficient over the total surface to yield average values of fouling resistance over the entire fouled surface [3]. Localized measurements are more advantageous as they correspond to values of R_f and $\frac{dR_f}{d\theta}$ at specific fouling surface temperature T_w, fouling deposit surface (deposit fluid interface) temperature T_s, and bulk temperature of the fluid T_b rather than averaged values over the entire fouling surface [13]. Other methods of monitoring deposits have been ascertaining growth of fouling deposit simply by observation through transparent outer shells. Post-test measurements include thickness and weight. X-ray and electron microprobe techniques have been employed by Braun et al. [4] and Hopkins et al. [23] to visually examine and analyze the fouling deposit. These indirect methods suffer from a drawback that growth of the fouling deposit with time cannot be measured and only fouling tendencies can be ascertained. As no time history measurements can be made with these methods no significant quantitative data are possible.

Studies on fouling can be carried out under conditions of constant heat flux or constant medium heating temperature [1,11]. Under constant heat flux conditions, e.g., with electrical heating, the metal wall temperature increases as the fouling builds up and local values of R_f are easily determinable at any instant just from readings on the thermal sensor mounted on the surface (T_c) and heat flux q'.

$$\text{At time} \quad t = 0, \quad \frac{1}{U_o} = \frac{X_w}{k_w} + \frac{1}{h_o} = \frac{T_{co} - T_b}{q'} \tag{1.4}$$

$$\text{At time} \quad t = t, \quad \frac{1}{U} = \frac{X_w}{k_w} + R_f + \frac{1}{h} = \frac{T_c - T_b}{q'} \tag{1.5}$$

$$\therefore \quad \frac{1}{U} - \frac{1}{U_o} = R_f = \frac{T_c - T_{co}}{q'} \tag{1.6}$$

Under constant flux operation and in the absence of blockage or surface roughness effects, the heat transfer coefficient h and hence, the fluid-scale interface temperature T_s should remain constant as fouling proceeds[13,23]. Thus, as long as there are no significant changes in the chemical composition of the fouling fluid, the deposition rate should also be uniform with time [11].Removal forces however would prevent a constantly increasing fouling resistance, but the deposition rate would be constant. Consequently, asymptotic conditions would be reached after a much longer period than in constant heating medium temperature situation [1] as the removal mechanism will be only fluid shear. In the latter situation the temperature difference across the fouling layer increases thus giving a lower temperature at the interface. The fouling rate decreases under this situation as the rate is a function of temperature at the interface leading to an asymptotic fouling resistance being reached much quicker than in the previous case [11].

The belief that the asymptotic condition under constant flux operation is due to a balance between the constant deposition rate and release mechanism (caused by fluid shear according to Kern and Seaton [6]) is still controversial. If particles are subject to removal forces as they approach the surface, how do they ever get deposited? Many researchers [13,20] in the area feel that asymptotic fouling behaviour is the result of a suppression of fouling rather than a balance between deposition and removal rates. Removal can be a factor but usually occurs suddenly in large chunks. Kern himself in his later work [24] spoke of the retardation process as a "suppressant of deposition." Epstein [13] discusses this conceptual problem and analyzes some of the mechanisms suggested to resolve this controversy. The Cleaver and Yates 'turbulent bursts' and 'back sweep' model [25,26] appears particularly convincing in this respect.

Fouling fluid flow may be either once through or recirculating. Industrial cooling processes using large quantities of water are typically once through flow. Hasson [27] studying fouling of condenser tubes in water desalination employed once through flow of municipal water fed by gravity from a constant level tank. Recycled test fluid has been used in a number of studies [3,22,28]. This is advantageous as it enables fouling fluid properties to be regulated and maintained constant but requires additional forced cooling to maintain thermal equilibrium of the fouling fluid.

In addition to using thermal data to determine fouling resistances Epstein [13] expresses the desirability of using supplementary methods. Watkinson [3] used pressure drop increases to monitor fouling but there was poor correlation between the measured $\frac{d(\Delta P)}{d\theta}$ and $\frac{dR_f}{d\theta}$ [29]. Such data, however, may be very useful in understanding the physical mechanisms of fouling. HTRI [10,20], in its extensive work carried out in the cooling tower water fouling field, has also investigated several supplementary aspects of the fouling process. Some of these are: visual observation of the fouling process by a time-lapse movies, determination of the thermal conductivity of the deposit (which is one way of characterizing the deposit structure), by photographic measurements, and use of an electron scanning microscope to observe the initial deposition mechanism. A factor closely associated with fouling rates and significantly influencing the interpretation of experimental results is the deposit morphology which, it should be noted, could also strongly affect the heat transfer coefficient. Visual observation and scanning electron micrographs can provide easy confirmation of quanitative results by qualitative inspection and help in correlating morphology with feed chemistry and oxygen concentration [4]. Analyses of the fouling deposit and the fouling fluid can greatly help in correlation of fouling rates and experimental variables monitored. For example in the case of particulate fouling, characterization of the fouling fluid in terms of concentration and size of particles could provide an answer to what size range of particles participate in the fouling process. Chemical analyses of the fouling deposit could offer a substantial explanation to fluid chemistry effects and also corrosion controlled fouling.

Finally, the experimental apparatus used in any fouling study is important as it establishes the applicability of the results obtained to the actual operation and design of heat exchangers [10]. Most of the fouling measuring equipment which have been designed, built and operated have used some of the techniques described above; the primary difference between them has rested in the design of the test section, the heating medium and the measurement techniques.

1.2.2. Fouling Studies Results (Thermal Fouling Resistance Versus Time Behaviour)

Three distinct types of fouling curves have generally been reported in the literature for thermal fouling studies [11,20] as illustrated in Fig. 1.1 and can be termed as asymptotic, falling rate and linear. The asymptotic mode is the most frequent type of fouling behaviour observed and it exhibits the classical fouling model of Kern and Seaton [6]. This curve is described by an increase in fouling resistance with time to an asymptotic value and the time dependence of the fouling resistance is approximated by

$$R_f = R_f^* (1-e^{-bt}). \tag{1.7}$$

In contrast to the simple falling rate behaviour the asymptotic behaviour raises the possibilities of the suggestions made by Kern [7] that the heat transfer surface can be designed to operate indefinitely under fouling conditions without cleaning at the asymptotic value. In practice, however, this has been rarely observed [10].

In the linear model there is a near linear dependence of fouling resistance with time. Another point which should be borne in mind, as cautioned by Epstein, [13] is that unless the fouling process has been carried out for sufficient time one cannot be certain whether or not an observed linear behaviour is really the beginning of what

TABLE I

Resumé of Some Fouling Models

Model	Deposition Term $_{d}$ $_{r}$	Removal Term $_{d}$ $_{r}$	Characteristics of Fouling Type
1. Kern and Seaton	Proportional to concentration of foulant and bulk fluid velocity.	Proportional to fouling layer thickness and shear stress.	Particulate and other fouling.
2. Watkinson and Epstein	Proportional to concentration difference and to Arrhenius temperature function.	Used same as Kern and Seaton.	Particulate and chemical reaction fouling. Reaction rate controlled or diffusion rate controlled.
3. Beal	Proportional to concentration gradient as function of turbulent and Brownian diffusivity.	None postulated. Assumed all particles reaching the wall stuck	Particle deposition by eddy and Brownian diffusion and inertial coasting.
4. Hasson	Function of the temperature of the scale surface. As scale accumulates scale surface temperature drops decreasing rate of scale formation.	None postulated.	Sensible heat scaling of calcium carbonate solution.
5. Taborek	Function of scale surface, surface temperature and a water chemistry parameter.	Function of wall shear stress, scale thickness and scale strength.	Cooling water service.

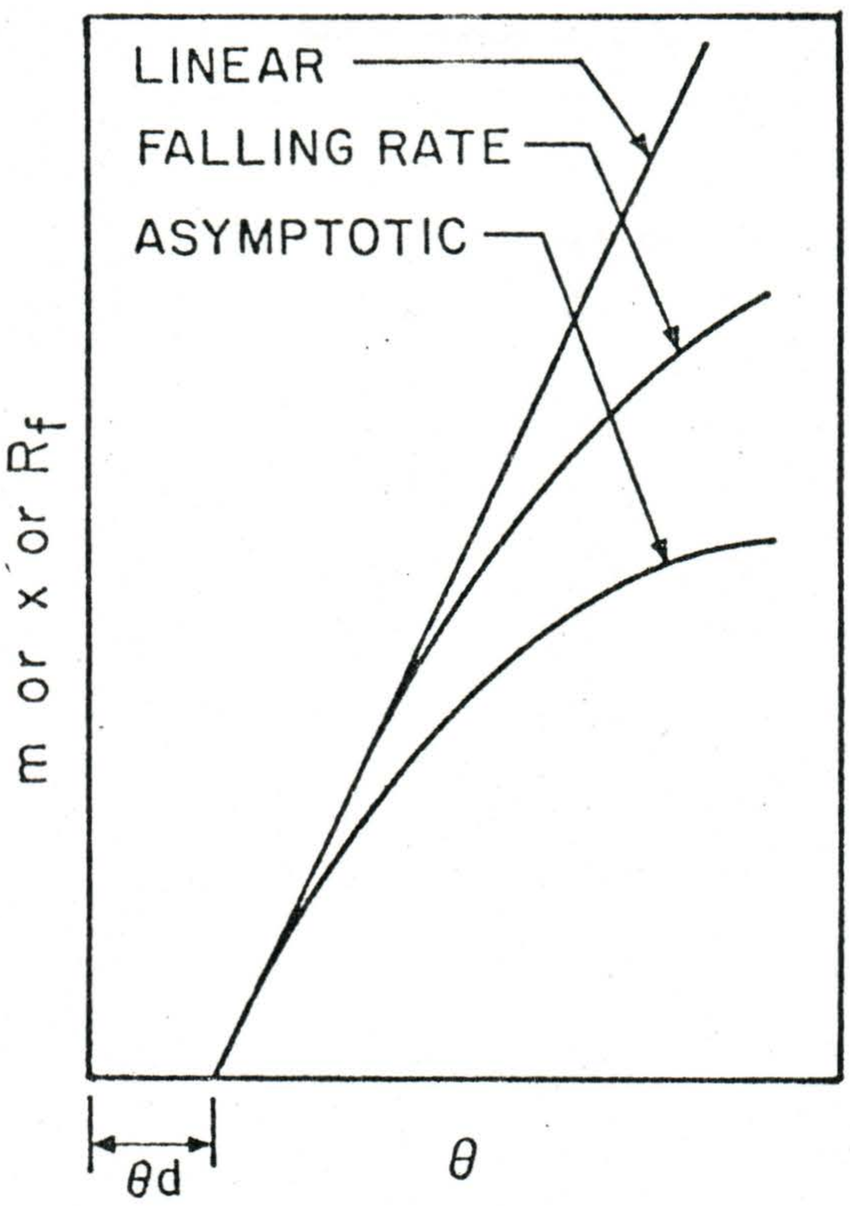


Fig. 1.1 Characteristic Fouling Curves

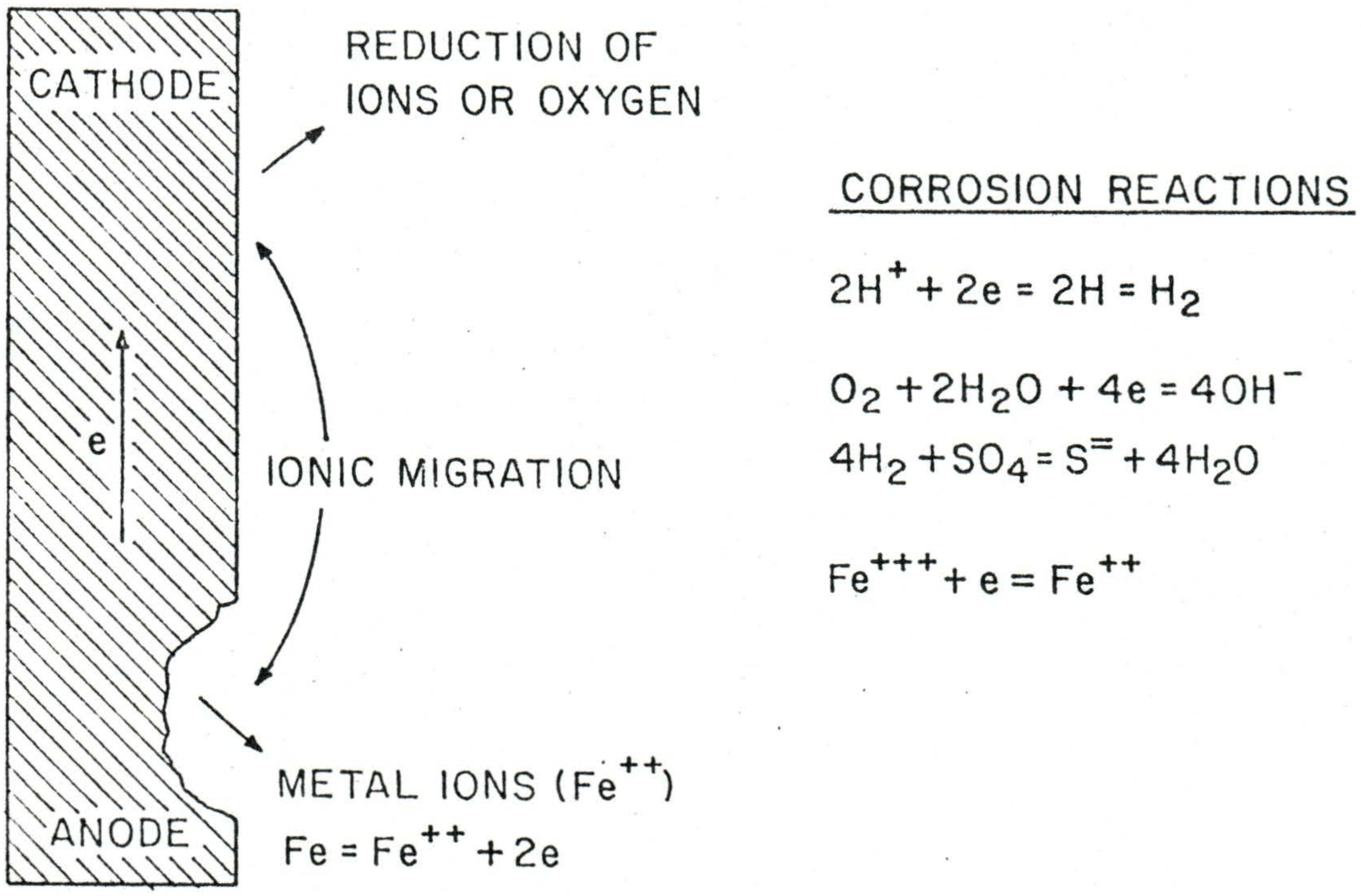


Fig. 1.2 Galvanic Cell in Water

would finally turn into a falling rate mode or whether a falling rate curve is the start of an ultimately asymptotic behaviour. And this could be of considerable significance especially when there is much scatter in the observed data.

A large number of models essentially describing these curves has been presented in the literature. Reviews by Taborek et al., [10] Suitor et al., [11] and Epstein [13] give descriptions, physical significance, assumptions and limitations of each of these models. Table I summarizes some of these models. None of these models, with the exception of scaling, however, has been extensively tested.

1.2.3. Interrelationship of Fouling and Corrosion

Little work has appeared in the literature with respect to the effect of corrosion in promoting fouling. Most of the early reviews [10,11] have just introduced this aspect of fouling. A comprehensive treatment has been given by Epstein in his recent review paper [13]. Hopkins and Epstein [23] had earlier explained their results on the fouling of 304 stainless steel with ferric oxide by invoking electro-chemical crevice corrosion as the mechanism governing the fouling.

It is generally recognized that corrosion in aqueous systems gives rise to the creation of a protective oxide film which has been estimated to be typically in the range of about one micron in thickness [29]. This passivating film in itself does not constitute a significant fouling resistance. However, when this film is disrupted, by erosion or spalling, a corrosion cell of the type illustrated in Fig. 1.2 [30] is set up and the corrosion products start to accumulate

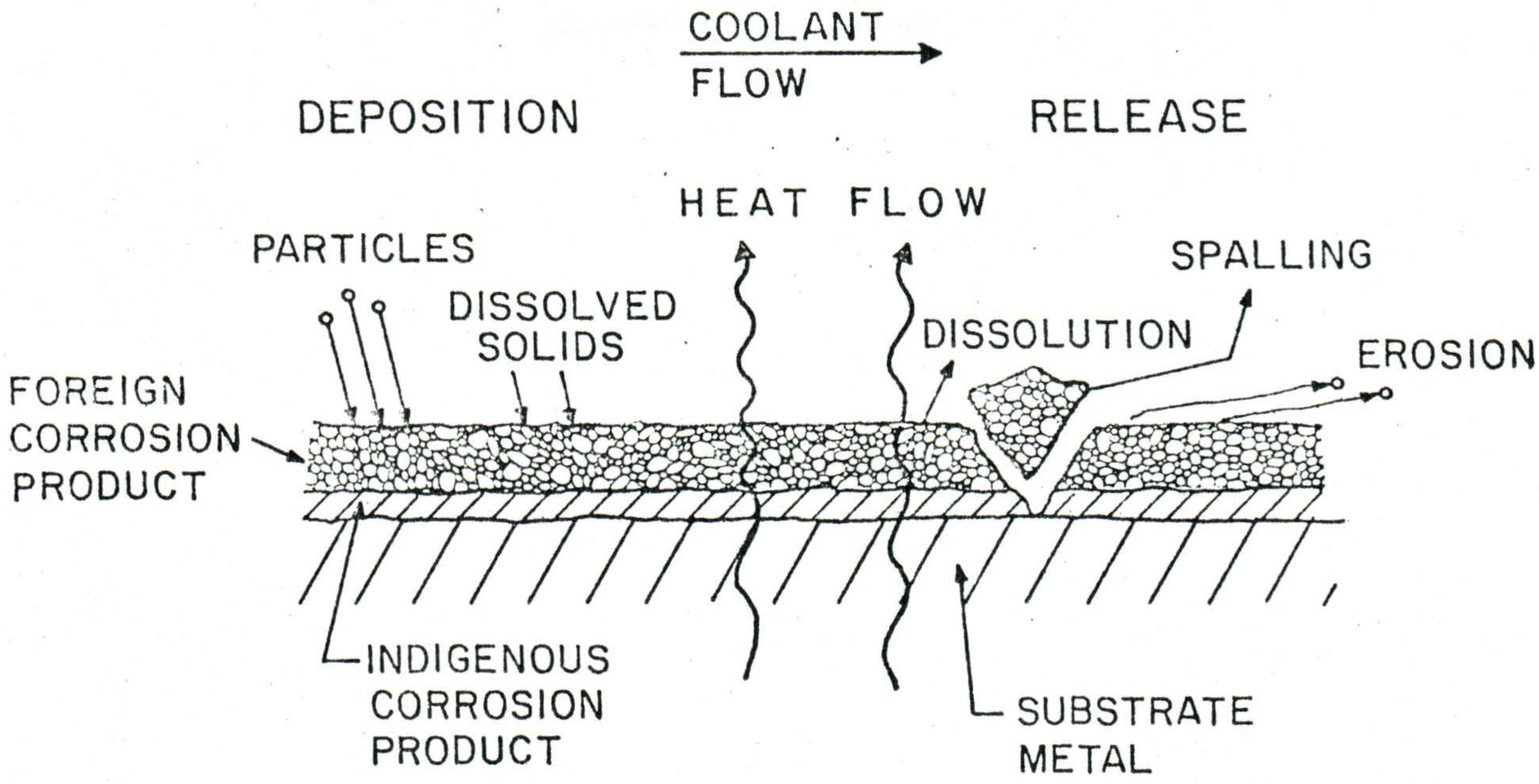


Fig. 1.3 The Deposit Environment

unevenly on the surface. These initial growths have the effect of roughening the surface and thus providing nucleation sites for deposits to initiate [11,13]. Also, they serve to trap suspended particulates and give rise to small pockets of stagnant liquid which become subject to crevice corrosion [31] especially in the presence of an aggressive ion such as the chloride ion. A cycle of corrosion and fouling thus arises [22,23]. The complete deposition environment can then be depicted by Fig. 1.3 from Charlesworth [32]. The fouling corrosion cycle can be thus initiated by particulate fouling followed by crevice corrosion in which case the corrosion products would serve to bind the particulates to the surface [23].

1.3. Scope of this Work

Hopkins [22] concludes his study on the 'Fouling of Heated Stainless Steel Tubes by Flowing Suspension of Ferric Oxide' by recommending the extension of laboratory fouling studies techniques to 'insitu' study of fouling of heat transfer surfaces in plant situations. Systems to date have generally been developed to meet the requirements of a specific fouling study and are unsuitable for a variety of applications. Also, there was evidence to believe, based upon his experimental results, that corrosion processes play a significant role in the fouling of heat transfer surfaces and a detailed study of the interrelationship between particulate fouling and corrosion was recommended. A criticism of the work mentioned in reference [22] was that by electrically heating the heat transfer surface by passing a current through the test section, magnetic and/or electrical effects could be created which could affect fouling, invoke corrosion, and therefore influence the observed results.

Also the work done in the above reference with respect to particle size and fouling was beset with many difficulties and remained quite inconclusive. Nijsing [33] considers basic experimental research on fouling requires use of methods for characterization of the fouling fluid with respect to concentration and size of particulates.

For the above reasons the objectives of the proposed research covered in this thesis were:

(1) Design and construction of an experimental apparatus for study of fouling and its interrelationship to corrosion which would eliminate the possible sources of error and limitations of existing design used in reference [22] and afford means by which all of the variables recognized to influence the fouling process could be monitored and controlled. The system would have adequate facilities for characterizing the fouling fluid with respect to size and concentration of particulates and a suitable method for analyzing the fouling deposit;

(2) Testing and evaluation of the apparatus by attempting to duplicate a selected number of runs from the 1969-1973 University of British Columbia study [22] using ferric oxide as a contaminant and stainless steel as the heat transfer surface material to establish reproducibility of data--a problem which has plagued researchers in the fouling field. A few runs to investigate the crevice corrosion hypothesis would also be attempted.

CHAPTER 2

DESIGN AND CONSTRUCTION OF HEAT LOOP

2.1 Design Approach

Any research unit designed to carry out fouling studies should allow a relatively easy method for measurement and control of critical process parameters such as heat flux, flow rate and fluid and wall temperatures. In addition, the system should be constructed such that a variety of fouling fluids and heat transfer material can be studied [18]. Another feature which must be incorporated, particularly in the study of particulate fouling and corrosion controlled fouling, should be a provision to analyze the deposits formed both qualitatively and quantitatively. Means of controlling the fouling fluid composition with respect to size and concentration of suspended particulate matter, the dissolved oxygen concentration and pH are also desirable. Although most of the experimental rigs designed to study the fouling phenomena, have been based on the measurement of changes in heat transfer resistance which reflect changes in the fouling resistance, each one has had a special and unique design, suited to meet the objectives of the particular investigation carried out. For example the fouling units developed by HTRI [1, 20] were primarily designed to measure scaling rates in cooling water. The heat loop designed by Watkinson [3] and later modified [22, 34] employed a recirculating system where fluid was pumped from a storage tank held at a given temperature through an electrical resistance heated test section. This system was designed specifically for the study of fouling by particulate matter. In neither of the above systems was provision made for the easy examination of fouling deposits and neither could detect the presence of thin deposits because of inconvenient and imprecise control of process variables such as flow rate, inlet temperature and heat flux. Consequently, it was decided to design and construct a heat loop which would detect fouling with more precision than other loops and at the same time allow a quick and convenient method for examination of the fouling deposits.

2.2 Design Criteria

The criteria adopted for the design of the heat loop were developed to overcome the disadvantages of the loop designed by Watkinson, modified by Mayo and used by Hopkins [22] for his studies. These criteria were as follows:

(1) Incorporated in the loop should be means by which the fluid chemistry can be carefully monitored and controlled particularly with regard to variables known to influence corrosion controlled fouling. These include pH, dissolved oxygen concentration and presence of ions from outside sources such as loop piping and other loop components.

(2) Provision for more precise control of the heat transfer variables maintained constant during a fouling run such as the flow rate and heat flux.

(3) Elimination of heating the test section by passing an electric current through it since this could conceivably result in electric and magnetic effects which might influence the fouling rate.

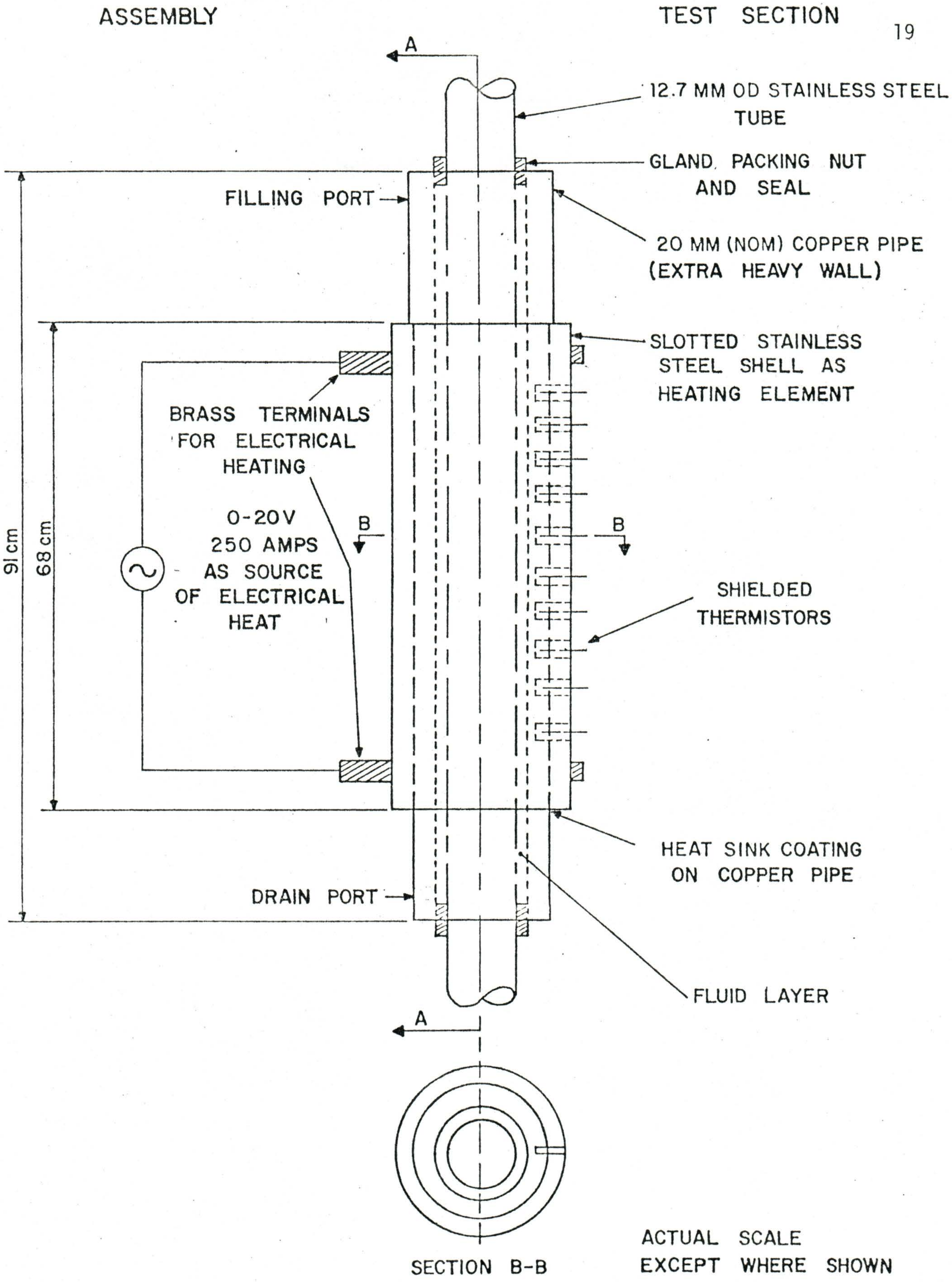


Fig. 2.1 Test Section Design Concept.

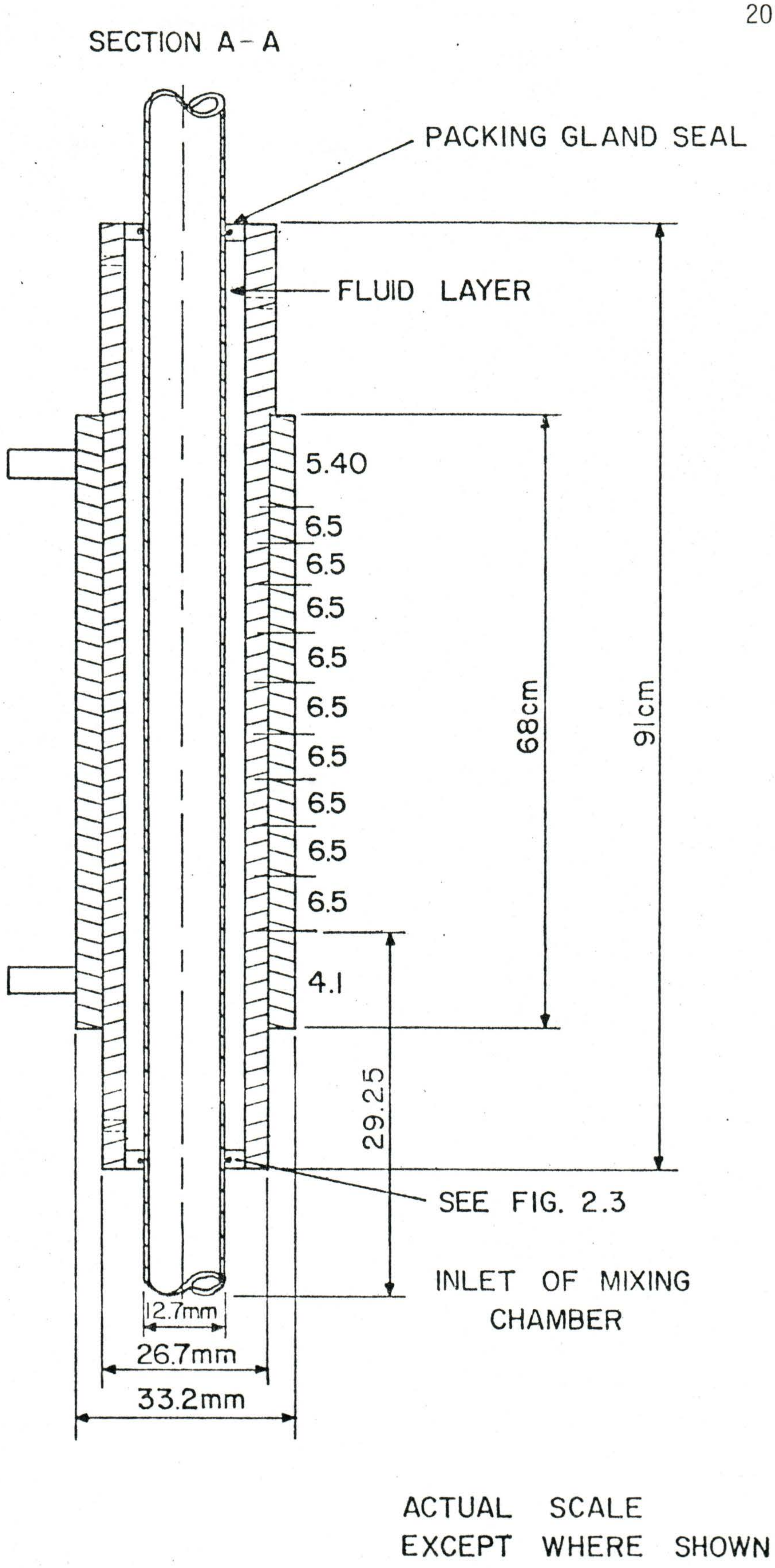


Fig.2.1 (continued)

(4) A means of easily removing the test section without dismantling the loop.

(5) A leak proof system such that fluid would not require make-up if a test were carried over an extended time period.

(6) A portable system that could be transported to an industrial site and run on a continuous basis by tapping a line from a process stream to the heat loop without loss of control of the loop.

(7) A data logging system capable of monitoring the process parameters and the fouling data.

(8) A control system such that the heat loop could be left unattended for long periods of time. (In the range of weeks.)

2.3 Heat Transfer Loop

The test section assembly developed to meet the above requirements is shown in Fig. 2.1. The system consisted essentially of a hollow cylindrical thick walled copper core, an inner annulus of the sensible heating liquid mercury, and a centrally positioned sample of the tube to be studied. The copper core served as a containment tube for the mercury and as a housing block for the location of the thermal sensor. Heat to the test section was provided by electric resistance heating of an external slotted cylindrical stainless steel shell mounted on the copper tube. Thermal sensors were positioned on the external surface of the copper core to monitor changes in wall temperature of the tube as it fouled.

Fig. 2.2 shows a schematic of the heat loop and Table II lists the sizes, specifications and materials of construction of the system

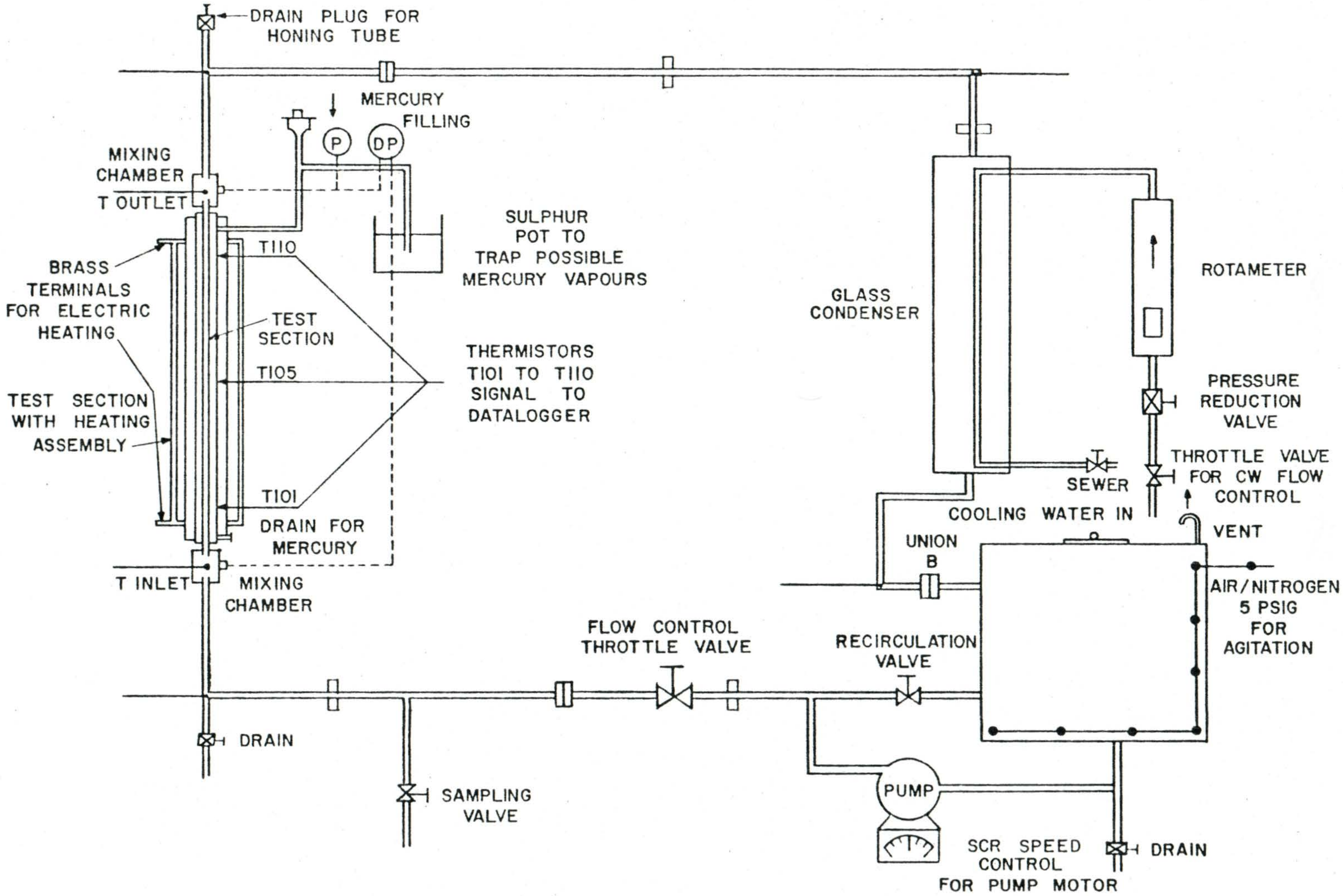


FIG.2.2 HEAT TRANSFER LOOP SCHEMATIC.

Table II

Equipment Components of Heat Loop

Component	Description
Storage Tank	250 litres - plexiglass tank equipped with air line for agitation.
Recirculation Pump	Fluorocarbon 'Jupiter' teflon self priming centrifugal pump with silicon controlled rectifier (SCR) speed control, HT Model MCP25-1255. Head assembly - TFE teflon Impeller assembly - TFE and FEP teflon Bearings - Fluorolog G (proprietary impregnated teflon)
Motor	115 V, 60 Hz, single phase $\frac{1}{4}$ HP, 3450 RPM, totally enclosed, explosion proof, fan cooled.
Pump Throttle Valve	Globe valve straight pattern teflon valve. 12.5 mm orfice, 12.5 mm NPT female connections. Model PVI-88. Fluorocarbon.
Test Section	12.7 mm OD, 10.92 mm ID type 316 stainless steel seamless tubing.
Pressure Taps	Teflon, spaced at inlet and outlet mixing chambers.
Thermistors	Fenwal Electronics Model GB31P8 glass shielded standard probe thermistors. 3 mm diameter. Range 0-150°C, Ro at 25°C = $1k_\Omega \pm 10\%$
Bypass Valve	Teflon model PV5-68. Fluorocarbon. 10 mm orfice and 12.5 mm NPT male port connection.
Pressure Transducer	Viatran, model 209, 0-1.5 N/M^2 pressure transducer. (on order)
Electrical Terminals	Brass, silver soldered to heating element.

continued

Table II (Continued)

Electrical Cable	Philips welding cable size 4/0 AWG.
Primary Transformer	Sola constant voltage transformer type CVS. Rated VA5000, 60 HZ. Input volts 465-630, output volts 120 V-42.4 amps and 240 V-21.2 amps.
Powerstat (variable auto-transformer)	Type 1156 D3P Superior Electrical. Input 120 V, output 0-140 V, 150 amps, 21 KVA.
Current Transformer	Hammond CT type CT 500. 500:5A ratio, 20 VA, 50 Hz.
Secondary Transformer	Hammond type F, single phase transformer, 17 KVA, 60 Hz. Input 112-128 V, output 20-25 V.
Cooler	Glass condenser 138 cms long. Inner tube 12.7/10.92mm ID/OD 316 stainless steel tubing. Outer glass jacket 25 mm inner diameter.
Cooler Rotameter	Fischer and Porter, precision bore Flowrator. Range 0-10 USGPM.
Power Meter (for measurement of voltage and amperes and power across test section)	Digital ac Power meter Type 2503 Yokogawa Electrical Works Ltd. Range volts - 3 to 600 V currents - 100 MA to 30 A wattage - 300 MW to 18 KW Accuracy - 0.1% High resolution - 1 mV/digit, 0.1 mW/digit and 10 μA/digit.
Test Section Insulation	Inside - 4 x 4.0 mm Outside - 30 mm inch fibreglass pipe insulation

components. The essential features of the recirculation heat loop employed were the use of teflon for system piping and a constant flow metering pump with a non mechanical drive to minimize flow control valves and pump seals. Valves, elbows and fittings were kept at a minimum in the loop as they provide potential lodging grounds for deposited material and can be responsible for flow variations.

The 200 kg of fouling fluid used in a typical test run was stored in a plexiglass tank equipped with a compressed air line, for fluid agitation which extended around the bottom of the tank. Use of plexiglass tank helped in reducing heat losses from the storage tank. A recirculation line was provided on the storage tank which in conjunction with the compressed air line, helped to minimize settling of any particulates added to the fluid for study purposes and ensured that the test fluid remained saturated with oxygen during the course of a run. For experiments designed to study the effect of oxygen concentration on corrosion controlled fouling, the particulates were kept dispersed by using nitrogen in place of air. In order to study the interrelationship of fouling and corrosion, it was necessary to use a totally non corroding material of construction for the remainder of the loop. By doing so, the only corrosion products present in the system would be these from the section under study or those deliberately added, and not those released by the corrosion of the loop itself.

2.4 Heat Loop Subsystems

2.4.1 Test Section

A number of alternate designs were investigated before adopting the test section configuration described above. Appendix II describes and briefly evaluates these alternate solutions. As the test section design called for making the heating and temperature sensing devices to be independent of each other in order to reduce individual test section preparations, an indirect method of heating the test section was considered desirable. To meet the test requirements of a constant high heat flux (of the order of 200 KW/M^2) with precise control and measurement, it was decided to use a sensible heating medium between an electrical heated surface and the test section. This also eliminated any possible influence that electric and magnetic effects might have on the deposit growth as the test section would remain electrically isolated from the heating element. This arrangement served to shield the test surface from electric fields and reduce the magnetic field to a negligible amount. (A similar arrangement adopted in another study to analyze waterside corrosion in LMFBR evaporator tubes [35] estimates the magnetic field for that system to be less than 10^{-8} tesla at full power (26 KW)).

Since indirect electrical heating was to be adopted, any media offering high thermal resistance in the path of the heat flow to the test section was eliminated otherwise it could have led to an over heating of the copper core and a possible melt down at high heat fluxes. Consequently, the choice of the sensible heating medium which would heat the outer surface of the test section was restricted to a high boiling point, high thermal conductivity fluid. A number of fluids, hot water, glycerol and special heating oils such as "ESSOTHERM", were experimented with. At high heat fluxes, all failed or tended to boil over without transferring much heat to the fluid in the test section tube. With some initial reluctance, it was finally decided to try mercury. The use of mercury however initiated a series of elaborate sealing and filling arrangements. Fig. 2.3 and 2.4 give the scheme adopted for preventing the mercury from leaking past the test section and for filling and draining of the mercury annulus. An escape passage for hazardous mercury or mercury vapor distilling over in the event of a sudden increase in the copper wall temperature due to fluid flow failure through the test section was provided as a precautionary measure. In Fig. 2.4, the outlet of the mercury escape tube was kept immersed in a pot of sulphur which would prevent any hot mercury vapors from escaping to the atmosphere by neutralizing it to mercurous sulphide. Some compromise had to be effected in the flexibility of dismantling and installation of test sections by adopting the above sealing mechanism as earlier attempts to use simple sealing devices (e.g. viton 'O' rings) failed at high heat fluxes owing to weight of the mercury column and the heat.

2.4.2 Heating Element

To provide heat to the test section, a special type of heating element was developed. It consisted of a heat treated slotted cylindrical stainless steel shell (thickness 5.5 mm) for ensuring circumferential heat flux symmetry mounted on the outer surface of the copper core. Fig. 2.5 gives the details of the heating element.

Earlier, an attempt was made to use a hollow stainless steel pipe as the heating element but this had to be abandoned because the electrical resistance was too low and sufficient potential drop could

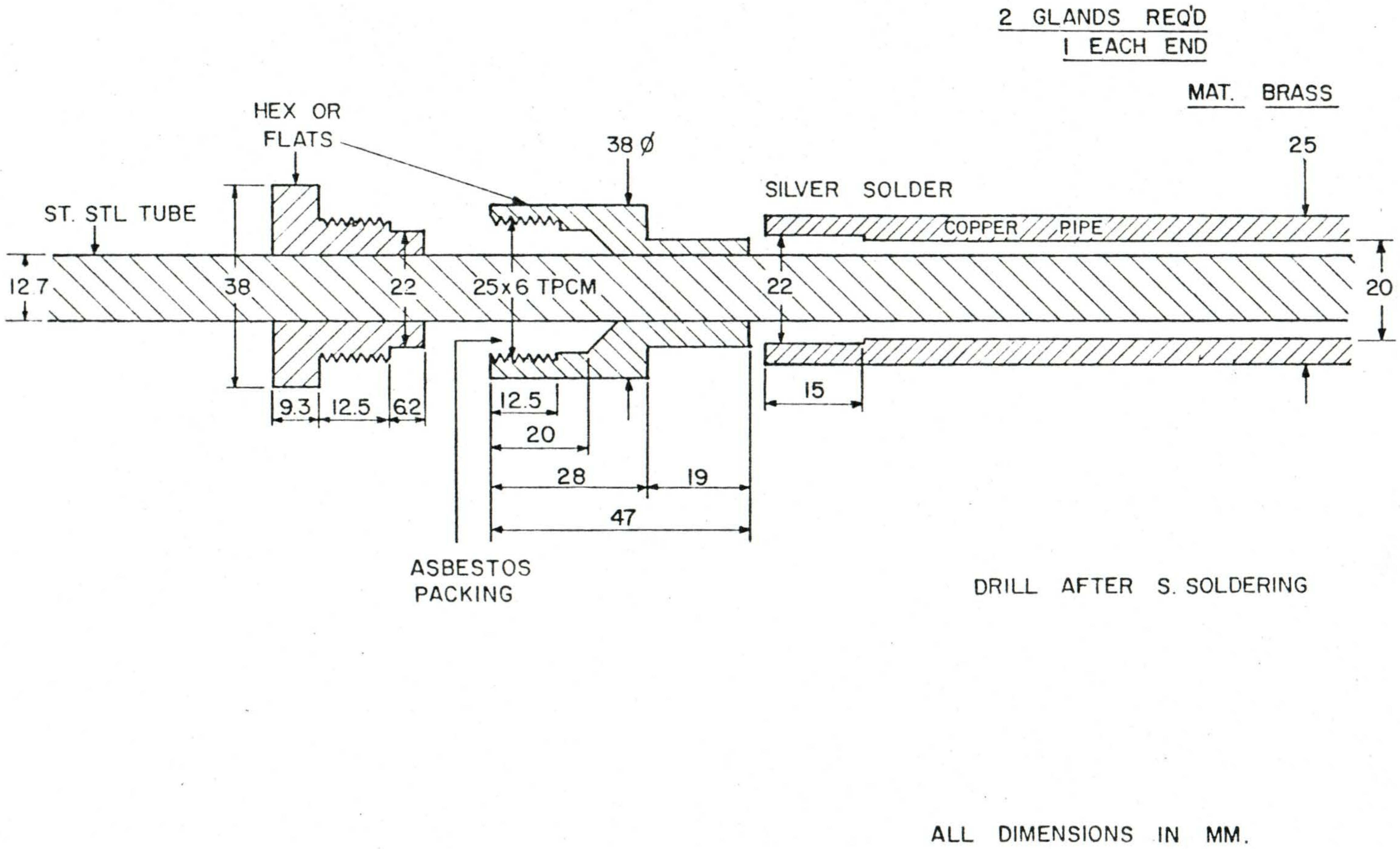


Fig. 2.3. Sealing Arrangement for Mercury.

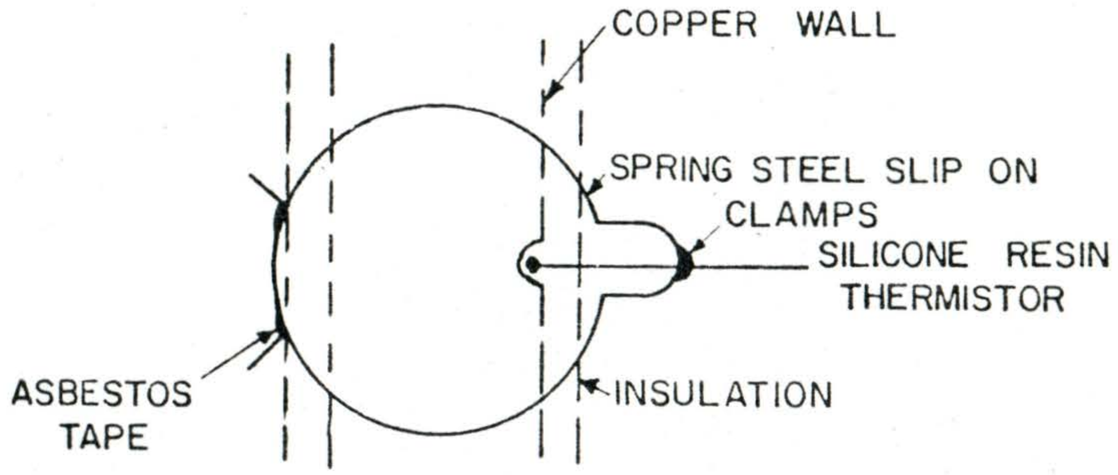


Fig. 2.6. Slip on Attachment
Clamps for Thermistors.

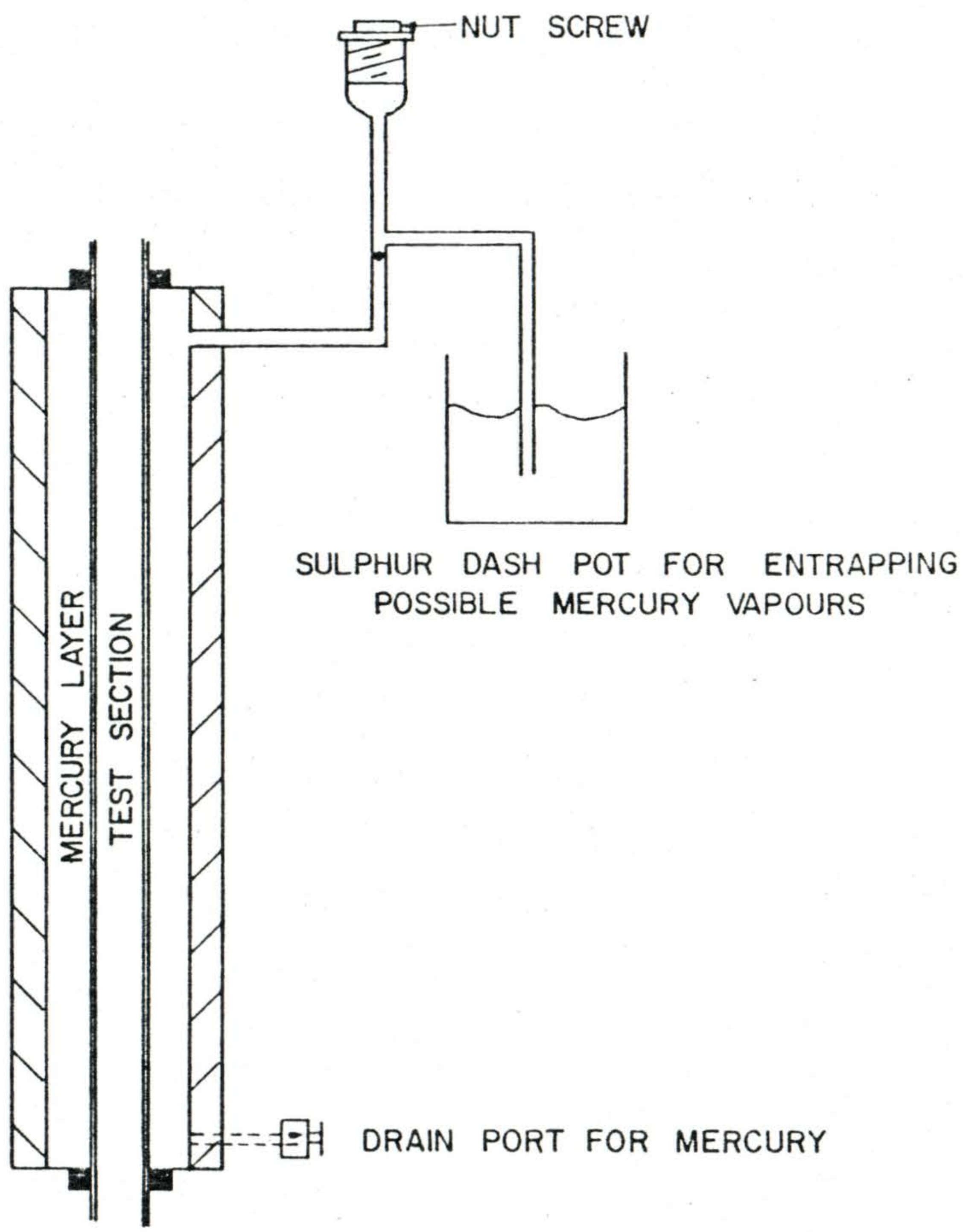


Fig. 2.4. Filling and Draining Scheme for Mercury.

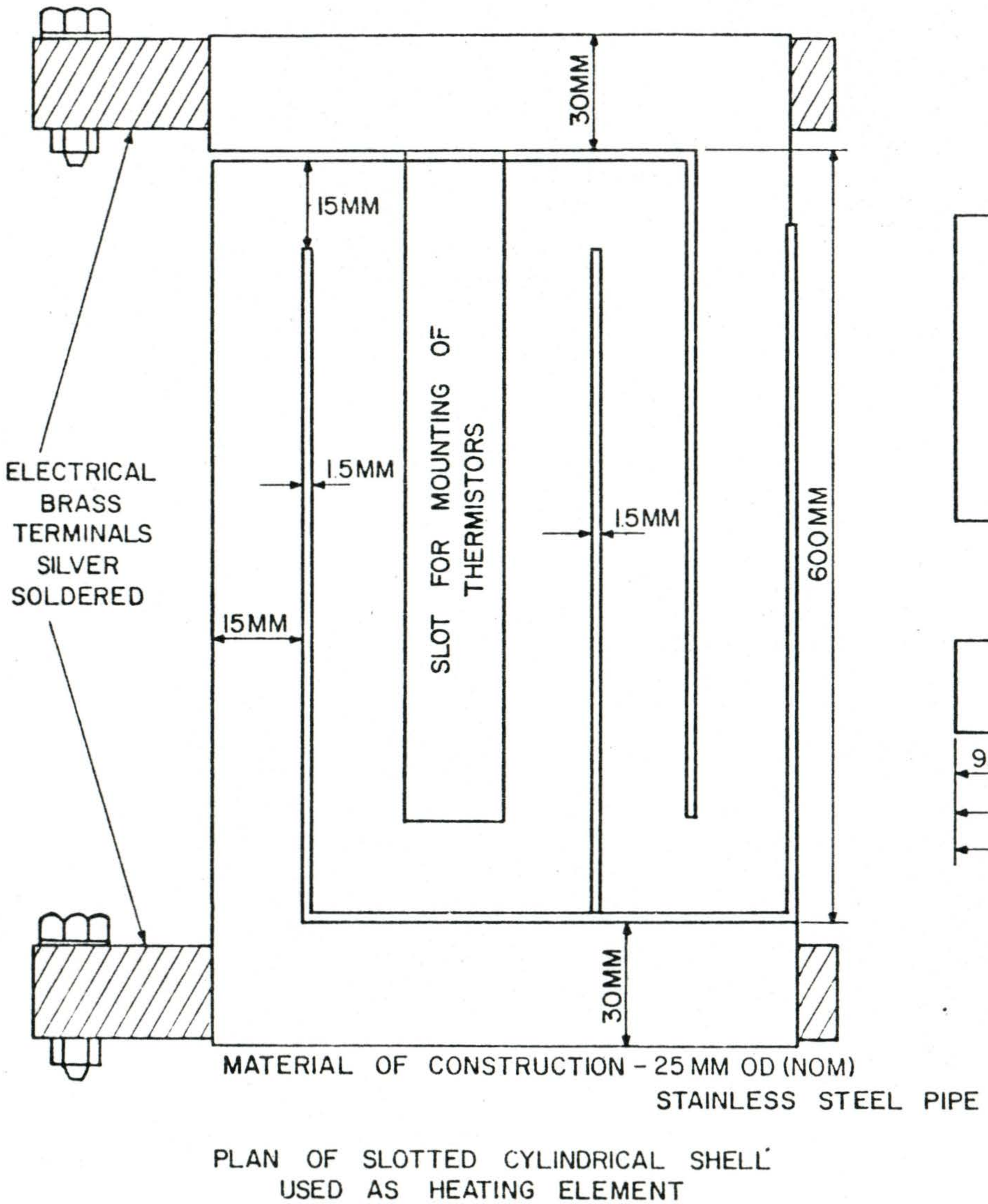


Fig. 2.5. Heating Element.

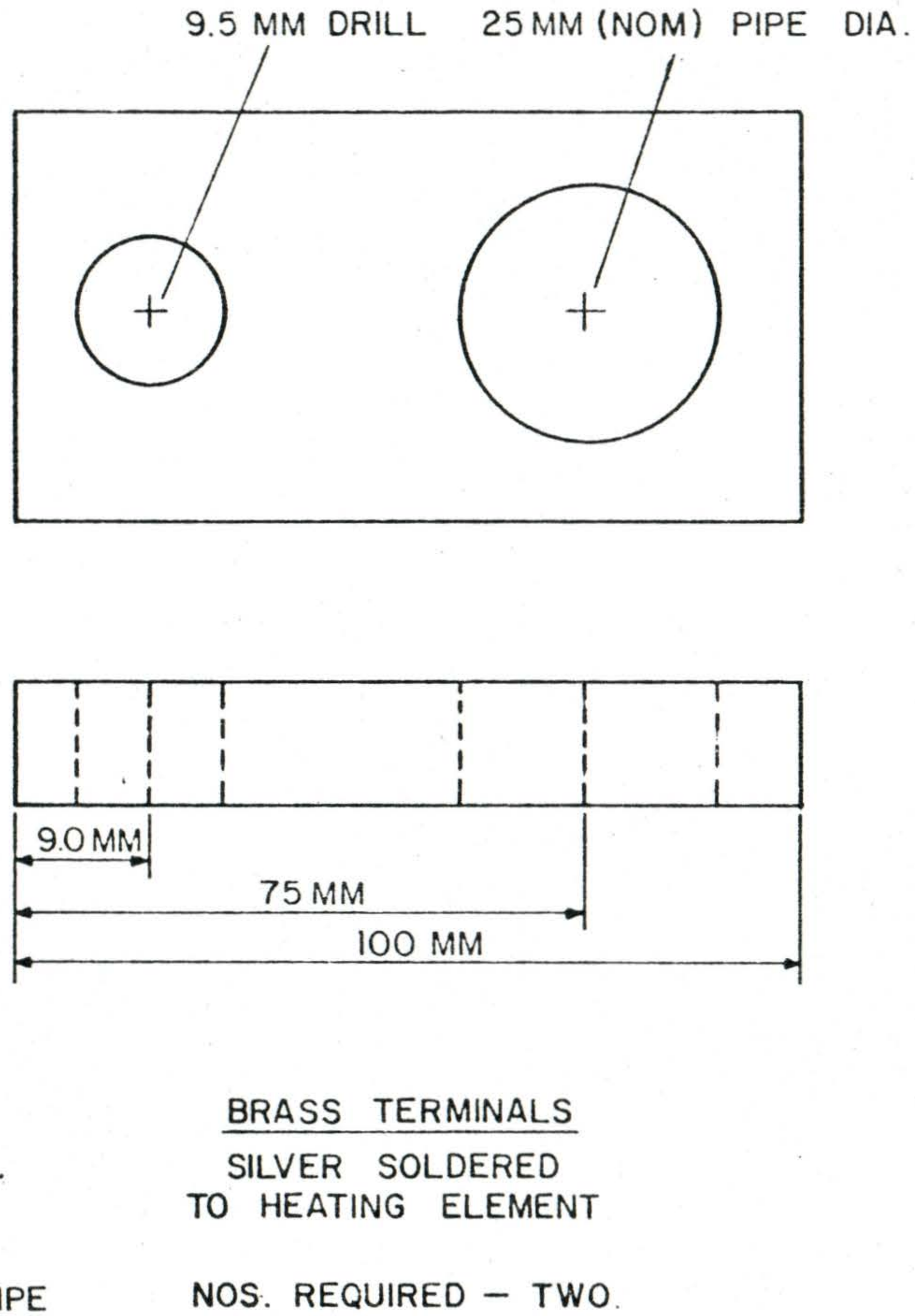


Fig. 2.8. Electrical Terminals.

not be attained to give the required heating of 5 KW max. Use of a thinner wall piping was also undersirable, as this could lead to very high shell temperatures and create problems with material of construction and insulation. Therefore an outside shell temperature of 180^{o}C was established as a safe limit. At maximum power level, the outside shell temperature has been recorded as 150^{o}C. One of the disadvantages associated with electrical resistance heating is the instrumentation problems it can create by a possible a.c. leakage through the thermal sensors to the data logging system. Reference [22] cites the elaborate procedures and precautions that had to be undertaken to overcome it, and inspite of great care, failures were frequently encountered. Thus a method for electrically insulating the copper core (housing block for attachment of thermal sensors) from the shell heater was devised while at the same time the insulating gap or medium was kept such that it offered minimal resistance to the flow of heat from the heater to the test section. A very close tolerance therefore was necessary in the gap between the heater and the copper wall in order to avoid direct contact. The use of a high thermal conductivity and electrical resitivity medium to fill this gap was also needed. Dow Corning's heat sink compound basically an epoxy resin - had properties to match these requirements. Typical properties are shown in Table III. A very thin uniform layer of this compound was applied over the copper core. The use of a slotted heater greatly facilitated this procedure.

The test section was designed to achieve under steady running a total heat flow of 5 KW corresponding to the highest rated output from the electrical system. This corresponds to a heat flux of 205 KW/M^2

Table III

Properties of Dow Corning's Epoxy Heat Sink Compound

Properties	
Thermal Conductivity (W/M^oC)	1.7
Dielectric Strength (volts/mil)	460
Thermal Expansion Coefficient (M/M^oC)	10×10^{-6}
Volume Resitivity (ohm-cm)	10^{15}
Dielectric Constant at 1 KHz	7.2
Dissipation Factor at 1 KHz	0.04
Service Temperature, max ^oC	300

related to the inside surface of the 10.75/12.70 mm ID/OD 316 stainless steel tube used as the test section. The mercury filled annular gap was sized to give temperatures below 150^{o}C on the surface where the thermistors were located. As the loop would operate well below the boiling point of the mercury effects due to convection currents in the mercury were not considered. However effects due to the thermal expansion of mercury were taken into account in fixing dimensions.

2.4.3 Thermal Sensors

The temperature distribution along the test section wall was monitored by shielded (glass coated) probe thermistors. The shielded thermistors had an added advantage as the glass coating ensured the thermistors remained insulated from any possible a-c leakage.

As the local fouling resistances were determinable from the increase in wall temperature from the clean condition divided by the applied heat flux i.e.

$$R_f = \left(\frac{T_{foul} - T_b}{q'}\right) - \left(\frac{T_{clean} - T_b}{q'}\right) \qquad (2.1)$$

the thermal measurements during the course of a fouling run were reduced to monitoring the temperature differentials with respect to the initial temperatures measured when the tube was clean. Thermistors with their high sensitivity to temperature changes were extremely well suited for the above purpose. A high negative temperature coefficient of resistance (typical values of 6% decrease in resistance over 1^{o}C rise in temperature), combined with a stable response and good repeatability made thermistors a better choice then the conventional thermocouples used in a number of fouling studies [1, 3, 22]. The thermistors were positioned in 4 mm holes drilled on the outer copper wall using spring steel slip-on attachment clamps mounted on the S.S. heater and kept electrically insulated as shown in Fig. 2.6. The thermistors were sealed in position at the top of the clamp by silicone resin and at all times remained detachable from the system. 10 thermistors placed equidistant from each other were used to measure the temperature profile along the tube wall. Table IV shows the location of the thermistors.

2.4.4 Insulation

Insulation of the test section consisted of 8 mm thick and 40 mm wide asbestos tape wrapped over the test assembly and held in place by a 30 mm thick layer of 'Fibre glass' pipe insulation.

2.4.5 Electrical Heating System

The central portion of the test section tube was heated electrically from the outer shell heater by employing a power circuit as shown in Fig. 2.7. The power source used was a single phase, 550 V line with a circuit breaker rated at 30 KVA which was connected in parallel to two 'SOLA' basic constant voltage transformers with a regulated output voltage of 120 V and capacity 5 KVA. These transformers had a characteristic feature which held the output voltage to $\pm\frac{1}{2}\%$ for input variations as great as $\pm 15\%$ of nominal voltage. Variations in line voltage can be a source of great potential error as high as 0.4×10^{-5} M^2 - ^oC/Watts at a heat flux of 200 KW/M^2 in the measured thermal resistances, as witnessed in Ref. [22]. The output from these

Table IV

Thermistor Locations on Test Section

No.	Test Section Position Designation	Location: Distance from Lower Tube End, cms.
1	T101	25.25
2	T102	31.75
3	T103	38.25
4	T104	44.75
5	T105	51.25
6	T106	57.75
7	T107	64.25
8	T108	70.75
9	T109	77.25
10	T110	83.75
11	TIN	Inlet Mixing Chamber
12	TOUT	Outlet Mixing Chamger

transformers was fed to a 'Superior Electric 1156D-3P' powerstat unit which was a variable autotransformer designed to deliver continuously adjustable voltage from a.c. power lines. The power input (and thus the heat flux) to the test section was controlled by this variac the rating on which was as follows:

Input: Volts 120 $\pm$ 0.5%

Output: Volts 0-140, Max. Amps. 150, Max. KVA 21

The powerstat output was further stepped down through a 'Hammond' custom made 120 V/20 V single phase 17 KVA air cooled transformer to give the desired power level of maximum 5 KW (heat flux of 200 KW/M^2) at 15-20 V and 250-300 amps. Heat losses through insulation and to surroundings were usually very low estimated to be around 3% [3]. Heavy wires (cable size 4/0 AWG) was used to connect the transformers and the brass terminals on the test assembly. The amperage flowing across the test assembly brass terminals was measured by reduction with a 500:5 current ratio CT 500 Hammond current tansformer. The current and the voltage across the test section was measured using a digital universal Power meter.

As the whole loop was constructed out of teflon, the electrical heating unit mounted on the outer copper tube and kept insulated from it also remained insulated from the rest of the loop.

2.4.6 Electrical Terminals

The power cables were clamped in position on two brass terminals at the upper and lower end of the heating element. Fig. 2.8 gives details of these brass terminals which were silver soldered onto the stainless steel heating element.

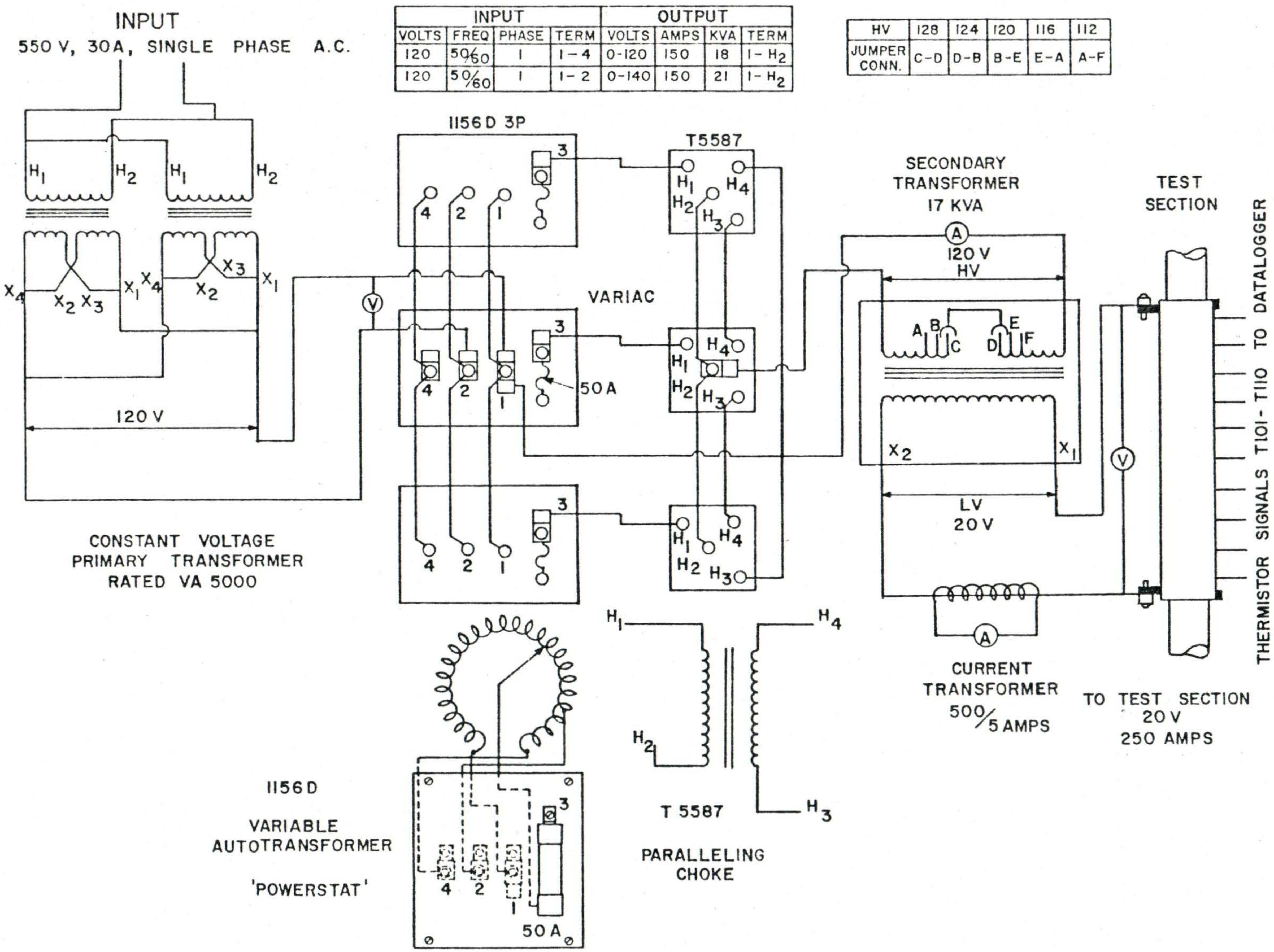


Fig. 2.7. Electrical Heating System Schematic.

2.4.7 Recirculation Pump and Motor

A teflon flow metering pump combined with a SCR (Silicon Controlled Rectifier) speed control on the pump motor was chosen with two basic considerations in mind. Test requirements called for a constant flow through the test section over long periods of time which was readily achieved by the silicon controlled rectifier speed control on the pump motor. Elaborate devices for monitoring flow such as orfice meters and flow control valves which are predisposed to trapping deposit material [34] were thus eliminated. In fact, the temperature increase (ΔT) across the test section has been observed to be a more precise method of measuring flow rate than an orfice meter on the loop in a similiar set up [22]. The special type pump selected for pumping the fluid around the loop featured a magnetic drive to eliminate shaft wear and leakage. The head assembly incorporated a press fit, teflon-to-teflon static seal, leaving only one moving part - the impeller. All wetted parts were teflon, except the internal shaft, which was ceramic and rated for high temperature as well as, being highly corrosion resistant. A teflon throttle valve was provided at the outlet of the pump for manual throttling to control the flow. Flow rate through the loop was determined by decoupling the loop at Union B (Fig. 2.2) and measuring the mass flow rate.

2.4.8 Recirculation Loop

The recirculating loop consisted mainly of 1.25/2.50 cms ID/OD teflon piping. A 65 cms (52 pipe diameters) hydrodynamic entrance length was provided upstream of the heated test section to establish the velocity profile. The inlet and outlet bulk liquid temperatures were measured by thermistors positioned in mixing chambers at the entrance and exit of the test section. Location of all thermistors on the heat loop are shown in Fig. 2.2. A sampling point was provided upstream of the test section for periodical analysis of fouling fluid for particulate size and concentration and presence of trace metal ions. Two drain plugs were provided at the top and bottom of the vertical limb of the loop containing the test section to facilitate honing of the test section and quick drainage of the tube at the end of a fouling run.

Pressure drop across the test section will be measured using a Viatran, Model 209, 0-15 psi pressure transducer. This equipment is on order and will be installed when received.

2.4.9 Heat Loop Cooler

On exit from the test section, the fluid was cooled in a double pipe cooler, before returning to the storage tank so that its temperature was lowered to the bulk fluid temperature in the tank. The inlet temperature to the test section was controlled by varying the water flow rate through this cooler. Two alternate designs shown in Fig. 2.9 were constructed. The first consisted of two double pipe coolers (1.55 M in length) in parallel, with the shell made of 1.25/2.5 cm ID/OD Teflon tube and the inner tube of 0.75 cms diameter copper tube coated with Dow Corning's heat sink compound to prevent fluid contamination from copper. The test fluid flowed through the outer annulus while the cooling water remained on the inner tube side. This design had two drawbacks. Since a very thin layer of the heat sink compound was desirable for efficient

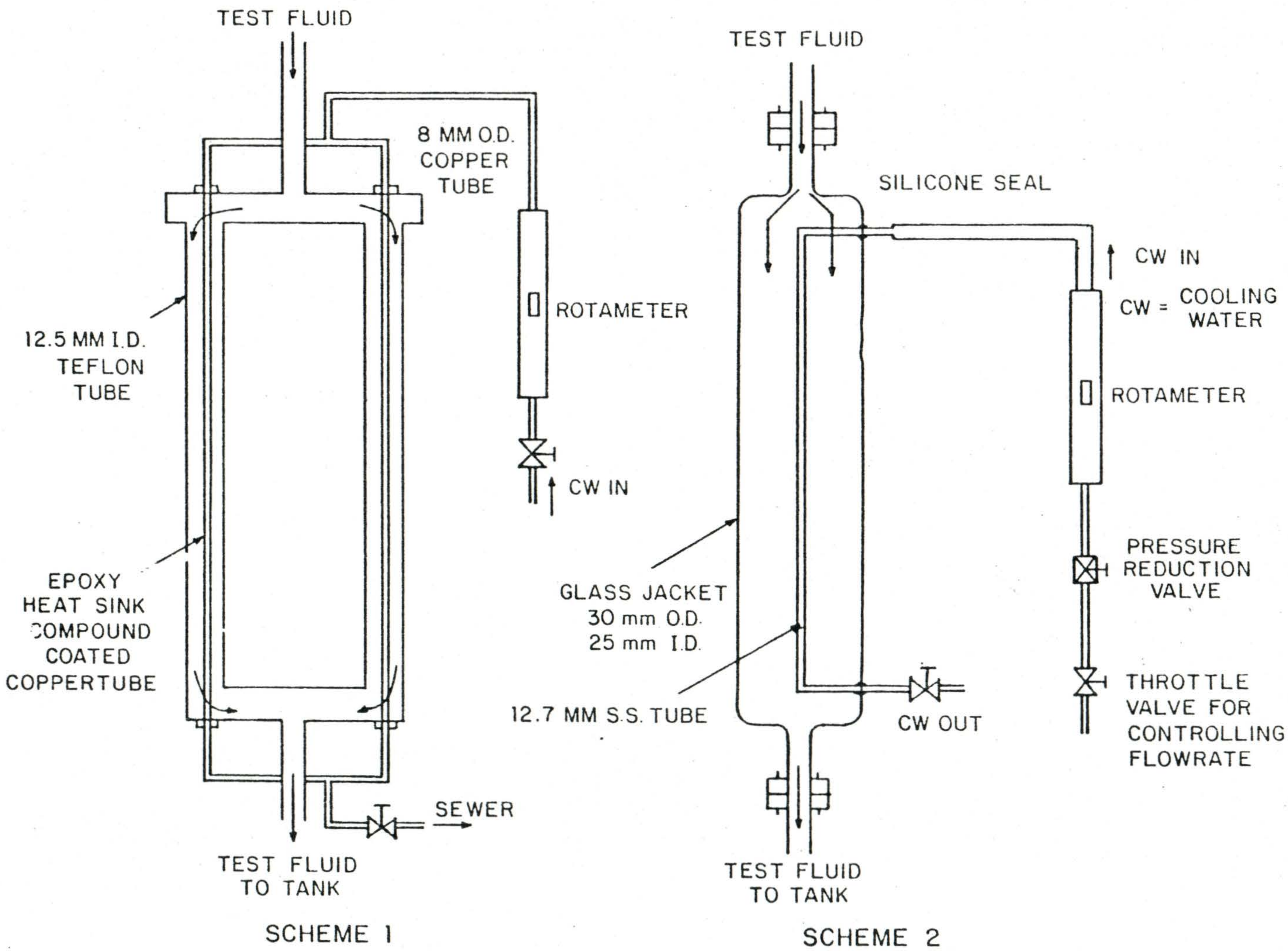
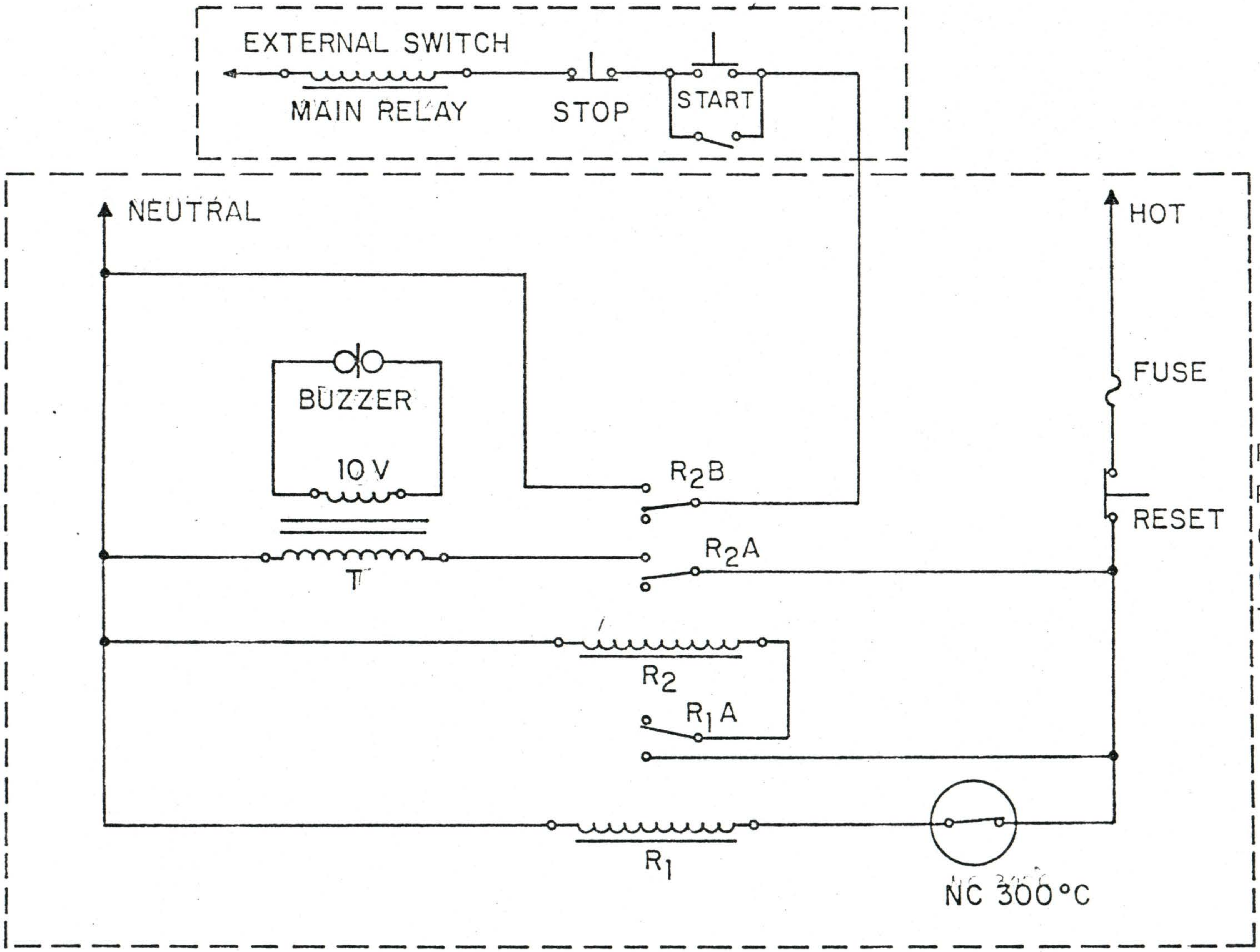


Fig. 2.9. Heat Loop Cooler Schemes.



R_1, R_2-120V Relays
R_1A, R_2B - Relay Contact Switch (10 Amp. Contacts)
T - 120 Volts at
10 Volts ou

Fig. 2.10. Safety Relay System.

heat exchange, the heat sink layer was easily smeared and bare copper exposed during assembly. During running, small portions of the compound were observed to be washed and carried down to the storage tank. A second design was consequently tried, which featured a 25/28 mm ID/OD glass shell and a inner tube of the same material and diameter as the test section tube. Effectively this became a second heat transfer test section with the hot fouling fluid on the outer surface and the cooling water on the inner side. Any deposit on the heated section could thus be visually observed. Co-current flow of cooling water was employed to avoid fluctuations in the hot fluid exit temperature and the cooling water was measured by a rotameter and controlled by a combination of a brass globe valve and a pressure reduction valve.

2.5 Safety Relay System

Since experiments would run typically for days, it would have to run unattended and thus a safety system was installed to switch off power to the system and sound an alarm buzzer in the event of pump failure or tube wall over heating. Mayo [34] gives a detailed description of a relay system devised for the purpose. Fig. 2.10 gives a schematic representation of a similar scheme adopted in the present design with suitable changes.

2.6 Data Logging System

The advantages of an automatic data acquisition system for data logging of temperatures and pressure drops continuously has been discussed in detail by Mayo [34]. Consequently an automatic data logging system was devised for data collection. Fig. 2.11 gives a schematic representation of the system adopted to monitor and record automatically the resistance signals from the thermistors while Table V lists the specifications of the basic components. Basically, it consisted of a digital voltmeter, scanner, digital clock, calculator, plotter and a line printer. The signals from the test section thermistors (T101-T110) along with the output signals from thermistors at other locations on the heat loop were fed to the scanner for sampling by the digital voltmeter, which translated these analogue signals to digital signals for every channel being scanned. A systems program was used on the calculator which set the clock to real time (Month, Day, Hours, Minutes, Seconds) and gave instruction to the scanner to scan with a set rate interval of 100 m sec per channel at a set scanning interval e.g. 1 scan every minute for first four hours and 1 scan every 5 minutes thereafter. The systems program also contained instructions to display the digital signals for each channel being scanned for 3.5 seconds, and record these val es on the data cartridge mounted on the calculator which were then printed out in a line format through the thermal line printer. The use of an additional plotter in conjunction with the calculator helped to obtain a graph of the thermistor signals versus time. Recorded along with the thermistor data would also be the output from the pressure transducer. The thermistor signals were directly compatible to the data acquisition system and needed no amplification or reference junction as in the case of thermo couples.

2.7 Coulter Counter

Concentration and particle size determinations were carried out

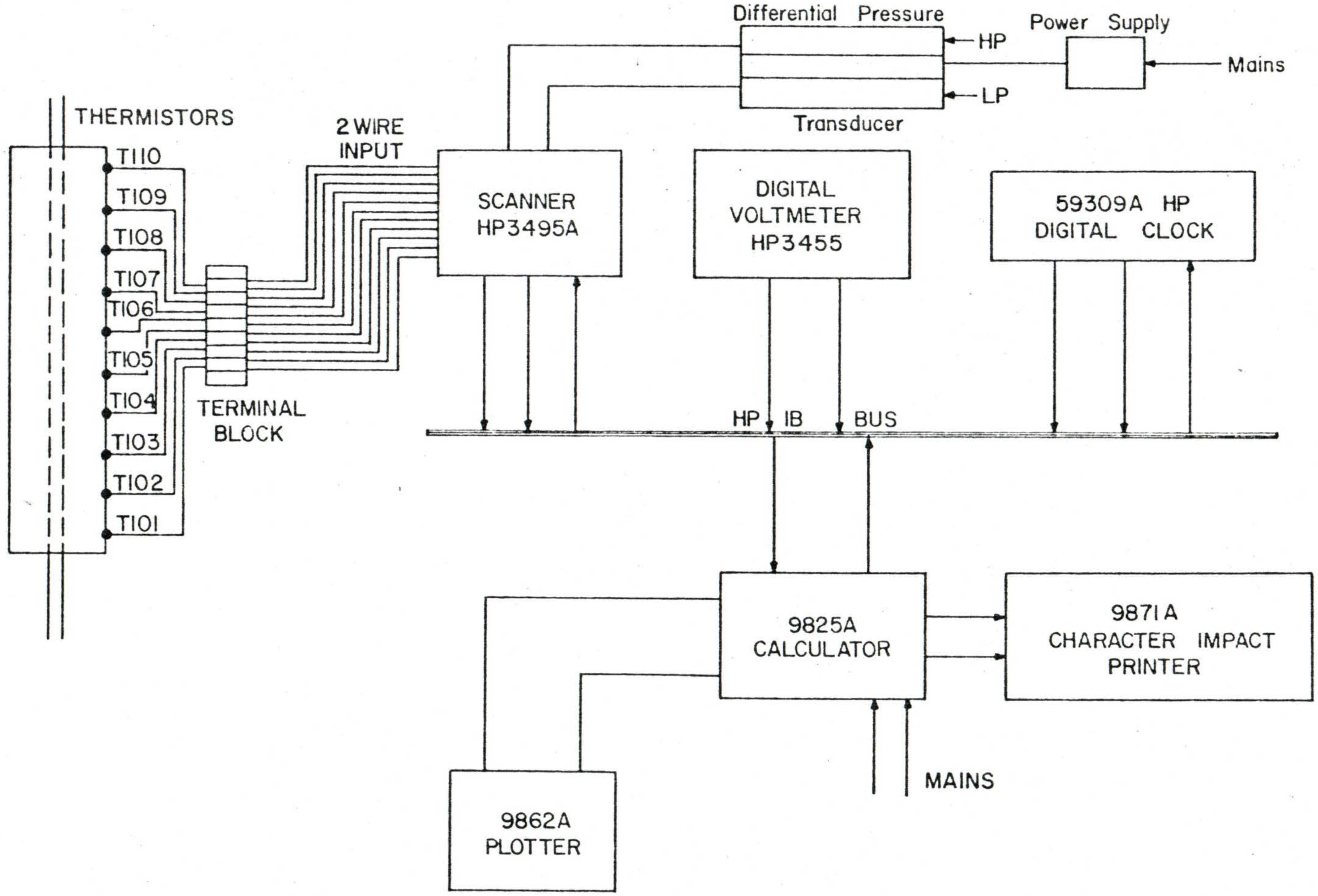


Fig.2.11.Schematic diagram of Data Logging System.

Table V

Data Logging System Components

Component	Model Number
Scanner	HP 3495A
Digital Voltmeter	HP 3455A
Innterconnections HP-1B interface Bus	HP-1B
Calculator	HP 9825A
Plotter	HP 9862A
Character Impact Printer	HP 9871A
Digital Clock	HP 59309A
Data Recording	HP 9865A Data Cartridge

HP - Hewlett Packard.

using the Coulter Counter model TAII. Fig. 2.12 shows the block diagram of the system explaining its working principles. The basic principle of its operation is as follows: The number and sizes of particles in suspension in a conductive liquid is determined by forcing the suspension to flow through a small aperture and monitoring an electric current which also passes through the aperture. Electrodes immersed in the liquid are placed on both sides of the aperture. The passage of a particle through the aperture induces changes in the resistance between the electrodes which produces a current pulse of short duration of magnitude proportional to particle volume. This resulting series of pulses is electronically scaled and counted. With reference to Fig. 2.12, a vacuum is applied to the manometer to force the sample suspension through the aperture tube where an electrode inside it holds that part of the electrolyte at ground potential. A second electrode, fed by a constant current supply (from the preamp card) is immersed in the sample heater, the current through which must go through the aperture to return to ground. The principle limiting resistance to the current is the electrolyte within the aperture. A particle in suspension passing through the aperture increases resistance and reduces current (momentarily) and the percentage of current change is proportional to the ratio of particle volume to volumetric aperture size (cross section x length through the wafer). The preamp card controls the current flow to external electrode and converts the current change pulses into voltage pulses. The voltage pulses from the preamp are amplified, in a main amplifier and pulse stretcher (M.A.P.S.) to bring all pulses to a measurable levels. Pulses from the M.A.P.S. are fed to the sixteen integrators,

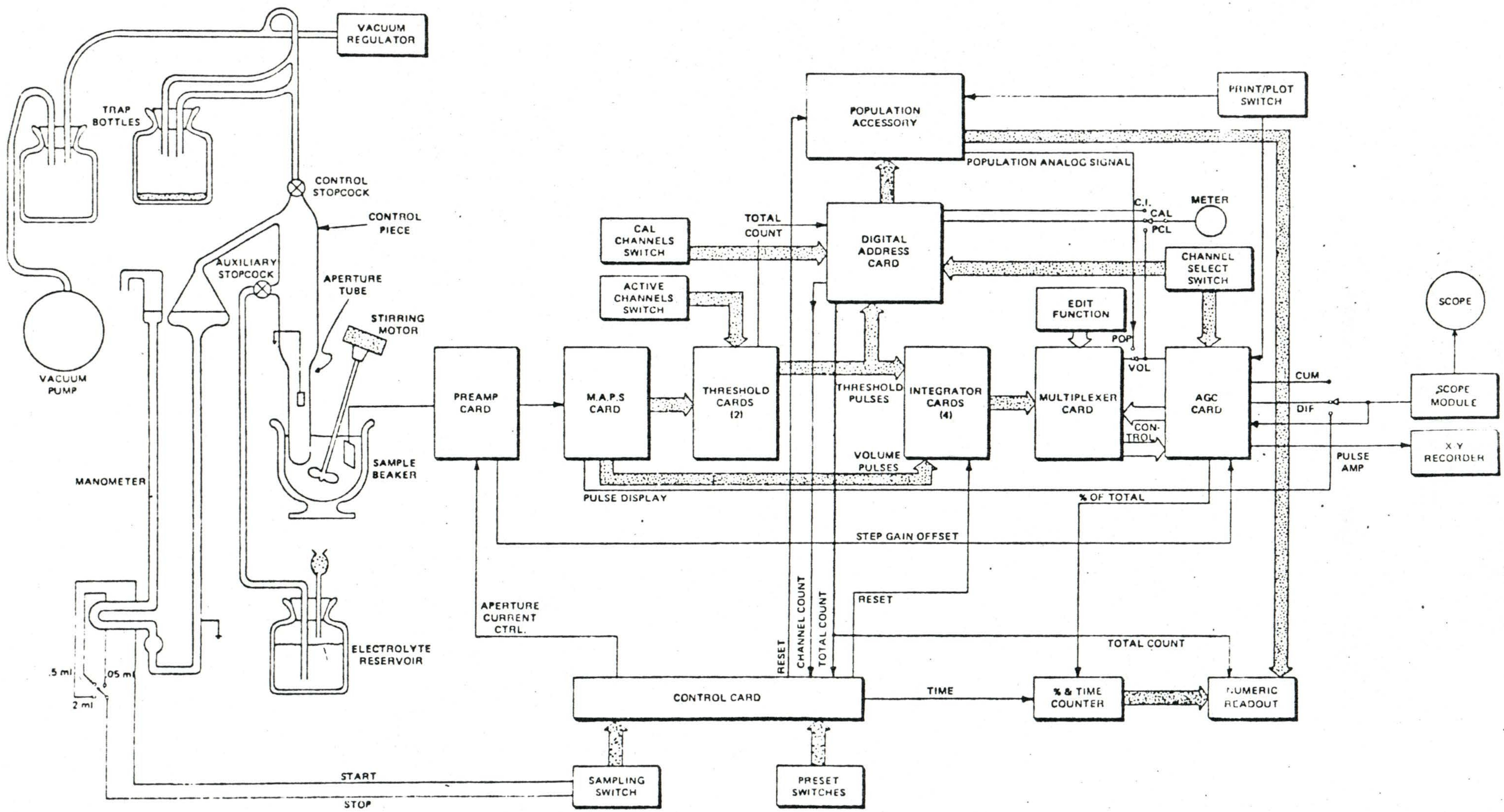


Fig.2.12. Coulter Counter Block Diagram

which accumulate the volume data; the integration corresponds to total volume of particles in corresponding size range. The differential volume data from the integrators are passed to the multiplexer which adds these to generate cumulative results. The AGC card then scales and normalizes the data to 100% and converts it to digital form which is available for numeric readout or printer.

For details of operation and fundamental theory, reference should be made to the work of Eckhoff[36].

2.8 Dissolved Oxygen Analyser

The Galvanic Cell Oxygen Analyser (GCOA) is used to determine the dissolved oxygen concentration. The galvanic cell probe consists of a rod shaped silver electrode (the cathode) separated by an insulating layer from a concentric cylindrical lead anode. The probe tip is sealed with a gas permeable polyethylene membrane and is covered with a pad soaked with 2 molar KOH electrolyte. Oxygen from the test stream is absorbed on the silver(cathode) on permeation through the membrane and dissolves in the 2 M KOH electrolyte as OH ions oxidizing the lead to PbO_2 ions. The magnitude of the current generated by this oxidation reduction is a direct measure of the dissolved oxygen in the sample which is proportional to the partial pressure of oxygen. The lead serves best as anode material as no external voltage is necessary to initiate oxidation reduction and the KOH is most desirable electrolyte due to its high conductivity and its very small residual current in absence of oxygen.

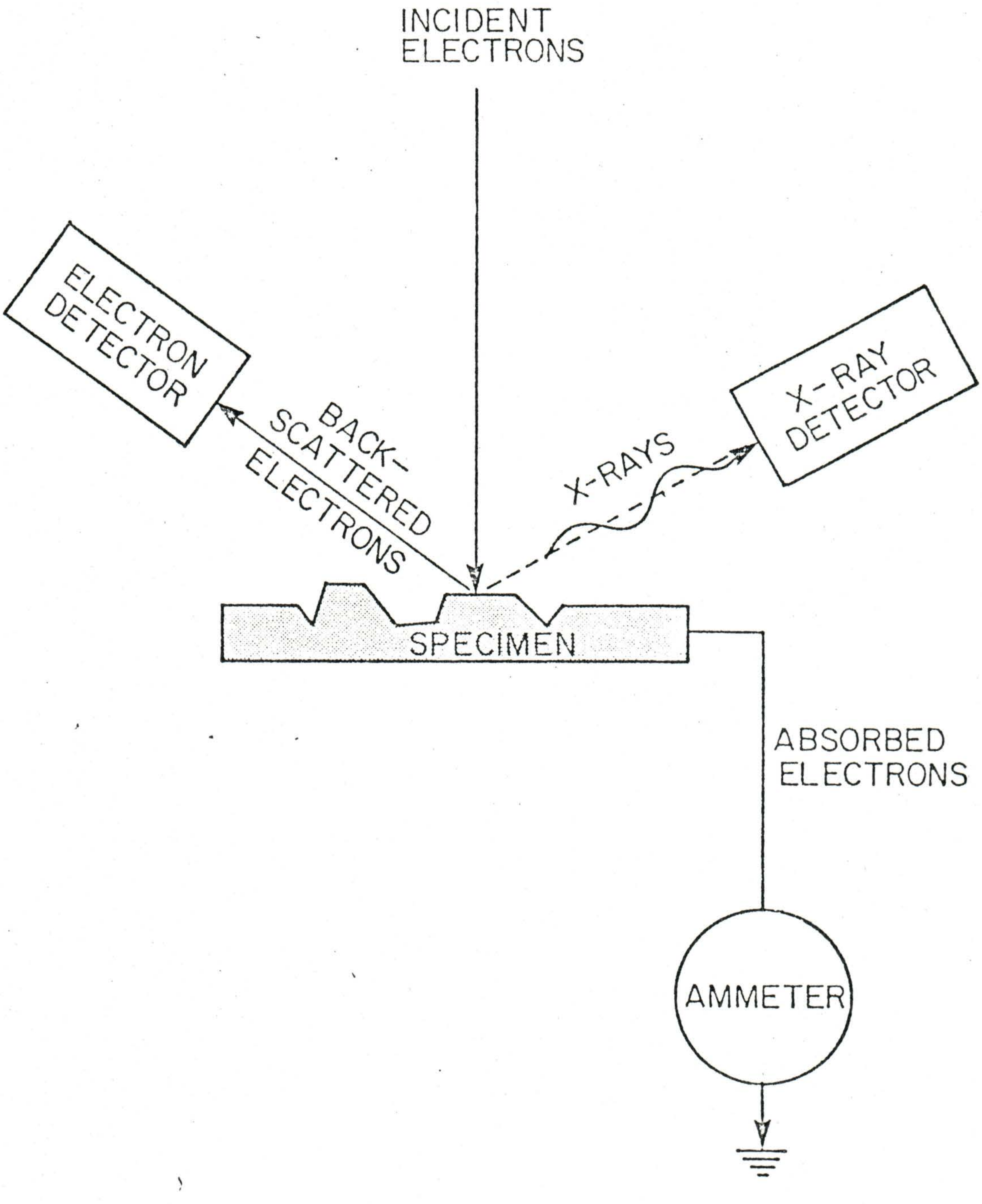


Fig. 2.13. Illustration Demonstrating Fundamental Principles of Electron Microprobe Analysis. (from Hopkins).

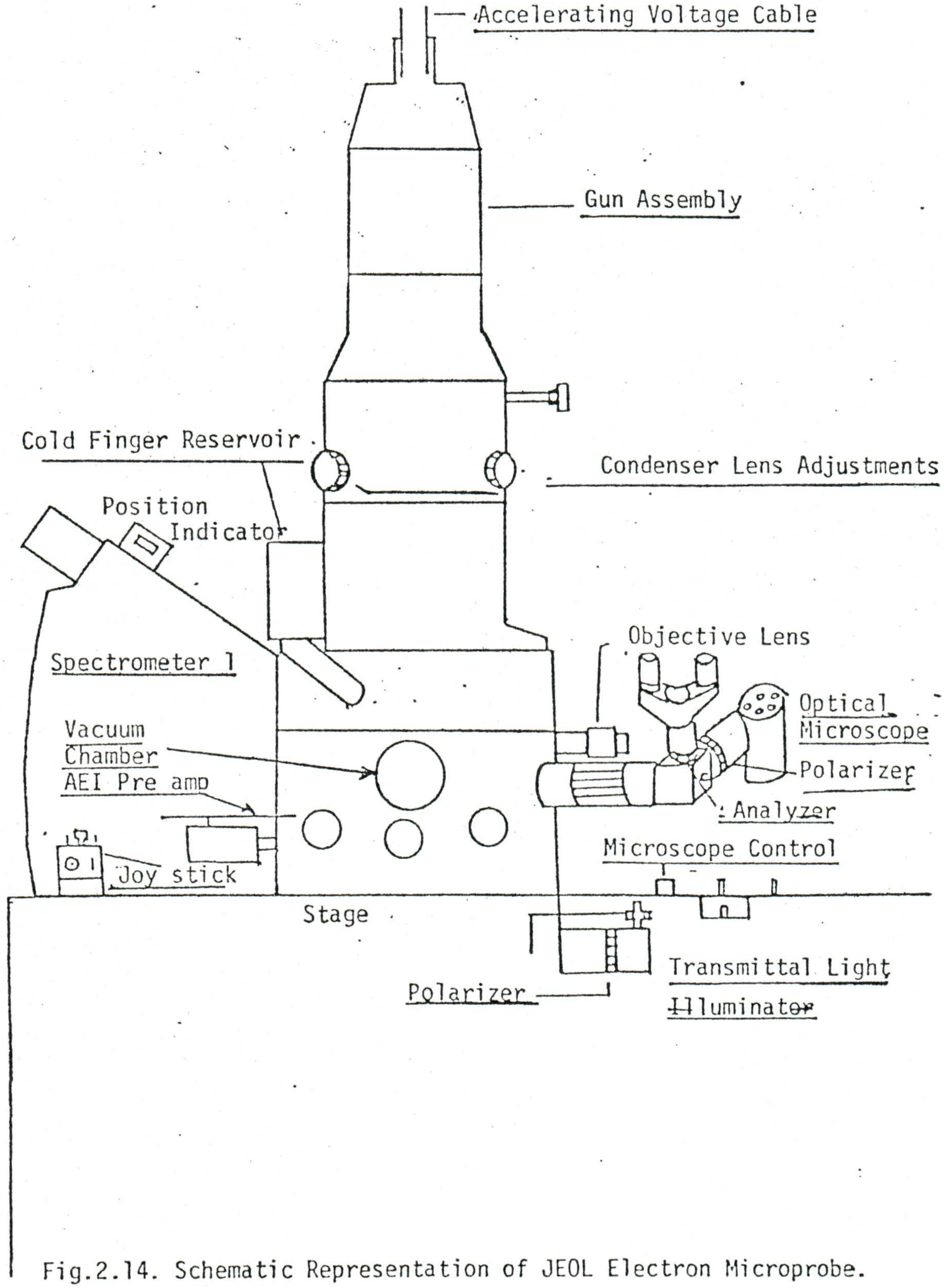


Fig.2.14. Schematic Representation of JEOL Electron Microprobe.

2.9 Electron Microprobe

Analysis of deposits from fouling runs, is carried out using the JEOL (Japanese Election Optical Limited) 50A electron probe microanalyzer available at the Department of Geology, Memorial University. Figs. 2.13 and 2.14 illustrates its principle of operation and its major components. The basic principle of its operation is relatively simple. An electron gun is used as a source of electrons. A condensor lens is used to focus the electrons into a 1 micron beam which is accelerated through a high potential, in the vicinity of 25 KV, and directed upon the sample being analyzed. Here the electrons either (a) collide with the nucleus of an atom in the sample and rebound in which case it is received in a detector and utilized to form an optical image of the material surface being examined or (b) it collides and displaces an orbital electron of an atom in the sample.

Due to this, the atom moves into an excited state and starts emitting x-rays of a particular frequency which is characteristic of the element. A crystal system is utilized to determine the frequency of this x-ray which aids in the positive identification of the element. The emitted x-rays are measured to give an estimate of the concentration of the element present in the sample. Further details on the electron probe microanalyzer, its operation and theory can be obtained from Van Olphen [37].

2.10 Properties of Foulant Used

The ferric oxide used as a foulant in the fouling trials conducted in this study was obtained from Fisher Chemical Co. Ltd. Bulk, mixed-size analytical grade ferric oxide was used, the physical and chemical properties of which are reported in Table VI.

The particle size of this bulk ferric oxide was determined using the Coulter counter and average particle size range was (5-6) microns. During size determination, the particles had to be kept dispersed as they tended to coagulate and settle.

Table VI

Properties of Ferric Oxide Powder
Fisher Chemicals Batch I-116

Fe_2O_3 Mol. wt	F.W. 159.69
Assay (Fe_2O_3) Min	98.1%
Solubility Product	
$Fe(OH)_3 \rightarrow Fe^{3+} + 3\ OH^-$	1.15×10^{-36}
Specific Gravity	5.17

Maximum Limit of Impurities

Arsenic (AS)	(about 0.002%) P.T
Nitrate (NO_3)	0.01%
Phosphate PO_4	0.02%
Sulphate SO_4	0.05%
Manganese Mn	0.01%
Copper Cu	0.004%
Substances not ppt'd by NH_4OH	0.04%
Zinc (Zn)	0.01%

Particle Size Determination

Particle size microns	Differential Volume %
4.00	10.4%
5.04	39.2%
6.35	38.8%
8.00	5.2%

CHAPTER 3

EXPERIMENTAL PROCEDURE

3.1. Experimental Runs

Twenty-six experimental trials were made during the present study. Although there were some variations in procedure for carrying out speciality trials with unique objectives, the procedure for carrying out most of the fouling trials was as follows.

3.1.1. Test Section Installation

The test section tube of the desired material, in the present work 316 stainless steel, 1.27/1.092 cms ID/OD and 91 cms. long was slipped into position in the test assembly and attached to the recirculation loop at the inlet and outlet mixing chambers. The sealing glands for preventing leakage of the sensible heating fluid mercury were tightened and the annular gap between the copper containment core and the test section was filled with mercury.

3.1.2. System Cleaning and Heating Period

For cleaning the heat loop, water was charged to the storage tank and the circulation pump started. During cleaning, the test section was replaced with another steel tube of similar dimensions. After a brief period of flow through the loop the system was drained through the drain valve at the bottom of the storage tank and the procedure repeated till all traces of particulate matter (ferric oxide in the present case) added for study were removed. This procedure was followed if the previous run had been made with ferric oxide. Prior to the initial run, the system was cleaned with an acid rinse (50% hydrochloric acid and 10% hydrochloric acid), followed by a water-alkali (10% sodium hydroxide-water) rinse. The last water rinse was repeated till the pH of the circulating water was the same as the pH of the tap water.

After cleaning the tank was filled with 200 kg. of tap water and heated to a temperature slightly above the desired inlet temperature for a fouling run using the heater mounted on the test section. The inlet temperature for most of the fouling runs was standardized at 50^oC. After the desired temperature had been reached in the tank, the heat flux was turned off and the steel tube replaced with the test section tube. The above procedure to accomplish bulk of the heating of the circulating fluid through the electrical heating unit on the test section assembly was followed since it was rapid and contributed to eliminate thermal transients associated with bringing the test section insulation to steady state.

3.1.3. Start-up

On start-up the following sequence was followed. The mixing air to the tank was turned on, the circulation pump started and the 'Powerstat' unit turned up to give the desired test section heating and the cooling water turned on. The data logging system was also switched on. Adjustments were then made with the help of the pump speed regulator and the control valve on the cooling water line to bring the fluid to the target outlet and inlet temperatures, respectively.

The heat loop was then operated at this condition on tap water for over two hours in order to eliminate thermal transients associated with heat absorption of the test section insulation till steady state was reached.

Following this, final adjustments were then made so that flow rate, inlet temperature, outlet temperature and test section power consumption were precisely at target conditions. Table VII shows the variations from target conditions in these operating parameters tolerated for a typical run. After fifteen minutes, the observed wall temperatures were considered to correspond to the clean wall condition and free from errors caused by thermal transients.

3.1.4. Addition of Particulates and Subsequent Operating Procedure During Tube Fouling

After clean wall temperatures had been attained a weighed amount of ferric oxide was added to the storage tank. The ferric oxide was added as a slug dose after slurrying it in a five litre sample of system tap water. Difficulty was experienced in adding all the ferric oxide to the system as it tended to agglomerate and settle to the bottom of the beaker. The time of addition of ferric oxide was taken as time zero for a trial.

During the run, the inlet temperature was held at the target value by controlling the cooling water flow rate while the flow rate through the test section was maintained at the desired target value by holding the outlet temperature at its target value. For with the heat input and inlet temperature to the test section remaining at their respective target values, variations in flow rate caused

TABLE VII

Variance from target conditions tolerated for a typical run
Run Number 020

Variable	Target Value	Maximum Value	Minimum Value
Inlet temperature thermistor (TIN) resistance signal (ohms)	365.81 (50.0^oC)	364.2 (50.1^oC)	366.73 (49.9^oC)
Outlet temperature thermistor (TOUT) resistance signal (ohms)	332.51 (58.5^oC)	331.02 (58.6^oC)	333.12 (58.4^oC)
Test section volts	12.80	12.81	12.79
Test section amperes	220	219	221

variations in the outlet temperature. The speed regulator on the pump motor and at times the throttle valve at the exit of the circulation pump were used to control the flow rate.

3.1.5. Shut-down Procedure and Measurement of Flow-rate

On completion of a trial, the test section heating was stopped, and the loop decoupled at Union B (refer Fig. 2.2) on the return line to the storage tank. The circulating fluid was collected in plastic buckets for a fixed time period and weighed to determine the mass flow rate through the system. Following this the circulation pump was stopped.

3.1.6. Fouling Deposit Sample Preparation

Although this step was not carried out during the present study, following a fouling trial the test section can be removed and fouling deposit samples for electron microprobe analysis prepared as outlined in reference [22].

3.2. Subsequent Fouling Runs

For later trials made, in which the ferric oxide was already present in the system, the procedure for carrying out a fouling trial was greatly reduced. The fouling fluid was brought to target inlet temperature by circulation and heating through the test section. On reaching the desired inlet temperature adjustments were made as stated previously to bring the flow rate, inlet temperature and outlet temperature to the desired target conditions. The heat loop was operated for over three hours to eliminate the errors caused due to thermal transients as before. Following this, the heat flux and the circulation pump was stopped and the deposit from the tube wall removed by quickly draining and honing the hot tube using a 303 calibre bronze rifle brush attached to a half-inch drill.

3.3. Data Acquisition

Automatic scanning and recording of the thermal data made possible the collection of a large number of thermal measurements. In addition, flow rate measurements and electrical measurements were done manually. The steps followed in collection of data are outlined below.

3.3.1. Setting of Trial Conditions

Before carrying out any trial it was necessary to record the objectives of making a trial and establishing the conditions under which it had to be run. Table VIII outlines the objectives and conditions recorded for a typical run number 020. Computer program 'PAR' was then run to determine that the parameters selected did meet the desired trial conditions. 'PAR' basically calculates the flow parameters and carries out a heat balance over the test section and contains data covering test section dimensions, thermistor calibrations and properties of fluid. For run 020, input data to 'PAR' was

020 x 12.80 x 220

0.0750

02400

6.1 x 5.2

365.82 x 331.60

where

020	=	Run Number
12.80	=	Test Section Volts

TABLE VIII

Typical Log Sheet Showing Run Objectives and Target Conditions

Run Number 020	Date: 23 October 1979
Objective:	To determine thermal fouling resistance versus time curve for a ferric oxide concentration of 2400 PPM and heat flux 120,000 watts/SQ.M and Reynolds number 17,500.
Flow rate:	0.0750 kgs.m/sec (pump speed setting 60%)
Inlet Fluid:	365.5 (thermistor resistance reading)
Outlet Fluid:	332.5 (thermistor resistance reading)
Variac Setting:	60% (gauge units)
Test Section Volts:	12.80
Test Section Amps:	220
Fluid pH:	6.1
Dissolved oxygen concentration	5.2 (PPM)
Cooling water setting	1.8 (gauge units)
Air:	On
Ferric oxide in solution	480 gms.

TABLE IX

Output from Program PAR

```
******RUN NO20.*******

VOLTS12.80          AMPS 220.

FERRIC OXIDE CONC (PPM)    2400.

FLOW RATE 0.0750  KGS.M/SEC

PH:6.1              DISS.O2 CONC (PPM)   5.2

HEAT FLOW SUPPLIED  2816.0     WATTS
HEAT FLUX SUPPLIED   120708.   WATTS/SQ.M

TOR=TINLET 49.9                      DEG C
DENSITY: 985.5KGS./CU.M
                   T OUTLET 58.5     DEG C

AVG TEMP 54.2       DEG C
KINEMATIC
VISCOSITYX100 0.000052                SQ.M/SEC

FLUID VELOCITY 0.813    M/SEC
REYNOLDS NO  17173.9
PRANDTL NO   3.71

HEAT SUPP      2816.0    WATTS
HEAT TRANS      2690.1   WATTS
HEAT LOST       125.9    WATTS
PERCENT HEAT LOST     4.47
HEAT FLUX TRANS  115309WATTS/SQ.M


NUSSELT NO      90.8
RFILM     0.210
RWALL     0.058
RTOTAL     0.268      SQ.M-DEG.C/WATTS
```

220	=	Test Section Amperes
0.0750	=	Flow rate (kg.m/sec)
02400	=	Ferric Oxide Concentration (PPM)
6.1	=	pH of fouling fluid
5.2	=	Dissolved Oxygen Concentration (PPM)
365.82	=	Inlet thermistor resistance reading (ohms)
331.60	=	Outlet thermistor resistance reading (ohms)

Output from 'PAR' is shown in Table IX. 'PAR' also computes the wall resistances and the film coefficient based on the Seider-Tate equation.

3.3.2. Data Collection and Data Processing

The procedure used to gather data was as follows: On commencement of a run, which as stated previously was taken as the time of addition of ferric oxide into the system, the thermistor signals were monitored every minute for the first four hours of a run and every five minutes thereafter. The resistance signals from all the thermistors on the heat loop were displayed on the data logging system calculator display for 3.5 seconds and were recorded on the data cartridge from where it was printed out in a line format using the thermal line printer. The display facilitated observations to see that the inlet and outlet temperatures and the flow rate were maintained at the target conditions, and if a variation occurred what corrective action was to be taken. As the run progressed, 'lines of data' were selected at regular intervals and recorded on a separate log sheet, subject to the provision that the inlet and outlet temperatures, flow rate and the voltage and current were at target or very near target conditions. Variations in all these operating parameters have an influence on the

TABLE X

Log Sheet Maintained for Recording Thermal Data for a Typical Run

Date: 23 October 1979
Run No. 020
Test Section Volts: 12.80 Test Section Amps: 220
Flow rate: 0.0750 Kgs-m/sec. pH: 6.1
Ferric Oxide Conc.: 2400 Dissolved Oxygen Conc.: 5.2 PPM
Thermistors reading correctly: T102, T103, T104, T105, T106, T107, T108, T109, T110.

Real Time	TIME	TIN	TOUT	T101	T102	T103	T104	T105	T106	T107	T108	T109	T110	Volts	Amps.
2115	0.00	365.94	333.12	113.25	70.66	73.13	62.42	66.65	64.17	63.24	54.99	59.86	48.92	12.80	220
2121	0.10	365.86	332.72	113.02	70.46	73.01	62.40	66.50	64.17	63.18	54.99	59.84	48.90	12.79	219
2133	0.29	364.79	332.51	112.79	70.10	72.89	62.33	66.42	64.07	63.06	54.92	59.84	48.86	12.79	219
2140	0.40	365.79	332.75	112.52	69.83	72.58	62.09	66.16	63.90	62.81	54.76	59.42	48.42	12.80	220
2145	0.49	365.81	331.93	112.35	69.91	72.29	61.81	65.87	63.71	62.58	54.41	59.22	48.23	12.80	220
2150	0.57	365.71	331.45	112.51	69.45	72.35	61.91	66.01	63.81	62.63	54.52	59.28	48.20	12.80	220
2203	0.87	365.82	331.60	111.92	68.96	71.86	61.55	65.52	63.52	62.19	54.25	50.09	47.99	12.80	220
2209	0.97	366.66	331.80	111.84	68.73	71.59	61.31	65.29	63.35	62.01	53.98	58.88	47.87	12.79	219
2228	1.23	366.52	331.81	112.13	69.06	71.87	61.60	65.51	63.61	62.20	54.14	59.09	48.11	12.80	220
2234	1.33	365.29	331.02	111.92	69.13	72.00	61.65	65.69	63.60	62.23	54.44	59.06	48.08	12.81	220
2259	1.40	365.78	332.06	112.26	69.26	72.25	61.83	65.85	63.72	62.54	54.34	59.11	48.12	12.80	220
2321	1.60	365.93	331.93	112.02	69.01	71.79	61.59	65.49	63.56	62.13	54.30	59.04	47.97	12.80	220
2334	1.85	365.79	331.26	112.26	69.05	72.03	61.70	65.73	63.65	62.30	54.13	59.01	47.94	12.80	220
2352	2.11	366.73	331.98	112.27	68.94	71.94	61.61	65.61	63.61	62.25	54.11	58.96	47.91	12.80	220
2356	2.18	366.07	331.37	112.29	68.99	72.09	61.67	65.71	63.65	62.29	54.01	58.98	47.99	12.80	220

Trial stopped at 00.05 hours

accuracy of the results which has been discussed in Chapter 4. Table X shows this log sheet which was used to provide input to program FOUL for computing thermal fouling resistances.

CHAPTER 4

EXPERIMENTAL ERROR STUDY

In order to determine the precision of the thermal resistance measurements made during the course of a run, a series of trials were conducted on tap water to identify and examine the effects of thermal transients and test loop operating variables which, if improperly controlled, could cause significant error in the results. It was recognized that, since the loop would operate under constant heat flux and constant flow rate conditions, variations in the prime operating variables viz the fluid inlet temperature,flow rate and the heat flux could cause appreciable error on the measured longitudinal wall temperature profile and hence in the measured thermal resistances. From the few initial trials made on tap water, it was seen that the values of the above operating variables were affected by the following fluctuations:

(i) Variation in input power supplied to the test section which manifests itself as a variation in the heat flux.

(ii) Variation in flow rate caused by, as later runs on ferric oxide showed, particulate deposition on throttle valve and pipe fittings.

(iii) Fluctuations in cooling water inlet temperature and flow rate which caused cyclic variations in the inlet temperatures to the test section.

Also, on starting a trial, an initial unsteady type behaviour was observed, in which from the time of start-up to a time ranging from 0.5 to 1.5 hours the apparent thermal resistances tended to rise before reaching a final steady state value. Trials were conducted to study each of these factors separately and are discussed below.

4.1. Effect of Initial Thermal Transients

It was evident from observations reported by Mayo [34] and Hopkins [22] and the results of the dilute sand-water slurry fouling trials of Watkinson [3], that for many test loops, the measurement of initial fouling rates could be in error due to a thermal transient situation which prevailed in the beginning of a run. A trial was made using tap water as the fouling fluid to study the effect of this transient period. The method employed for this run was to heat the fluid to target inlet conditions before introduction into the test section. The following conditions were maintained. At time zero minus the test section remained at room temperature while at time zero plus, the flow rate and the heat flux were at their target values. Fig. 4.1 shows the results of this trial and Fig. 4.2 shows the inlet outlet and a few typical thermistor signals. The apparent thermal resistance versus time curve exhibits a typical die-away behaviour of thermal transients. The results clearly show that thermal transients could significantly vary the fouling resistance versus time curves, especially the initial fouling rate. Since no measurable fouling could be observed in the results, the transient behaviour discussed above is believed to be caused by the following. During the initial period of a run the supplied heat flux to the test section is not

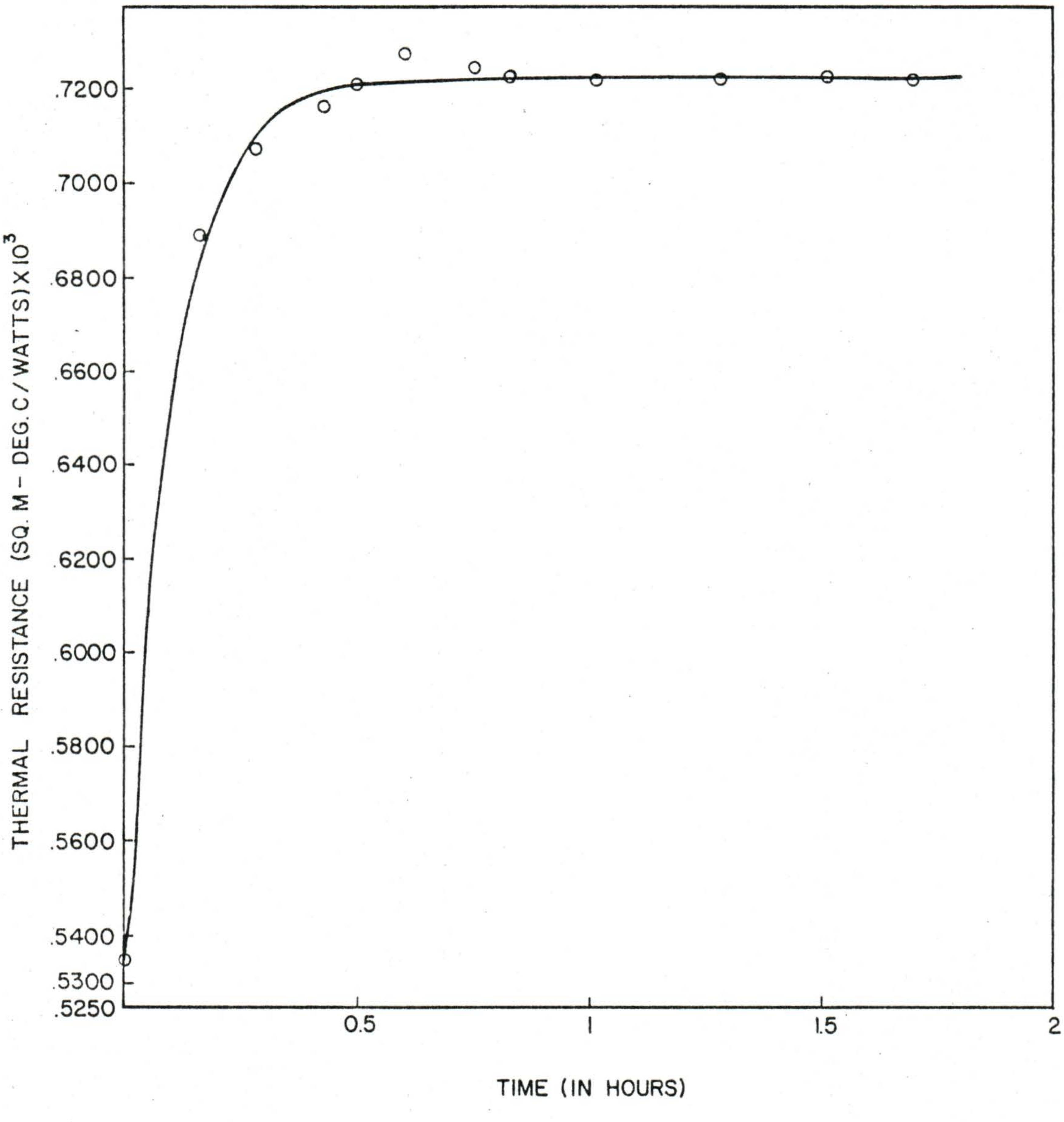


Fig.4.1. Apparent Thermal Resistance versus Time for Run 001 on Tap Water.

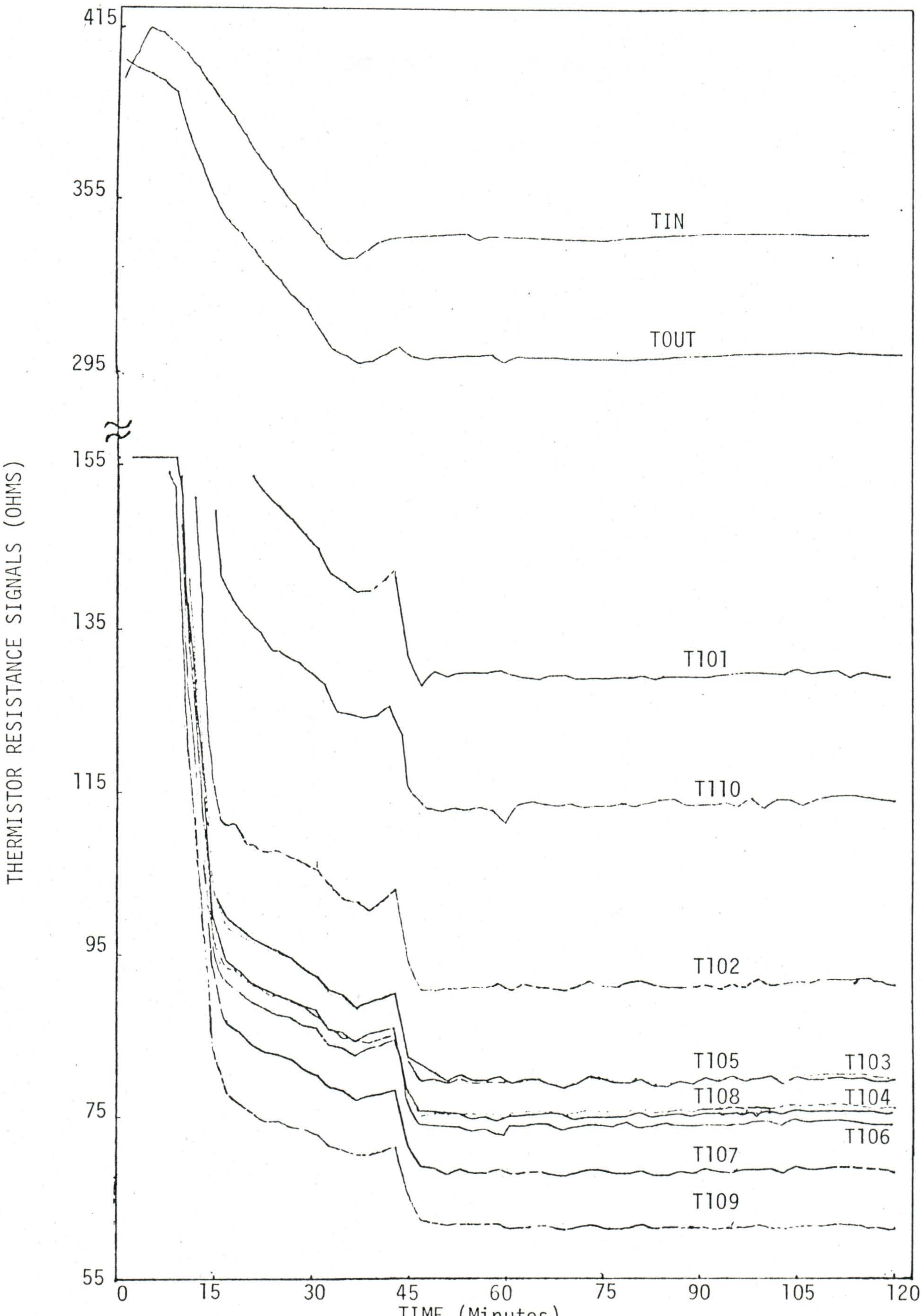


Fig.4.2. Thermistor Resistance Signals for Run 001.

transferred completely to the fluid but partly to the test section insulation which absorbs heat until thermal equilibrium is attained.

In order to eliminate errors which could result due to this effect the following procedure was adopted in making fouling trials: (a) If no particulate matter was present in the system, the loop was operated for over two hours till steady state had been achieved and then the contaminant added; (b) if ferric oxide was already in the system, operating for a minimum of two hours and then removing any deposit by quickly draining and honing the hot tube before time zero. Either method is known to give the same fouling curve [22].

4.2. Effect of Variation in Line Voltage

Although precautions to elmininate errors due to uncontrolled variations in the input supply voltage had been taken in the design of the heat loop by using a constant voltage transformer (see Chapter 2) the performance of this equipment remained less than satisfactory and fluctuations as high as 80 watts in the input power to the test section were observed. Fig. 4.3 shows the variations in the line voltage to the test section during the course of a typical ferric oxide fouling run (Run No. 26). This variation of 80 watts could cause an error of 0.20×10^{-5} m^2-Deg C/watts in the measured thermal resistances. Since the fouling resistances for the ferric oxide trials ranged from $0.5 - 1.1 \times 10^{-5}$ m^2-Deg C/watts, it was necessary to eliminate this source of error. To achieve this the following method was employed. When variations of over ± 0.2 volts were observed in the line voltage to the test section, adjustments were made on the 'Powerstat' unit

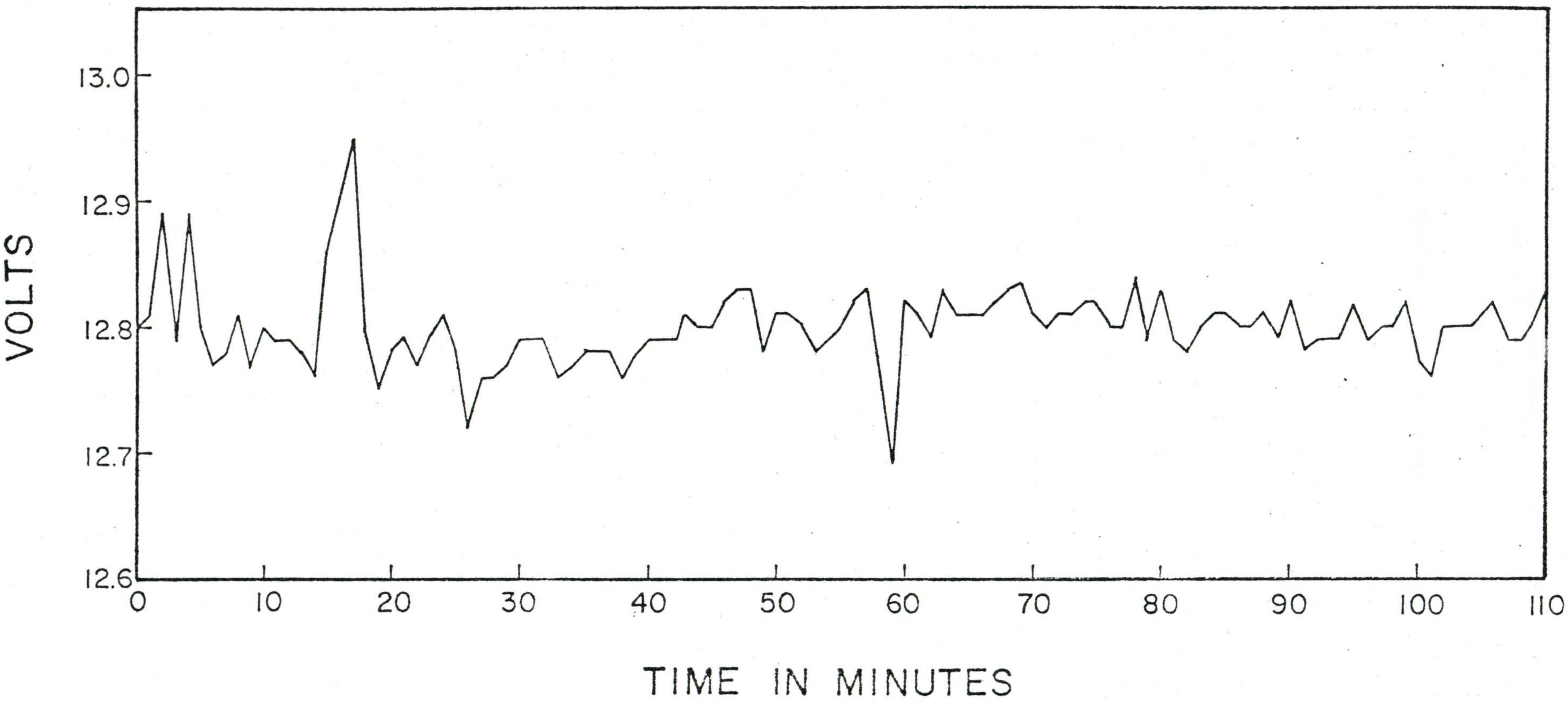


Fig.4.3. Variation in Line Voltage to Test Section for a Typical Run (026).

to return the line voltage to set conditions. Furthermore, only those thermal data for which the line voltage remained within ± 0.01 volts of the target value were used for computing the thermal fouling resistances. This method reduced the error due to line voltage variations to around 0.02×10^{-5} m^2-Deg C/watts which is less than 2% of the typical ferric oxide fouling resistances measured.

Although this procedure served to meet the requirements of accuracy in computing thermal fouling resistance versus time plots manual attendance of the loop became necessary to make the readjustments. Also, some data had to be sacrificed due to the above method. To overcome this limitation a better electrical power circuit is desirable.

4.3. Effect of Variation in Inlet Temperature

Variations in the fluid inlet temperature to the test section were seen usually to be caused due to fluctuations in the cooling water temperature and flow rate and small adjustments on the control valve on the cooling water line returned the inlet temperature to target conditions. Fig. 4.4 shows the results of a run made to study the effect of variations in inlet temperature on measured thermal resistance. The total variation in the thermal resistance during an uncontrolled run in which the inlet temperature varied by 1.6^{o}C was seen to be 0.37×10^{-5} m^2-Deg C/watts. The decrease in the thermal resistance with increase in temperature is due to a change in the fluid viscosity (a change of $1.44 \times 10^{-4} cm^2/s$ corresponding to a change of 1.6^{o}C in temperature). To eliminate this source of error the inlet temperature was held at its target value and only data in which the inlet

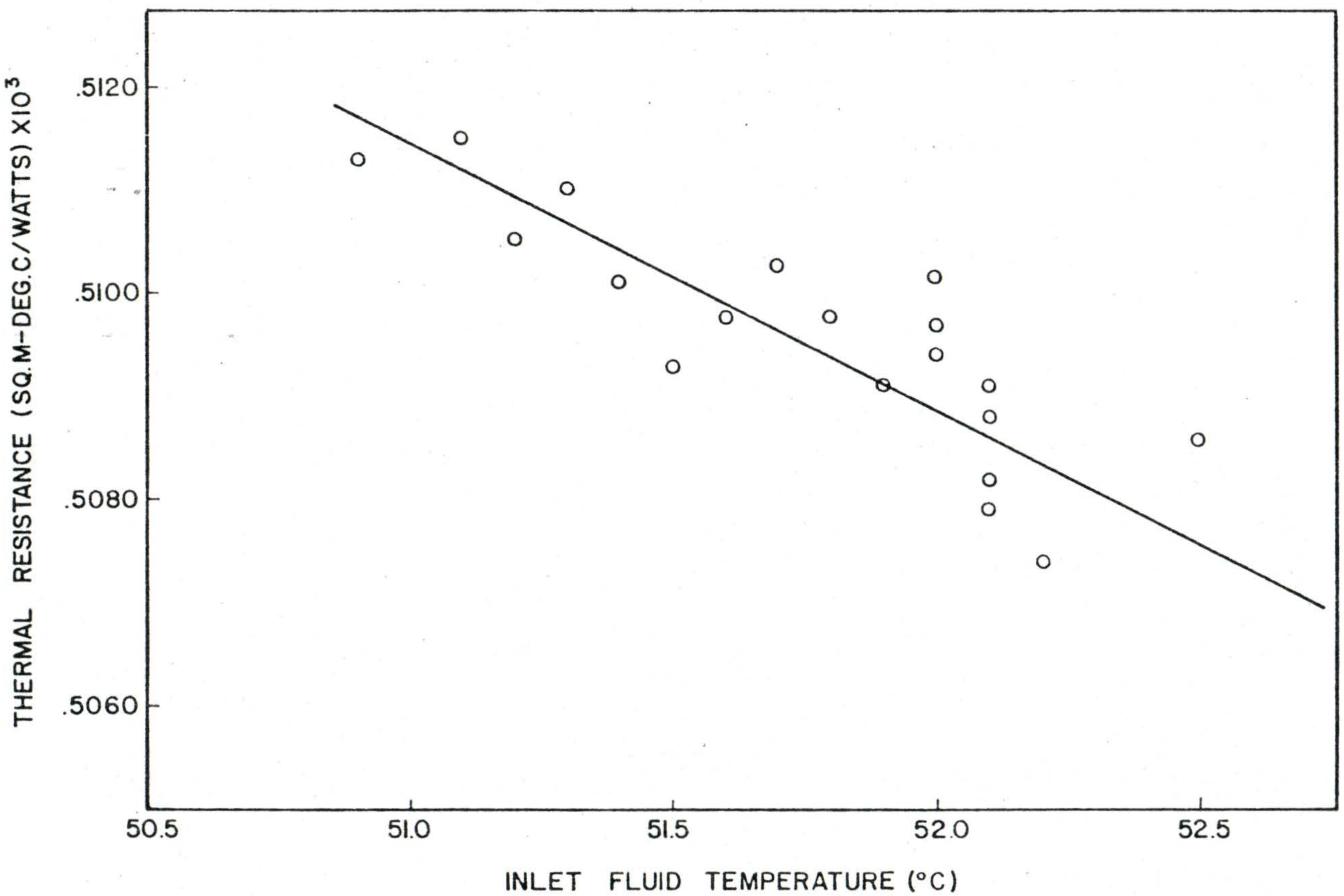


Fig.4.4. Inlet Temperature for Run 003 on Tap Water.

temperature was at its target value ± the allowable tolerance was processed to determine fouling resistances.

4.4. Effect of Flow Rate Variations

Flow rate variations were observed to be generally owing to ferric oxide deposition on the throttle valve and pipe fittings in the heat loop. Variations in the flow rate would cause changes in the thermal resistance and thus could cause significant error in the measured fouling resistances. As the heat input q to the test section and the inlet temperature TIN was held constant, this variation manifested itself in causing variations in the fluid outlet temperature as is evident from the overall heat balance equation $q = \dot{m}c_p$ (Tout-Tin). To determine the extent to which variations in the flow rate would produce changes in the measured thermal resistances a run was made on tap water in which no effort was made to control the flow rate. Fig. 4.5 shows the results of this trial. The total variation in the measured thermal resistance corresponding to a change of 0.6^{o}C in the fluid temperature rise was observed to be 1.0×10^{-5} m^2-Deg C/watts. This variation can be readily explained on the basis of the Seider-Tate equation for fully developed turbulent flows. An examination of the equation

$$\frac{hid}{k} = 0.023 \left(\frac{Du\rho}{\mu}\right)^{0.8} \left(\frac{C\rho\mu}{k}\right)^{0.33} \left(\frac{\mu}{\mu w}\right)^{0.14}$$

shows that with the fluid properties remaining constant a change in velocity caused by a change in the flow rate would cause a variation in hi, the film coefficient of heat transfer as hi is seen to be directly proportional to $u^{0.8}$. Also, with heat flux remaining

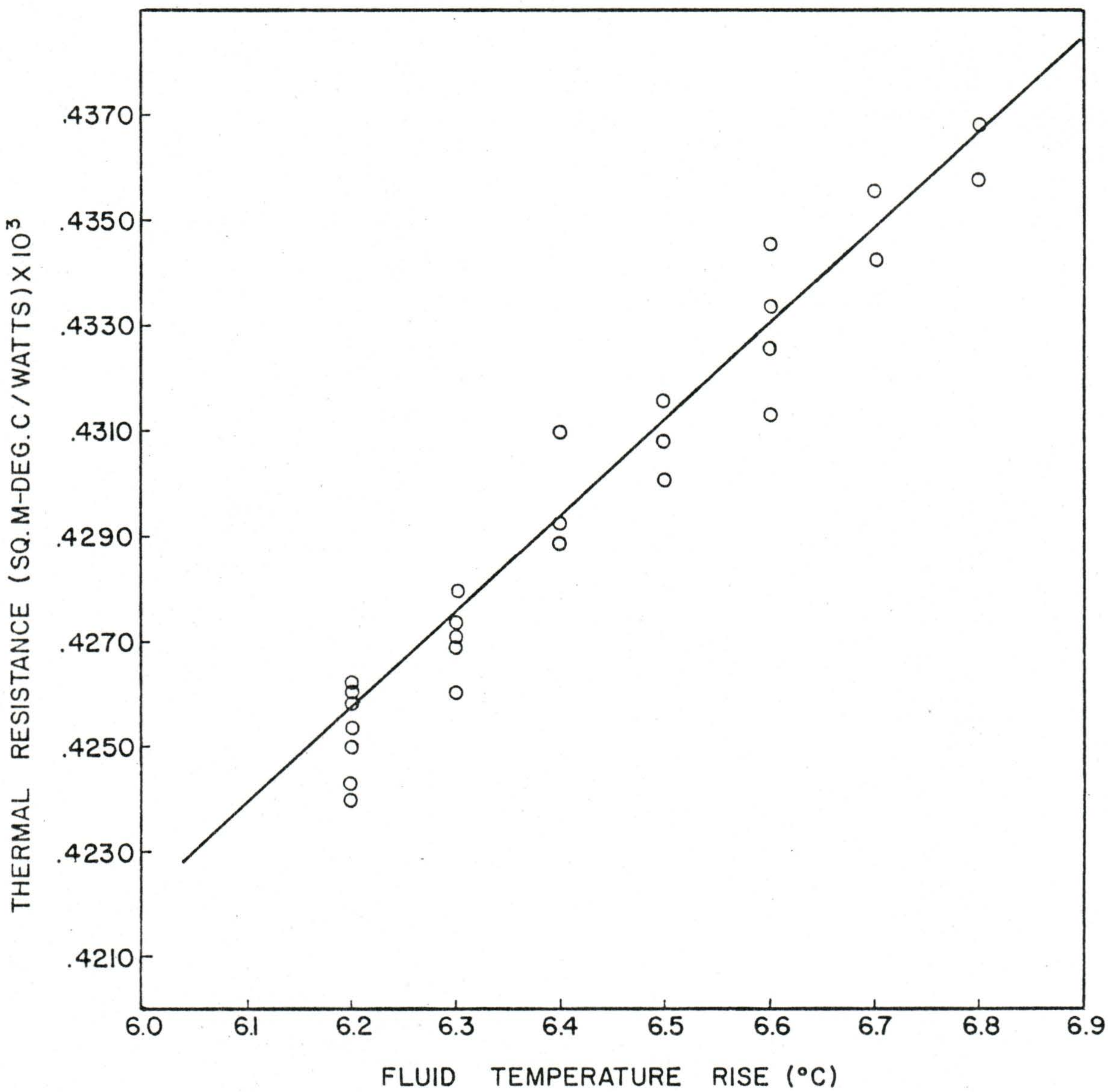


Fig.4.5. Thermal Resistance versus Fluid Temperature Rise for Run 004 on Tap Water.

constant a change in the flow rate would be reflected by a change in the wall temperatures. To overcome the error in the measured thermal resistances on this account, the following methodology was adopted. The flow rate through the test section was maintained constant by making adjustments on the speed control of the recirculation pump and on the throttle valve so that the outlet temperature TOUT remained constant. Also, only those data in which the fluid temperature rise (Delta) remained at its target value was used for computation purposes.

The results of these trials showed that all the three operating variables were inter-dependent and usually required small adjustments to maintain the desired conditions. Also, in order to maintain comparable precision in the thermal fouling resistances measured the variations in the prime operating variables viz the line voltage (hence heat flux), flow rate (hence fluid outlet temperature) and the fluid inlet temperature which can be tolerated are small. In addition, the procedure of processing only those data for computation in which TIN, TOUT and line voltage V remain at the desired target conditions eliminates possibilities of error due to fluctuations in the operating conditions of the heat loop.

4.5. System Sensitivity

In order to establish the sensitivity of the thermal sensors in following fluctuations in temperature a trial was made on tap water in which a step change was made in the fluid inlet temperature and the resistance signals from the wall thermistors logged continuously to determine the response delay time for the thermistors. Saturated steam at 1 KPa and 99.8^{o}C was passed through the test section and after the thermistor readings showed steady value, cold water at room temperature was pushed through the next instant. The procedure was repeated in the reverse order. Fig. 4.6 shows the results of this trial. The delay time for the thermistors to reach final response is seen to be small.

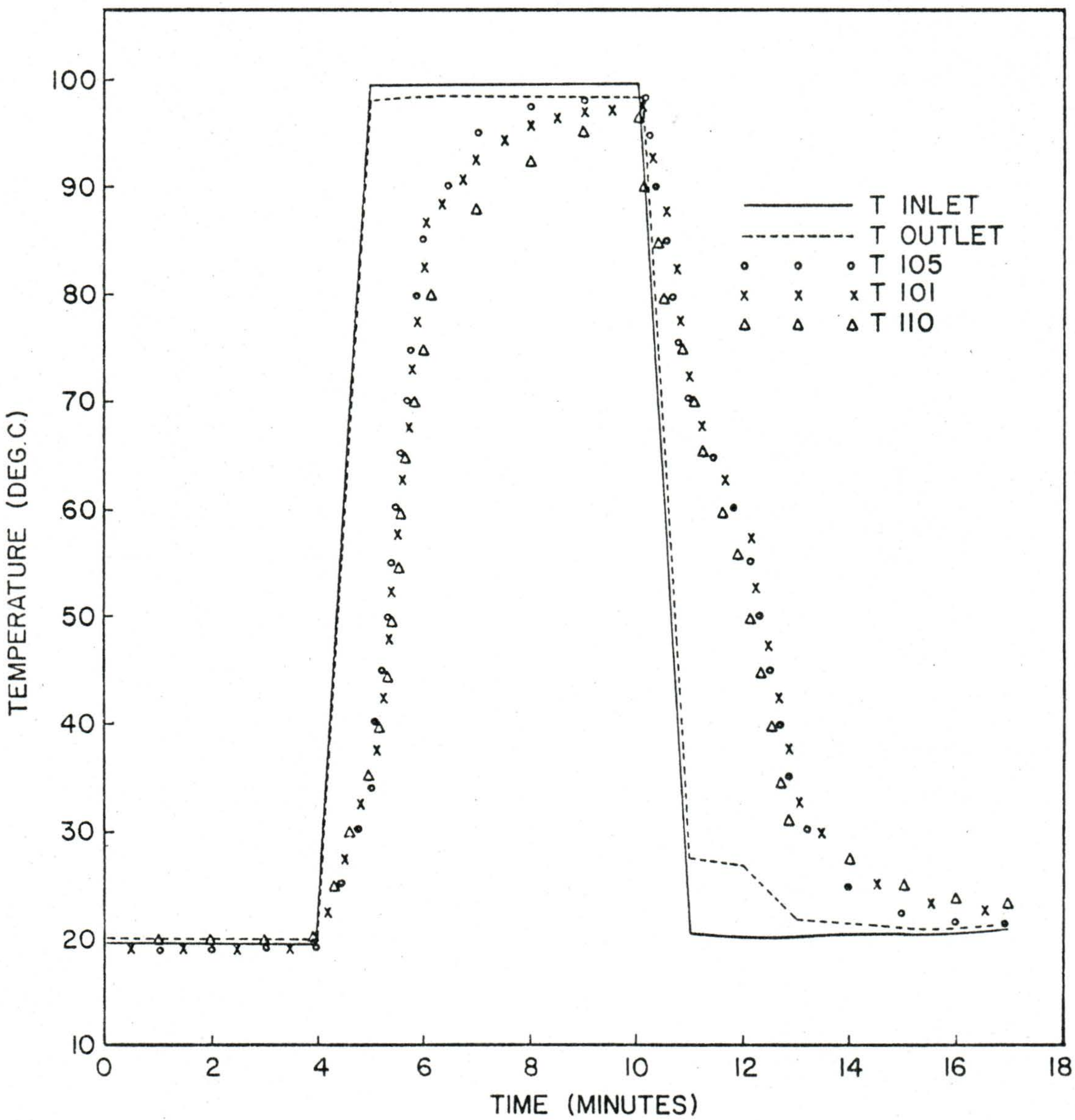


Fig. 4.6. Thermistors Response to Step Changes in Temperature.

CHAPTER 5

RESULTS AND DISCUSSION

5.1. Summary of Fouling Trials

Following construction of the heat loop, 26 trial runs were made to study the fouling behaviour of an aqueous suspension of ferric oxide in 10.92 mm ID 316 type stainless steel tube. These runs which constituted the testing process of the heat loop, can be divided into three categories.

(i) Runs made on tap water to study the effect of various sources of error, e.g., variations in the prime operating variables which if inadequately controlled during the course of a run, would bear upon the accuracy of the measured thermal resistances as a function of time. (Results of these runs have been presented in Chapter 4).

(ii) Trials to study the effect of fluid velocity, heat flux, ferric oxide concentration and tube wall temperature on the fouling behaviour.

(iii) Two specialty trials designed to study the effect of oxygen concentration and the action of an aggressive chloride ion on constant rate ferric oxide fouling behaviour in an attempt to test the validity of the crevice corrosion hypothesis concerning fouling behaviour presented in reference [22].

An important aim behind the runs made in category (ii) in addition to studying the effect of some known primary variables

TABLE XI

Summary of Ferric Oxide Fouling Trials

Run No.	Heat Flux	Reynolds Number	Mixed Size Ferric Oxide Particles Conc.	Asymptotic Fouling Resistance $R_f^* \times 10^5$	b	Initial Fouling Rate bR_f^*	Run Duration	Comments
	Watts/M^2		ppM	SQ.M-DEGC/ WATTS	Hr^{-1}	SQ.M-DEGC/ WATTS-HR.	Hrs.	
005	111401	16313	2400	0.78	4.3	3.35	3.13	First successful run with thermal fouling.
006	102828	16638	2400	-			2.42	Successful run to induce tube into linear fouling.
007	93227	16381	2400	0.88	1.67	1.50	2.42 / 10.22	Run to study the effect of extended operation.
008	112624	15657	2400	0.51				Attempt to duplicate run 005. Data limited and inaccurate owing to voltage dip and C.W. temperature fluctuation.
009	110936	20576	3400	1.22	1.32	1.61	2.40	Run to study effect of increased concentration of Fe_2O_3 3400 ppM.
010	110622	20578	3400	1.42	2.01	2.8	2.37	Attempt to duplicate run 009 to study reproducibility.
011	112679	20560	2400	0.58	6.15	3.57	1.40	Set of runs to study effect of incomplete deposit removal (residual deposits) on tube wall.
012	112679	20560	2400	0.91	3.02	2.75	2.10	
026	117115	16094	2400	-			3.01	Run to examine crevice corrosion hypothesis by addition of chloride ions.
016	111257	18314	2400	0.72	5.86	4.22	1.9	Run to study effect of local wall temp. on fouling resistance at high heat flux.
017	91183	17790	2400	1.01	2.15	2.17	1.85	Similar to run 016 above except at low heat flux condition.
018	121998	28347	2400	0.47	4.01	1.88	1.91	Runs to study effect of Reynolds number and heat flux at high heat flux.
019	119336	22566	2400	0.55	4.93	2.71	1.71	As above.
020	115309	17174	2400	0.62	1.97	1.22	2.18	As above.
021	116967	12933	2400	0.50	2.02	1.02	2.26	As above.
022	96918	29737	2400	0.44	2.09	0.92	2.01	Run to study effect of Reynolds number and heat flux at low heat flux.
023	97094	20192	2400	0.74	7.7	5.7	1.83	As above.
024	89116	15843	2400	0.82	2.23	1.83	2.20	As above.
025	92950	11874	2400	0.67	2.10	1.41	1.75	As above.
015	90766	29077	2400	-	Tube in	linear fouling	4.61	Run to study the effect of oxygen concentration on fouling rate.

affecting fouling was to examine reproducibility of data with that already reported for a similar system in the literature [22,23]. Lack of reproducibility of data has constantly plagued researchers in the fouling field. Even for similar systems studied [15,23] wide variations in the results have been reported. Also, one criticism of the results reported in the above reference was that by electric heating of the test section stray magnetic or electrical effects could have been induced which could have affected the fouling resistances obtained. With the present test section design, the heat transfer surface was segregated from electric currents and therefore offered an opportunity to test the validity of that criticism.

The purpose, operating conditions and the results obtained for the ferric oxide fouling trials are summarized in Table XI below. Fouling resistance data for trials in which thermal fouling was observed, as witnessed by increase in the wall temperature, have been fitted to the classical Kern-Seaton model [6]

$$R_f = R_f^* \left(1-e^{-bt}\right) \tag{5.1}$$

Values of the initial fouling rate $\left[\left.\frac{dR_f}{dt}\right|_{t=0} = bR_f^*\right]$ are also included in Table XI

5.2. Calculation of Fouling Resistances

Local fouling resistances at each thermistor station and the mean value of the fouling resistances (RFM) based on the mean heat transfer coefficient for the whole tube, at any specified instant, have been computed from the generated thermal data. As mentioned in Chapter 1 local values of fouling resistances are more desirable;

however, to reduce the amount of data handled, mean fouling resistances were considered adequate for study of fouling behaviour with time. The mean fouling resistance versus time curves are reported to be similar to the local fouling resistance versus time curves [3]. Local fouling resistance at any time t is given by the rise in wall temperature from the clean wall condition divided by the heat flux or simply

$$R_f = \frac{T_{wt} - T_{wc}}{q'} \tag{5.2}$$

The above equation can be readily deduced as follows:

At time t = 0, total resistance $= R_o = \dfrac{T_{wc} - T_b}{q'}$. (5.3)

After initiation of fouling, an additional resistance due to fouling is built on the inside surface of the tube, thus increasing the total thermal resistance which increases the wall temperature to a new value T_{wt} since other conditions, i.e., heat flux supplied and bulk temperature remains constant.

$$\therefore \; R_o + R_f = \frac{T_{wt} - T_b}{q'} \tag{5.4}$$

From (5.2) to (5.4)

$$R_f = \frac{T_{wt} - T_{wc}}{q'} \; . \tag{5.5}$$

The assumptions implicit in the use of Eq. (5.5) are

(i) Heat losses from the insulated test section are very low (negligible) and/or do not alter significantly with increase in wall temperature. This is validated by the fact that ΔT across the test section (Tin-Tout) remains constant through the course of a trial. The error due to this assumption can be reduced if q' is calculated from

$$q' = \dot{m}\, C_p \, [\text{Tout-Tin}]/A \tag{5.6}$$

If the mass flow rate is accurately determined value of q' using (5.6) is very accurate [22].

(ii) R_o = sum of wall resistances + fluid film resistances + resistance due to the mercury layer does not change as the fouling run proceeds. As wall temperature increases were typically around 1^oC this assumption appears reasonable. In case of large increases in wall temperatures, a correction term may have to be employed for change in R_o, or for any blockage effects or surface roughness effects on deposit-to-fluid heat transfer.

Thus for run 020 at time 1.60 hrs. and thermistor station T 109 the local fouling resistance is

$$R_f = \frac{T_{wt} - T_{wc}}{q'} = \frac{124.4 - 123.7}{115309} = 0.57 \times 10^{-5}\ M^2\text{ -Deg C/Watt}$$

Table XII below gives the results from computer program FOUL used to compute the fouling resistances. Thermistor stations which register fouling resistance of 0.0 after time zero are excluded from calculations as they may contain defective thermistors.

The first section of FOUL constitutes program PAR which evaluates properties, inlet and outlet temperatures, performs heat balance, calculates the Reynolds and Prandtl numbers and the Nusselt number using the Seider-Tate equation

$$\frac{hiD}{k} = 0.023\ (Re)^{0.8}\ (Pr)^{0.33}\ (\frac{\mu}{\mu w})^{0.14} \qquad (5.7)$$

Part 2 evaluates the local wall temperatures and the local fouling resistance at each thermistor station. Included in FOUL is also a method for calculating (RFM) based on computation of the film resistance and the fouling resistance for the whole tube at any specified time. This is based on the following considerations. The fouling resistance at any instant is given by

$$R_f = \frac{1}{u_{mean\ (fouled\ condition)}} - \frac{1}{u_{mean\ (clean)}} \tag{5.8}$$

Where the instantaneous mean heat transfer coefficient is given by

$$u_{mean} = \frac{q'}{\Delta T_m} \tag{5.9}$$

Where ΔT_m = mean temperature difference and is equal to

$$\Delta T_m = \frac{T_{b2} - T_{b1}}{\int_{T_{b1}}^{T_{b2}} \frac{dT_b}{T_w - T_b}} \tag{5.10}$$

Derivation for ΔT_m is presented in Appendix 4.

The temperature difference $T_w - T_b$ is evaluated at the central eight locations, thus excluding the thermal entrance and exit regions, and fitted to a quadratic equation in distance by least squares. The integral in Eq. (5.10) is then evaluated numerically. A linear increase in bulk temperature with length is assumed a condition equivalent to assuming a uniform heat flux with distance. The combined heat transfer coefficient and RFM is evaluated from Eqs. (5.8) and (5.9). Output from FOUL also lists out the following data: inlet fluid temperature (TIN), outlet fluid temperature (TOUT), mean wall temperature (TM), fluid temperature rise (DELTA), film plus fouling heat transfer coefficient (H), film plus fouling thermal resistance (R).

TABLE XII

Output from Program 'FOUL'

```
*********RUN NO29.*******

VM.TS12.HO          AMPS 220.

FERRIC OXIDE CONC (PPM)    2400.

FLOW RATE 0.0750   KGS.M/SEC

PH:6.1             DISS.O2 CONC (PPM)  5.2

HEAT FLOW SUPPLIED   2816.0     WATTS
HEAT FLUX SUPPLIED    120708.   WATTS/SQ.M

TOR=TINLET 49.9                       DEG C
DENSITY: 985.5KGS./CU.M
                    T OUTLET 58.5     DEG C

AVG TEMP 54.2       DEG C
KINEMATIC
VISCOSITYX100 0.000052                SQ.M/SEC

FLUID VELOCITY 0.813   M/SEC
REYNOLDS NO  17173.9
PRANDTL NO    3.71

HEAT SUPP      2816.0     WATTS
HEAT TRANS     2690.1     WATTS
HEAT LOST       125.9     WATTS
PERCENT HEAT LOST     4.47
HEAT FLUX TRANS  115309WATTS/SQ.M

NUSSELT NO       90.8
RFILM      0.210
RWALL      0.058
RTOTAL      0.268        SQ.M-DEG.C/WATTS
```

```
STIMATES OF ROOT MEAN SQUARE STATISTICAL ERROR IN THEPA  RAMETE
    0.88942               2.93631
STIMATES OF ROOT MEAN SQUARE TOTAL ERROR IN THE PARAMET  IRS
    0.09832               0.29155
STIMATE OF R0,RINF,AND B IN RF=RINF((1.-EXP(-B*TIME)
    0.00000               0.61677                1.97676
```

TIME HURS	CALC. RESISTANCE ((SQ.M-DEGC/WATTS)X(100,000))	FITTED VALUE
0.00	0.00	0.00
0.29	0.19	0.27
0.40	0.26	0.34
0.49	0.43	0.38
0.57	0.38	0.42
0.87	0.60	0.51
0.90	0.74	0.51
1.23	0.60	0.56
1.33	0.54	0.57
1.40	0.46	0.58
1.60	0.61	0.59
1.85	0.56	0.60
2.11	0.60	0.61
2.18	0.58	0.61

LOCALIZED WALL TEMPERATURES (DEG.C)

T101 DEG.C	T102 DEG.C	T103 DEG.C	T104 DEG.C	T105 DEG.C	T106 DEG.C	T107 DEG.C	T108 DEG.C	T109 DEG.C	T110 DEG.C	TIN DEG.C	TOUT DEG.C	TH DEG.C	DELTA DEG.C	H	H X1000	TIME HOURS
88.2	115.0	112.7	112.6	113.3	114.9	116.3	123.8	123.7	127.2	49.9	58.4	116.5	8.5	1615.4	0.6190	0.00
88.4	115.3	112.9	112.7	113.5	115.0	116.4	123.9	123.7	127.3	50.0	58.4	116.7	8.4	1614.5	0.6194	0.29
88.5	115.5	113.1	112.8	113.7	115.1	116.6	124.0	124.0	127.7	50.0	58.4	116.8	8.5	1608.7	0.6216	0.40
88.5	115.7	113.2	113.0	113.9	115.3	116.8	124.3	124.2	127.9	50.0	58.5	117.0	8.6	1604.7	0.6232	0.49
88.5	115.7	113.2	112.9	113.8	115.2	116.7	124.2	124.2	127.9	50.0	58.5	117.0	8.6	1607.0	0.6223	0.57
88.7	116.0	113.5	113.2	114.1	115.4	117.0	124.4	124.3	128.1	49.9	58.5	117.2	8.6	1599.9	0.6250	0.87
88.7	116.2	113.7	113.3	114.3	115.5	117.2	124.7	124.5	128.2	49.9	58.5	117.4	8.6	1594.8	0.6270	0.90
88.6	116.0	113.5	113.1	114.1	115.3	117.0	124.5	124.3	128.0	49.9	58.5	117.2	8.6	1599.2	0.6253	1.23
88.7	115.9	113.4	113.1	114.0	115.4	117.0	124.3	124.3	128.0	50.0	58.6	117.2	8.6	1603.1	0.6238	1.33
88.5	115.8	113.3	113.0	113.9	115.3	116.8	124.4	124.3	127.9	50.0	58.5	117.1	8.5	1603.9	0.6235	1.40
88.6	116.0	113.5	113.1	114.1	115.4	117.1	124.4	124.4	128.1	49.9	58.5	117.2	8.6	1599.4	0.6252	1.60
88.5	116.0	113.4	113.1	114.0	115.3	117.0	124.5	124.4	128.1	50.0	58.6	117.2	8.6	1602.0	0.6242	1.85
88.5	116.0	113.4	113.1	114.0	115.3	117.0	124.5	124.4	128.1	49.9	58.5	117.2	8.5	1598.9	0.6254	2.11
88.5	116.0	113.4	113.1	114.0	115.3	117.0	124.6	124.4	128.1	49.9	58.6	117.2	8.6	1601.1	0.6246	2.18

LOCALIZED FOULING RESISTANCE (SQ.M-DEG.C/WATTS)X100,000

T101	T102	T103	T104	T105	T106	T107	T108	T109	T110	TIN DEG.C	TOUT DEG.C	RFM	DELTA DEG.C	H	RTOT X1000	TIME HOURS
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	49.9	58.4	0.00	8.5	1615.4	0.6190	0.00
0.14	0.29	0.12	0.05	0.13	0.06	0.11	0.05	0.01	0.05	50.0	58.4	0.10	8.4	1614.5	0.6194	0.29
0.22	0.44	0.28	0.19	0.20	0.16	0.26	0.17	0.27	0.40	50.0	58.4	0.26	8.5	1620.7	0.6216	0.40
0.27	0.66	0.43	0.35	0.45	0.29	0.40	0.43	0.44	0.55	50.0	58.5	0.43	8.6	1604.7	0.6232	0.49
0.22	0.64	0.40	0.30	0.37	0.22	0.37	0.35	0.40	0.38	50.0	58.5	0.38	8.6	1607.0	0.6223	0.57
0.30	0.99	0.66	0.51	0.65	0.42	0.64	0.55	0.53	0.75	49.9	58.5	0.67	8.6	1599.9	0.6250	0.87
0.47	1.03	0.80	0.65	0.78	0.50	0.76	0.75	0.69	0.85	49.9	58.5	0.74	8.6	1594.8	0.6270	0.90
0.33	0.85	0.65	0.48	0.66	0.34	0.64	0.63	0.53	0.65	49.9	58.5	0.60	8.6	1599.2	0.6253	1.23
0.30	0.81	0.58	0.45	0.55	0.35	0.62	0.41	0.55	0.72	50.0	58.6	0.54	8.6	1603.1	0.6238	1.33
0.29	0.74	0.45	0.34	0.46	0.29	0.43	0.48	0.52	0.64	50.0	58.5	0.46	8.5	1603.9	0.6235	1.40
0.36	0.88	0.69	0.49	0.67	0.37	0.68	0.51	0.57	0.76	49.9	58.5	0.61	8.6	1599.4	0.6252	1.60
0.29	0.86	0.57	0.42	0.53	0.32	0.58	0.64	0.59	0.79	50.0	58.6	0.56	8.6	1602.0	0.6242	1.85
0.29	0.91	0.61	0.47	0.60	0.34	0.61	0.65	0.62	0.81	49.9	58.5	0.60	8.5	1598.9	0.6254	2.11
0.28	0.89	0.54	0.44	0.54	0.32	0.59	0.73	0.61	0.75	49.9	58.6	0.58	8.6	1601.1	0.6246	2.18

Subroutine BFIT has been used in the latter part of the program to curve fit the mean fouling resistance (RFM) by least squares method to the equation

$$R_f = R_f^* \ (1-e^{-bt}) \qquad (5.11)$$

Output from this subroutine, shown in Table XII above, gives the fitted values of R_f and of R_f^* and b in Eq. (5.11). Units of WATTS, DEGC, HOUR AND METRE have been used throughout in all computations.

5.3. Fouling Resistance Versus Time Behaviour for Ferric Oxide Fouling Runs

5.3.1. Nature of Fouling Curves

Three distinct behaviour modes were observed in the curves obtained from trials made for ferric oxide-tap water suspension fouling of 316 stainless steel as seen in Figs. 5.1, 5.2 and 5.3. A brief discussion for each type follows below.

Asymptotic increase in fouling resistance with time is depicted in Fig. 5.1 which was the most frequently obtained type of fouling curve. Fouling behaviour as suggested by Kern and Seaton [6] is borne out. The solid line is the least square fit of R_f to the equation

$$R_f = R_f^* \ (1-e^{-bt}) \qquad (5.11)$$

Fouling occurs at a decreasing rate before reaching an asymptotic value and an examination of the curve shows that Eq. (5.11) adequately characterizes the fouling behaviour and is a fairly good fit of the experimental data.

Fig. 5.2 shows another type of fouling curve obtained for the system studied. This curve was obtained when the test section was

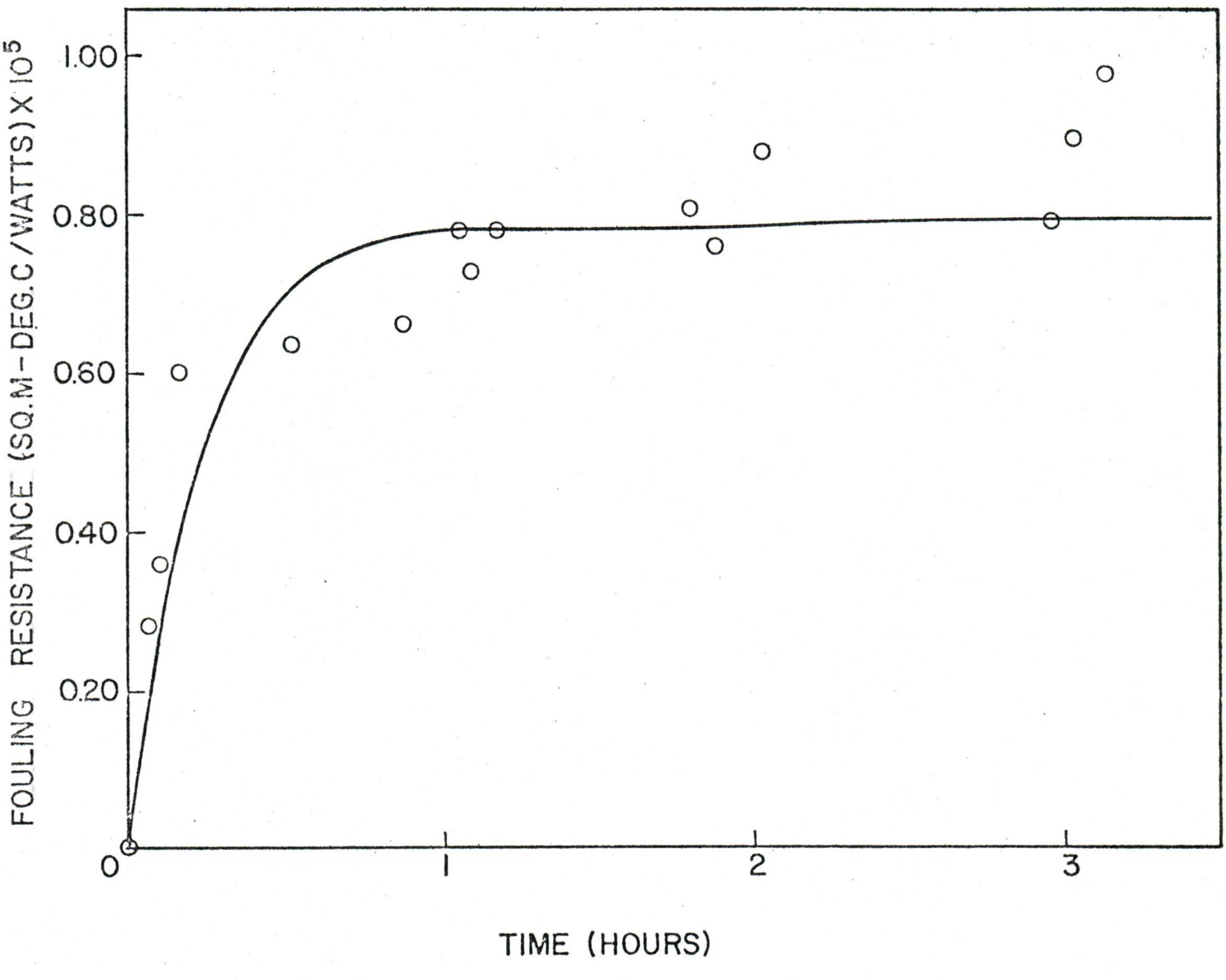


Fig.5.1. Fouling Curve Illustrating Asymptotic Type Behaviour.

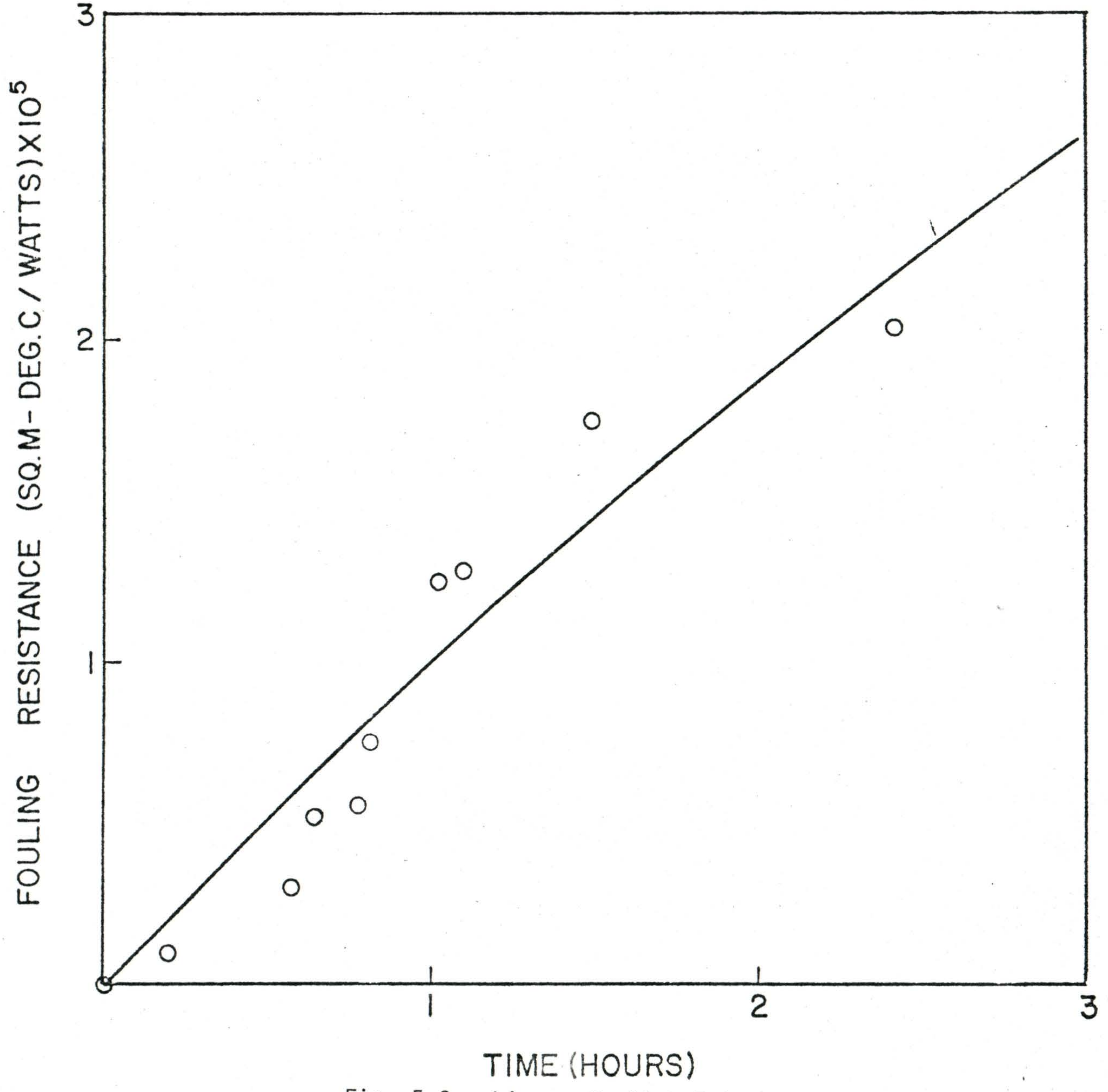


Fig. 5.2. Linear Fouling Behaviour.

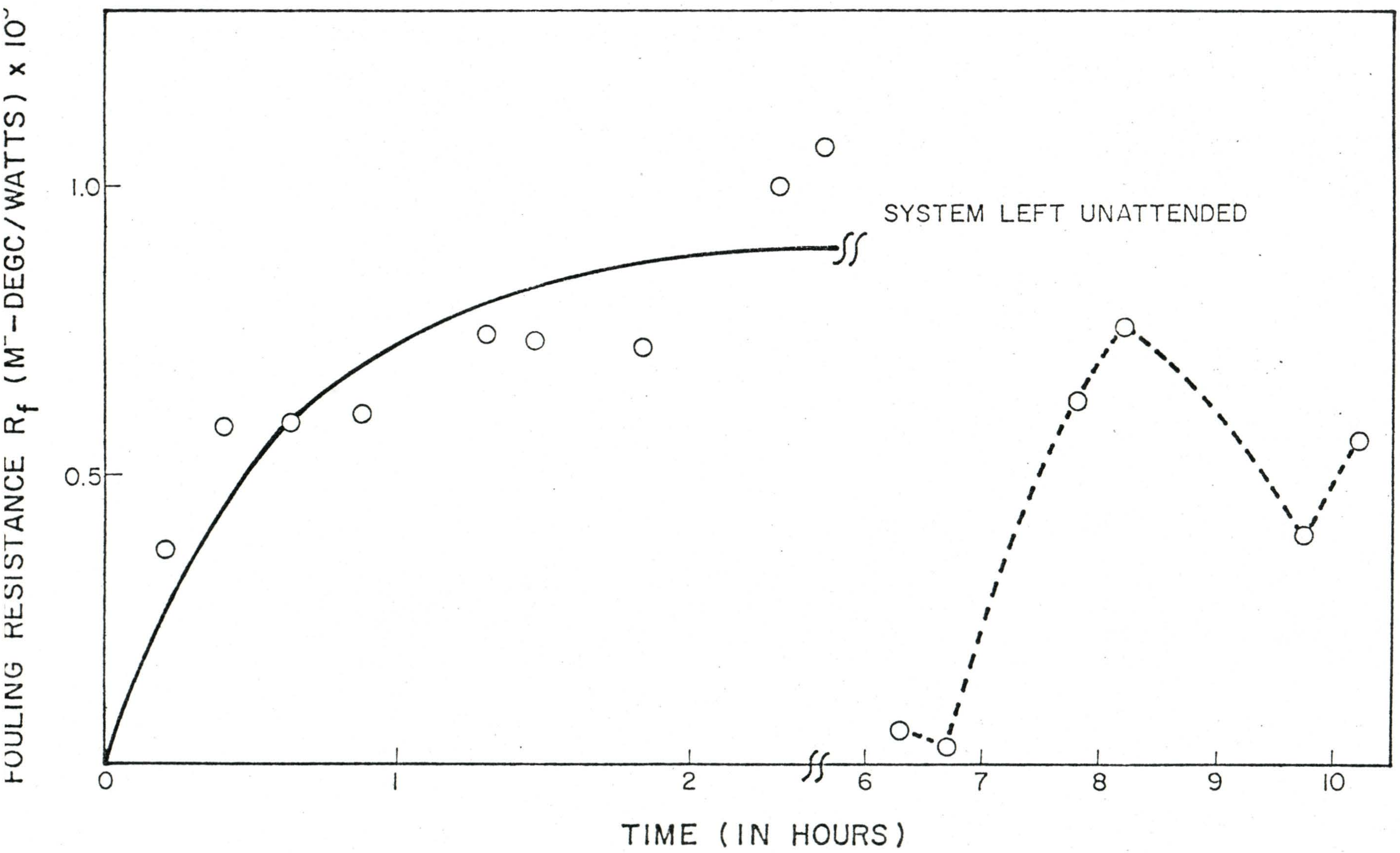


Fig.5.3. Effect of Prolonged Operation on Fouling Behaviour.

prefouled at zero heat flux or at low heat fluxes with alternate heating and cooling for periods over eight hours before commencing a run. As is evident in the figure it shows a near linear dependence of fouling resistance with time.

A third type of fouling curve was obtained when the operating time for an asymptotically fouled tube was extended beyond 2-5 hours to 10 hours. Fig. 5.3 shows the nature of the fouling curve obtained for this run. An examination of the experimental data for this run (Appendix 5) shows that extension of the operating time results in fouling becoming an unsteady state process whereby fouling resistances decrease followed again by refouling (increase in fouling resistances). Taborek et al. [10] have also observed curves of this type. For the first 2.42 hours it is seen that the tube fouls asymptotically to a level A. At 6.30 hours the wall temperatures almost return to clean wall conditions. Then the tube refouls at an increasing rate and finally decreases. Decrease in the fouling resistance is interpreted as deposit release from the wall, in which case refouling would occur as observed. Data from this single run is, however, insufficient to reach any conclusions with respect to deposit release rates. Also, during the course of this run, the equipment was left unattended for long periods of time and consequently data processed is limited. More controlled and planned experimentation as outlined in reference [22] would have to be carried out to determine refouling and release rates.

The difference in these three curves is due to difference in their operating mode and all three types of fouling curves can be obtained while running under identical operating conditions.

5.3.2. Reproducibility of Fouling Curves

An important criterion which must be met in the setting up of any experimental research unit is that of reproducibility and that the results or data obtained are valid. In order to establish reproducibility of ferric oxide fouling versus time curves two trials were conducted under identical operating conditions of Re No. 20575, heat flux 110936 Watts/SQ.M and ferric oxide concentration of 3400 ppM. Fig. 5.4 gives the results of these trials. As it can be seen, the curves appear to be reasonably reproducible. The coefficient of variation for the parameters R_f* and b for the least squares fit of the data to the equation

$$R_f = R_f^* \; (1-e^{-bt})$$

are 8% and 20%, respectively, as seen in Table XIII.

Fig. 5.5 shows the fouling curves obtained for runs 007 and 024 at near identical conditions. Taking into consideration the small difference in the operating conditions both the curves appear fairly similar.

One question which must be answered before the observed increase in wall temperatures is taken as valid data representing the fouling process is whether these increases actually reflect a fouling process or whether they are induced by thermal transients, a possible source of error in a previously reported study on dilute sand-water slurry [3]. Analysis of the thermal data for the ferric oxide fouling runs shows that fouling curves obtained are an accurate representation of the fouling deposit growth. Since most of the trials were made by operating for over three hours with ferric oxide in the system, and

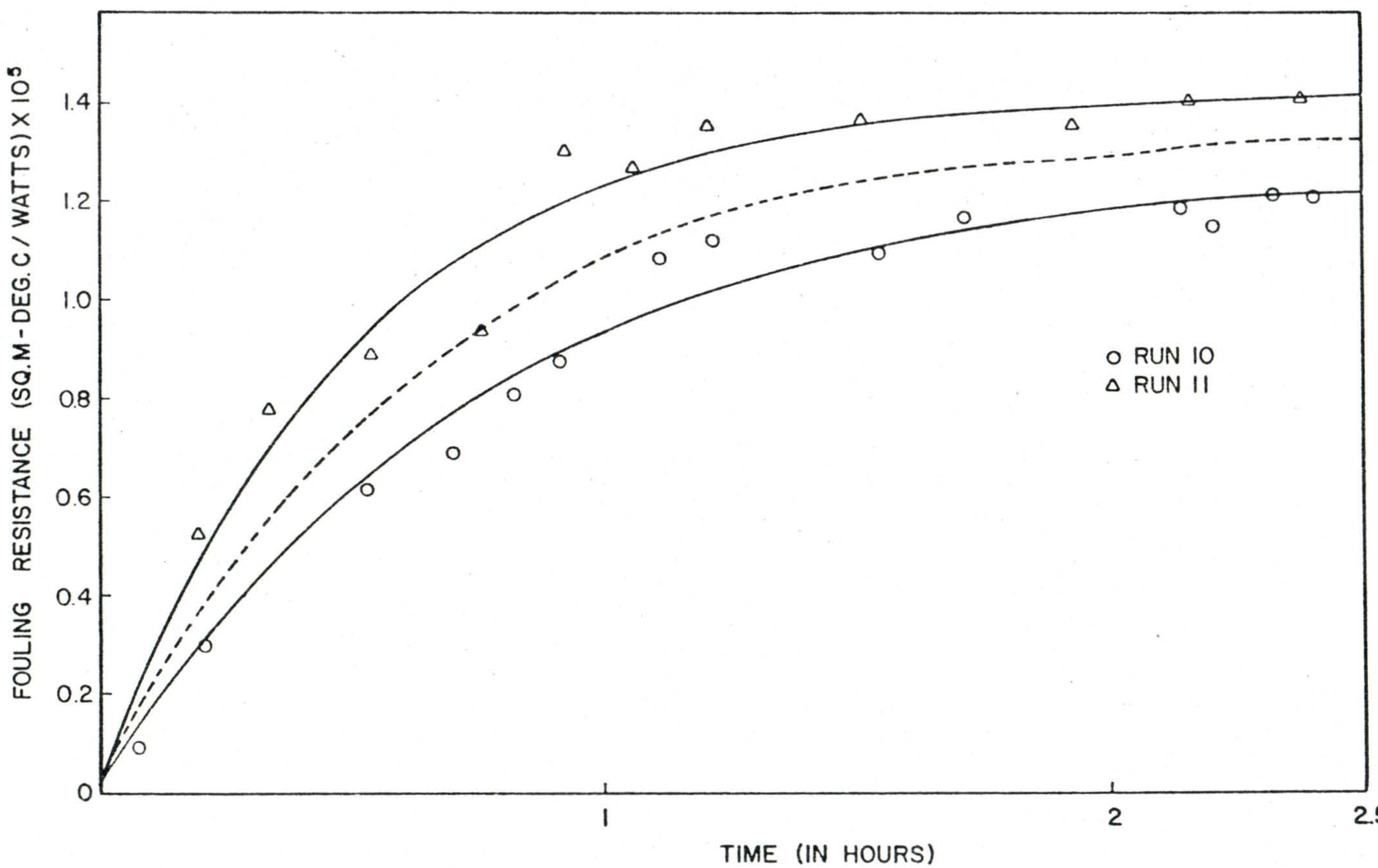


Fig. 5.4. Reproducibility of Fouling Curves at Identical Conditions.

TABLE XIII

Reproducibility of Fouling Curve Parameters by Fitting Fouling Data to $R_f = R_f^* \ (1-e^{-bt})$

Heat Flux: 110936 WATTS/SQ.M

Reynolds No. 20575

Ferric Oxide Concentration: 3400 ppM

Run No.	R_f^* (SQ.M-DEGC/WATTS)x10^{-5}	b hr^{-1}
009	1.22	1.32
010	1.42	2.0
Average	1.32	1.66
Std.Deviation	.10	0.34
Coeff. of Variance	7.58	20

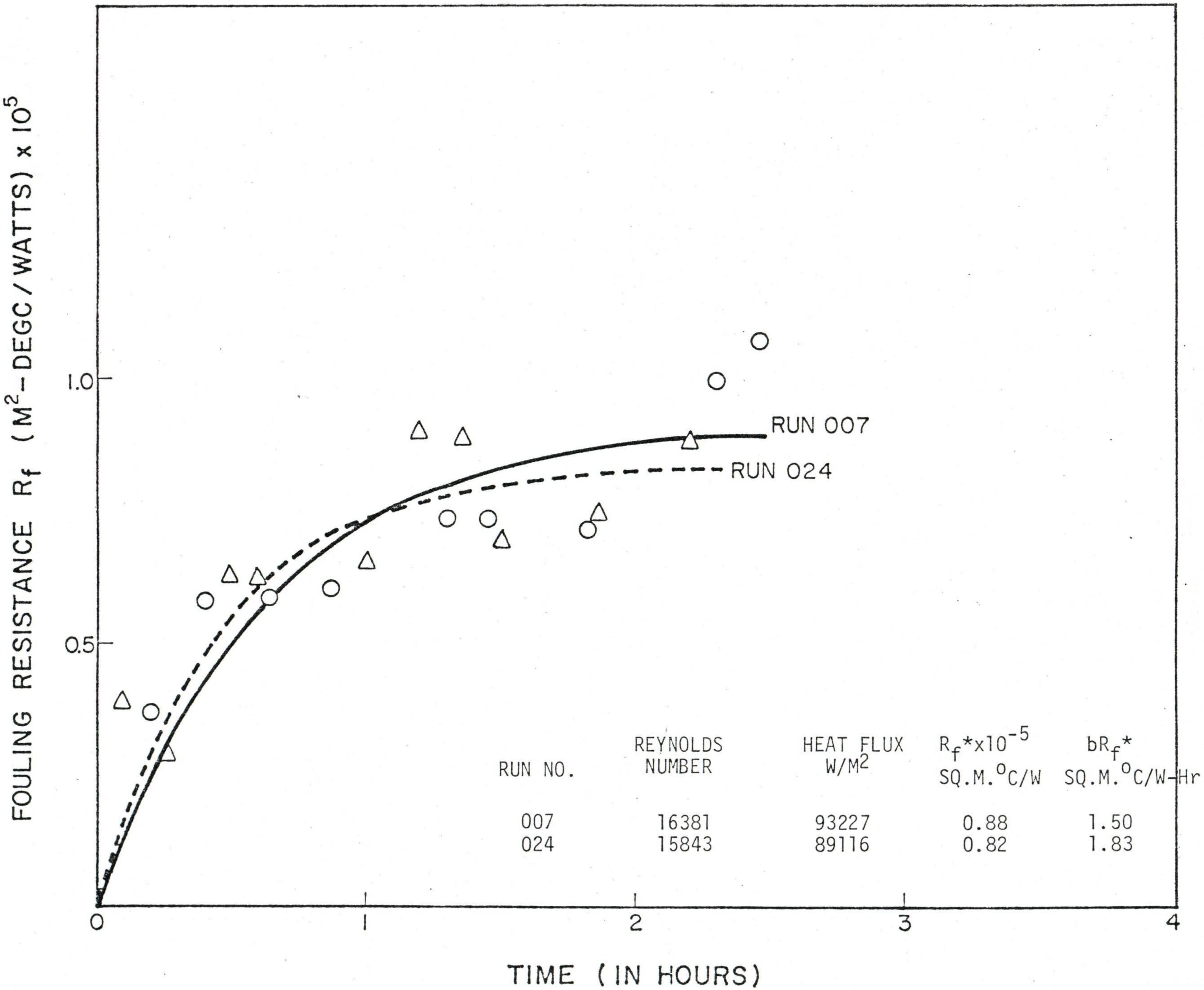


Fig.5.5. Reproducibility of Fouling Curves at Near Identical Conditions.

then removing any deposit by quick draining and honing of the tube before time zero, the bulk fluid properties remained the same before and after commencement of a run and would not contribute to any thermal transients arising from change in bulk fluid properties--a point made in reference [22]. Also, honing of the test sections returned the wall temperatures to the clean wall conditions. Table XIV shows the clean wall temperatures prior to starting a run, wall temperatures on completion of a run (i.e., at fouled condition) and temperatures after honing the tube. Even if the system were being operated on tap water before commencement of a trial and addition of ferric oxide, the possible change in the fluid viscosity, fluid property which would affect most the heat transfer coefficient, would be negligible to cause the temperature increase observed [22].

5.3.3. Reproducibility of Fouling Data with that Reported in Literature [22]

To establish the reproducibility of the fouling resistance data for ferric oxide fouling of stainless steel, the thermal fouling resistance versus time curves obtained were compared with the fouling curves of a similar system used in a previous study [22] for identical or near identical conditions. Figs. 5.6 and 5.7 show the fouling curves obtained for runs 020 and 024. Superimposed on the same plot are the fouling curves for runs 38 and 55 (converted in SI units) from Hopkins [22]. An examination of the above figure shows that under near or identical conditions the previously reported results are similar to that obtained in the present study. The small deviations seen in Figs. F.6 and 5.7 are due to the minor differences in operating conditions (heat

TABLE XIV

Thermal Data from Runs 009 and 010 to Determine Effect of Honing Tube Wall on Thermal Resistance

Mean

No	T IN °C	T OUT-LET °C	TEMP. RISE DELTA °C	T 1 0 1	T 1 0 2	T 1 0 3	T 1 0 4	T 1 0 5	T 1 0 6	T 1 0 7	T 1 0 8	T 1 0 9	T 1 1 0	Mean Temp.	Thermal Resistance x 10^3 (M^2-DEGC/Watt
Clean wall temps. after reaching steady states prior to a trial	50.1	56.9	6.8	82	99.7	101.0	103.4	102.4	104.6	101.7	107.6	111.5	109.3	104	.5229
Temperatures on completion of a run (fouled condition	50.1	56.9	6.8	82.3	102.5	101.9	103.8	103.1	104.8	104.4	110.1	111.9	111.1	105.3	.5359
Temps. at steady state after hon-ing tube	50.1	56.9	6.8	82.3	99.4	99	103.3	101.0	104.7	101.8	108.2	111.1	107.9	103.2	.5152

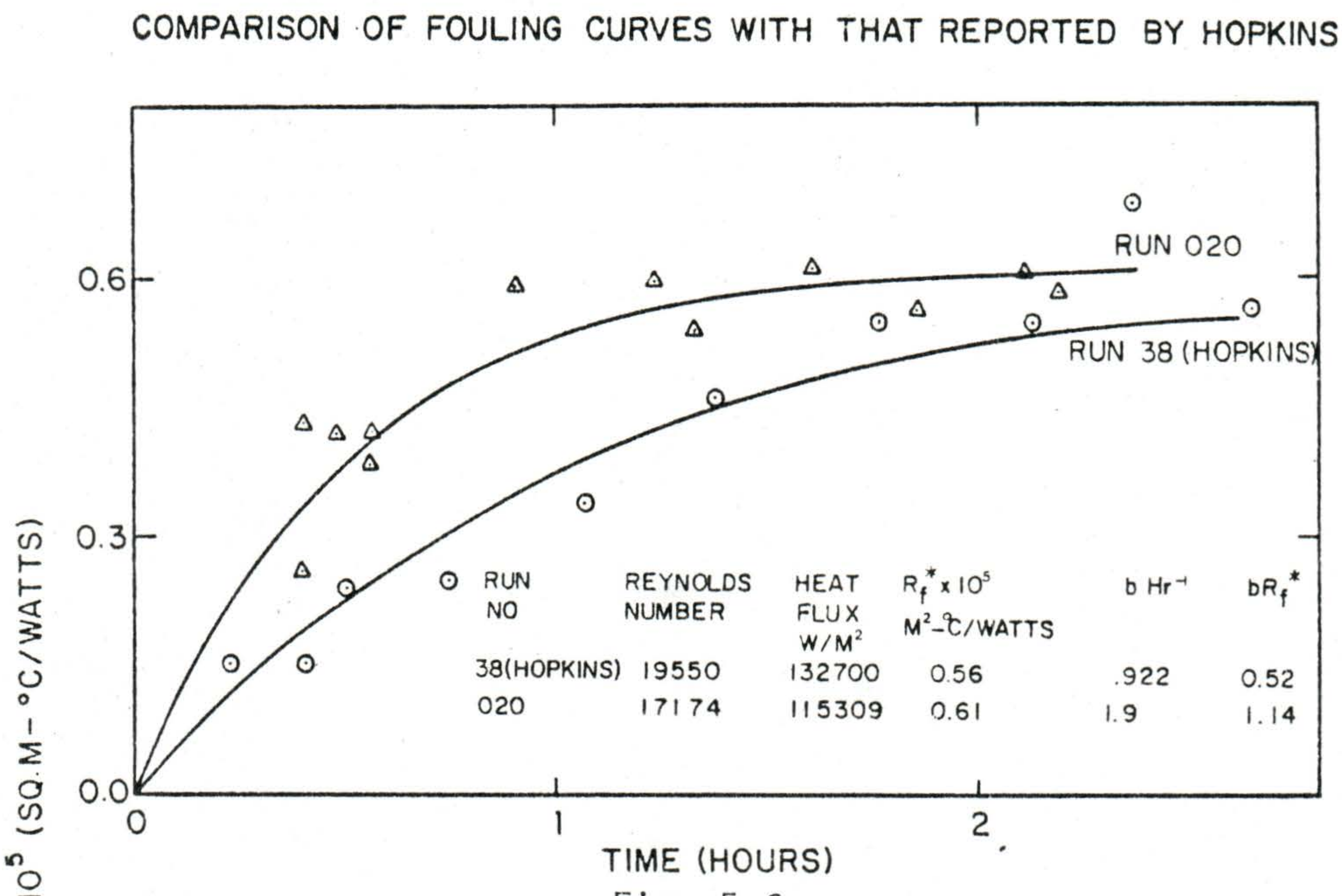


Fig. 5.6.

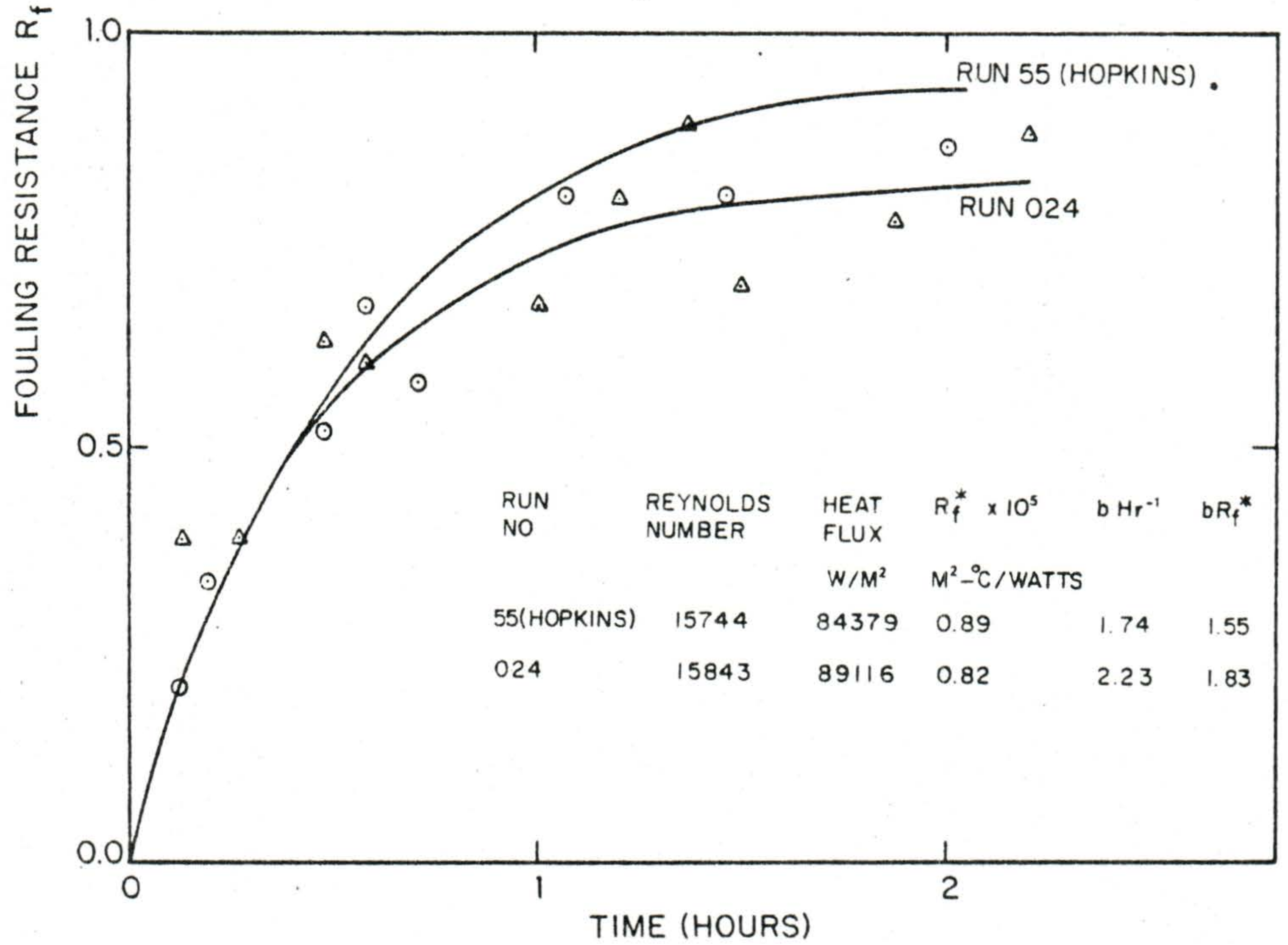


Fig. 5.7.

Fig. 5.6. Comparison of Fouling Curves for Run 020 with Hopkins Run No. 038.

Fig. 5.7. Comparison of Fouling Curve for Run 024 with Hopkins Run No. 55.

flux and Reynolds number) for the two runs. Fouling data for ferric oxide fouling of stainless steel from both studies appear to be fairly reproducible. Also, it seems that the fouling behaviour observed by Hopkins was not influenced by any magnetic or electric effects since nearly similar results are obtained in the case of keeping the test section electrically isolated, as in the present study.

5.3.4. Effect of Reynolds Number and Heat Flux

To study the effect of Reynolds number and heat flux on the fouling behaviour, two sets of trials were conducted at heat fluxes of 115-122 KW/M^2 and 89-96 KW/M^2 for a Reynolds number range of 11870-29740. All the runs were made at the standard ferric oxide concentration of 2400 PPM. The results of these trials are shown in Table XV and the generated fouling curves in Figs. 5.8 and 5.9. An examination of these results show that lowering the heat flux or the Reynolds number generally causes an increase in fouling. Increasing the Reynolds number increases the shear stress and consequently, the scouring of already deposited material. Because of the competition between deposition and release, the net effect of an increased scouring rate will be a lowering of the asymptotic fouling resistance. This relationship between R_f^* and Reynolds number has been observed previously by other investigators [7,10]. The effect of fluid velocity on the asymptotic fouling resistance at two heat flux levels is shown in Figs. 5.10 and 5.11. Asymptotic fouling resistance is seen to first increase with velocity, go through a maximum and decrease with increasing velocity. Maximum value of R_f^* is seen to occur at low velocities. Watkinson et al. [15] have discussed the possible reasons for the velocity maximum and the maximum in the R_f^*

TABLE XV

Effect of Reynolds Number and Heat Flux for Mixed Size Ferric Oxide Particles Concentration 2400 ppM

RUN NO.	Heat Flux W/M^2	Reynolds No.	Run Time Hrs.	Wall Temp. Clean ^oC	Wall Temp. Increase ^oC	Mass Flow Rate Kg/sec	$R_f \times 10^{-5}$ M^2-DegC/Watt	b hr^{-1}	Initial Fouling Rate $\left.\frac{\partial R_f}{\partial t}\right\|_{t=o} = bR_f^*$
018	121998	28347	1.91	108.7	0.6	0.1270	0.47	4.01	1.88
019	119336	22566	1.71	112.0	0.8	0.1000	0.55	4.93	2.71
020	115309	17174	2.18	116.5	0.7	0.0750	0.62	1.97	1.22
021	116967	12933	2.26	124.8	1.1	0.0550	0.50	2.02	1.01
022	96918	29737	2.01	95.9	0.4	0.1350	0.44	2.09	0.92
023	97094	20192	1.83	101.6	0.9	0.0900	0.74	7.7	5.70
024	89116	15843	2.20	104.4	0.8	0.0700	0.82	2.23	1.83
025	92950	11874	1.75	112.6	0.6	0.0510	0.67	2.1	1.41

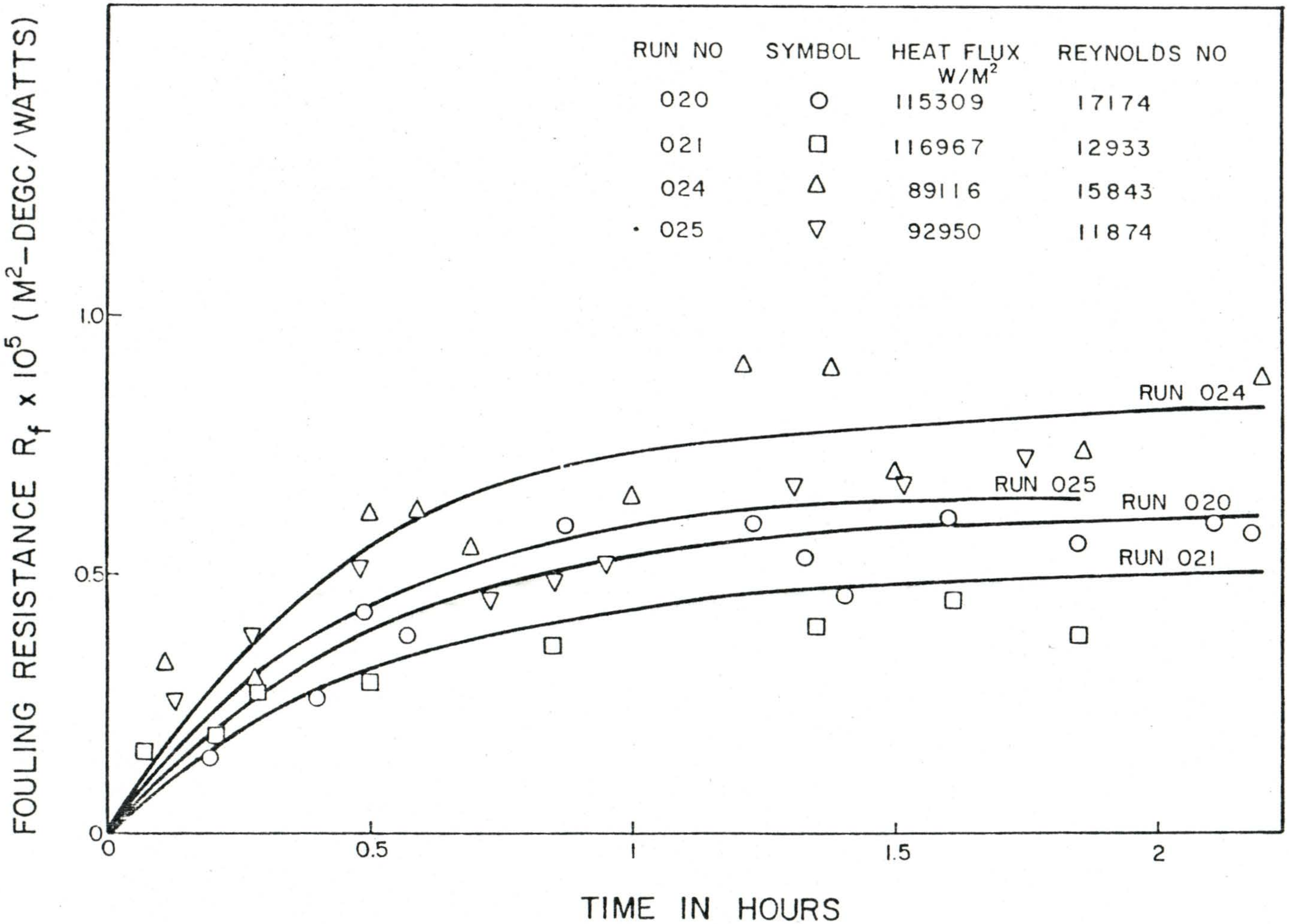


Fig. 5.8. Effect of Reynolds Number and Heat Flux on Fouling Behaviour at Reynolds Number $\leq$ 17,174 and Heat Flux 89116-115307 W/M^2.

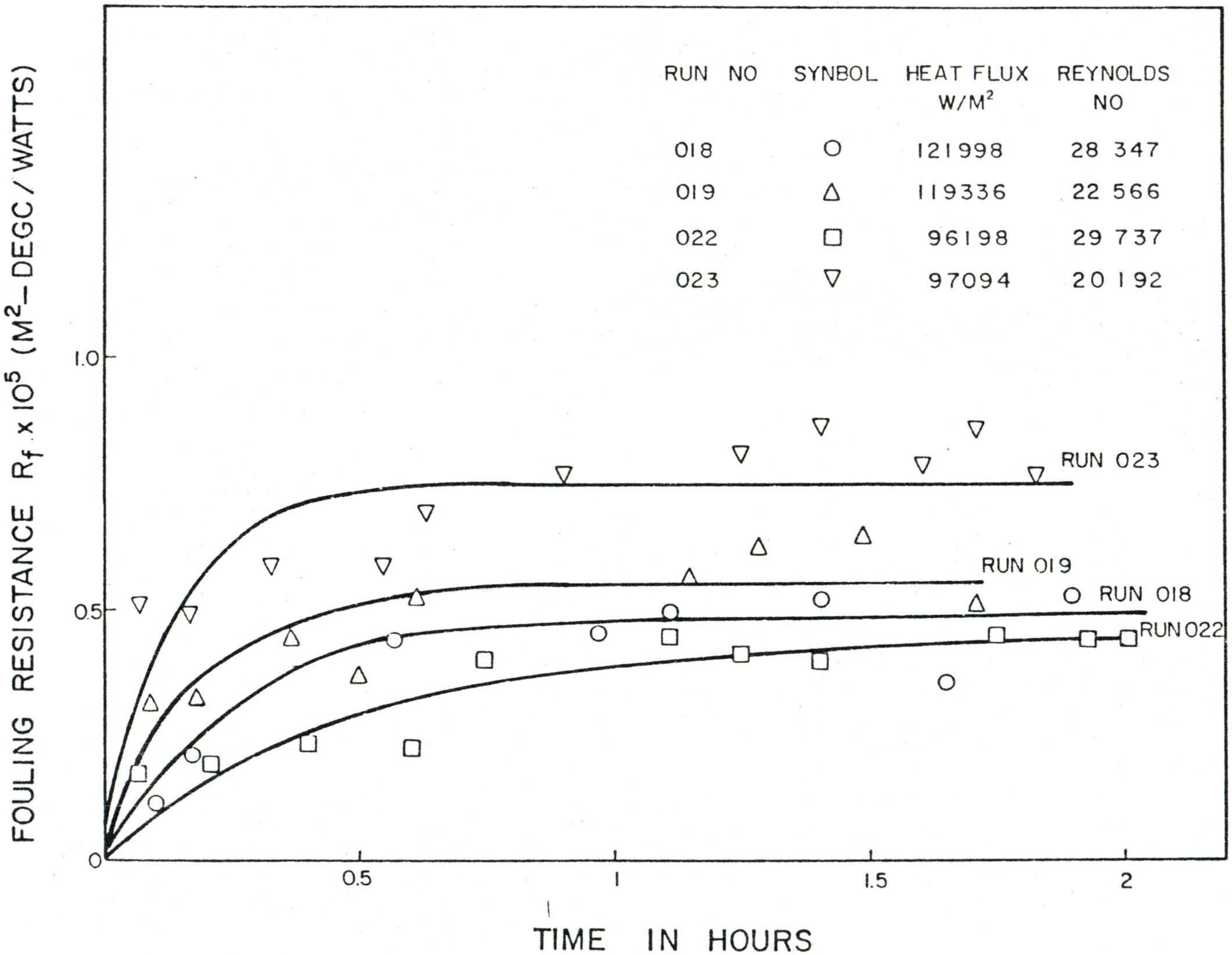


Fig. 5.9. Effect of Reynolds Number and Heat Flux on Fouling Behaviour Reynolds number ≥ 20192 and Heat Flux 96198-121998 W/M^2.

velocity curve is therefore not surprising. From the above figure it can also be seen that the effect of the Reynolds number on the asymptotic fouling resistance is more pronounced at low heat fluxes than at a higher level.

In an attempt to establish the compatibility of experimental data obtained for these runs with the fouling models presented in the literature it was decided to examine these data against specific fouling theories to test whether it would bear out the theoretically predicted results. As most of the fouling data were routinely fitted to the Kern-Seaton model equation $R_f = R_f^* (1-e^{-bt})$, the experimental data were examined against this equation to see whether it shows the same dependence of R_f^* and initial fouling rate $\left.\frac{dR_f}{dt}\right|_{t=0}$ on the mass flow rate.

The basic differential equation for the Kern-Seaton model is given by

$$\frac{dx}{dt} = K_1 CW - K_2 \tau x \qquad (5.12)$$

where x = foulant deposit thickness

W = mass flow rate

τ = shear stress at the tube wall

C = concentration of foulant in the fluid

t = time and K_1 and K_2 are proportionality constants

Assuming that all variables on the right hand side of the above equation are constant except for x, integration from x = 0, at t = 0 gives

$$x = \frac{K_1 CW}{K_2 \tau} [1-e^{-K_2 \tau t}] \qquad (5.13)$$

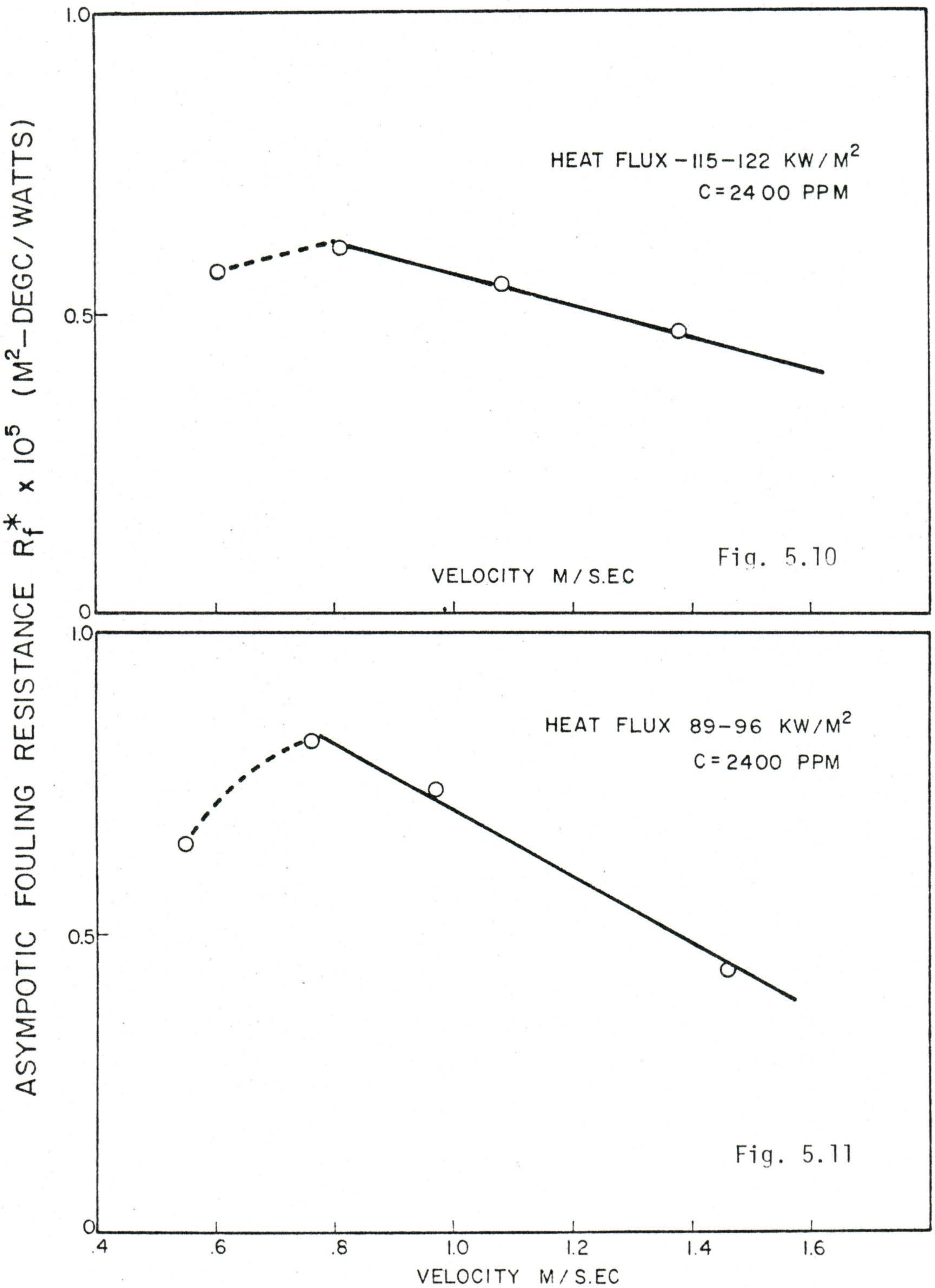


Fig. 5.10. Effect of Fluid Velocity on Asymptotic Fouling Resistance at Heat Fluxes 115-122 KW/M^2.

Fig. 5.11. Effect of Fluid Velocity on Asymptotic Fouling Resistance at Heat Fluxes 89-96 KW/M^2.

Defining R_f by $R_f = \frac{x}{k_d}$ where k_d = thermal conductivity of the deposit

$$R_f = \frac{K_1 CW}{K_2 \tau k_d} [1-e^{-K_2 \tau t}] \tag{5.14}$$

By definition the asymptotic fouling resistance is given by

$$R_f^* = [R_f]_{t=\infty} = \frac{K_1 CW}{K_2 \tau k_d} \quad \text{from Eq. (5.14).}$$

Also, examining this equation against $R_f = R_f^* (1-e^{-bt})$ gives $b = K_2\tau$. Further assuming the Blasius expression for friction factor to be valid in this case, then

$$\tau = \rho U_b^2 f/2 = 0.79 \rho U_b^2 [\frac{DU_b\rho}{\mu}]^{-0.25} \tag{5.15}$$

or

$$\tau \alpha U_b^{1.75} \alpha W^{1.75} \tag{5.16}$$

Thus, according to the Kern-Seaton model the asymptotic fouling resistance, R_f^*, should vary as $W^{-0.75}$ and the initial fouling rate bR_f^* should vary directly as W.

Log-Log plots in Figs. 5.12 and 5.13 of the asymptotic fouling resistance and the initial fouling rates against mass flow rates for four runs 018, 019, 020 and 025, all made at a ferric oxide concentration of 2400 PPM, show that R_f^* varies inversely as mass flow rate raised to the power of 0.62 which appears to be in keeping with the general fouling theory presented by Kern [6]. This result appears also to be supportive of the mass-transfer controlled fouling theory of Watkinson and Epstein [5], which predicts that in the absence of blockage, R_f^* should vary inversely as mass flow rate W raised to a power of 0.75-1.0 depending upon the degree of roughness. For the same fouling runs the initial fouling rate $\frac{dR_f}{dt}\Big|_{t=0} = bR_f^*$ is seen to vary directly as the mass flow rate raised to a power of 0.97 which appears to be in keeping with the above cited theories of Kern [6] and Watkinson and Epstein [5] which predict the initial fouling rate to vary directly as the mass flow rate raised to the power unity.

The reason for restricting analyses of data for these four runs was that they showed a two-and-a-half times increase in the mass flow rate with the wall temperature at time zero remaining relatively constant at 112 ± 4^{0}C. Since fouling behaviour is known to be temperature dependent, an appropriate condition which must be met in studying the effect of mass flow rate on R_f^* and initial fouling rate is that the fluid-deposit interface temperature should be constant. Range of Reynolds number studied in Figs. 5.12 and 5.13 is 28347-11874. Superimposed on the above figures are also the results reported for ferric oxide fouling of 304 stainless steel by Hopkins [22]. An examination of the two results show that the results of effect of mass flow rate on R_f^* are comparable.

Comparison of runs 019 and 020 with 023 and 024, respectively, in Figs. 5.14 and 5.15 illustrates the effect of heat flux on the fouling resistance at nearly constant Reynolds number. It is seen that a decrease in the heat flux raises the fouling curve, i.e., R_f^* increases. One possible explanation for this behaviour could be that high heat fluxes are associated with higher thermophoretic forces which drive the particles away from wall [38]. The above reasoning,

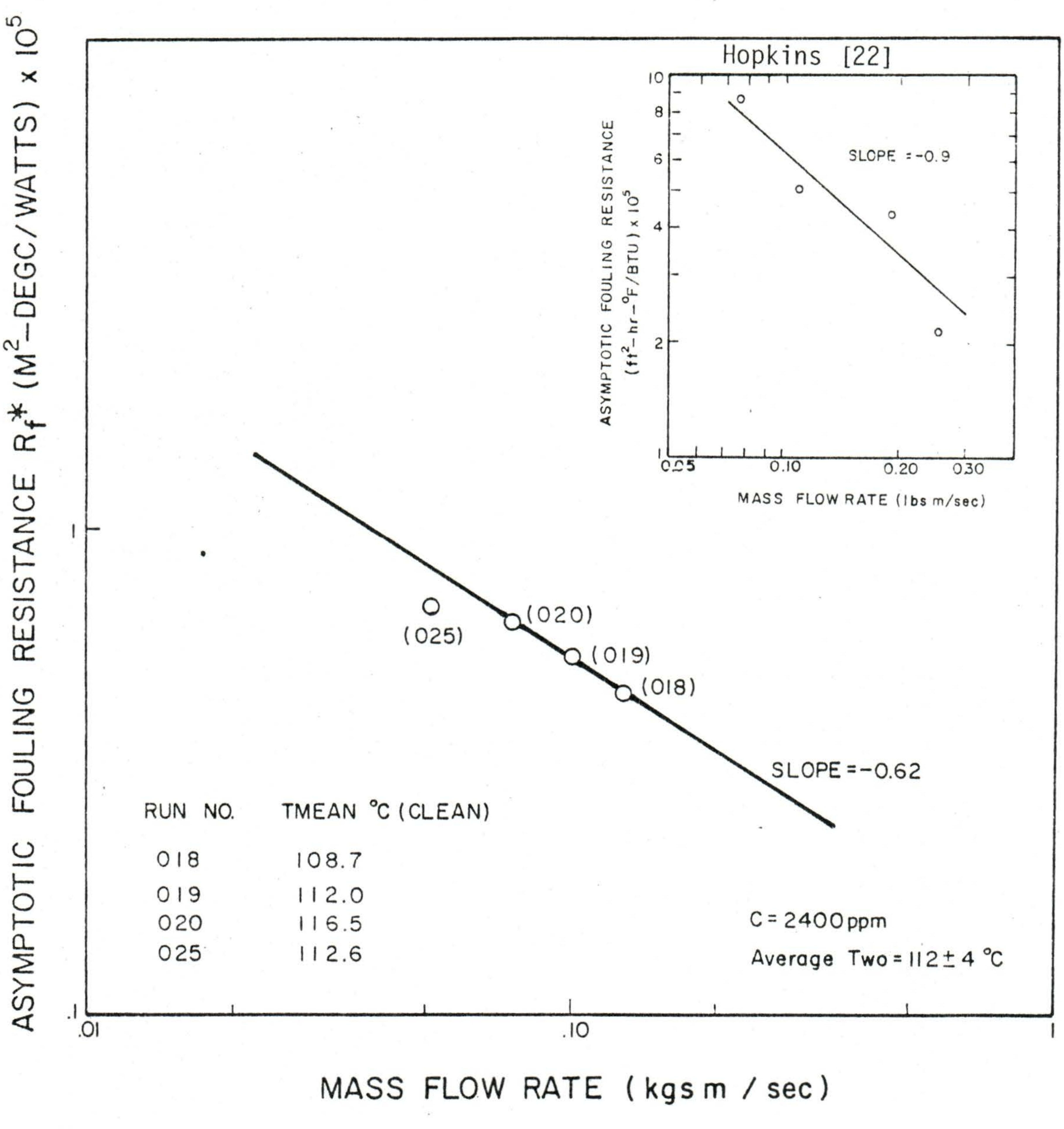


Fig. 5.12. Dependence of Asymptotic Fouling Resistance on Mass Flow Rate for (Runs 018, 019, 020, 025). Wall Temperature Two at Time Zero 112 ± 4°C.

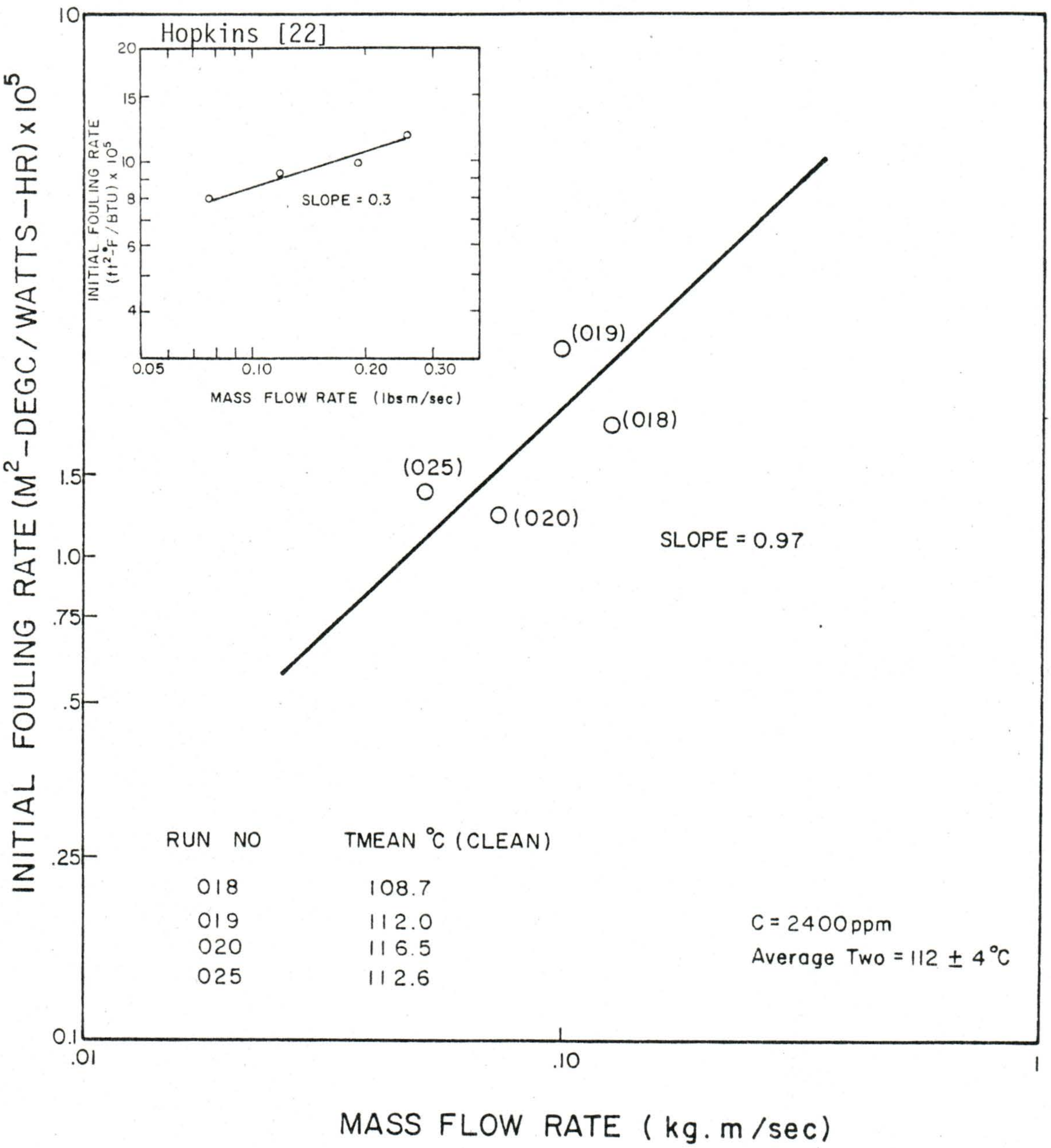


Fig. 5.13. Dependence of Initial Fouling Rate on Mass Flow Rate for Runs 018, 019, 020, 025. Wall Temperature Two at Time Zero 112 ± 4^{0}C.

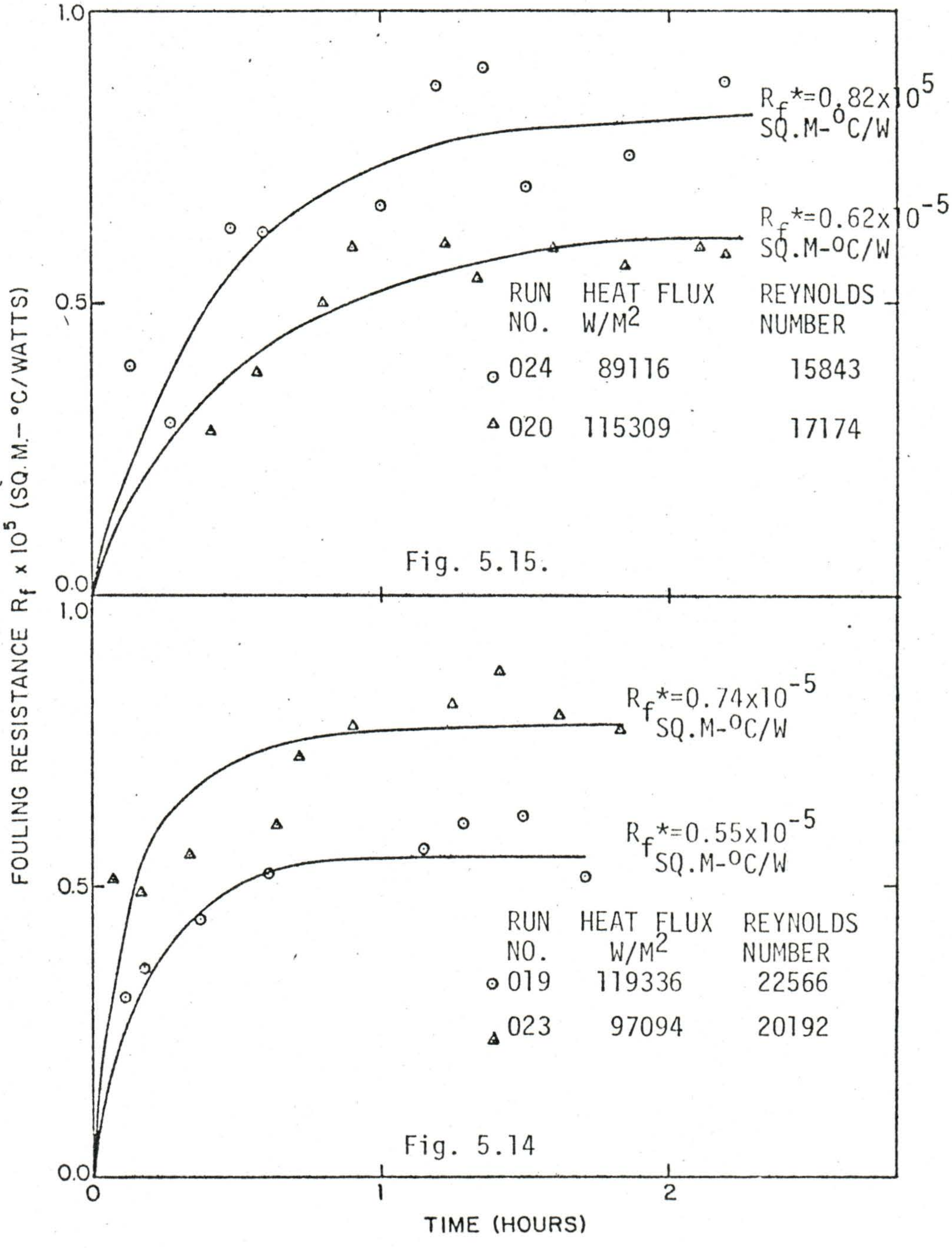


Fig. 5.14. Effect of Heat Flux on Fouling Behaviour at Similar Reynolds Numbers for Runs 019 and 023.

Fig. 5.15. Effect of Heat Flux on Fouling Behaviour at Similar Reynolds Numbers for Runs 020 and 024.

however, does not appear to be universal and entirely in consistence with the experimental observations. Fouling trials, in which the tube had been prefouled at low heat flux prior to time zero and then subjected to high heat flux showed a constant fouling rate at an enhanced rate over a conventional run at similar conditions. The thermophoresis hypothesis in this case fails to explain fully the inverse dependence of fouling resistance on heat flux. A more plausible explanation, it appears in this case, is the one provided by Hopkins [22] and Epstein [13,23]. At high heat fluxes the wall temperatures are higher. Also, the solubility of oxygen is known to decrease with increasing temperature [40]. Therefore, at a high heat flux operating condition, the solubility of oxygen is decreased at the wall. As it was seen in a later run that by purging out the oxygen by nitrogen from the circulating fluid the fouling rate was seen to decrease and since the fouling rate also decreases with increasing temperature it appears that the decrease in fouling resistance at high heat flux is explainable by the decrease in the solubility of oxygen at higher wall temperatures, i.e., at high heat fluxes.

5.3.5. Effect of Local Wall Temperatures on Fouling Behaviour

At constant heat flux operation, the heat flux together with the flow rate establishes the clean wall temperature profile with wall temperatures increasing in the direction of fluid flow. By plotting the local fouling resistances along the tube wall at each thermistor station against the corresponding clean wall temperatures, the influence of local wall temperature on fouling resistance can be determined. Fig. 5.16 shows a plot of local values of R_f at time $t = 1$ hour against

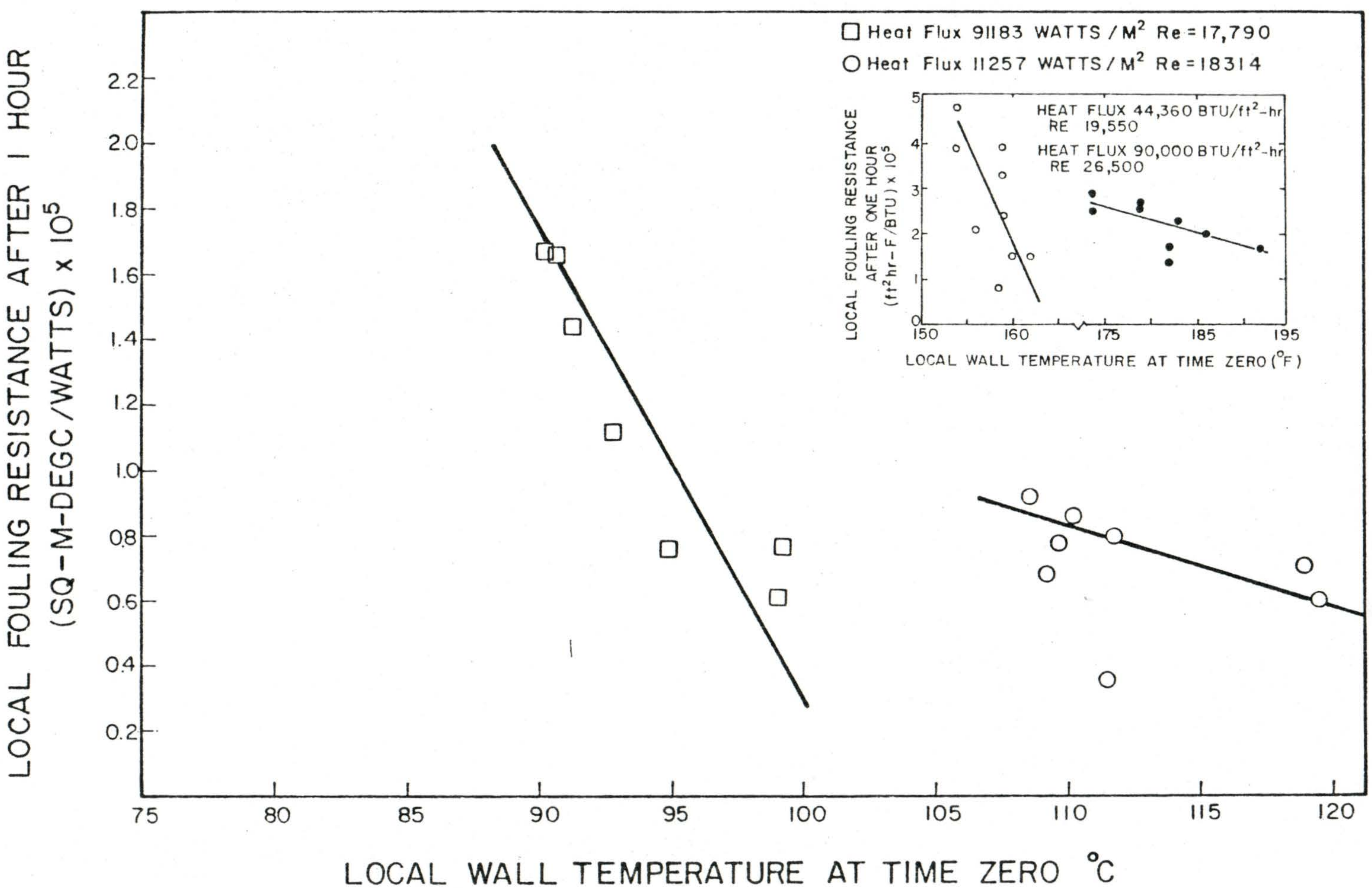


Fig. 5.16. Local Fouling Resistance After One Hour versus Local Wall Temperature at Time Zero for Runs 016 and 017.

TABLE XVI

Local Fouling Resistances After One Hour as a Function of Local Wall Temperature for Runs 016 and 017

Thermistor Station	RUN NO.016	Heat Flux 111257W/M^2	RUN NO.017	Heat Flux 91183W/M^2
	Local Fouling Res. (M^2-Deg C/Watt x 10^5	Local Wall Temp. at t=0	Local Fouling Res.(M^2-Deg C/Watt x 10^5	Local Wall Temp. at t=0
T101	-	-	-	-
T102	0.86	110.2	1.17	92.8
T103	0.92	108.6	1.53	91.2
T104	0.68	109.4	1.70	90.6
T105	0.78	109.7	1.70	90.3
T106	0.36	111.5	-	-
T107	0.80	111.7	0.63	94.8
T108	0.71	119.0	0.58	99.2
T109	0.60	119.4	0.61	99.1
T110	-	-	-	-

corresponding clean wall temperature at time t = 0. Table XVI shows the results of two trials conducted to investigate the above effect. From the figure it is observed that for the lower heat flux condition higher overall fouling resistances were observed for operating times in excess of one hour than the high heat flux condition. Also, for the lower heat flux situation where local wall temperatures ranged between 77°C and 100°C there is a sharp decrease in the fouling resistance with local wall temperatures as opposed to the higher heat flux situation where the wall temperatures ranged between 86-121°C and which shows only a small decrease compared to the former condition.

The probable reason for the observed inverse dependence of fouling rate on the wall temperature is believed to be due to decrease in solubility of oxygen at the tube wall as temperature increases. Since another run designed to study the effect of oxygen concentration on the fouling resistance showed that the fouling rate decreased with decrease in oxygen concentration, the above reasoning appears valid.

5.3.6. Effect of Concentration of Ferric Oxide Particles on Fouling Resistance Versus Time Curves

Two concentrations, 2400 and 3400 PPM, of mixed size ferric oxide particulates were used to investigate the effect of increasing concentration of Fe_2O_3 on fouling curves. For both the cases, thermal fouling was readily observed and the resulting curves are shown in Fig. 5.17 and Table XVII shows the results of these two trials. The data generated for these two runs clearly show an increase in the initial rate of fouling with an increase in concentration supporting the view that the deposition rate is a direct function of the concentration

TABLE XVII

Effect of Ferric Oxide Concentration on parameters b and R_f*
and Initial Fouling Rate by Least Squares Fit of Fouling
Data to $R_f = R_f^* (1-e^{-bt})$

RUN	Ferric Oxide Conc. (ppM)	b hr^{-1}	Asymptotic Fouling Resistance R_f^* M^2-DegC/Watts	Initial Fouling Rate $\left.\frac{dR_f}{dt}\right\|_{t=o} = bR_f^*$ $\frac{M^2\text{-DegC}}{\text{w-hr}}$
011	2400	6.15	0.58	3.57
009	3400	1.32	1.22	1.61

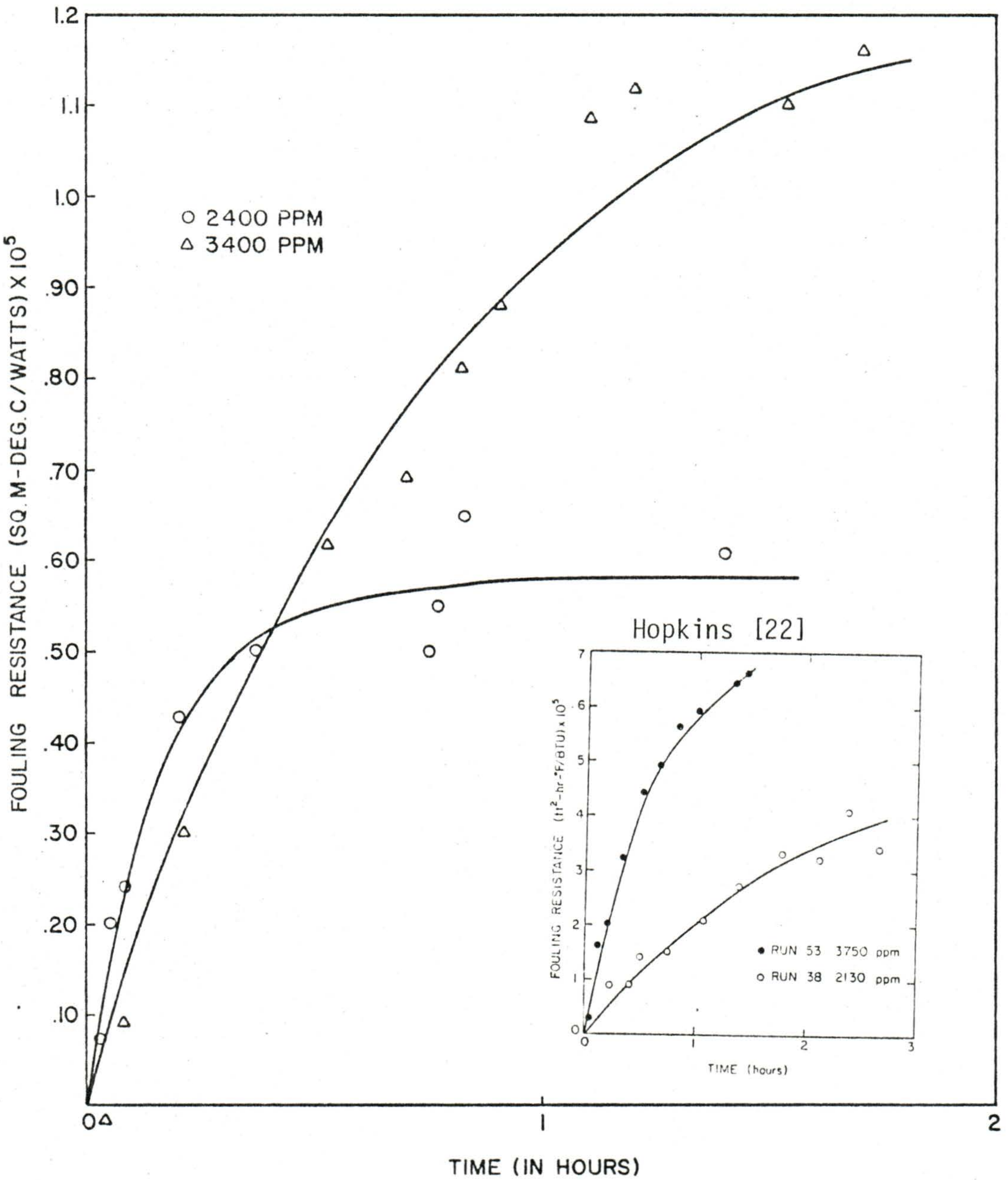


Fig. 5.17. Effect of Mixed-Size Ferric Oxide Concentration (2400 ppM and 3400 ppM) on Fouling Behaviour (Runs No. 009 and 011).

of the particulate matter present in the system.

5.3.7. Effect of Residual Tube Wall Deposits on the Fouling Curve

A trial carried out by Hopkins [22] using a prefouled tube and at low ferric oxide concentration had shown that even though the thermal sensors gave no indication of thermal fouling (the wall temperatures remaining at clean wall conditions) deposits were present on the wall; consequently, residual deposits would always be present on the tube wall for any tube used in a trial unless it was honed prior to commencement of a run.

The effect of these residual deposits on the fouling resistance versus time curves was studied as follows. On completion of a fouling run, heat flux to the test section was cut off and the circulation flow rate raised to a maximum (pump speed increased to 100%) for five minutes. Next, the set conditions for the heat flux and the flow rate were re-established and the data logged as before. Analysis of the thermal data, allowing sufficient time to eliminate the effects of thermal transients, showed the tube to return to clean wall conditions. On continuing the fouling trial it was observed that the tube fouled to a much higher level than before. Fig. 5.18 shows the two fouling curves generated for the above two trials. Superimposed on the above figure are the results of a set of similar runs reported in references [22,23]. Both the runs 011 and 012 were conducted under identical conditions except that the tube in run 011 was honed prior to time zero while in the second run 012, the deposit from the previous run had been removed due to a possible deposit cracking and fluid shear

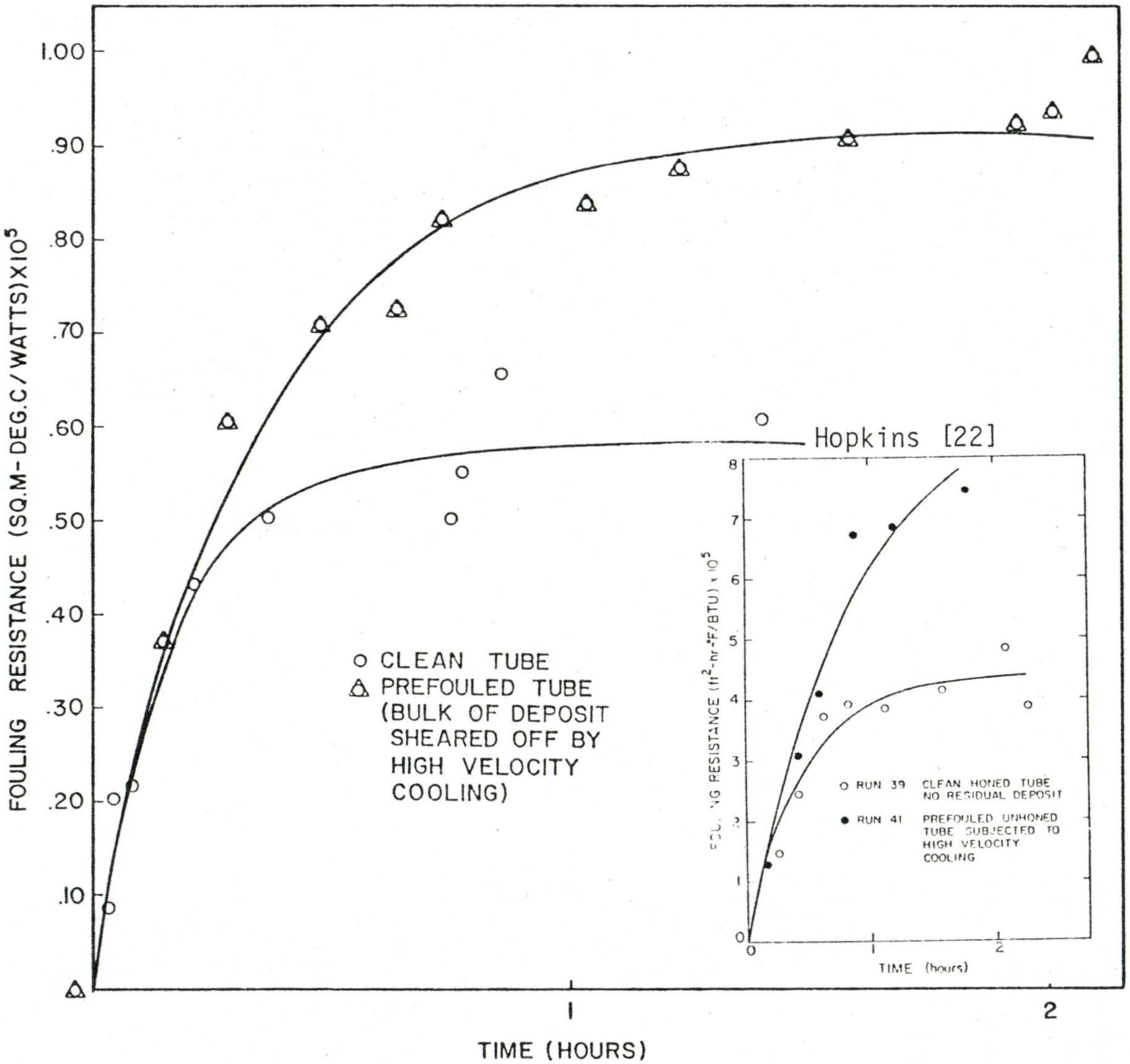


Fig. 5.18. Comparison of Fouling Behaviour for a Clean Honed Tube (Free of Residual Deposits) with a Prefouled Tube Subjected to High Velocity Cooling (Runs No. 011 and 012.

by increasing the velocity [22] and contained some residual deposits present on the tube wall. From these curves it could be concluded that residual deposits present on a tube wall promote fouling. Return of the tube wall temperatures to clean wall conditions by cooling and raising the velocity is interpreted as spalling or cracking of the deposits due to thermal stresses set up by sudden cooling of the tube wall and the high velocity assists in shearing off and removal of the deposit. Also, since tubes containing residual deposits foul at a higher level than clean tubes, it could be postulated that the fouling rate is a function of some mechanism which is increased by the presence of spotty residual deposits--a view also held by Hopkins [22].

5.3.8. Effect of Oxygen Concentration on Fouling Behaviour

To study the effect of oxygen concentration on fouling behaviour an experiment was conducted in which the tube was induced into the linear fouling condition by cooling an asymptotically fouled tube with rapid fluid circulation at zero heat flux for over eight hours and then restarting the flow of heat. After 2.16 hours the air line in the storage tank which served to keep the suspension agitated and insured that the fouling fluid remained saturated with oxygen, was replaced by nitrogen. At 3.40 hours, the nitrogen was switched off and air re-introduced. Results for this run are shown in Fig. 5.19. On introduction of the nitrogen it was seen that although the tube remained in a state fouling, the rate had dropped to about half of that when the agitation was being carried out by air and the suspension remained saturated with oxygen. On re-introduction of air, however, no change in the slope of the curve was observed. Included in Fig. 5.19 is a fouling curve at near similar conditions of heat flux, Reynolds number and particle concentration starting with a clean honed tube, for the sake of comparison. From the results of this run it is inferred that the fouling behaviour of stainless steel with a ferric oxide suspension, under the experimental conditions investigated here, is intimately associated with the presence of oxygen in the suspension and the rate of fouling is dependent upon the oxygen concentration and rate of oxygen transport to the wall.

Physically, the above results can be interpreted as follows: Thermal stresses are set on the tube wall by procedures adopted to bring the tube in linear fouling. This causes deposits on the tube wall to crack making possible the ingression of dissolved oxygen from the fluid to the tube wall. This results in rapid crevice corrosion [13,22] at the tube wall and consequently rapid fouling (curve 2) allowing the wall temperatures to increase rapidly (at constant heat flux). Rapid increases in tube wall temperature triggers further cracking of deposit and thus a self-perpetuating cycle of deposit breakup and fouling is set up. As the oxygen is replaced with nitrogen, oxygen transport to the tube wall decreases, thus there is less corrosion and fouling rate drops (curve 3). Also, the increase in wall temperature decreases as compared to the previous position (curve 2) and hence there is less cracking of the deposit. Thus, on re-introduction of air the accessibility of the oxygen to the tube wall is markedly decreased than from the initial condition and hence the tube fouls at a decreased rate compared to the initial position (curve 4).

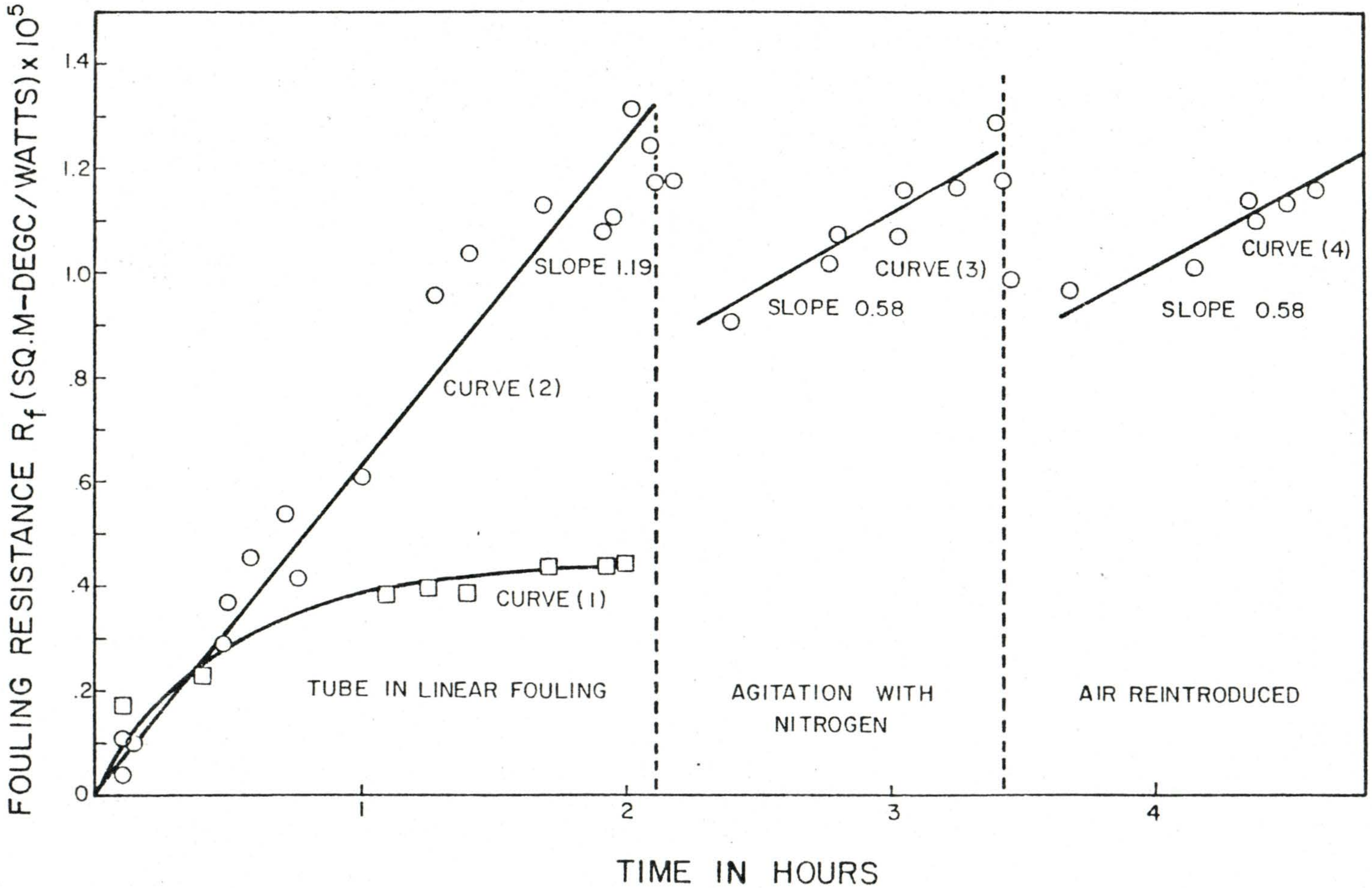


Fig. 5.19. Comparison of Fouling Rates for a Clean Honed Tube (Curve 1), Prefouled Tube in Linear Fouling with System Agitation by Air and Prefouled Tube with System Agitation by Nitrogen to Determine Effect of Oxygen Concentration on Fouling Behaviour.

5.3.9. Fouling Trial to Study the Crevice Corrosion Hypotheses of Ferric Oxide Fouling of Stainless Steel

An experiment was attempted to study crevice corrosion controlled fouling of the stainless steel test section, in which the tube was inducted into the linear fouling situation and then an aggressive ion (chloride ion Cl^-) was added to the system. The addition of chloride ion was done to initiate an accelerated corrosion of the stainless steel surface which would be reflected by an immediate jump in the thermal fouling resistance. Fig. 5.20 shows the results of this run. Analysis of the data generated for this run shows that although the tube had been prefouled to induce it into linear fouling, it cannot be held for certain that the tube was in the linear fouling situation. Comparison of the fouling resistances at time 2.15 hours just before the addition of the chloride ions, with that of run 020 at nearly the same Reynolds number and heat flux is more supportive of the idea of the tube being in a falling rate situation than in linear fouling.

According to the crevice corrosion hypothesis postulated in reference [22] during the falling rate period fouling proceeds at a decreasing rate, with the localized deposits growing at the expense of the unfouled tube surface which is reduced [23]. Also, the corrosion products from the crevice corrosion become continually incorporated in the deposit. Therefore, as the run progresses the corrosion or the cathodic reaction rate drops as the bare surface which acts as the cathode decreases and consequently the fouling rate drops. Thus, in the falling rate period although the corrosion reactions do not completely cease, as compared to the asymptotic situation, the corrosion reaction rate continuously declines. Addition of aggressive chloride ions, of which trace amounts are capable of "portering" [41] substantial amount of metallic ions from the metal surface, in this situation, would attack the remaining bare surface (which is on the decrease) present, disrupting the protective oxide film and exposing fresh metal surface. This would cause a rapid burst of corrosion and consequently a sudden jump in the fouling rate. The corrosion products from this rapid burst of corrosion reaction would immediately be incorporated in the tube wall deposit and cover the tube wall surface reducing once again the unfouled wall area. If the run is continued further the corrosion reactions would totally cease and the fouling rate drop off. The results of run 026 in Fig. 5.20 exhibit a similar situation and behaviour as discussed above. However, due to the limited amount of data no firm conclusions can be drawn but the results do warrant further investigations of the effect of addition of an aggressive ion in constant fouling rate situations to examine the crevice corrosion hypothesis.

5.4. Fouling Deposit Examination Results

Fouling deposits were analyzed and examined in situ, using

(i) a light microscope

(ii) scanning electron microscope

(iii) an electron microprobe.

The light microscope was helpful in observing the physical nature of deposits while photomicrographs of the deposit were obtainable from the scanning electron microscope. From the microprobe results valuable information was made available as,

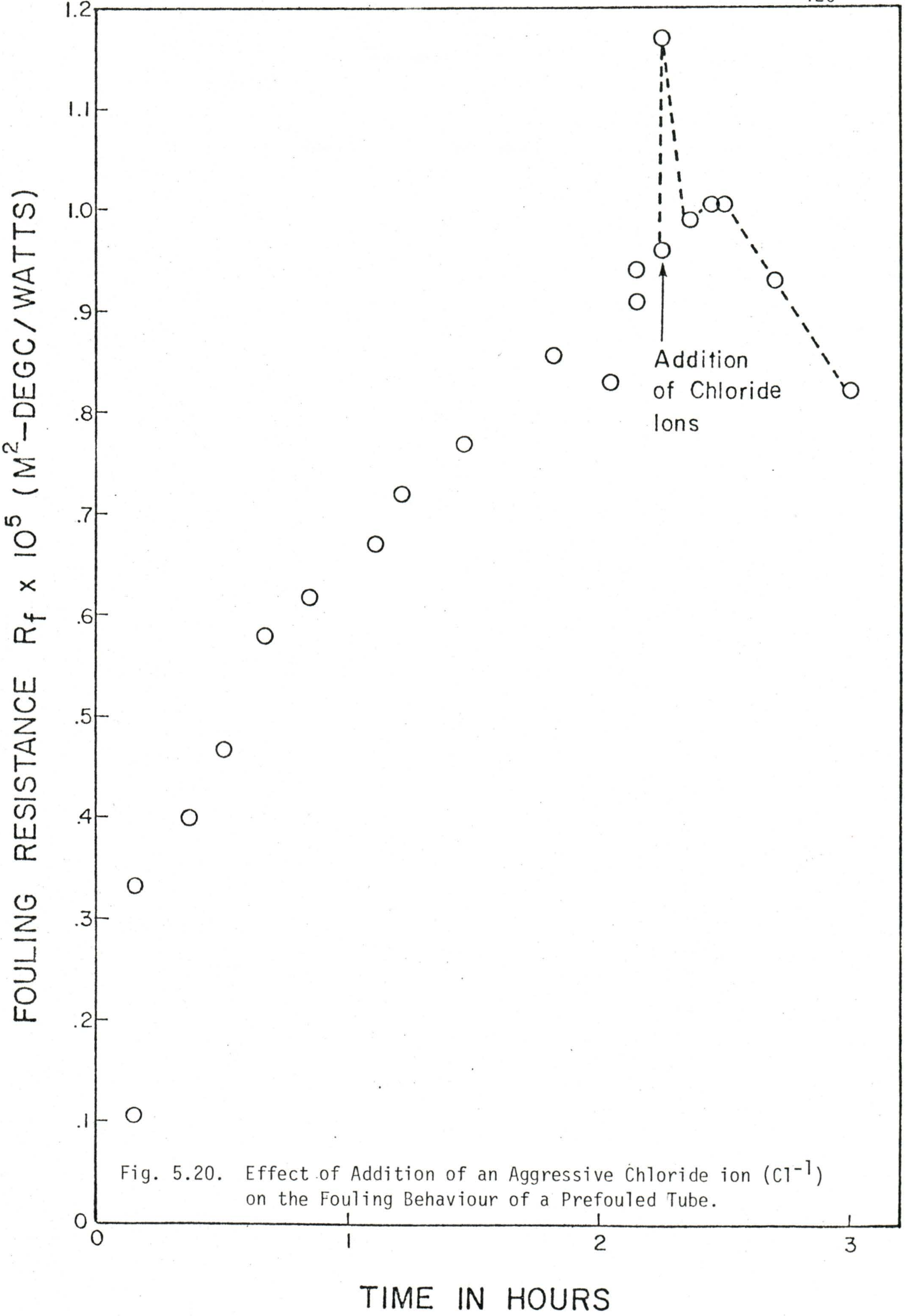


Fig. 5.20. Effect of Addition of an Aggressive Chloride ion (Cl^{-1}) on the Fouling Behaviour of a Prefouled Tube.

(a) An absorbed electron image AEI and back scattered electron image BEI showing the physical appearance and topography of the deposit, respectively.

(b) X-ray intensity photomicrographs showing qualitatively the distribution of individual elements at any point in the deposit. Also, by measurement of x-ray intensities correlation could be affected to yield a quantitative analysis of the deposit.

Procedures for analyzing the deposit have been already mentioned in Chapter 2. No results could be obtained from samples of the present study, since no speciality trials requiring analysis of deposit had been made to warrant such an analysis to be carried out. The instrument has, however, been programmed and calibration standards set up using a clean unfouled tube and the methodology for carrying out the analysis established. Results obtained from samples of a previous fouling study are presented in Appendix 5.

5.5. Determination of Concentration and Particle Size of Ferric Oxide Particles

The concentration and size of ferric oxide particles used in the study was determined using the Coulter Counter, a description of which has been given in Chapter 2. Results of these analyses for a typical run and the particle size distribution during the course of the run, determined from periodic analysis of samples of fouling fluid drawn from the heat loop as the run progressed, are presented in Appendix 5. Table XVIII gives the particle size analysis before commencement and on completion of the fouling run, while Fig. 5.21 shows the particle size distribution at the two time periods. The results of the Coulter Counter analysis indicates a particle size of 5.0-6.3

TABLE XVIII

Particle Size Determination and Distribution in Fouling Fluid Samples

Particle Size Microns	Differential Volume % Before Commencement of Fouling Run	Differential Volume % After Completion of Fouling Run
1.59	0.1	0.4
2.00	7.5	1.5
2.52	11.1	2.4
3.17	16.8	5.8
4.00	25.6	15.1
5.04	19.1	40.6
6.35	10.0	31.4
8.00	4.8	6.5
10.08	2.7	3.0
12.7	1.2	1.2
16.0	0.4	0.6
20.2	0.2	0.5
25.4	0.1	0.5
32.0	0.02	0.6
40.3	0.0	0.5
Concentration ppM	2536	2470

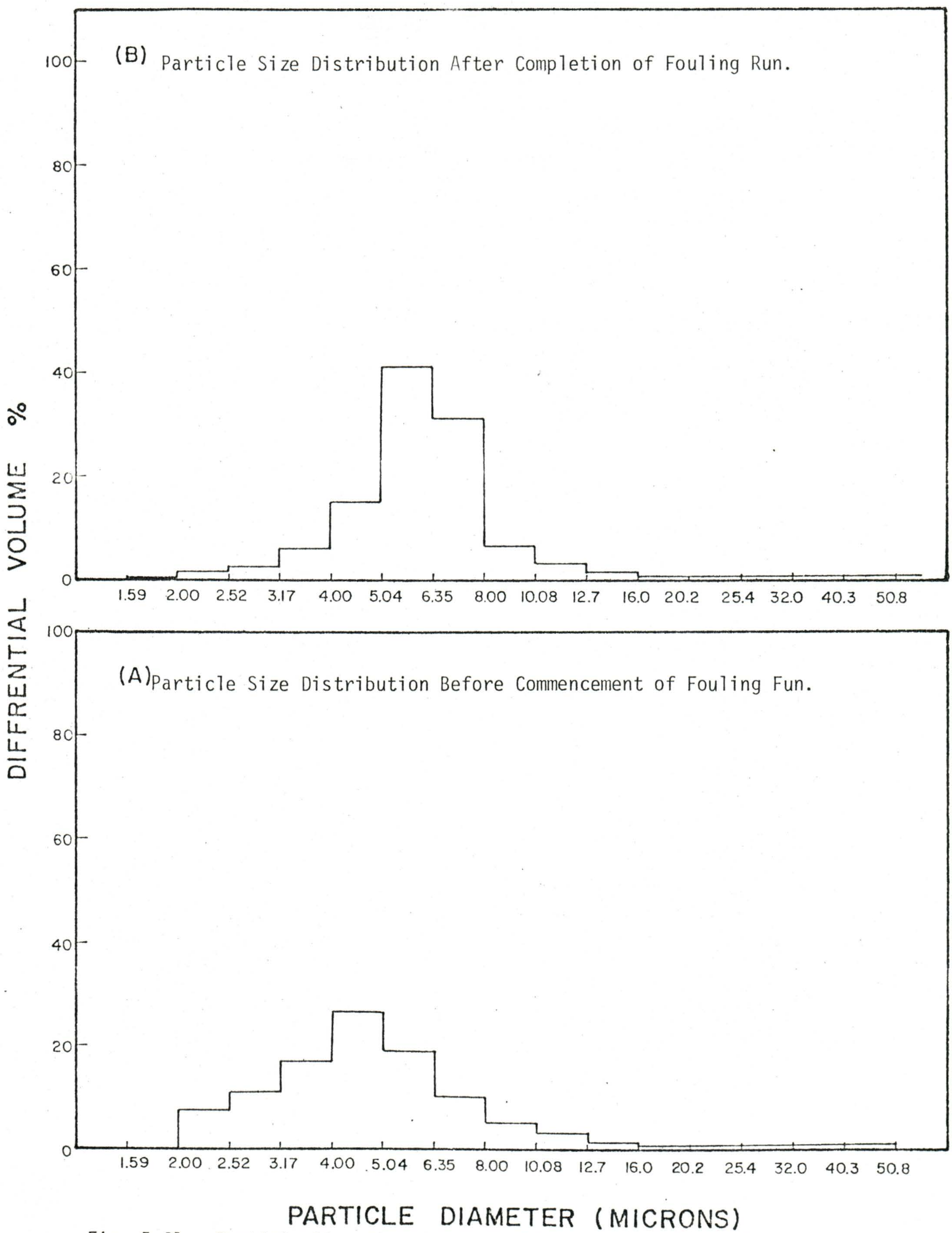


Fig. 5.21. Particle Size Distribution of Ferric Oxide Particles in System Before and After a Fouling Run.

microns for bulk of the particles. Electron microprobe photographs for a similar mixed size batch of ferric oxide particles used by Hopkins [22] to estimate the particle size of the ferric oxide particulates had shown a particle size of about 5 microns.

The difference in the particle size distribution of ferric oxide particulates before and after a fouling run as shown in Fig. 5.21, appears to indicate that it is the smaller size particles in the range of 2-5 microns which are deposited on the wall and cause fouling. However, due to the limited amount of data no firm conclusions can be made at this stage.

Two problems were encountered in carrying out the concentration and particle size analysis. Firstly, on introduction of the particles in the storage tank settling of the particles occurred in spite of agitation. Secondly, ferric oxide particles show a strong tendency to agglomerate. As pointed out by Adamson [42], colloidal ferric oxide particles tend to settle out in platelets. Also, as ferric oxide has a high dipole moment it would tend to produce agglomerates which would be fairly stable. Consequently, it may not be wholly correct to assign the size of the particles estimated by the Coulter Counter analysis to the depositing particle, for the size determined by analysis may be the size of an agglomerate consisting of a number of particles of a basic size much smaller than that of the agglomerate.

CHAPTER 6

CONCLUSIONS

(1) A useful experimental apparatus for studying thermal fouling and its interrelationship to corrosion, under representative conditions, as in Process Heat Exchangers, on short lengths of heat exchanger tubes has been developed and constructed. The technique of transmitting the high heat flux from an externally mounted resistance heater (insulated electrically from the test surface) via a mercury annulus surrounding the test tube leaves the test surface unaffected by unwanted electrical or mechanical disturbances and offers much flexibility and ease of operation as individual test section preparations are greatly reduced. This also eliminates the possibilities of fouling results being influenced by electrical and magnetic effects due to the passage of an electric current through the test section--a criticism made of a similar study [22] earlier. The system permits long periods of steady running at constant heat flux and simple control. The use of Teflon and other non-corrodible material of construction for all parts of the loop in contact with the fouling fluid allows to control the chemistry of the environment in that any trace metal ions, e.g., Cr and Ni detected in periodic analyses of the circulating fluid as a fouling run progresses can be traced to have emanated from corrosion of the stainless steel test surface thus permitting a direct correlation between deposition and corrosion on the test section.

(2) Based on trials conducted on tap water, which showed no fouling at all, it was seen that variations in the heat flux supplied due to fluctuations in line voltage, fluid inlet temperature and the mass flow rate could be sources of potential error in the measurement of thermal fouling resistances. Another prominent error can result from thermal transients associated with heat absorption by the insulation in the initial period of a run and to eliminate this system was brought to steady state before commencing any trial.

(3) Thermal resistance as a function of time was determined during the course of a fouling trial and three types of fouling behaviour were observed depending on the mode of operation.

(i) Asymptotic type fouling behaviour similar to that of many earlier fouling studies [3,6,22] was the one most commonly observed. This occurs at a steadily decreasing rate before reaching a final asymptotic value.

(ii) Extended operation of asymptotically fouled tube in (i) resulted in an unsteady state with sudden decrease in fouling resistances followed again by an increase. The decrease is interpreted as release of deposited material from the wall.

(iii) If an asymptotically fouled tube was cooled with rapid circulation for periods up to eight hours at zero heat flux and heating restarted, fouling recommenced usually at a higher linear rate.

(4) It was possible to duplicate, quite closely, the results reported by Hopkins [22] for a similar system. The minor difference observed is believed due to the variation in the operating parameters.

(5) It was also seen that under near or identical conditions, values of R_f* and the fouling curve are similar to that in reference [22]. This supports the contention of Hopkins [22] that the fouling results obtained were due to a crevice corrosion process and not an artifact of that heat loop which might have caused electrical and magnetic effects influencing the fouling.

(6) A study of the effects of velocity, heat flux and concentrations at Reynolds number (11000-29000), heat flux (89000-121000 W/M^2) and ferric oxide concentration (2400 and 3400 ppM) shows that

(i) Asymptotic fouling resistance varies as mass flow rate raised to a power of 0.62.

(ii) Lowering the heat flux raises the fouling curve.

(iii) Higher values of asymptotic fouling resistance at higher concentrations.

(7) An experiment conducted to study the effect of oxygen concentration on fouling rate shows that the fouling rate decreases as the oxygen concentration at the wall is reduced. However, no firm conclusions are warranted at this stage owing to insufficient data gathered.

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NOMENCLATURE

Symbol	Description	Typical Units
A	heat transfer area	M^2
b	parameter of equation $R_f = R_f^* \, (1-e^{-bt})$	hr^{-1}
C	ferric oxide concentration	PPM
Cp	heat capacity of fouling fluid at constant pressure	KJ/Kg^oC
d	tube diameter	M
e	base of natural logarithms	dimensionless
f	fanning friction factor	dimensionless
h	heat transfer coefficient	$W/M^2 \, ^oC$
ho	heat transfer coefficient at time zero	$W/M^2 \, ^oC$
kw	thermal conductivity of wall	W/M^oC
kd	thermal conductivity of deposit	W/M^oC
m	mass flow rate	Kg.m/sec
ID/OD	inner/outer diameter of tube	M
Q	heat flow	watts
q	heat flux	W/M^2
q'	heat flux	W/M^2
R	total thermal resistance	$M^2\text{-}^oC$/watts
R_o	total thermal resistance at time zero	$M^2\text{-}^oC$/watts
R_f	fouling resistance	$M^2\text{-}^oC$/watts
R_f^*	Asymptotic fouling resistance	$M^2\text{-}^oC$/watts
t	time	hours
Tw	wall temperature	^oC

		Typical Units
t_b, T_b	fluid bulk temperature	^oC
T	temperature	^oC
t_s, T_s	fouling deposit surface temperature	^oC
t_{tc}, T_c	wall thermocouple temperature	^oC
ΔT	temperature difference	^oC
TIN	inlet temperature	^oC
TOUT	outlet temperature	^oC
T_{bo}	fluid temperature at time zero	^oC
T_{wo}	outer wall temperature at time zero	^oC
U	overall heat transfer coefficient	$W/M^2\ ^oC$
U_o	overall heat transfer coefficient at time zero	$W/M^2\ ^oC$
u	velocity	m/sec
W	mass flow rate	Kg.m/sec
X	deposit thickness	M
HTRI	Heat Transfer Research Inc.	
OTEC	Ocean Thermal Energy Conference	

DIMENSIONLESS GROUPS

Nu	Nusselt number	hd/k
Pr	Prandtl number	$\frac{C_p\mu}{k}$
Re	Reynolds number	$\frac{Du}{\nu}$

GREEK LETTERS

ϕ	power factor	dimensionless
μ	viscosity	Kg/M.sec
ν	kinematic viscosity	M^2/sec

Greek Letters (Cont'd)

		Typical Units
τ	shear stress	N/M^2
Θ	time	hour
Θ_d	time of inducation (Fig.1.1)	hour
ρ	density	Kg/M^3
Δ	difference	dimensionless

APPENDIX 1

(ALTERNATE TEST SECTION DESIGNS)

ALTERNATIVE 1

Refer: Figs. A 1.1 and A 1.2.

Summary: - System to use standard pipe split into two ½-cores - one half to be the fixed portion of the heating element (electrical heating).

- Provides direct contact between heating core and the test section (no fluid layer used).
- Welded plate sections provide clamp position in test section.
- To use 10-glass shielded thermistors as temperature sensors spaced equally along the removable half core of the heating element (and are fixed in place with epoxy).
- Eccocoat coating on test section provides electrical insulation for thermistors.

Major components:

- 1 - 12.7/10.9 MM ID/OD stainless steel tube (104 CM long)
- 1 - 20 MM nominal steel pipe (12MMID) 76 CM. long.
- 4 - 1.52 MM steel plate sections (as shown).
- 10 - 3 MM ϕ shielded thermistors (wells drilled as shown).

Limitations: Efficient operation would depend greatly on the quality of the heat sink epoxy coating on the test section. As with the original heat loop used by Mayo [35] and Hopkins [22] it provides direct contact between heating element and the test section and hence was considered unsuitable with the objectives of the study, as electrical and magnetic disturbances would not be eliminated.

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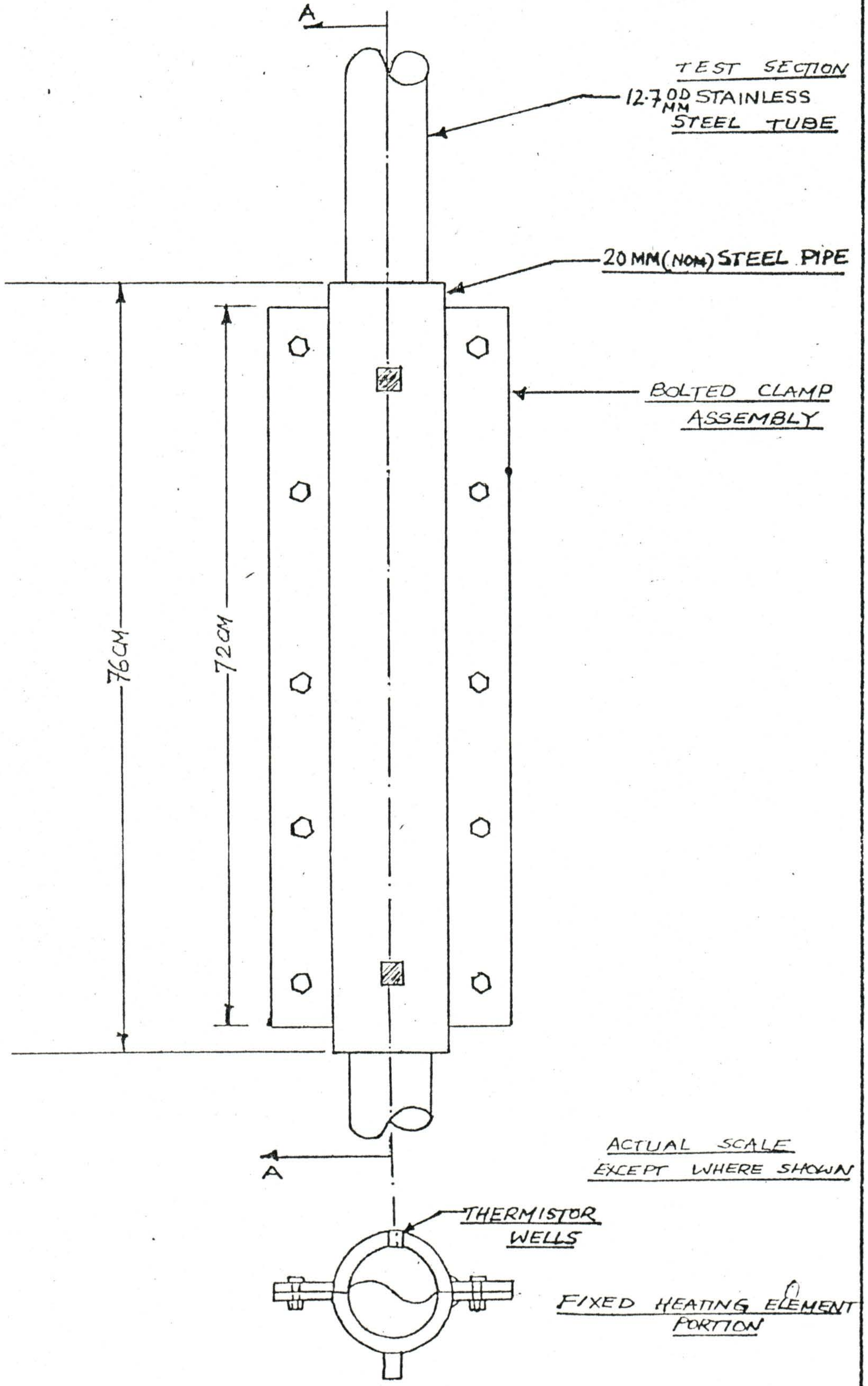
APPV'D ______ DATE ______		REF DWG. NO. A.1.1
FOR HEAT LOOP TEST SECTION	DESIGN CALCULATIONS	SHEET 1 OF 2

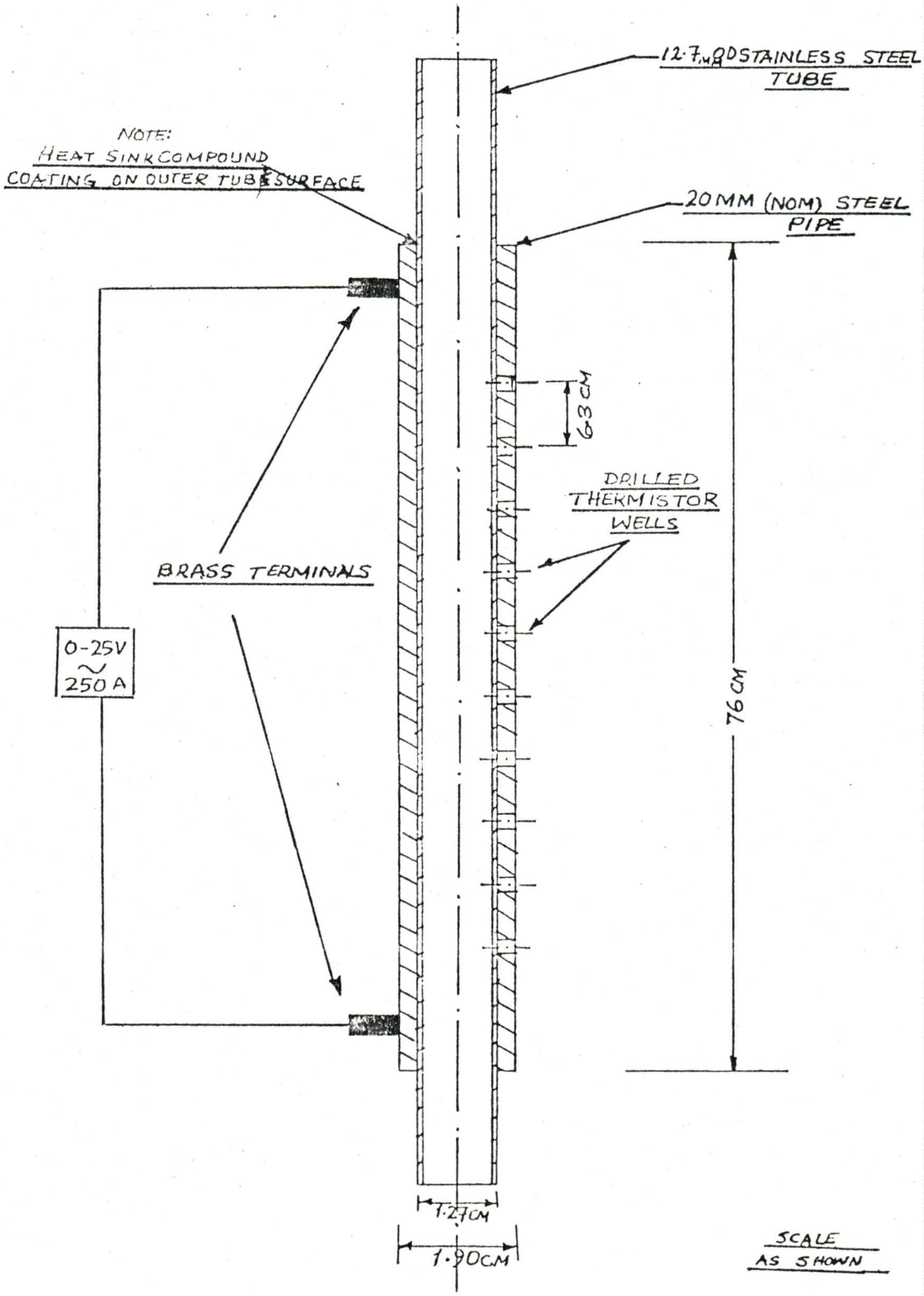
REFERENCE | TITLE ALTERNATIVE NO. 1 | ANSWER



BY ——— ——— DATE ———	MEMORIAL UNIVERSITY OF NEWFOUNDLAND	JOB NO. ——— DATE ———
CH'K'D ——— DATE ———	FACULTY of ENGINEERING & APPLIED SCIENCE	DRFT'G. REQ.NO. ——— DATE ———
APPV'D ——— DATE ———	DESIGN CALCULATIONS	REF DWG.NO. A.1.2
FOR HEAT LOOP TEST SECTION		SHEET 2 OF 2

REFERENCE	TITLE ALTERNATIVE 1	ANSWER

SECTION 'A-A'



SCALE AS SHOWN

ALTERNATIVE 2

Refer: Figs. A 1.3, A 1.4, A 1.5

<u>Summary</u>: - System to use a 2-core combination--the inner to provide a housing for temperature sensors (thermistors); the outer core to be the heating element (electrical heating with attached brass terminals).

- A fluid layer between the inner sensing element core and the test section provide a consistent and efficient heat transfer medium while permitting the test section to be removed independently from both heating and sensing cleanant.
- An O-ring sealing system (see Figs. A.4 and A.5) is used whereby a viton O-ring bushing is soldered in position at both ends of the sensing element core (silver solder).
- 10-shielded thermistors are located within the wall of the sensing core and are fixed in place with the heat sink epoxy resin. (Holes are drilled as shown--not to penetrate the inner wall of the sensing core).
- The outer surface of the sensing element core is coated with Dow Corning's heat sink epoxy compound to electrically insulate it from the heating element.

<u>Major components</u>:

- 1 - 12.7/10.9 MM ID/OD stainless steel tube (130 CM long)
- 1 - 20 MM (Nom.) copper pipe (extra heavy wall) (91 CM)

- 1 - 25 MM (Nom.) stainless steel pipe (66 CM)
- 2 - Copper bushings (as shown - sketch 5)
- 2 - Viton O-rings (high temperature resistant)
- 10 - Shielded thermistors (3 MM O.D.)

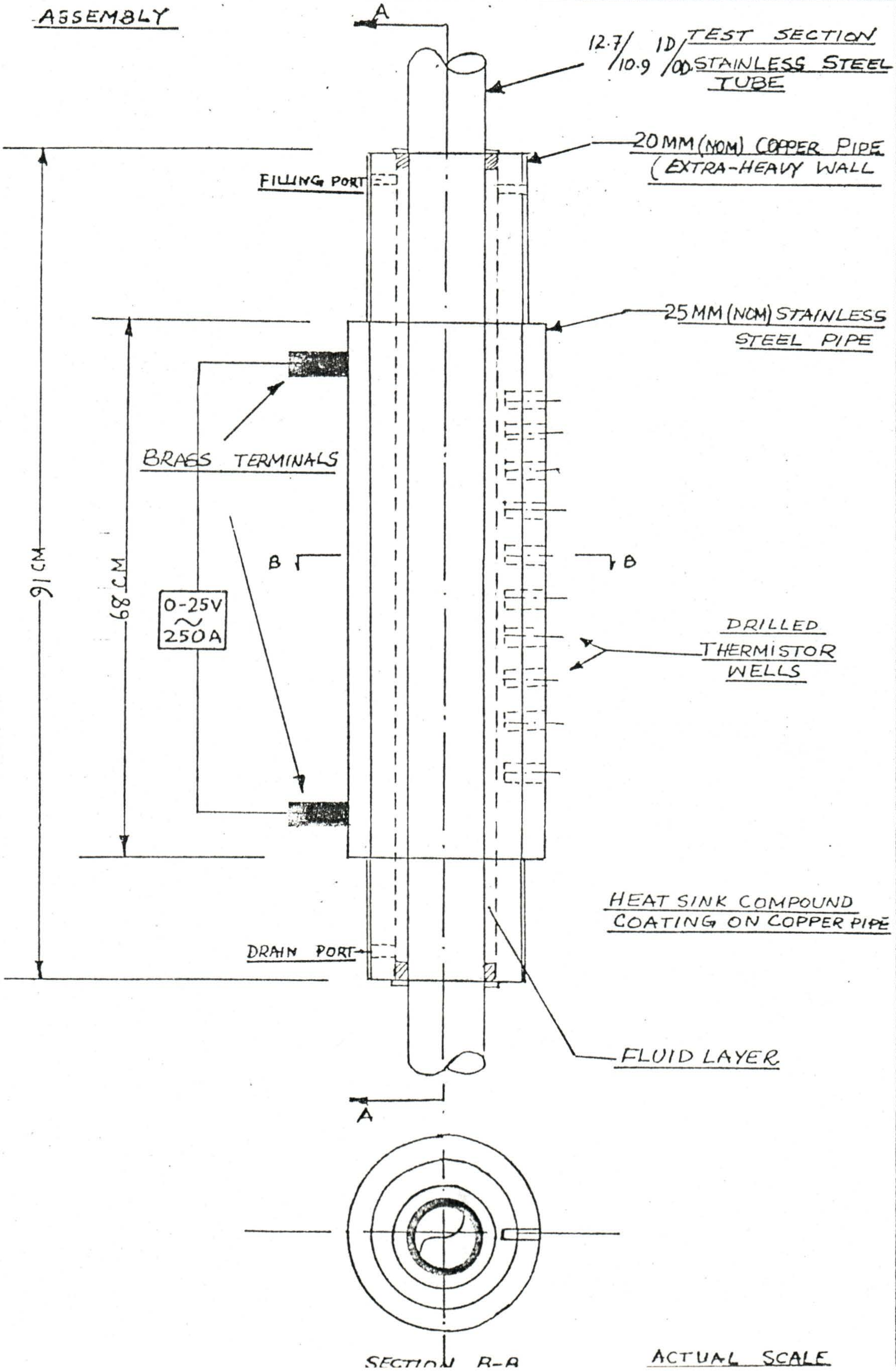
Limitations: This system adds the requirement of a sealing system which must be resistant to 250^{o}C. The viton O-ring is a high temperature resistant ring (~350^{o}C) and provided a simple means of sealing the pipe. On construction the proposed sealing mechanism failed at high temperatures. The fluid layer also introduces the need for filling, draining and vapor escape parts. Also for fixing the O-ring bushings in position in the copper pipe special soldering procedures (silver solder) will have to be employed. Problems could be encountered with damage to O-rings when installing the test section.

Advantages: Heating and sensing devices remain independent of each other and individual test section preparations are greatly reduced. Test section remains free from electrical and magnetic disturbances.

BY	DATE	MEMORIAL UNIVERSITY OF NEWFOUNDLAND FACULTY of ENGINEERING & APPLIED SCIENCE DESIGN CALCULATIONS	JOB NO.	DATE
CH'K'D	DATE		DRFT'G. REQ.NO	DATE
APPV'D	DATE		REF DWG.NO. A.1.3	
FOR HEAT LOOP TEST SECTION			SHEET 1 OF 3	

REFERENCE	TITLE ALTERNATIVE 2	ANSWER

ASSEMBLY



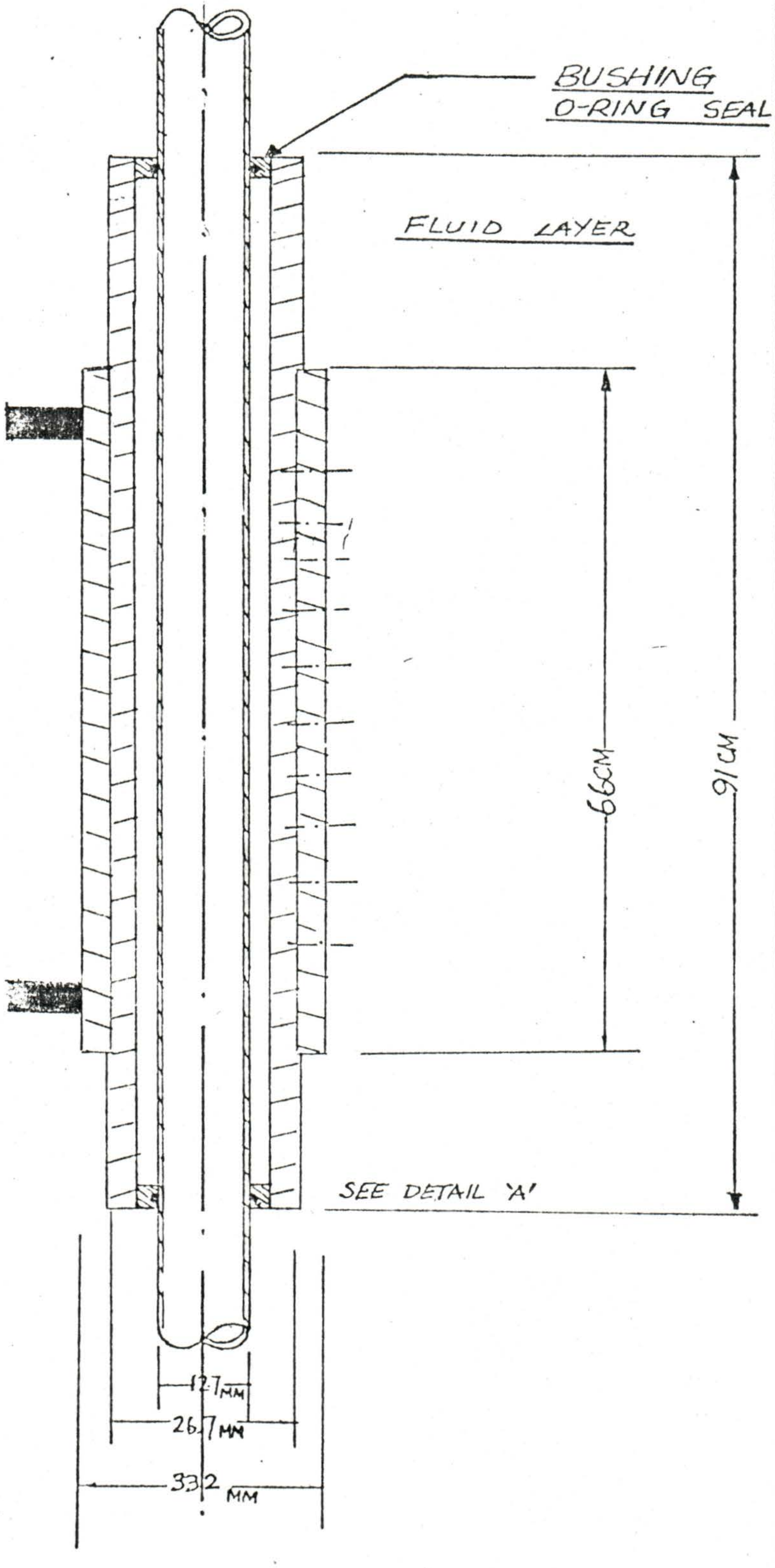
SECTION B-B

ACTUAL SCALE

BY ______ DATE ______ CH'K'D ______ DATE ______ APPV'D ______ DATE ______ FOR *HEAT LOOP TEST SECTION*	MEMORIAL UNIVERSITY OF NEWFOUNDLAND FACULTY of ENGINEERING & APPLIED SCIENCE DESIGN CALCULATIONS	JOB NO. ______ DATE ______ DRFT'G. REQ.NO. ______ DATE ______ REF DWG.NO. *A·1·4* SHEET *2* OF *3*

REFERENCE	TITLE *ALTERNATIVE 2*	ANSWER

SECTION A-A



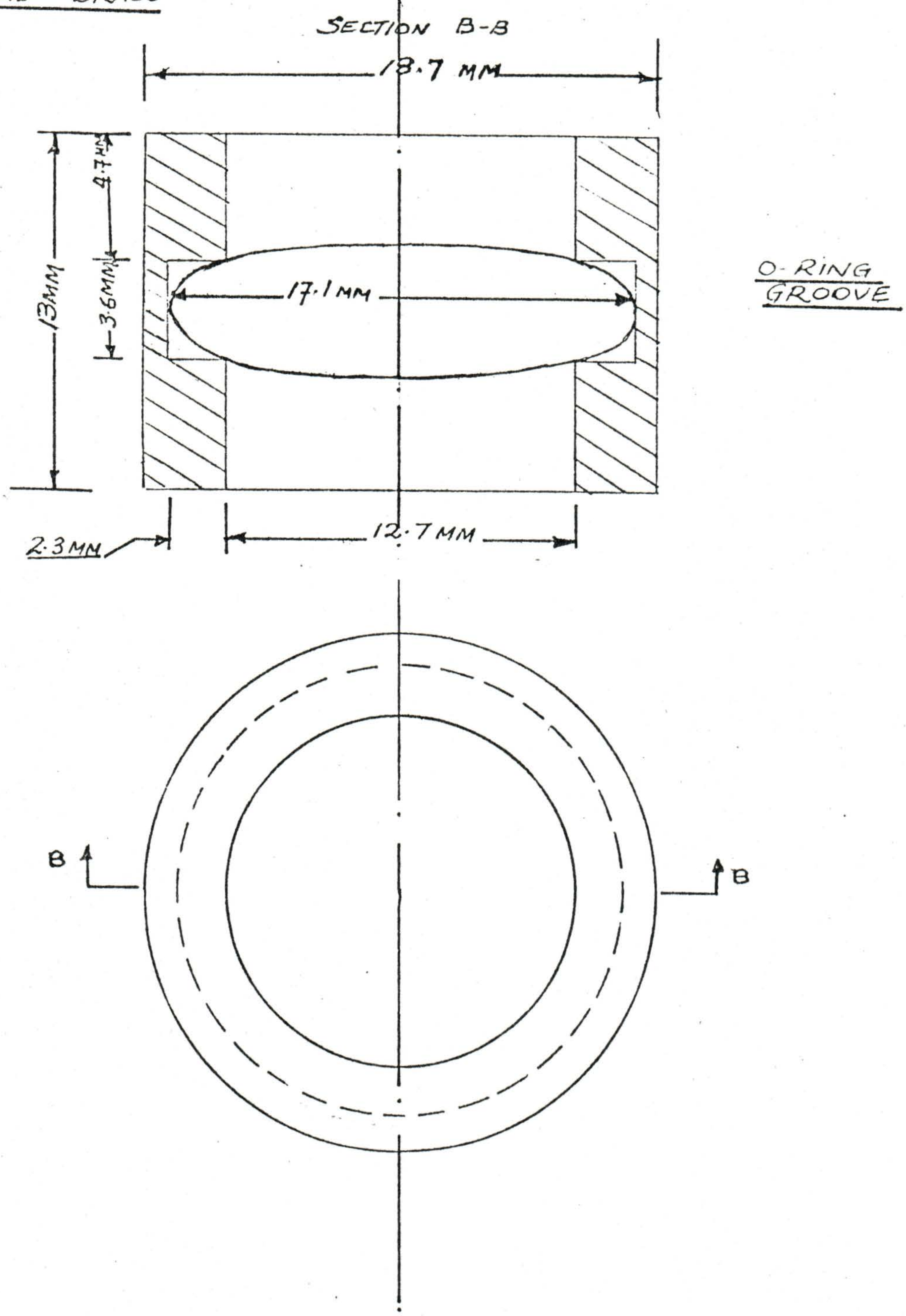
ACTUAL SCALE EXCEPT WHERE SHOWN

BY ———— DATE ————	MEMORIAL UNIVERSITY OF NEWFOUNDLAND	JOB NO. 1 DATE ————
CH'K'D ———— DATE ————	FACULTY of ENGINEERING & APPLIED SCIENCE	DRFT'G. REQ.NO ———— DATE ————
APPV'D ———— DATE ————	DESIGN CALCULATIONS	REF DWG.NO. A·1·5
FOR HEAT LOOP TEST SECTION		SHEET 3 OF 3

REFERENCE | TITLE ALTERNATIVE 2 | ANSWER

DETAIL 'A'
INSIDE DIAMETER SEALING

MATERIAL - BRASS



ALTERNATIVE 3

Refer: Figs. A 1.6 and A 1.7

Summary: - This method is essentially the same principle as alternative 2 -- with the sealing mechanism changed.

- Where alternative 2 used a fixed O-ring system, this method makes use of modified standard pipe caps for a removable scaling system.
- Shielded thermistors are used in the same way as described for alternative 2 and the electrical method of heating is the same.
- Steel bushings are machined for an O-ring groove and located in modified pipe caps as shown in sketch A 1.7.
- Standard steel pipe nipples (to provide threaded sections for pipe caps) are silver soldered to both ends of the copper sensing element (operating atmosphere is not corrosive).

Major components:

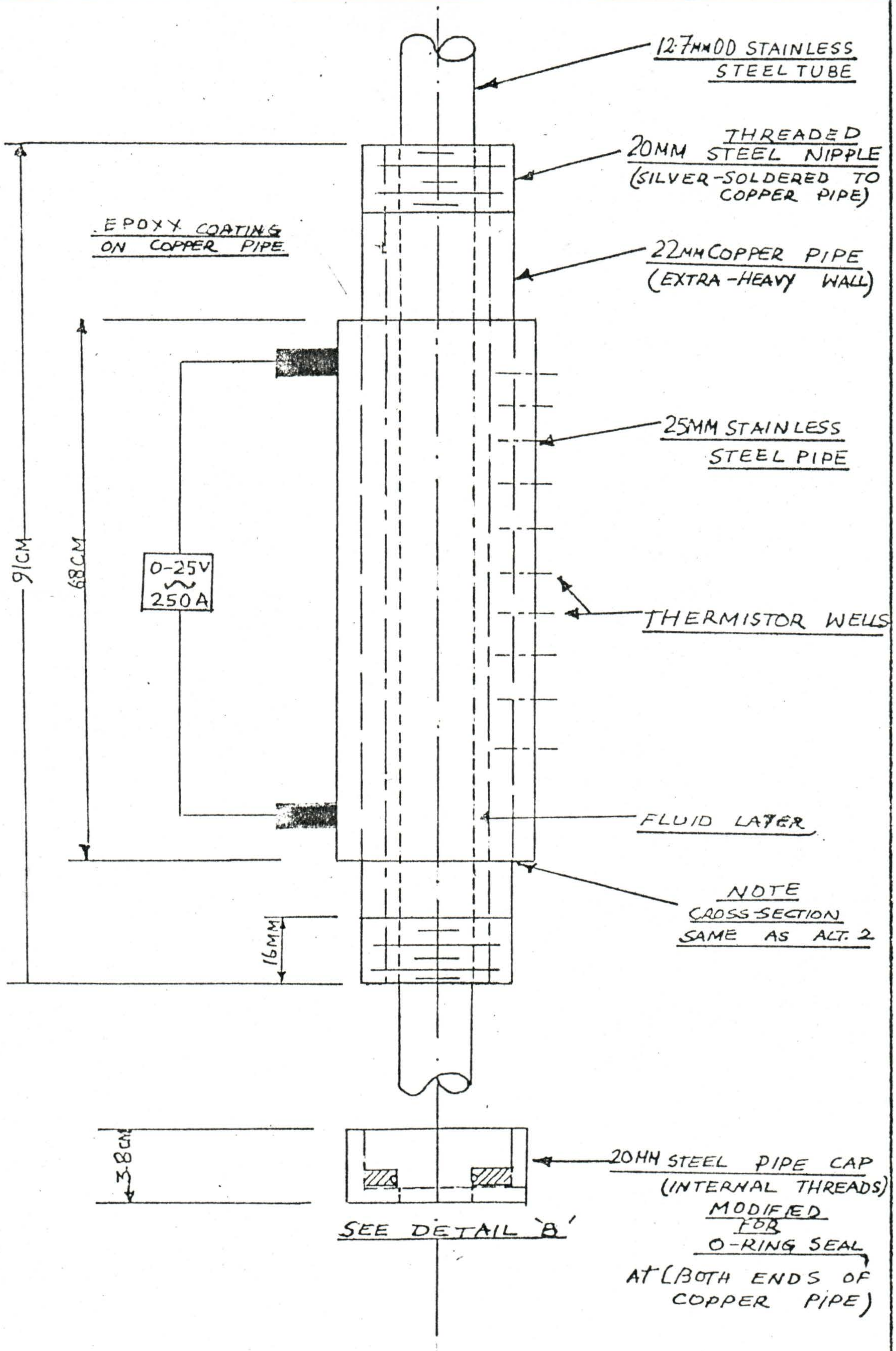
- 1 - 12.7/10.9 ID/OD stainless steel tube (104 CM long)
- 1 - 20 MM (Nom.) copper pipe (91 CM long)
- 1 - 25 MM (Nom.) stainless steel pipe (68 CM long)
- 2 - Standard 20 MM steel nipples
- 2 - Steel bushings (as shown sketch 7)
- 2 - Viton O-rings
- 2 - Standard 20 MM steel pipe caps

Limitations: Use of sealing mechanism shown in Fig. A 1.7 introduces elaborate fabrication procedures and compromises with easy installation of test sections for study.

Advantages: As in alternative 2. In addition, this sealing mechanism ensures that the prevention of any leakage of the sensible heating fluid is foolproof.

BY ______ DATE ______	MEMORIAL UNIVERSITY OF NEWFOUNDLAND FACULTY of ENGINEERING & APPLIED SCIENCE DESIGN CALCULATIONS	JOB NO. ______ DATE ______
CH'K'D ______ DATE ______		DRFT'G. REQ.NO ______ DATE ______
APPV'D ______ DATE ______		REF DWG.NO. A.1.6
FOR HEAT LOOP TEST SECTION		SHEET 1 OF 2

REFERENCE	TITLE ALTERNATIVE 3	ANSWER



ACTUAL SCALE

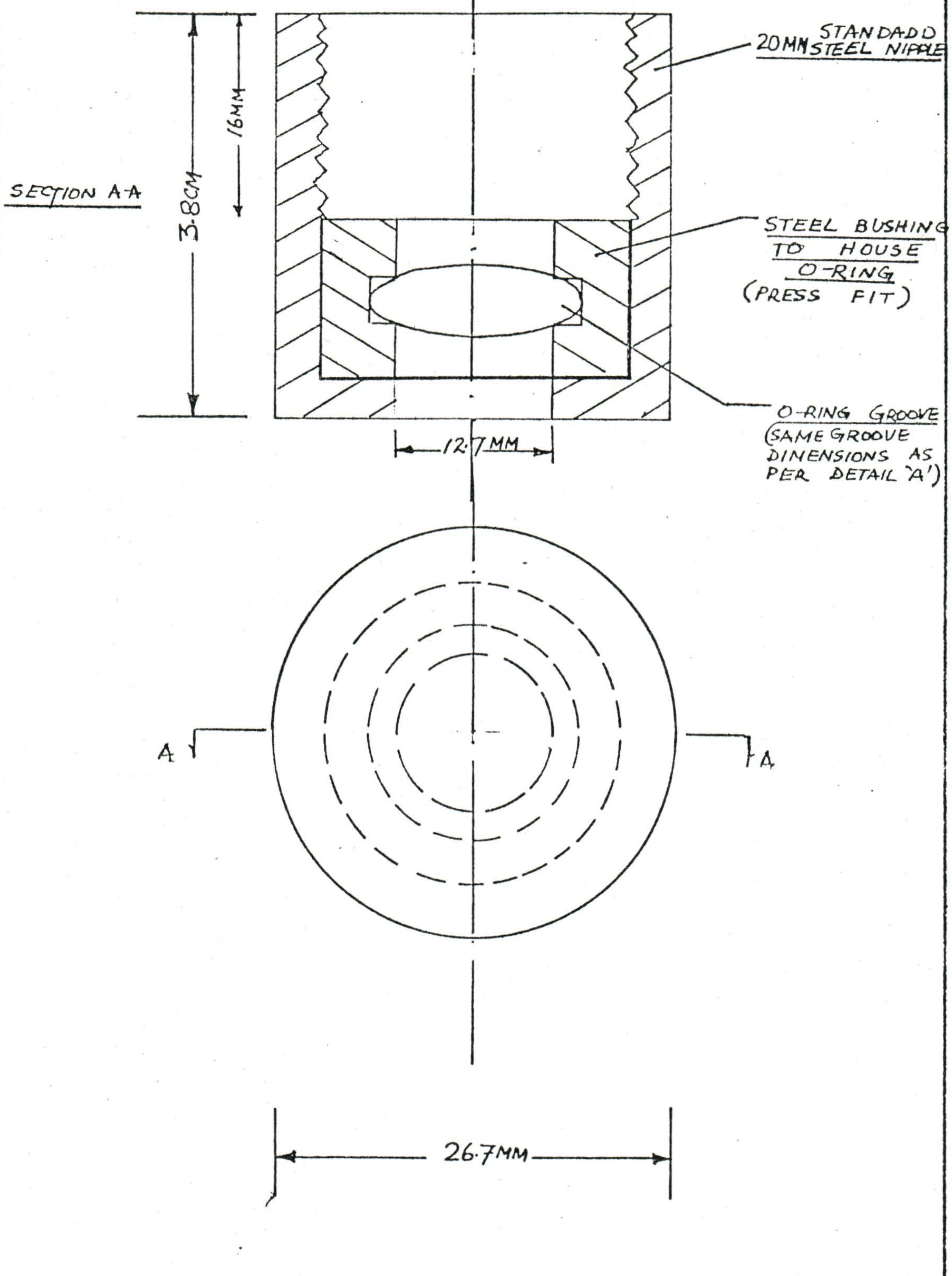
BY ______ DATE ______	MEMORIAL UNIVERSITY OF NEWFOUNDLAND	JOB NO. ______ DATE ______
CH'K'D ______ DATE ______	FACULTY of ENGINEERING & APPLIED SCIENCE	DRFT'G. REQ.NO ______ DATE ______
APPV'D ______ DATE ______		REF DWG.NO. A. 1. 7.
FOR HEAT LOOP TEST SECTION	DESIGN CALCULATIONS	SHEET 2 OF 2

REFERENCE	TITLE	ANSWER
	ALTERNATIVE 3	

DETAIL 'B'

MODIFIED STEEL NIPPLE (2 REQ'D)

MATERIAL- MILD STEEL



SCALE: 2:1

APPENDIX 2

(CALIBRATION OF THERMISTORS)

APPENDIX 2

Calibration of Thermistors

All thermistors positioned on the test section to monitor wall temperatures were calibrated "in situ" by running tap water and saturated steam at high flow rates through the test tube at several temperatures. The temperature of the water and the saturated steam was measured by precalibrated inlet and outlet thermistors. The latter thermistors were calibrated beforehand in a constant temperature oil bath for temperatures above $100^{O}C$ and in a constant temperature water bath equipped with a thermoregulator for temperatures below $100^{O}C$. The bath temperatures were measured with a mercury-in glass thermometer calibrated to $0.1^{O}C$ divisions. Calibration results for the inlet and outlet thermistors are presented in Table A.1.

Thermistors positioned on the test section were calibrated by running fluid through the test section over a range of temperatures which the wall was expected to reach during running. The temperature changes with time were kept small because of insulation transient situation. No external heat was supplied to the test section during the course of the calibration run in order to maintain approximately isothermal liquid conditions. The resistance signal measurements from the thermistors were made using the same channel on the HP scanner as during the course of a run. Since the surface temperatures measured by these thermistors were expected to be greater than $100^{O}C$ during a run, for calibrating at temperatures higher than $100^{O}C$ the circulating hot water was replaced with saturated steam, the temperature of which could be raised by increasing the steam pressure. Calibration up to a temperature of 130°C was carried out using steam. For temperatures over 130°C the wall temperatures have been calculated by extrapolation of the developed calibration equation. In order to determine that the above method was precise, a few of the thermistors were recalibrated in an oil bath and the calibration data compared. Difference between the two methods was found to be unappreciable. Also, since in fouling we are primarily interested in temperature deviations from the clean wall situation, thermistors calibrated by the method adopted above, will not give appreciably different results than those obtained by individually calibrating each thermistor in an oil bath using standard procedures.

The resistance readings of the thermistors were fitted by least squares to the following equation:

$$\frac{R}{R_o} = e^{\beta\left(\frac{1}{T} - \frac{1}{T_o}\right)} \tag{1.1}$$

where R = Resistance at Temperature T, ohms

R_o = Resistance at Temperature T_o, ohms

β = Constant, characteristic of material, °K

T = Absolute temperature, °K

T_o = Absolute reference temperature, °K (usually taken as 298°K)

or

$$R = R_o e^{\beta\left(\frac{1}{T} - \frac{1}{T_o}\right)} \tag{1.2}$$

replacing by $y = R$, $x = \frac{1}{T} - \frac{1}{T_o}$, $A = R_o$

Equation (I.2) reduces to

$$y = Ae^{\beta x} \tag{I.3}$$

The fitted calibration equations for all the thermistors along with the values of R_0, β and r^2, the regression coefficient for the least squares fit, are given in Table A.II below. A value of r close to 1.00 indicates a good fit of the experimental data to the above equation.

TABLE A-I

Calibration data for test section inlet and outlet thermistors TIN AND TOUT

Temperature °C	Thermistor Resistance Reading TIN ohms	Temperature °C	Thermistor Resistance Reading TOUT ohms
2.0	2320.0	2.0	2120.0
24.0	956.0	28.25	959.0
37.8	570.0	31.7	850.0
44.9	442.0	35.1	735.0
48.3	394.0	40.1	627.0
51.0	358.0	48.0	475.0
56.2	302.0	50.0	443.0
60.5	264.0	52.3	410.0
65.8	224.0		
70.3	190.0	58.0	339.0
75.0	168.0	60.0	319.0
80.5	143.0		
85.5	124.0	64.0	280.0
89.0	112.0	66.0	266.0
91.5	103.0	70.0	234.0
93.0	100.0	74.0	195.2
95.8	93.0	80.0	173.9
98.7	90.0	84.0	154.7
105.0	87.3	88.0	140.4
110.0	78.1	93.0	119.1
115.0	72.8	95.0	112.7
120.0	64.1	97.0	107.4
125.0	59.2	98.8	104
128.3	55.4	105.0	93.6
		110.0	89.0
		115.0	78.9
		120.0	68.3
		125.0	59.5
		128.3	54.41

TABLE A-II

Least squares fit of calibration data to equation $\frac{R}{Ro} = e^{\beta(\frac{1}{T} - \frac{1}{T_o})}$ for thermistors TIN, TOUT, and T101 to T110

Thermistor Number	β Constant in Eq. (AI-1)	Ro Resistance at temperature 298°K	Calibration Equation	Regression coefficient r^2
TIN	3516.14	910.22	$T = \frac{3516.14}{11.80+\ln(R/910.22)}$	1.00
TOUT	3562.20	1110.95	$T = \frac{3562.20}{11.95+\ln(R/1110.95)}$	1.00
T101	3394.75	831.31	$T = \frac{3394.75}{11.39+\ln(R/831.31)}$	1.00
T102	3340.50	863.15	$T = \frac{3340.75}{11.21+\ln(R/863.15)}$	1.00
T103	3317.72	955.33	$T = \frac{3317.72}{11.13+\ln(R/955.33)}$	0.98
T104	3573.73	951.55	$T = \frac{3573.73}{11.99+\ln(R/951.55)}$	1.00
T105	3416.29	916.92	$T = \frac{3416.29}{11.46+\ln(R/916.92)}$	1.00
T106	3454.36	1021.20	$T = \frac{3454.36}{11.59+\ln(R/1021.20)}$	0.98
T107	3570.74	1043.32	$T = \frac{3570.74}{11.98+\ln(R/1043.32)}$	0.98
T108	3525.72	1098.38	$T = \frac{3525.72}{11.83+\ln(R/1098.38)}$	1.00
T109	3421.48	934.11	$T = \frac{3421.48}{11.48+\ln(R/934.11)}$	0.98
T110	3388.61	933.01	$T = \frac{3388.61}{11.37+\ln(R/933.09)}$	1.00

APPENDIX 3

(COMPUTER PROGRAM)

```
C      HEAT TRANSFER FOULING (ALL UNITS IN SI SYSTEM)
       DIMENSION Z(13),IREAD(12),M(13),T(12),TC(12),X(12),Y(12),TB(12),R
      1TOT(700),TIM(700),TCON(12),COR(12),FOUL(700),W(700)
       DIMENSION TZERO(12),DT(12),RF(12),XA(10),CA(10),TK(10)
C      PROGRAM 'PAR' TO CALCULATE RUN PARAMETERS FLOW RATE AND HEAT
C      BALANCE
       REAL ID,LEN,NREIN,NREOT,NTEMP,INARE,INSAR
       DATA ID/.01092/,OD/.01270/,LEN/.680/,CP/4.179/
       DATA NREIN/910.22/,NREOT/1110.95/
       DATA BETIN/3516.14/,BETOT/3562.20/
       DATA NTEMP/298.0/
  1    READ(5,101,END=100)R,V,A
       READ(5,428)WR
       READ(5,417)CONC
       READ(5,528)PH,DOXC
  101  FORMAT(F3.0,1X,F5.1,1X,F5.1)
  417  FORMAT(F6.0)
  428  FORMAT(F7.4)
  528  FORMAT(F3.1,1X,F5.1)
       WRITE(6,103)R
  103  FORMAT(1H1,T7,7('*'),'RUN NO',F3.0,7('*'))
       WRITE(6,104)V,A
  104  FORMAT(1H0,T7,'VOLTS',F5.2,T25,'AMPS',F5.0)
       WRITE(6,418)CONC
  418  FORMAT(1H0,T7,'FERRIC OXIDE CONC (PPM)',F8.0)
       WRITE(6,107)WR
  107  FORMAT(1H0,T7,'FLOW RATE',F7.4,T25,'KGS.M/SEC')
       WRITE(6,191)PH,DOXC
  191  FORMAT(1H0,T7,'PH:',F3.1,T25,'DISS.O2 CONC (PPM)',F5.1)
       READ(5,102)ZIN,ZOUT
  102  FORMAT(F7.2,1X,F7.2)
       XIN=ZIN/NREIN
       CIN=BETIN/NTEMP
       TINK=BETIN/(ALOG(XIN)+CIN)
       TIN=TINK-273.0
       XOT=ZOUT/NREOT
       COT=BETOT/NTEMP
       TOTK=BETOT/(ALOG(XOT)+COT)
       TOUT=(TOTK-273.0)
       TBULK=(TIN+TOUT)/2.0
       TOR=TIN
       Q=V*A
       INSAR=3.1417*ID*LEN
       OSARE=3.1417*OD*LEN
       QF=Q/INSAR
       WRITE(6,105)Q,QF
  105  FORMAT(1H0,T7,'HEAT FLOW SUPPLIED',F8.1,T37,'WATTS'/
      1T7,'HEAT FLUX SUPPLIED',F10.0,T37,'WATTS/SQ.M')
  106  FORMAT(1H0,T7,'TOR=TINLET',F5.1,T43,'DEG C',/
      1T7,'DENSITY:',F6.1,T21,'KGS./CU.M',/
      2T25,'T OUTLET',F5.1,T43,'DEG C')
       CALL PROP(RHO,VISK,THK,TBULK)
```

```
      WRITE(6,106)TOR,RHO,TOUT
      INARE=3.1417*(ID**2)/4
      CUARE=3.1417*(OD**2)/4
      UBULK=WR/(RHO*INARE)
      RE=(UBULK*ID/VISK)
      PR=(CP*VISK*RHO/THK)
      WRITE(6,108)TBULK,VISK
  108 FORMAT(1H0,T7,'AVG TEMP',F5.1,T25,'DEG C',
     1/T7,'KINEMATIC',/T7,'VISCOSITYX100',F9.6,T43,'SQ.M/SEC')
      WRITE(6,109)UBULK,RE,PR
  109 FORMAT(1H0,T7,'FLUID VELOCITY',F6.3,T30,'M/SEC',
     1/T7,'REYNOLDS NO',F9.1,/T7,'PRANDTL NO',F7.2)
      HTTR=WR*1000.*(TOUT-TIN)*CP
      HLOSS=Q-HTTR
      PERL=HLOSS/Q*100
      QFT=HTTR/INSAR
      WRITE(6,110)Q,HTTR,HLOSS,PERL,QFT
  110 FORMAT(1H0,T7,'HEAT SUPP',F10.1,T30,'WATTS',/
     1T7,'HEAT TRANS',F10.1,T30,'WATTS',/
     2T7,'HEAT LOST',F10.1,T30,'WATTS',/
     3T7,'PERCENT HEAT LOST',F8.2,/
     4T7,'HEAT FLUX TRANS',F9.0,T30,'WATTS/SQ.M')
C     PREDICTED CLEAN WALL RESISTANCES FROM THE
C     SEIDER-TATE EQUATION
      XNU=0.023*(RE**0.8)*(PR**0.33)
      CALLPROP(RHO,VISK,THK,TBULK)
      XH=XNU*THK/ID
      TWALL=QFT/XH+TBULK
      A=VISK
      C=THK
      CALL PROP(RHO,VISK,THK,TWALL)
      B=VISK
      XNU=XNU*((A/B)**0.14)
      RFILM=1000.0*ID/(XNU*C)
      WTHIC=(OD-ID)/2.0
      RWALL=WTHIC/(14.274+0.01332*TWALL)*1000
      RTOTAL=RFILM+RWALL
      XHTOT=1000.0/RTOTAL
      WRITE(6,120)XNU
  120 FORMAT(//T7,'NUSSELT NO',F9.1)
      WRITE(6,121)RFILM,RWALL,RTOTAL
  121 FORMAT(T7,'RFILM',F9.3,/T7,'RWALL',F9.3,/T7,'RTOTAL',
     1F9.3,T27,'SQ.M-DEG.C/WATTS')
      WRITE(6,150)
      WRITE(10,151)
      DO 830 I=1,10
      DT(I)=0.0
      RF(I)=0.0
      TZERO(I)=0.0
  830 CONTINUE
C     DATA TRANSFORMATION AND LINES TRANSFORMATION
```

```
      NLINE=0
      READ(5,171)M
      JP=0
      ZERO=0.0
    2 READ(5,112,END=10)RLTIM,(Z(I),I=1,13)
      JP=JP+1
      TIME=Z(1)
  112 FORMAT(2X,F5.2,F7.2,/1X,11F7.2)
      NLINE=NLINE+1
C     TEMPERATURE EVALUATIONS
      XIN=Z(2)/NREIN
      CIN=BETIN/NTEMP
      TINK=BETIN/(ALOG(XIN)+CIN)
      TIN=TINK-273.0
      XOT=Z(3)/NREOT
      COT=BETOT/NTEMP
      TOTK=BETOT/(ALOG(XOT)+CCT)
      TOUT=(TOTK-273.0)
      CALL TEMP(Z,T)
      DELTA=TOUT-TIN
C     CORRECTION FOR DROP THROUGH TUBE WALL
      DO 5 I=1,10
      TCON(I)=14.274+0.01332*T(I)
      COR(I)=0.0
      TC(I)=T(I)-COR(I)
      IF(M(I+3).NE.0)TC(I)=0
      IF(JP.EQ.1)TZERO(I)=T(I)
      DT(I)=T(I)-TZERO(I)
      IF(M(I+3).NE.0)DT(I)=0.0
      IF(DT(I).LE.0.0)GO TO 87
      RF(I)=DT(I)/QFT*100000
      GO TO 5
   87 RF(I)=0.0
    5 CONTINUE
      M1=0
      X0=4.05
      DO 6 I=1,8
      X0=X0+6.5
      X(I)=X0
      TB(I)=DELTA/67.5*X(I)+TIN
      M1=M1+M(I+4)
      Y(I)=TC(I+1)-TB(I)
    6 CONTINUE
       TM=0
      SY=0.
      SX1=0.
      SX2=0.
      SX1Y=0.
      SX2Y=0.
      SX1X2=0.
      SSX1=0.
```

```
      SSX2=0.
       DO 7 I=1,8
      IF(M(I+4).NE.0) GO TO 7
      TM=TM+TC(I+1)
      SY=SY+Y(I)
      SX1=SX1+X(I)
      SSX1=SSX1+X(I)*X(I)
      SSX2=SSX2+X(I)**4
      SX1X2=SX1X2+X(I)**3
      SX1Y=SX1Y+X(I)*Y(I)
      SX2Y=SX2Y+X(I)*X(I)*Y(I)
    7 CONTINUE
      FN=8-M1
      TM=TM/FN
      IF(JP.EQ.1)ZERO=TM
      FOUL(NLINE)=(TM-ZERO)/GFT*100000.
      FOUX=FOUL(NLINE)
      SX2=SSX1
      B=SSX1-((SX1**2)/FN)
      C=SX1X2-SX1*SX2/FN
      D=SX1Y-SX1*SY/FN
      F=SSX2-(SX2**2)/FN
      G=SX2Y-SX2*SY/FN
      B2=(D*C-G*B)/(C*C-F*B)
      B1=(D-B2*C)/B
      B0=(SY-B1*SX1-B2*SX2)/FN
      AA=B2
      BB=B1
      CC=B0
      VV1=2*AA*56.50+BB
      VV2=2*AA*11.0+BB
      DISC=BB**2-4.*AA*CC
      IF(DISC.GT.0) GO TO 8
      RMDIS=SQRT(-1.*DISC)
      AREA1=2./RMDIS*(ATAN(VV1/RMDIS))
      AREA2=2./RMDIS*(ATAN(VV2/RMDIS))
      GO TO 9
    8 CONTINUE
      RDIS=SQRT(DISC)
      VV3=ABS((VV1-RDIS)/(VV1+RDIS))
      VV4=ABS((VV2-RDIS)/(VV2+RDIS))
      AREA1=1/RDIS*ALOG(VV3)
      AREA2=1/RDIS*ALOG(VV4)
    9 AREA=AREA1-AREA2
      QW=QFT*58.5/67.5
      DTM=67.505/AREA*(TB(8)-TB(1))/(DELTA)
      H=QW/DTM
      R=1000/H
      TIM(NLINE)=TIME
      IF(NLINE.EQ.1)W(NLINE)=1
      IF(NLINE.GT.1)W(NLINE)=(TIM(NLINE)-TIM(NLINE-1))/.6
```

```
      WRITE(6,113)(TC(I),I=1,10),TIN,TOUT,TM,DELTA,H,R,TIME
      WRITE(10,114)(RF(I),I=1,10),TIN,TOUT,FOUX,DELTA,H,R,TIME
      RTOT(NLINE)=1/H
      GO TO 2
 10   WRITE(6,73)
 73   FORMAT('1')
      CALL BFIT(RTOT,TIM,NLINE)
      CALL PFIT(FCUL,TIM,NLINE)
      GO TO 100
150   FORMAT('1',T3,'LOCALIZED WALL TEMPERATURES (DEG.C)'
     1,/T3,'T101',T10,'T102',T17,'T103',T24,'T104',
     2T31,'T105',T38,'T106',T45,'T107',T52,'T108',T59,'T109',T66,
     3'T110',T73,'TIN',T80,'TCUT',T88,
     2T73,'TIN',T80,'TOUT',T88,'TM',T94,'DELTA',T102,'H',
     3T109,'R',T114,'TIME',/14(2X,'DEG.C'),T107,'X1000',T114,'HOURS',/)
151   FORMAT('1',T3,'LOCALIZED FOULING RESISTANCE (SQ.M-DEG.C/WATTS)'
     1,T50,'X100,000',/T3,'T101',T10,'T102',T17,'T103',T24,'T104',
     2T31,'T105',T38,'T106',T45,'T107',T52,'T108',T59,'T109',T66,
     3'T110',T73,'TIN',T80,'TCUT',T88,'RFM',T94,'DELTA',T102,'H',
     4T106,'RTOT',T114,'TIME',/T70,
     5(2X,'DEG.C',2X,'DEG.C',9X,'DEG.C'),T106,'X1000',T114,'HOURS',/)
171   FORMAT(13I1)
113   FORMAT(13F7.1,F6.1,F7.1,F7.4,F7.2)
114   FORMAT(10F7.2,2F7.1,F7.2,F6.1,F7.1,F7.4,F7.2)
100   STOP
      END
      SUBROUTINE PROP(RHO,VISK,THK,T)
      RHOC=0.988-(T-50.)*0.0006
      RHO=RHOC*1000.
      VISCC=10.**((1.3272*(20.-T)-0.001053*(T-20.)**2)
     1/(T+105))
      VISC=VISCC*0.10
      VISK=VISC/RHO
      THKF=0.296938+0.834355E-3*T-0.180265E-5*T*T
      THK=THKF*1.703
      RETURN
      END
      SUBROUTINE TEMP (Z,T)
      REAL NTEMP,NRES
      DIMENSION Z(13),T(10),NRES(10),BETA(10),XA(10),CA(10),TK(10)
      DATA NTEMP/298.0/
      DATA NRES/831.31,1098.38,1021.20,951.55,916.92,863.15,934.11,
     1933.01,955.03,1043.32/
      DATA BETA/3394.75,3525.72,3454.36,3573.73,3416.29,3340.50,
     13421.48,3388.61,3317.32,3570.74/
      DO 620 I=1,10
      XA(I)=Z(I+3)/NRES(I)
      CA(I)=BETA(I)/NTEMP
      TK(I)=BETA(I)/(ALOG(XA(I))+CA(I))
      T(I)=TK(I)-273.0
620   CONTINUE
```

```
      RETURN
      END
      SUBROUTINE BFIT(Y,X,N)
C     PROGRAM TO FIND THE BEST FIT OF AN EXPONENTIAL CURVE
C     N=NUMBER OF POINTS,NI=NUMBER OF ITERATIONS,EP=ERROR PERMITTED
C     THE EXPONENTIAL EQ. IS Y=A+B(1-EXP(-C*X))
C     AB&C ARE SUBSTITUTED BY A=EXP(P(1)), B=EXP(P(2)), C=EXP(P(3))
      EXTERNAL AUX
      DIMENSION X(700),Y(700),W(700),E1(50),E2(50),P(50),YF(700)
      DATA M,NI,EP/3,20,0.001/
      P(1)=ALOG(Y(1))
      P(2)=0.0
      P(3)=0
      CALL DPLQF(X,Y,YF,W,E1,E2,P,0.0,N,M,NI,ND,EP,AUX)
      WRITE(6,100)
      WRITE(6,20)
   20 FORMAT('ESTIMATES OF ROOT MEAN SQUARE STSTISTICAL ERROR IN THE
     1RAMETER')
      WRITE(6,103)(E1(I),I=1,M)
      WRITE(6,30)
   30 FORMAT('ESTIMATES OF ROOT MEAN SQUARE TOTAL ERROR IN THE PARAMET
     1RS')
      WRITE(6,103)(E2(I),I=1,M)
      A=EXP(P(1))*1000
      B=EXP(P(2))*1000
      C=EXP(P(3))
      WRITE(6,60)
   60 FORMAT('ESTIMATES OF PARAMETERS RO,RINF AND B')
      WRITE(6,103)A,B,C
      WRITE(6,40)
   40 FORMAT(T6,'TIME',T20,'CALC. RESISTANCE',T40,'FITTED VALUE',/T6,'HO
     1URS',T25,'((SQ.M-DEGC/WATTS)X1000)',/)
      DO 50 I=1,N
      Y(I)=Y(I)*1000
      YF(I)=YF(I)*1000
   50 WRITE(6,102)X(I),Y(I),YF(I)
      WRITE(6,100)
  100 FORMAT(1H1)
  102 FORMAT(F10.2,2(10X,F10.4))
  103 FORMAT(3(F10.5,10X))
      RETURN
      END
      FUNCTION AUX(P,D,X,L)
      DIMENSION P(3),D(3)
      D(1)=EXP(P(1))
      D(2)=-EXP(P(2))*EXP(-EXP(P(3))*X)
      D(3)=D(2)*(-EXP(P(3)))*X
      AUX=D(1)+D(2)
      RETURN
      END
      SUBROUTINE PFIT(Y,X,N)
```

```
C     PROGRAM TO FIND THE BEST FIT OF AN EXPONENTIAL CURVE FOR THE
C     FOULING TOTAL RESISTANCE VS. TIME DATA
C     N=NUMBER OF POINTS,NI=NUMBER OF ITERATIONS,EP=ERROR PERMITTED
C     THE EXPONENTIAL EQ. IS Y=B(1-EXP(-C*X))
C     AB&C ARE SUBSTITUTED BY B=EXP(P(1)), C=EXP(P(2))
      DIMENSION X(700),Y(700),YF(700),W(700),E1(50),E2(50),P(50)
      EXTERNAL PAUX
      DATA M,NI,EP/2,20,0.001/
      P(1)=1.79
      P(2)=0.0
      CALL DPLQF(X,Y,YF,W,E1,E2,P,0.0,N,M,NI,ND,EP,PAUX)
      WRITE(6,100)
      WRITE(6,20)
   20 FORMAT('ESTIMATES OF ROOT MEAN SQUARE STATISTICAL ERROR IN THEPA
     1RAMETER')
      WRITE(6,103)(E1(I),I=1,M)
      WRITE(6,30)
   30 FORMAT('ESTIMATES OF ROOT MEAN SQUARE TOTAL ERROR IN THE PARAMET
     11RS')
      WRITE(6,103)(E2(I),I=1,M)
      A=0.0
      B=EXP(P(1))
      C=EXP(P(2))
      WRITE(6,60)
   60 FORMAT('ESTIMATE OF RO,RINF,AND B IN RF=RINF((1.-EXP(-B*TIME)')
      WRITE(6,103)A,B,C
      WRITE(6,40)
   40 FORMAT (T6,'TIME',T20,'CALC. RESISTANCE',T40,'FITTED VALUE',/T6,'H
     1URS',T22,'((SQ.M-DEGC/WATTS)X100,000)',/)
      DO 50 I=1,N
   50 WRITE(6,102)X(I),Y(I),YF(I)
      WRITE(6,100)
  100 FORMAT(1H1)
  102 FORMAT(F10.2,2(10X,F10.2))
  103 FORMAT(2X,3(F10.5,10X))
      RETURN
      END
      FUNCTION PAUX(P,D,X,L)
      DIMENSION P(2),D(2)
      D(1)=EXP(P(1))*(1.0-EXP(-(EXP(P(2))*X)))
      D(2)=EXP(P(1))*EXP(P(2))*X*EXP(-EXP(P(2))*X)
      PAUX=D(1)
      RETURN
      END
      SUBROUTINE DPLQF(X,Y,YF,W,E1,E2,P,WZ,N,M,NI,ND,EP,AUX)
      DIMENSION X(50),Y(50),P(50),E1(50),E2(50),W(50),YF(50)
      DIMENSION V(50),D(50),CU(50,50),VV(50,1)
      EQUIVALENCE (V(1),VV(1))
      LOGICAL SWITCH
      DOUBLE PRECISION DB, C(1275)
      DOUBLE PRECISION DSQRT,DABS
```

```
      DOUBLE PRECISICN DP,WT
      IF (N.LE.M) GO TO 200
      SWITCH=.FALSE.
      IF(NI.LT.0) SWITCH=.TRUE.
      NII=IABS(NI)
      ND=1
      IF(SWITCH) GO TO 1000
      WRITE(6,71)
1000   NT=1
      IV=0
5     IJ=0
      DO 10 I=1,M
      V(I)=0.0
      DO 10 J=1,I
      IJ=IJ+1
10    C(IJ)=0.0
      TT=0.
      XX=0.
      DO 20 L=1,N
      IF(WZ) 6,7,6
6     WT=W(L)
22    GO TO 8
7     WT=1.
8     U=AUX(P,D,X(L),L)
      XX=XX+WT*(U-Y(L))*(U-Y(L))
      IJ=0
      DO 30 J=1,M
      DO 30 I=J,M
      IJ=IJ+1
      DP=WT*D(I)*D(J)
30    C(IJ)=C(IJ)+DP
      DO 40 I=1,M
40    V(I)=V(I)+WT*(Y(L)-U)*D(I)
20    CONTINUE
      IF(SWITCH) GO TO 1001
      WRITE(6,3)(P(I),I=1,M),XX
1001   IF(IV.EQ.1) GO TO 45
      IF(NT-NII) 35,45,55
35    CALL DSOLMT(C,VV,1,IJ,M,KEY)
      IF (KEY .EQ. 1) GO TO 65
      DO 75 I=1,M
      P(I)=P(I)+V(I)
      TC=ABS(V(I)/P(I))
      IF(TC.GT.TT) TT=TC
75    CONTINUE
      NT=NT+1
      IF(TT.LT.EP) IV=1
      GO TO 5
45    DO 46 I=1,M
      DO 46 J=1,M
46    CU(I,J)=0.0
```

```
      DO 47 I=1,M
47    CU(I,I)=1.0
      CALL DSOLMT(C,CU,M,IJ,M,KEY)
      IF (KEY .EQ. 1) GO TO 65
      DO 85 I=1,M
      DO 85 J=1,M
85    P(I)=P(I)+CU(I,J)*V(J)
55    DO 95 I=1,M
95    E1(I)=SQRT(CU(I,I))
      IF (SWITCH) GO TO 1002
      WRITE(6,72) NT
      WRITE(6,3)(P(I),I=1,M)
3     FORMAT(1X,8G15.5,G10.3)
      WRITE(6,3)
1002  S=0.0
      DO 105 L=1,N
      IF(WZ) 16,17,16
16    WT=W(L)
      GO TO 18
17    WT=1.0
18    YF(L)=AUX(P,D,X(L),L)
      XX=(Y(L)-YF(L))**2
      S=XX*WT + S
105   CONTINUE
      PP=N-M
      FI=SQRT(S/PP)
      DO 115 I=1,M
  115 E2(I)=FI *E1(I)
      IF(SWITCH) GO TO 1003
      WRITE (6,73) S
1003  IF (IV .NE. 1 .AND. NII .NE.1) ND=-1
      RETURN
65    WRITE(6,2)
2     FORMAT(22H LINEAR EQUATIONS FAIL)
      ND=0
      RETURN
71    FORMAT(//53H INTERMEDIATE ESTIMATES OF PARAMETERS, SUM OF SQUARES)
72    FORMAT(/30H FINAL ESTIMATES OF PARAMETERS,35X,17HNO OF ITERATIONS,
     1I5)
73    FORMAT(1H0,14HSUM OF SQUARES,G15.5)
200   WRITE(6,210)
210   FORMAT('THE NUMBER OF DATA POINTS MUST EXCEED THE NUMBER OF'
     1,'PARAMETERS')
      ND=0
      RETURN
      END
      SUBROUTINE DSOLMT(A,B,L,M,N,KEY)
      DIMENSION B(50,L)
      DOUBLE PRECISION A(M),X,Y
      DOUBLE PRECISION DSQRT,DABS
C
```

```
C
      IF (A(1).LE.0.D0) GO TO 150
      IF (M .EQ. 1) GC TO 160
            A(1) = 1.0/DSQRT(A(1))
      DO 10 I=2,N
10          A(I) = A(I)*A(1)
C
C
            INC = N
            I1  = 1
            IN  = N
            NM1 = N - 1
C
20          INC = INC - 1
            I1 = IN + 1
            IN = IN + INC
            NS = N - INC
C
            X = 0.
            ISUB = I1
            DO 30 I=INC,NM1
           ISUB = ISUB - I
30          X = X + A(ISUB)*A(ISUB)
      IF (A(I1) - X .LT.0.) GC TC 150
            A(I1) = DSQRT(A(I1) - X)
C
C
      IF (A(I1).EQ.0.) GO TO 150
            A(I1) = 1./A(I1)
      IF (INC .EQ. 1) GO TO 90
C
            I11 =I1 + 1
            L11 = I1 - INC
      DO 50 I=I11,IN
            X=0.
            L1 = L11
            L2 = I - INC
      DO 40 J=1,NS
            X = X + A(L1)*A(L2)
            L1 = L1 - INC - J
40          L2 = L2 - INC - J
50          A(I) =(A(I) - X)*A(I1)
      GO TO 20
90    DO 130 K=1,L
      Y = B(1,K)
      B(1,K) = Y*A(1)
      DO 110 I=2,N
            JM = I-1
            ISUB = I
            INC = N
            X = 0.
```

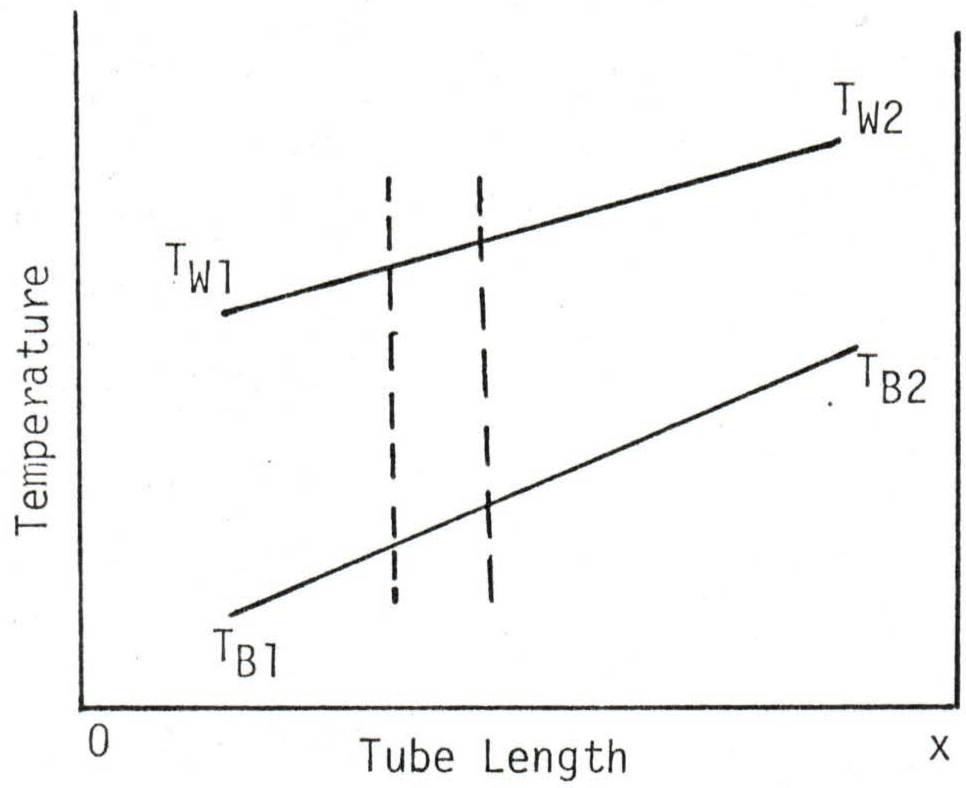
```
      DO 100 J=1,JM
      Y = B(J,K)
      X = A(ISUB)*Y + X
            INC = INC - 1
100         ISUB = ISUB + INC
      Y = B(I,K)
  110 B(I,K) = (Y-X)*A(ISUB)
C
      Y=B(N,K)
      B(N,K)=Y*A(M)
            INC = -1
            J1  = M+1
      DO 125 I=2,N
            INC = INC + 1
            JM = J1 - 2
            J1 = JM - INC
            JSUB = N-INC-1
            II = JSUB
            X = 0.
      DO 120 J=J1,JM
            JSUB = JSUB + 1
      Y = B(JSUB,K)
 120  X = X + A(J)*Y
      Y = B(II,K)
 125  B(II,K) = (Y-X)*A(J1-1)
130         CONTINUE
            KEY=0
            RETURN
150         KEY = 1
            RETURN
160   B(1,1)=B(1,1)/A(1)
      KEY=0
      RETURN
      END
```

APPENDIX 4

(DERIVATION OF APPROPRIATE ΔT_m FOR COMPUTING FOULING RESISTANCES)

APPENDIX 4

Derivation of an Appropriate ΔT_m (ΔT_{mean}) for Use in Calculating Fouling Resistances



Symbols: T_W = Wall Temperature

T_B = T bulk (fluid)

ΔT_m = Mean Temperature difference.

Assumptions: $T_B = mx + k$ (1)

$T_W = ax^2 + bx + C$ (2)

Derivation:

Consider an elemental unit of area dx. The differential heat balance is

$$dq = mcd\,T_B = U\pi Ddx\,(T_W - T_B) \quad (3)$$

where m is the mass flow rate of the bulk fluid and c is the specific heat.

Rearranging (3) we have

$$\frac{U\pi Ddx}{mc} = \frac{dT_B}{T_W - T_B} \tag{4}$$

integrating between limits of 0 - X, $T_{B1} \rightarrow T_{B2}$ yields

$$\frac{U\pi DX}{mc} = \int_{T_{B1}}^{T_{B2}} \frac{dT_B}{T_W - T_B} \tag{5}$$

Writing the overall heat balance for the heat section we have

$$q_T = U\pi DX\ \Delta Tm = mc(T_{B2} - T_{B1}) \tag{6}$$

Rearranging (6) we have

$$\frac{U\pi DX}{mc} = \frac{T_{B2} - T_{B1}}{\Delta T_m} \tag{7}$$

Substituting (7) into (5) yields

$$\frac{T_{B2} - T_{B1}}{\Delta T_m} = \int_{T_{B1}}^{T_{B2}} \frac{dT_B}{T_W - T_B} \tag{8}$$

which yields on rearrangement

$$\Delta T_m = \frac{T_{B2} - T_{B1}}{\int_{T_{B1}}^{T_{B2}} \frac{dT_B}{T_W - T_B}} \tag{9}$$

APPENDIX 5

(EXPERIMENTAL DATA)

(i) FOULING RESULTS
(ii) ELECTRON MICROPROBE RESULTS
(iii) COULTER COUNTER RESULTS

*******RUN NO 5.*******

VOLTS12.60 AMPS 210.

FERRIC OXIDE CONC (PPM) 2400.

FLOW RATE 0.0710 KGS.M/SEC

PH:6.4 DISS.O2 CONC (PPM) 5.2

HEAT FLOW SUPPLIED 2646.0 WATTS
HEAT FLUX SUPPLIED 113421. WATTS/SQ.M

TOR=TINLET 50.1 DEG C
DENSITY: 985.3KGS./CU.M
T OUTLET 58.8 DEG C

AVG TEMP 54.5 DEG C
KINEMATIC
VISCOSITYX100 0.000052 SQ.M/SEC

FLUID VELOCITY 0.769 M/SEC.
REYNOLDS NO 16313.2
PRANDTL NO 3.69

HEAT SUPP 2646.0 WATTS
HEAT TRANS 2598.9 WATTS
HEAT LOST 47.1 WATTS
PERCENT HEAT LOST 1.78
HEAT FLUX TRANS 111401WATTS/SQ.M

NUSSELT NO 87.1
RFILM 0.218
RWALL 0.058
RTOTAL 0.276 SQ.M-DEG.C/WATTS

STIMATES OF ROOT MEAN SQUARE STATISTICAL ERROR IN THEPA RAMETER
0.40588 2.45137
STIMATES OF ROOT MEAN SQUARE TOTAL ERROR IN THE PARAMET IRS
0.05173 0.31243
STIMATE OF RC,RINF,AND B IN RF=RINF((1.-EXP(-B*TIME)
0.00000 0.78518 4.35389

TIME HURS	CALC. RESISTANCE ((SQ.M-DEGC/WATTS)X100,000)	FITTED VALUE
0.00	0.00	0.00
0.07	0.27	0.21
0.10	0.36	0.28
0.18	0.60	0.43
0.53	0.41	0.71
0.85	0.64	0.77
0.88	0.65	0.77
1.05	0.78	0.78
1.10	0.73	0.78
1.17	0.78	0.78
1.80	0.81	0.78
1.89	0.76	0.78
2.01	0.88	0.79
2.96	0.78	0.79
3.01	0.90	0.79
3.13	0.99	0.79

LOCALIZED WALL TEMPERATURES (DEG.C)

T101 DEG.C	T102 DEG.C	T103 DEG.C	T104 DEG.C	T105 DEG.C	T106 DEG.C	T107 DEG.C	T108 DEG.C	T109 DEG.C	T110 DEG.C	TIN DEG.C	TOUT DEG.C	TM DEG.C	DELTA DEG.C	H	R X1000	TIME HOURS
84.2	107.1	107.7	108.4	108.5	109.4	110.4	114.7	116.1	115.5	50.1	58.8	110.2	8.8	1740.8	0.5744	0.00
84.4	108.0	107.9	108.6	108.7	108.7	110.6	114.7	116.4	116.1	50.0	58.8	110.5	8.8	1732.3	0.5773	0.07
84.6	108.6	107.8	108.6	108.7	109.7	110.5	115.3	116.4	116.1	50.1	58.8	110.6	8.8	1730.5	0.5779	0.10
84.7	108.6	108.1	108.9	109.0	109.0	110.8	115.4	116.7	116.6	50.1	58.8	110.8	8.7	1721.4	0.5809	0.18
84.5	108.3	108.0	108.7	108.8	109.0	110.7	114.9	116.4	116.3	50.0	58.8	110.6	8.8	1726.9	0.5791	0.53
84.7	108.6	108.2	109.0	109.1	109.0	110.9	115.4	116.7	116.6	50.0	58.9	110.9	8.9	1720.1	0.5813	0.85
84.8	108.7	108.2	109.0	109.1	109.0	110.9	115.4	116.8	116.5	50.0	58.9	110.9	8.8	1720.1	0.5814	0.88
84.9	108.8	108.3	109.1	109.2	109.1	111.0	115.7	116.9	116.6	50.1	58.9	111.0	8.8	1716.7	0.5825	1.05
84.8	108.8	108.4	109.0	109.2	109.1	111.0	115.5	116.8	116.6	50.1	58.9	111.0	8.8	1719.4	0.5816	1.10
84.9	108.9	108.4	109.2	109.3	109.2	111.1	115.6	116.5	116.7	50.1	59.0	111.0	8.9	1717.1	0.5824	1.17
84.8	108.9	108.4	109.1	109.3	109.1	111.1	115.8	116.8	116.7	50.0	59.0	111.1	9.0	1716.5	0.5826	1.80
84.9	108.8	108.4	109.0	109.3	109.1	111.0	115.5	116.8	116.7	50.1	59.0	111.0	8.8	1719.1	0.5817	1.89
84.9	109.0	108.6	109.2	109.4	109.2	111.2	115.7	116.9	116.8	50.0	59.0	111.1	9.0	1713.6	0.5836	2.01
84.8	108.9	108.5	109.1	109.3	109.0	111.1	115.4	116.8	116.7	50.1	58.9	111.0	8.9	1717.0	0.5824	2.96
84.8	109.0	108.6	109.2	109.5	109.1	111.2	115.8	116.9	116.9	50.1	59.0	111.2	8.9	1715.7	0.5829	3.01
84.9	109.2	108.7	109.3	109.6	109.2	111.3	115.8	117.0	116.9	50.0	59.0	111.3	9.0	1710.5	0.5846	3.13

LOCALIZED FOULING RESISTANCE (SQ.M-DEG.C/WATTS)X100,000

T101	T102	T103	T104	T105	T106	T107	T108	T109	T110	TIN DEG.C	TOUT DEG.C	RFM	DELTA DEG.C	H	RTOT X1000	TIME HOURS
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	50.1	58.8	0.00	8.8	1740.8	0.5744	0.00
0.24	0.83	0.19	0.17	0.22	0.27	0.16	0.05	0.24	0.57	50.0	58.8	0.27	8.8	1732.3	0.5773	0.07
0.39	1.36	0.09	0.12	0.16	0.30	0.04	0.54	0.24	0.56	50.1	58.8	0.36	8.8	1730.5	0.5779	0.10
0.53	1.32	0.42	0.42	0.44	0.56	0.36	0.69	0.57	0.99	50.1	58.8	0.60	8.7	1721.4	0.5809	0.18
0.32	1.04	0.28	0.24	0.31	0.58	0.24	0.24	0.33	0.70	50.0	58.8	0.41	8.8	1726.9	0.5791	0.53
0.46	1.38	0.49	0.47	0.56	0.56	0.42	0.65	0.56	0.97	50.0	58.9	0.64	8.9	1720.1	0.5813	0.85
0.56	1.40	0.50	0.47	0.55	0.58	0.40	0.67	0.60	0.93	50.0	58.9	0.65	8.8	1720.1	0.5814	0.88
0.63	1.48	0.60	0.59	0.67	0.70	0.53	0.97	0.75	0.97	50.1	58.9	0.78	8.8	1716.7	0.5825	1.05
0.62	1.50	0.62	0.54	0.65	0.65	0.50	0.74	0.66	0.97	50.1	58.9	0.73	8.8	1719.4	0.5816	1.10
0.67	1.60	0.69	0.65	0.74	0.73	0.61	0.83	0.41	1.10	50.1	59.0	0.78	8.9	1717.1	0.5824	1.17
0.62	1.58	0.69	0.59	0.74	0.66	0.57	1.01	0.68	1.04	50.0	59.0	0.81	9.0	1716.5	0.5826	1.80
0.63	1.55	0.67	0.53	0.69	0.66	0.52	0.80	0.67	1.02	50.1	59.0	0.76	8.8	1719.1	0.5817	1.89
0.65	1.66	0.82	0.67	0.83	0.72	0.66	0.90	0.74	1.13	50.0	59.0	0.88	9.0	1713.6	0.5836	2.01
0.58	1.62	0.77	0.60	0.78	0.59	0.57	0.68	0.64	1.07	50.1	58.9	0.78	8.9	1717.0	0.5824	2.96
0.61	1.74	0.84	0.66	0.88	0.67	0.67	0.98	0.76	1.21	50.1	59.0	0.90	8.9	1715.7	0.5829	3.01
0.63	1.84	0.96	0.76	0.98	0.75	0.77	1.02	0.84	1.26	50.0	59.0	0.99	9.0	1710.5	0.5846	3.13

*******RUN NO 6.*******

VOLTS12.60 AMPS 200.

FERRIC OXIDE CONC (PPM) 2400.

FLOW RATE 0.0720 KGS.M/SEC

PH:6.5 DISS.O2 CONC (PPM) 5.1

HEAT FLOW SUPPLIED 2520.0 WATTS
HEAT FLUX SUPPLIED 108020. WATTS/SQ.M

TOR=TINLET 50.8 DEG C
DENSITY: 985.1KGS./CU.M
T OUTLET 58.8 DEG C

AVG TEMP 54.8 DEG C
KINEMATIC
VISCOSITYX100 0.000051 SQ.M/SEC

FLUID VELOCITY 0.780 M/SEC
REYNOLDS NO 16538.9
PRANDTL NO 3.67

HEAT SUPP 2520.0 WATTS
HEAT TRANS 2398.9 WATTS
HEAT LOST 121.1 WATTS
PERCENT HEAT LOST 4.81
HEAT FLUX TRANS 102828WATTS/SQ.M

NUSSELT NO 87.9
RFILM 0.216
RWALL 0.058
RTOTAL 0.274 SQ.M-DEG.C/WATTS

LOCALIZED WALL TEMPERATURES (DEG.C)

T101 DEG.C	T102 DEG.C	T103 DEG.C	T104 DEG.C	T105 DEG.C	T106 DEG.C	T107 DEG.C	T108 DEG.C	T109 DEG.C	T110 DEG.C	TIN DEG.C	TOUT DEG.C	TM DEG.C	DELTA DEG.C	H	R X1000	TIME HOURS
83.5	104.7	105.4	105.3	106.1	105.8	106.9	114.6	113.8	113.3	50.8	58.8	108.1	8.0	1682.0	0.5945	0.00
83.8	105.3	106.0	106.9	105.7	107.2	107.5	111.3	114.3	113.9	50.8	58.8	108.2	8.0	1677.3	0.5962	0.20
83.9	105.5	106.2	107.1	106.9	107.3	107.7	111.5	114.4	114.1	50.8	58.9	108.3	8.1	1673.7	0.5975	0.58
84.0	105.8	106.4	107.3	107.1	107.6	108.0	111.8	114.7	114.4	50.9	59.0	108.6	8.1	1669.2	0.5991	0.63
84.0	105.8	106.5	107.3	107.1	107.6	108.0	111.8	114.7	114.4	50.9	59.0	108.6	8.0	1668.4	0.5994	0.77
84.1	106.0	106.7	107.5	107.4	107.7	108.3	112.2	114.9	114.6	50.9	59.0	108.8	8.2	1661.3	0.6019	0.81
84.2	106.4	107.1	107.8	108.2	108.0	108.7	112.9	115.8	115.0	50.8	59.0	109.4	8.2	1643.6	0.6084	1.03
84.4	106.8	107.4	109.0	109.0	108.2	109.0	112.6	115.4	115.3	50.8	59.0	109.4	8.2	1640.4	0.6096	1.10
84.6	107.2	107.8	109.4	108.4	109.5	109.5	113.2	115.8	115.8	50.9	59.0	109.9	8.1	1629.7	0.6136	1.50
84.7	107.7	107.9	109.6	108.5	108.9	109.5	113.7	116.4	116.5	50.9	59.0	110.2	8.1	1622.2	0.6164	2.42

LOCALIZED FOULING RESISTANCE (SQ.M-DEG.C/WATTS)X100,000

T101	T102	T103	T104	T105	T106	T107	T108	T109	T110	TIN DEG.C	TOUT DEG.C	RFM	DELTA DEG.C	H	RTOT X1000	TIME HOURS
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	50.8	58.8	0.00	8.0	1682.0	0.5945	0.00
0.28	0.58	0.62	0.61	0.58	0.43	0.66	0.00	0.46	0.55	50.8	58.8	0.22	8.0	1677.3	0.5962	0.20
0.33	0.80	0.80	0.73	0.72	0.54	0.84	0.00	0.61	0.77	50.8	58.9	0.26	8.1	1673.7	0.5975	0.58
0.40	1.02	0.99	0.93	0.95	0.79	1.09	0.00	0.95	0.99	50.9	59.0	0.50	8.1	1669.2	0.5991	0.63
0.40	1.09	1.06	0.99	0.98	0.77	1.09	0.00	0.89	1.06	50.9	59.0	0.52	8.0	1668.4	0.5994	0.77
0.56	1.27	1.27	1.19	1.20	0.91	1.36	0.00	1.04	1.24	50.9	59.0	0.74	8.2	1661.3	0.6019	0.81
0.64	1.69	1.68	1.45	2.05	1.16	1.91	0.00	1.91	1.63	50.8	59.0	1.26	8.2	1643.6	0.6084	1.03
0.91	2.00	1.98	1.70	1.86	1.36	2.11	0.00	1.60	1.94	50.8	59.0	1.33	8.2	1640.4	0.6096	1.10
1.03	2.44	2.35	2.06	2.22	1.73	2.54	0.00	1.97	2.39	50.9	59.0	1.75	8.1	1629.7	0.6135	1.50
1.14	2.89	2.46	2.26	2.36	2.09	2.57	0.00	2.49	3.03	50.9	59.0	2.03	8.1	1622.2	0.6164	2.42

*******RUN NO 7.*******

VOLTS11.90 AMPS 191.

FERRIC OXIDE CONC (PPM) 2400.

FLOW RATE 0.0720 KGS.M/SEC

PH:6.9 DISS.O2 CONC (PPM) 5.8

HEAT FLOW SUPPLIED 2272.9 WATTS
HEAT FLUX SUPPLIED 97428. WATTS/SQ.M

IOR=TINLET 50.2 DEG C
DENSITY: 985.7KGS./CU.M
T OUTLET 57.5 DEG C

AVG TEMP 53.8 DEG C
KINEMATIC
VISCOSITYX100 0.000052 SQ.M/SEC

FLUID VELOCITY 0.780 M/SEC
REYNOLDS NO 16380.5
PRANDTL NO 3.74

HEAT SUPP 2272.9 WATTS
HEAT TRANS 2174.9 WATTS
HEAT LOST 98.0 WATTS
PERCENT HEAT LOST 4.31
HEAT FLUX TRANS 93227WATTS/SQ.M

NUSSELT NO 87.1
RFILM 0.219
RWALL 0.058
RTOTAL 0.277 SQ.M-DEG.C/WATTS

LOCALIZED FOULING RESISTANCE (SQ.M-DEG.C/WATTS)X100,000

T101	T102	T103	T104	T105	T106	T107	T108	T109	T110	TIN DEG.C	TOUT DEG.C	RFM	DELTA DEG.C	H	PTOT X1000	TIME HOURS
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	50.2	57.5	0.00	7.3	1527.7	0.6546	0.00
0.27	0.70	0.25	0.41	0.32	0.46	0.19	0.33	0.26	0.54	50.3	57.6	0.37	7.3	1519.3	0.6582	0.20
0.39	1.17	0.28	0.41	0.35	0.83	0.15	0.77	0.88	1.19	50.2	57.5	0.61	7.2	1512.5	0.6612	0.40
0.42	1.19	0.26	0.38	0.33	0.80	0.14	0.71	0.89	1.20	50.2	57.5	0.57	7.2	1513.2	0.6608	0.63
0.38	1.18	0.16	0.40	0.40	0.80	0.20	0.76	0.91	1.22	50.2	57.4	0.60	7.2	1512.5	0.6612	0.80
0.42	1.21	0.25	0.41	0.43	0.80	0.22	0.79	0.94	1.22	50.2	57.4	0.64	7.2	1511.4	0.6616	1.30
0.45	1.30	0.30	0.53	0.55	0.83	0.27	1.06	1.04	1.24	50.2	57.5	0.73	7.3	1509.9	0.6623	1.47
0.31	1.64	0.63	0.38	0.57	0.46	0.38	0.82	0.90	1.58	50.3	57.5	0.72	7.2	1511.1	0.6618	1.84
0.45	1.95	0.95	0.64	0.89	0.81	0.67	1.01	1.08	1.86	50.3	57.5	1.00	7.3	1504.5	0.6647	2.30
0.54	2.05	1.08	0.69	0.99	0.82	0.79	1.01	1.16	1.98	50.2	57.5	1.08	7.3	1501.7	0.6659	2.42
0.04	0.54	0.00	0.00	0.00	0.06	0.00	0.07	0.05	0.89	50.2	57.5	0.05	7.2	1527.7	0.6546	6.30
0.01	0.93	0.00	0.00	0.00	0.03	0.00	0.05	0.03	0.87	50.2	57.5	0.03	7.2	1527.9	0.6545	6.70
0.13	1.62	0.68	0.34	0.60	0.41	0.35	0.53	0.52	1.56	50.2	57.5	0.53	7.3	1512.0	0.6614	7.80
0.28	1.69	0.73	0.42	0.65	0.48	0.41	0.82	0.90	1.58	50.2	57.5	0.76	7.3	1509.7	0.6624	8.21
0.04	1.37	0.41	0.09	0.28	0.21	0.06	0.43	0.28	1.36	50.2	57.5	0.39	7.3	1518.5	0.6584	9.80
0.09	1.55	0.59	0.25	0.49	0.33	0.24	0.60	0.41	1.54	50.2	57.6	0.56	7.4	1515.9	0.6601	10.22

LOCALIZED WALL TEMPERATURES (DEG.C)

T101 DEG.C	T102 DEG.C	T103 DEG.C	T104 DEG.C	T105 DEG.C	T106 DEG.C	T107 DEG.C	T108 DEG.C	T109 DEG.C	T110 DEG.C	TIN DEG.C	TOUT DEG.C	TM DEG.C	DELTA DEG.C	H	R X1000	TIME HOURS
82.9	103.7	104.2	105.4	105.2	105.9	105.8	111.8	113.0	112.0	50.2	57.5	107.0	7.3	1527.7	0.6546	0.00
83.1	104.3	104.5	105.7	105.5	106.3	107.0	112.1	113.3	112.5	50.3	57.6	107.3	7.3	1519.3	0.6582	0.20
83.2	104.8	104.5	105.8	105.5	106.6	107.0	112.5	113.9	113.1	50.2	57.5	107.6	7.2	1512.5	0.6612	0.40
83.3	104.8	104.5	105.7	105.5	106.6	106.9	112.5	113.9	113.1	50.2	57.5	107.5	7.2	1513.2	0.6608	0.63
83.2	104.8	104.4	105.7	105.5	106.6	107.0	112.5	113.9	113.1	50.2	57.4	107.6	7.2	1512.5	0.6612	0.80
83.2	104.8	104.5	105.7	105.6	106.6	107.0	112.5	113.9	113.1	50.2	57.4	107.6	7.2	1511.4	0.6616	1.30
83.3	104.9	104.5	105.9	105.7	106.6	107.1	112.8	114.0	113.1	50.2	57.5	107.7	7.3	1509.9	0.6623	1.47
83.1	105.2	104.8	105.7	105.7	106.3	107.2	112.6	113.9	113.5	50.3	57.5	107.7	7.2	1511.1	0.6618	1.84
83.3	105.5	105.1	106.0	106.0	106.6	107.4	112.7	114.0	113.7	50.3	57.5	107.9	7.3	1504.5	0.6647	2.30
83.4	105.6	105.2	106.0	106.1	106.6	107.6	112.7	114.1	113.8	50.2	57.5	108.0	7.3	1501.7	0.6659	2.42
82.9	104.6	104.2	105.1	105.1	105.9	106.5	111.9	113.1	112.8	50.2	57.5	107.0	7.2	1527.7	0.6546	6.30
82.9	104.6	104.2	105.1	105.1	105.9	106.5	111.8	113.1	112.8	50.2	57.5	107.0	7.2	1527.9	0.6545	6.70
83.0	105.2	104.9	105.7	105.7	106.2	107.1	112.3	113.5	113.4	50.2	57.5	107.6	7.3	1512.0	0.6614	7.80
83.1	105.3	104.9	105.8	105.9	106.3	107.2	112.6	113.9	113.5	50.2	57.5	107.7	7.3	1509.7	0.6624	8.21
82.9	105.0	104.6	105.4	105.4	106.0	106.9	112.2	113.3	113.3	50.2	57.5	107.4	7.3	1518.8	0.6584	9.80
82.9	105.1	104.8	105.6	105.6	106.2	107.0	112.4	113.4	113.4	50.2	57.6	107.5	7.4	1515.0	0.6601	10.22

*******RUN NO 7.*******

VOLTS11.90 AMPS 191.

FERRIC OXIDE CONC (PPM) 2400.

FLOW RATE 0.0720 KGS.M/SEC

PH:6.9 DISS.O2 CONC (PPM) 5.8

HEAT FLOW SUPPLIED 2272.9 WATTS
HEAT FLUX SUPPLIED 97428. WATTS/SQ.M

TOR=TINLET 50.2 DEG C
DENSITY: 985.7KGS./CU.M
T OUTLET 57.5 DEG C

AVG TEMP 53.8 DEG C
KINEMATIC
VISCOSITYX100 0.000052 SQ.M/SEC

FLUID VELOCITY 0.780 M/SEC
REYNOLDS NO 16360.5
PRANDTL NO 3.74

HEAT SUPP 2272.9 WATTS
HEAT TRANS 2174.9 WATTS
HEAT LOST 98.0 WATTS
PERCENT HEAT LOST 4.31
HEAT FLUX TRANS 93227WATTS/SQ.M

NUSSELT NO 87.1
RFILM 0.219
RWALL 0.058
RTOTAL 0.277 SQ.M-DEG.C/WATTS

STIMATES OF ROOT MEAN SCUARE STATISTICAL ERROR IN THEPA RAMETER
0.76326 2.44526
STIMATES OF ROOT MEAN SQUARE TOTAL ERROR IN THE PARAMET IRS
0.10490 0.33608
STIMATE OF RO,RINF,AND B IN RF=RINF((1.-EXP(-B*TIME)
0.00000 0.99979 1.66477

TIME HURS	CALC. RESISTANCE ((SQ.M-DEGC/WATTS)X100,000)	FITTED VALUE
0.00	0.00	0.00
0.20	0.37	0.25
0.40	0.61	0.44
0.63	0.59	0.58
0.88	0.60	0.69
1.30	0.64	0.80
1.47	0.73	0.82
1.84	0.72	0.85
2.30	1.00	0.88
2.42	1.08	0.88

LOCALIZED WALL TEMPERATURES (DEG.C)

T101 DEG.C	T102 DEG.C	T103 DEG.C	T104 DEG.C	T105 DEG.C	T106 DEG.C	T107 DEG.C	T108 DEG.C	T109 DEG.C	T110 DEG.C	TIN DEG.C	TOUT DEG.C	TM DEG.C	DELTA DEG.C	H	R X1000	TIME HOURS
82.9	103.7	104.2	105.4	105.2	105.9	106.8	111.8	113.0	112.0	50.2	57.5	107.0	7.3	1527.7	0.6546	0.00
83.1	104.3	104.5	105.7	105.5	106.3	107.0	112.1	113.3	112.5	50.3	57.6	107.3	7.3	1519.3	0.6582	0.20
83.2	104.8	104.5	105.8	105.5	106.6	107.0	112.5	113.8	113.1	50.2	57.5	107.6	7.2	1512.5	0.6612	0.40
83.3	104.8	104.5	105.7	105.5	106.6	106.9	112.5	113.9	113.1	50.2	57.5	107.5	7.2	1513.2	0.6608	0.63
83.2	104.8	104.4	105.7	105.5	106.6	107.0	112.5	113.9	113.1	50.2	57.4	107.6	7.2	1512.5	0.6612	0.88
83.2	104.8	104.5	105.7	105.6	106.6	107.0	112.5	113.9	113.1	50.2	57.4	107.6	7.2	1511.4	0.6616	1.30
83.3	104.9	104.5	105.9	105.7	106.6	107.1	112.8	114.0	113.1	50.2	57.5	107.7	7.3	1509.9	0.6623	1.47
83.1	105.2	104.8	105.7	105.7	106.3	107.2	112.6	113.9	113.5	50.3	57.5	107.7	7.2	1511.1	0.6618	1.84
83.3	105.5	105.1	106.0	106.0	106.6	107.4	112.7	114.0	113.7	50.3	57.5	107.9	7.3	1504.5	0.6647	2.30
83.4	105.6	105.2	106.0	106.1	106.6	107.6	112.7	114.1	113.8	50.2	57.5	108.0	7.3	1501.7	0.6659	2.42

LOCALIZED FOULING RESISTANCE (SQ.M-DEG.C/WATTS)X100,000

T101	T102	T103	T104	T105	T106	T107	T108	T109	T110	TIN DEG.C	TOUT DEG.C	RFM	DELTA DEG.C	H	RTOT X1000	TIME HOURS
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	50.2	57.5	0.00	7.3	1527.7	0.6546	0.00
0.27	0.70	0.25	0.41	0.33	0.46	0.19	0.33	0.26	0.54	50.3	57.6	0.37	7.3	1519.3	0.6582	0.20
0.39	1.17	0.28	0.41	0.35	0.83	0.15	0.77	0.89	1.19	50.2	57.5	0.61	7.2	1512.5	0.6612	0.40
0.42	1.19	0.26	0.38	0.33	0.80	0.14	0.71	0.87	1.20	50.2	57.5	0.59	7.2	1513.2	0.6608	0.63
0.38	1.18	0.16	0.40	0.40	0.80	0.20	0.76	0.91	1.22	50.2	57.4	0.60	7.2	1512.5	0.6612	0.88
0.42	1.21	0.29	0.41	0.43	0.80	0.22	0.79	0.90	1.22	50.2	57.4	0.64	7.2	1511.4	0.6616	1.30
0.45	1.30	0.30	0.53	0.55	0.83	0.27	1.06	1.04	1.24	50.2	57.5	0.73	7.3	1509.9	0.6623	1.47
0.31	1.64	0.63	0.38	0.57	0.46	0.38	0.82	0.79	1.58	50.3	57.5	0.72	7.2	1511.1	0.6618	1.84
0.45	1.95	0.95	0.64	0.89	0.81	0.67	1.01	1.09	1.86	50.3	57.5	1.00	7.3	1504.5	0.6647	2.30
0.54	2.06	1.08	0.69	0.99	0.82	0.79	1.01	1.16	1.98	50.2	57.5	1.08	7.3	1501.7	0.6659	2.42

********RUN NO 8.*******

VOLTS12.60 AMPS 210.

FERRIC OXIDE CONC (PPM) 2400.

FLOW RATE 0.0680 KGS.M/SEC

PH:6.5 DISS.O2 CONC (PPM) 6.8

HEAT FLOW SUPPLIED 2646.0 WATTS
HEAT FLUX SUPPLIED 113421. WATTS/SQ.M

TOR=TINLET 50.0 DEG C
DENSITY: 985.2KGS./CU.M
T OUTLET 59.2 DEG C

AVG TEMP 54.6 DEG C
KINEMATIC
VISCOSITYX100 0.000051 SQ.M/SEC

FLUID VELOCITY 0.737 M/SEC
REYNOLDS NO 15656.9
PRANDTL NO 3.69

HEAT SUPP 2646.0 WATTS
HEAT TRANS 2627.4 WATTS
HEAT LOST 18.6 WATTS
PERCENT HEAT LOST 0.70
HEAT FLUX TRANS 112624WATTS/SQ.M

NUSSELT NO 84.4
RFILM 0.225
RWALL 0.058
RTOTAL 0.283 SQ.M-DEG.C/WATTS

STIMATES OF ROOT MEAN SQUARE STATISTICAL ERROR IN THEPA RAMETER
0.90040 4.58425
STIMATES OF ROOT MEAN SQUARE TOTAL ERROR IN THE PARAMET IRS
0.11618 0.99151
STIMATE OF RO,RINF.AND B IN RF=RINF((1.-EXP(-B*TIME)
0.00000 0.50595 10.10537

TIME HURS	CALC. RESISTANCE ((SQ.M-DEGC/WATTS)X100,000)	FITTEC VALUE
0.00	0.00	0.00
0.06	0.25	0.23
0.15	0.36	0.39
0.43	0.61	0.50
1.51	0.43	0.51
1.82	0.49	0.51
2.10	0.73	0.51
2.21	0.37	0.51

LOCALIZED FOULING RESISTANCE (SQ.M-DEG.C/WATTS)X100,000

T101	T102	T103	T104	T105	T106	T107	T108	T109	T110	TIN DEG.C	TOUT DEG.C	RFM	DELTA DEG.C	H	RTOT X1000	TIME HOURS
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	50.0	59.2	0.00	9.3	1739.6	0.5748	0.00
0.50	1.60	0.00	0.33	0.00	0.29	0.00	0.43	0.39	1.40	50.0	59.2	0.25	9.2	1734.5	0.5765	0.06
0.40	1.85	0.00	0.03	0.00	0.51	0.00	0.42	0.63	1.68	50.0	59.2	0.36	9.2	1730.4	0.5779	0.15
0.47	1.97	0.00	1.23	0.03	0.59	0.00	0.55	0.74	1.77	50.0	59.2	0.61	9.2	1722.4	0.5806	0.43
0.35	1.93	0.00	0.11	0.00	0.56	0.00	0.58	0.41	1.81	50.0	59.2	0.43	9.2	1725.7	0.5795	1.51
0.42	1.89	0.00	0.02	0.00	0.47	0.00	0.55	0.60	1.70	50.0	59.2	0.40	9.2	1730.1	0.5780	1.82
0.57	2.21	0.26	0.31	0.31	0.77	0.11	0.94	0.94	2.04	50.0	59.3	0.73	9.3	1719.2	0.5817	2.10
0.46	1.83	0.00	0.00	0.00	1.04	0.00	0.45	0.49	1.69	50.0	59.2	0.37	9.2	1729.9	0.5781	2.21

LOCALIZED WALL TEMPERATURES (DEG.C)

T101 DEG.C	T102 DEG.C	T103 DEG.C	T104 DEG.C	T105 DEG.C	T106 DEG.C	T107 DEG.C	T108 DEG.C	T109 DEG.C	T110 DEG.C	TIN DEG.C	TOUT DEG.C	TM DEG.C	DELTA DEG.C	H	R X1000	TIME HOURS
84.0	107.3	109.2	109.2	109.7	108.5	111.7	115.3	116.3	115.6	50.0	59.2	110.9	9.3	1739.6	0.5748	0.00
84.6	109.1	108.8	109.5	109.4	108.9	111.1	115.7	116.7	117.2	50.0	59.2	111.2	9.2	1734.5	0.5765	0.06
84.5	109.4	109.0	109.2	109.6	109.0	111.4	115.7	117.0	117.5	50.0	59.2	111.3	9.2	1730.4	0.5779	0.15
84.5	109.5	109.1	110.6	105.8	109.1	111.5	115.9	117.1	117.6	50.0	59.2	111.6	9.2	1722.4	0.5806	0.43
84.4	109.5	109.1	109.3	109.7	109.1	111.6	115.9	116.7	117.7	50.0	59.2	111.4	9.2	1728.7	0.5795	1.51
84.5	109.4	109.1	109.2	109.7	109.0	111.4	115.9	116.9	117.5	50.0	59.2	111.3	9.2	1730.1	0.5780	1.82
84.7	109.8	109.5	109.6	110.1	109.3	111.8	116.3	117.3	117.9	50.0	59.3	111.7	9.3	1719.2	0.5817	2.10
84.5	109.4	109.0	109.1	109.5	109.6	111.2	115.8	116.8	117.5	50.0	59.2	111.3	9.2	1729.9	0.5781	2.21

*******RUN NO 9.*******

VOLTS12.60 AMPS 210.

FERRIC OXIDE CONC (PPM) 34000.

FLOW RATE 0.0910 KGS.M/SEC

PH:6.9 DISS.O2 CONC (PPM) 6.4

HEAT FLOW SUPPLIED 2646.0 WATTS
HEAT FLUX SUPPLIED 113421. WATTS/SQ.M

TOR=TINLET 50.1 DEG C
DENSITY: 985.9KGS./CU.M
T OUTLET 56.5 DEG C

AVG TEMP 53.5 DEG C
KINEMATIC
VISCOSITYX100 0.000052 SQ.M/SEC

FLUID VELOCITY 0.985 M/SEC
REYNOLDS NO 20575.6
PRANDTL NO 3.76

HEAT SUPP 2646.0 WATTS
HEAT TRANS 2588.0 WATTS
HEAT LOST 58.0 WATTS
PERCENT HEAT LOST 2.19
HEAT FLUX TRANS 110936WATTS/SQ.M

NUSSELT NO 104.7
RFILM 0.182
RWALL 0.058
RTOTAL 0.240 SQ.M-DEG.C/WATTS

STIMATES OF ROOT MEAN SQUARE STATISTICAL ERROR IN THEPA RAMETER
0.56871 1.60048
STIMATES OF ROOT MEAN SQUARE TOTAL ERROR IN THE PARAMET IRS
0.02986 0.08404
STIMATE OF RO,RINF,AND B IN RF=RINF((1.-EXP(-B*TIME)
0.00000 1.27709 1.32083

TIME HURS	CALC. RESISTANCE ((SQ.M-DEGC/WATTS)X100.000)	FITTED VALUE
0.00	0.00	0.00
0.08	0.09	0.13
0.21	0.30	0.31
0.53	0.62	0.64
0.70	0.69	0.77
0.82	0.81	0.84
0.91	0.88	0.89
1.11	1.09	0.98
1.21	1.12	1.02
1.54	1.10	1.11
1.71	1.17	1.14
2.14	1.19	1.20
2.20	1.15	1.21
2.32	1.22	1.22
2.40	1.21	1.22

LOCALIZED WALL TEMPERATURES (DEG.C)

T101 DEG.C	T102 DEG.C	T103 DEG.C	T104 DEG.C	T105 DEG.C	T106 DEG.C	T107 DEG.C	T108 DEG.C	T109 DEG.C	T110 DEG.C	TIN DEG.C	TOUT DEG.C	TM DEG.C	DELTA DEG.C	H	R X1000	TIME HOURS
82.0	99.7	101.0	103.4	102.4	104.6	101.7	107.6	111.5	109.3	50.1	56.9	104.0	6.7	1912.6	0.5227	0.00
82.1	100.1	100.8	103.4	102.4	104.6	102.0	107.8	111.5	109.4	50.1	56.9	104.1	6.8	1908.3	0.5240	0.08
82.1	100.5	100.8	103.4	102.4	104.6	102.2	109.0	111.5	109.7	50.1	56.9	104.3	6.8	1900.7	0.5261	0.21
82.1	101.5	100.8	103.4	102.4	104.6	103.6	109.4	111.5	109.9	50.0	56.7	104.7	6.8	1884.3	0.5307	0.53
82.1	101.7	101.0	103.5	102.6	104.5	103.8	109.4	111.5	110.0	50.1	56.9	104.7	6.8	1885.7	0.5303	0.70
82.1	101.8	101.2	103.6	102.7	104.6	104.0	109.5	111.6	110.1	50.1	56.9	104.9	6.9	1881.3	0.5315	0.82
82.1	102.0	101.2	103.6	102.7	104.7	104.1	109.6	111.7	110.3	50.1	56.9	104.9	6.8	1878.1	0.5325	0.91
82.2	102.2	101.6	103.8	103.0	104.8	104.3	109.8	111.8	110.6	50.0	56.9	105.2	6.8	1868.8	0.5351	1.11
82.2	102.3	101.6	103.8	103.1	104.8	104.4	109.8	111.8	110.7	50.1	56.9	105.2	6.8	1868.8	0.5351	1.21
82.2	102.4	101.8	103.7	103.0	104.7	104.4	109.9	111.7	110.9	50.1	56.9	105.2	6.8	1869.4	0.5349	1.54
82.3	102.5	101.9	103.7	103.1	104.7	104.4	110.0	111.8	111.1	50.1	56.9	105.3	6.8	1867.5	0.5355	1.71
82.3	102.5	101.9	103.8	103.1	104.7	104.5	110.0	111.8	111.1	50.0	56.9	105.3	6.8	1865.0	0.5362	2.14
82.2	102.4	101.8	103.7	103.1	104.7	104.4	110.0	111.9	110.9	50.1	56.9	105.2	6.8	1867.4	0.5355	2.20
82.3	102.5	101.9	103.8	103.2	104.8	104.5	110.1	111.9	111.1	50.1	56.9	105.3	6.8	1865.7	0.5360	2.32
82.3	102.5	101.9	103.8	103.1	104.8	104.4	110.1	111.9	111.1	50.1	56.9	105.3	6.8	1866.1	0.5359	2.40

LOCALIZED FOULING RESISTANCE (SQ.M-DEG.C/WATTS)X100,000

T101	T102	T103	T104	T105	T106	T107	T108	T109	T110	TIN DEG.C	TOUT DEG.C	RFM	DELTA DEG.C	H	RTOT X1000	TIME HOURS
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	50.1	56.9	0.00	6.7	1912.6	0.5229	0.00
0.05	0.39	0.00	0.00	0.00	0.01	0.25	0.15	0.03	0.04	50.1	56.9	0.09	6.8	1908.3	0.5240	0.08
0.05	0.74	0.00	0.01	0.03	0.01	0.43	1.25	0.04	0.36	50.1	56.9	0.30	6.8	1900.7	0.5261	0.21
0.09	1.67	0.00	0.02	0.05	0.02	1.67	1.60	0.07	0.53	50.0	56.7	0.62	6.8	1884.3	0.5307	0.53
0.02	1.84	0.08	0.07	0.16	0.00	1.87	1.57	0.02	0.62	50.1	56.9	0.69	6.8	1885.7	0.5303	0.70
0.08	1.97	0.20	0.21	0.28	0.02	2.02	1.67	0.12	0.71	50.1	56.9	0.81	6.9	1881.3	0.5315	0.82
0.09	2.07	0.26	0.24	0.30	0.09	2.10	1.81	0.18	0.85	50.1	56.9	0.88	6.8	1878.1	0.5325	0.91
0.16	2.33	0.58	0.39	0.57	0.20	2.32	2.00	0.33	1.17	50.0	56.9	1.07	6.8	1868.8	0.5351	1.11
0.15	2.41	0.62	0.40	0.62	0.22	2.36	2.01	0.36	1.27	50.1	56.9	1.12	6.8	1868.8	0.5351	1.21
0.18	2.43	0.77	0.27	0.59	0.07	2.38	2.03	0.23	1.48	50.1	56.9	1.10	6.8	1869.4	0.5349	1.54
0.21	2.56	0.84	0.33	0.64	0.11	2.40	2.11	0.33	1.58	50.1	56.9	1.17	6.8	1867.5	0.5355	1.71
0.21	2.59	0.86	0.35	0.67	0.13	2.46	2.11	0.34	1.60	50.0	56.9	1.19	6.8	1865.0	0.5362	2.14
0.17	2.48	0.77	0.33	0.64	0.11	2.40	2.11	0.33	1.42	50.1	56.9	1.15	6.8	1867.4	0.5355	2.20
0.24	2.61	0.90	0.35	0.71	0.16	2.45	2.20	0.37	1.62	50.1	56.9	1.22	6.8	1865.7	0.5360	2.32
0.25	2.60	0.89	0.35	0.68	0.16	2.43	2.21	0.38	1.64	50.1	56.9	1.21	6.8	1866.1	0.5359	2.40

*******RUN NO10.*******

VOLTS12.60 AMPS 210.

FERRIC OXIDE CONC (PPM) 34000.

FLOW RATE 0.9919 KGS.M/SEC

PH:6.9 DISS.O2 CONC (PPM) 6.3

HEAT FLOW SUPPLIED 2646.0 WATTS
HEAT FLUX SUPPLIED 113421. WATTS/SQ.M

TOR=TINLET 50.1 DEG C
DENSITY: 983.9KGS./CU.M
T OUTLET 56.9 DEG C

AVG TEMP 53.5 DEG C
KINEMATIC
VISCOSITYX100 0.000052 SQ.M/SEC

FLUID VELOCITY 0.985 M/SEC
REYNOLDS NO 20577.8
PRANDTL NO 3.76

HEAT SUPP 2646.0 WATTS
HEAT TRANS 2580.7 WATTS
HEAT LOST 65.3 WATTS
PERCENT HEAT LOST 2.47
HEAT FLUX TRANS 110622WATTS/SQ.M

NUSSELT NO 104.7
RFILM 0.182
RWALL 0.058
RTOTAL 0.240 SQ.M-DEG.C/WATTS

STIMATES OF ROOT MEAN SQUARE STATISTICAL ERROR IN THECA PAMETER
0.40626 1.36518
STIMATES OF ROOT MEAN SQUARE TOTAL ERROR IN THE PARAMET IRS
0.03203 0.10764
STIMATE OF RO,RINF,AND B IN RF=RINF((1.-EXP(-B*TIME)
0.00000 1.42004 2.01162

TIME HURS	CALC. RESISTANCE ((SQ.M-DEGC/WATTS)X100,000)	FITTED VALUE
0.00	0.00	0.00
0.20	0.52	0.47
0.34	0.78	0.71
0.54	0.89	0.95
0.75	0.93	1.11
0.92	1.31	1.21
1.05	1.27	1.26
1.20	1.36	1.30
1.50	1.37	1.36
1.92	1.36	1.40
2.15	1.41	1.41
2.37	1.42	1.42

LOCALIZED WALL TEMPERATURES (DEG.C)

T101 DEG.C	T102 DEG.C	T103 DEG.C	T104 DEG.C	T105 DEG.C	T106 DEG.C	T107 DEG.C	T108 DEG.C	T109 DEG.C	T110 DEG.C	TIN DEG.C	TOUT DEG.C	TM DEG.C	DELTA DEG.C	H	R X1000	TIME HOURS
82.3	99.4	95.0	101.3	100.0	104.7	101.8	108.2	111.1	107.9	50.1	56.9	103.2	6.8	1941.0	0.5152	0.00
82.3	100.5	99.7	101.5	100.3	104.7	103.0	109.4	111.1	108.9	50.1	56.8	103.8	6.7	1918.6	0.5212	0.20
82.3	101.1	100.1	101.6	100.7	104.6	103.5	109.8	111.0	109.6	50.1	56.8	104.0	6.8	1908.2	0.5240	0.34
82.3	101.3	100.3	101.6	100.8	104.6	103.7	110.0	111.0	109.8	50.1	56.8	104.2	6.8	1903.8	0.5253	0.54
82.3	101.4	100.4	101.5	100.9	104.6	103.7	110.0	111.0	109.9	50.1	56.8	104.2	6.8	1902.5	0.5256	0.75
82.3	102.0	101.0	101.9	101.5	104.7	104.2	110.4	111.3	110.5	50.1	56.9	104.6	6.8	1887.7	0.5297	0.92
82.2	102.1	101.2	101.8	101.7	104.4	104.2	110.2	111.0	110.6	50.0	56.8	104.6	6.8	1887.6	0.5299	1.05
82.5	102.0	101.1	102.1	101.6	104.8	104.2	110.3	111.4	110.5	50.1	56.8	104.7	6.8	1884.3	0.5307	1.20
82.4	102.0	101.1	101.9	101.6	104.8	104.3	110.3	111.4	110.5	50.1	56.9	104.7	6.8	1884.8	0.5306	1.50
82.4	102.0	101.1	102.0	101.7	104.8	104.2	110.3	111.5	110.5	50.1	56.9	104.7	6.8	1885.0	0.5305	1.92
82.4	102.1	101.1	102.1	101.7	104.8	104.3	110.4	111.5	110.5	50.1	56.9	104.7	6.8	1883.3	0.5310	2.15
82.4	102.0	101.1	102.0	101.8	104.8	104.3	110.4	111.6	110.6	50.0	56.8	104.9	6.8	1881.7	0.5314	2.37

LOCALIZED FOULING RESISTANCE (SQ.M-DEG.C/WATTS)X100,000

T101	T102	T103	T104	T105	T106	T107	T108	T109	T110	TIN DEG.C	TOUT DEG.C	RFM	DELTA DEG.C	H	RTOT X1000	TIME HOURS
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	50.1	56.9	0.00	6.8	1941.0	0.5152	0.00
0.03	1.02	0.60	0.13	0.33	0.00	1.06	1.04	0.00	0.90	50.1	56.8	0.52	6.7	1918.6	0.5212	0.20
0.00	1.61	0.92	0.20	0.64	0.00	1.53	1.41	0.00	1.47	50.1	56.8	0.78	6.8	1908.2	0.5240	0.34
0.04	1.77	1.16	0.26	0.77	0.00	1.70	1.57	0.00	1.63	50.1	56.8	0.89	6.8	1903.8	0.5253	0.54
0.02	1.86	1.27	0.18	0.85	0.00	1.76	1.65	0.00	1.77	50.1	56.8	0.93	6.8	1902.5	0.5256	0.75
0.05	2.40	1.78	0.51	1.41	0.03	2.16	2.01	0.17	2.32	50.1	56.9	1.31	6.8	1887.7	0.5297	0.92
0.00	2.46	1.95	0.42	1.61	0.00	2.16	1.92	0.00	2.35	50.0	56.8	1.27	6.8	1887.6	0.5299	1.05
0.15	2.40	1.88	0.66	1.49	0.14	2.16	1.85	0.31	2.30	50.1	56.8	1.36	6.8	1884.3	0.5307	1.20
0.09	2.41	1.89	0.52	1.51	0.15	2.27	1.92	0.30	2.34	50.1	56.9	1.37	6.8	1884.8	0.5306	1.50
0.09	2.42	1.88	0.62	1.54	0.09	2.16	1.96	0.31	2.32	50.1	56.9	1.36	6.8	1885.0	0.5305	1.92
0.10	2.44	1.89	0.65	1.58	0.15	2.27	1.96	0.33	2.34	50.1	56.9	1.41	6.8	1883.3	0.5310	2.15
0.10	2.42	1.87	0.64	1.62	0.15	2.27	1.94	0.48	2.37	50.0	56.8	1.42	6.8	1881.7	0.5314	2.37

*******RUN NO11.*******

VOLTS12.60 AMPS 210.

FERRIC OXIDE CONC (PPM) 2400.

FLOW RATE 0.0910 KGS.M/SEC

PH:6.7 DISS.O2 CONC (PPM) 6.1

HEAT FLOW SUPPLIED 2646.0 WATTS
HEAT FLUX SUPPLIED 113421. WATTS/SQ.M

TOR=TINLET 50.0 DEG C
DENSITY: 986.0KGS./CU.M
T OUTLET 56.9 DEG C

AVG TEMP 53.4 DEG C
KINEMATIC
VISCOSITYX100 0.000052 SQ.M/SEC

FLUID VELOCITY 0.985 M/SEC
REYNOLDS NO 20360.1
PRANDTL NO 3.76

HEAT SUPP 2646.0 WATTS
HEAT TRANS 2628.7 WATTS
HEAT LOST 17.3 WATTS
PERCENT HEAT LOST 0.65
HEAT FLUX TRANS 112679WATTS/SQ.M

NUSSELT NO 104.8
RFILM 0.182
RWALL 0.058
RTOTAL 0.240 SQ.M-DEG.C/WATTS

STIMATES OF ROOT MEAN SQUARE STATISTICAL ERROR IN THEPA RAMETER
0.00933 3.53202
STIMATES OF ROOT MEAN SQUARE TOTAL ERROR IN THE PARAMET IRS
0.04166 0.16548
STIMATE OF RO.RINF.AND B IN RF=RINF((1.-EXP(-B*TIME)
0.00000 0.57996 6.15393

TIME HURS	CALC. RESISTANCE ((SQ.M-DEGC/WATTS)X100.000)	FITTED VALUE
0.00	0.00	0.00
0.03	0.07	0.10
0.05	0.20	0.15
0.08	0.22	0.23
0.21	0.43	0.42
0.37	0.50	0.52
0.75	0.50	0.57
0.77	0.55	0.57
0.83	0.66	0.58
1.40	0.61	0.58

LOCALIZED WALL TEMPERATURES (DEG.C)

T101 DEG.C	T102 DEG.C	T103 DEG.C	T104 DEG.C	T105 DEG.C	T106 DEG.C	T107 DEG.C	T108 DEG.C	T109 DEG.C	T110 DEG.C	TIN DEG.C	TOUT DEG.C	TM DEG.C	DELTA DEG.C	H	R X1000	TIME HOURS
81.8	102.3	102.7	103.7	103.6	104.5	104.8	109.6	115.9	107.1	50.1	56.8	105.9	6.8	1880.8	0.5317	0.00
81.8	102.6	102.6	103.7	103.6	104.6	104.8	109.7	116.1	107.1	50.0	56.8	106.0	6.9	1877.6	0.5325	0.03
81.9	102.8	102.8	103.8	103.8	104.7	104.9	109.8	116.2	107.2	50.0	56.8	106.1	6.9	1872.4	0.5341	0.05
81.9	102.9	102.8	103.9	103.8	104.7	104.9	109.9	116.3	107.2	50.0	56.8	106.1	6.9	1872.3	0.5341	0.08
82.0	103.3	103.0	104.0	104.0	104.9	105.1	110.2	116.5	107.3	50.0	56.9	106.4	6.9	1864.8	0.5363	0.21
82.1	103.4	103.1	104.1	104.0	104.9	105.2	110.4	116.6	107.4	49.9	56.9	106.4	7.0	1861.8	0.5371	0.37
82.1	103.3	103.1	104.1	104.1	104.9	105.2	110.2	116.6	107.5	49.9	56.9	106.4	6.9	1862.0	0.5371	0.75
82.1	103.4	103.2	104.1	104.1	104.9	105.2	110.3	116.7	107.5	50.0	56.9	106.5	6.9	1860.5	0.5375	0.77
82.2	103.6	103.3	104.2	104.3	105.0	105.4	110.3	116.0	107.6	50.0	57.0	106.6	7.0	1858.7	0.5380	0.83
82.2	103.5	103.2	104.2	104.2	105.0	105.2	110.5	116.7	107.6	50.0	56.9	106.6	6.9	1857.7	0.5383	1.40

LOCALIZED FOULING RESISTANCE (SQ.M-DEG.C/WATTS)X100.000

T101	T102	T103	T104	T105	T106	T107	T108	T109	T110	TIN DEG.C	TOUT DEG.C	REM	DELTA DEG.C	H	RTOT X1000	TIME HOURS
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	50.1	56.8	0.00	6.8	1880.8	0.5317	0.00
0.01	0.33	0.10	0.02	0.01	0.03	0.00	0.02	0.17	0.00	50.0	56.8	0.07	6.9	1877.6	0.5326	0.03
0.07	0.51	0.15	0.13	0.15	0.12	0.09	0.11	0.34	0.07	50.0	56.8	0.20	6.9	1872.4	0.5341	0.05
0.06	0.61	0.15	0.11	0.15	0.11	0.06	0.14	0.39	0.08	50.0	56.8	0.22	6.9	1872.3	0.5341	0.08
0.20	0.89	0.34	0.27	0.35	0.23	0.26	0.47	0.57	0.21	50.0	56.9	0.43	6.9	1864.8	0.5363	0.21
0.24	0.99	0.39	0.35	0.39	0.30	0.31	0.66	0.65	0.32	49.9	56.9	0.50	7.0	1861.8	0.5371	0.37
0.22	0.97	0.42	0.39	0.43	0.32	0.28	0.48	0.69	0.33	49.9	56.9	0.50	6.9	1862.0	0.5371	0.75
0.25	1.00	0.47	0.42	0.48	0.36	0.33	0.57	0.71	0.37	50.0	56.9	0.55	6.9	1860.5	0.5375	0.77
0.30	1.15	0.58	0.52	0.60	0.45	0.47	0.62	0.87	0.44	50.0	57.0	0.66	7.0	1858.7	0.5380	0.83
0.35	1.10	0.45	0.49	0.51	0.45	0.35	0.79	0.74	0.47	50.0	56.9	0.61	6.9	1857.7	0.5383	1.40

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*******RUN NO12.*******

VOLTS12.60          AMPS 210.

FERRIC OXIDE CONC (PPM)    2400.

FLOW RATE 0.0210  KGS.M/SEC

PH:6.7              DISS.O2 CONC (PPM)  5.0

HEAT FLOW SUPPLIED  2646.0     WATTS
HEAT FLUX SUPPLIED   113421.   WATTS/SQ.M

TOR=TINLET 50.0                        DEG C
DENSITY: 986.0KGS./CU.M
                  T OUTLET 56.9        DEG C

AVG TEMP 53.4       DEG C
KINEMATIC
VISCOSITYX100 0.000032                  SQ.M/SEC

FLUID VELOCITY 0.993    M/SEC
REYNOLDS NO  20560.1
PRANDTL NO   3.76

HEAT SUPP      2646.0    WATTS
HEAT TRANS      2628.7   WATTS
HEAT LOST        17.3    WATTS
PERCENT HEAT LOST     0.65
HEAT FLUX TRANS  112879WATTS/SQ.M

NUSSELT NO     104.8
RFILM     0.182
RWALL     0.050
RTOTAL      0.240      SQ.M-DEG.C/WATTS
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STIMATES OF ROOT MEAN SQUARE STATISTICAL ERROR IN THEPA  RAMETER
    0.48908              2.03125
STIMATES OF ROOT MEAN SQUARE TOTAL ERROR IN THE PARAMET  IRS
    0.02555              0.10610
STIMATE OF RO,RINF,AND B IN RF=RINF((1.-EXP(-B*TIME)
    0.00000              0.91423             3.02422
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TIME HORS	CALC. RESISTANCE ((SQ.M-DEGC/WATTS)X100,000)	FITTED VALUE
0.00	0.00	0.00
0.15	0.37	0.33
0.28	0.61	0.52
0.48	0.71	0.70
0.63	0.72	0.78
0.73	0.73	0.81
0.86	0.82	0.85
1.03	0.84	0.87
1.23	0.88	0.89
1.58	0.89	0.91
1.94	0.93	0.91
2.01	0.94	0.91
2.10	1.00	0.91

LOCALIZED WALL TEMPERATURES (DEG.C)

T101 DEG.C	T102 DEG.C	T103 DEG.C	T104 DEG.C	T105 DEG.C	T106 DEG.C	T107 DEG.C	T108 DEG.C	T109 DEG.C	T110 DEG.C	TIN DEG.C	TOUT DEG.C	TM DEG.C	DELTA DEG.C	H	R X1000	TIME HOURS
81.7	102.4	103.1	104.0	104.1	104.4	105.4	110.2	116.1	107.0	50.0	56.9	106.2	6.9	1867.7	0.5334	0.00
82.2	102.7	103.1	104.5	104.4	105.2	105.8	110.9	116.4	107.9	50.0	56.9	106.6	6.9	1853.9	0.5374	0.15
82.2	103.3	103.5	104.6	104.5	105.4	105.9	111.1	116.9	108.1	49.9	56.9	106.9	6.9	1844.6	0.5421	0.28
82.3	103.9	103.5	104.6	104.5	105.5	105.7	111.2	117.3	108.2	50.0	56.8	107.0	6.9	1842.1	0.5429	0.48
82.4	103.9	103.5	104.6	104.6	105.5	105.8	111.1	117.2	108.2	50.0	56.9	107.0	6.9	1842.7	0.5427	0.63
82.4	103.9	103.4	104.5	104.5	105.5	105.7	111.5	117.2	108.2	50.0	56.8	107.0	6.9	1841.2	0.5431	0.73
82.4	103.9	103.5	104.6	104.6	105.5	105.9	111.8	117.2	108.2	50.0	56.9	107.1	6.9	1839.5	0.5436	0.86
82.4	104.0	103.4	104.5	105.0	105.4	105.7	112.1	117.1	108.1	50.0	56.9	107.1	6.8	1839.1	0.5440	1.03
82.4	104.0	103.6	104.7	104.6	105.6	105.9	111.9	117.3	108.3	50.0	56.9	107.2	6.9	1836.5	0.5445	1.23
82.5	104.0	103.5	104.6	104.9	105.6	105.8	112.0	117.3	108.1	50.0	56.9	107.2	6.9	1835.9	0.5447	1.58
82.4	104.1	103.6	104.6	105.1	105.5	105.8	112.2	117.2	108.2	50.0	56.9	107.3	6.9	1835.2	0.5449	1.94
82.4	104.1	103.5	104.6	105.1	105.6	105.8	112.3	117.2	108.2	50.0	56.9	107.3	6.9	1834.1	0.5452	2.01
82.4	104.1	103.6	104.6	105.1	105.6	105.8	112.5	117.2	108.2	50.0	56.9	107.3	7.0	1831.2	0.5461	2.10

LOCALIZED FOULING RESISTANCE (SQ.M-DEG.C/WATTS)X100,000

T101	T102	T103	T104	T105	T106	T107	T108	T109	T110	TIN DEG.C	TOUT DEG.C	RFM	DELTA DEG.C	H	RTOT X1000	TIME HOURS
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	50.0	56.9	0.00	6.9	1867.7	0.5334	0.00
0.37	0.29	0.01	0.37	0.37	0.74	0.39	0.65	0.29	0.74	50.0	56.9	0.37	6.9	1853.9	0.5374	0.15
0.45	0.82	0.35	0.47	0.40	0.90	0.37	0.86	0.71	0.92	49.9	56.9	0.61	6.9	1844.6	0.5421	0.28
0.53	1.32	0.33	0.46	0.42	0.98	0.29	0.39	1.02	1.13	50.0	56.8	0.71	6.9	1842.1	0.5429	0.48
0.57	1.34	0.35	0.50	0.45	0.92	0.33	0.96	0.97	1.03	50.0	56.9	0.72	6.9	1842.7	0.5427	0.63
0.55	1.33	0.28	0.45	0.38	0.58	0.29	1.10	0.94	1.06	50.0	56.8	0.73	6.9	1841.2	0.5431	0.73
0.59	1.39	0.35	0.52	0.45	1.03	0.41	1.44	0.92	1.07	50.0	56.9	0.82	6.9	1839.5	0.5436	0.86
0.59	1.46	0.29	0.42	0.83	0.52	0.22	1.72	0.82	0.97	50.0	56.9	0.84	6.8	1838.1	0.5440	1.03
0.60	1.46	0.40	0.58	0.57	1.09	0.47	1.53	1.02	1.15	50.0	56.9	0.88	6.9	1836.5	0.5445	1.23
0.65	1.45	0.36	0.53	0.76	1.07	0.37	1.69	1.02	0.92	50.0	56.9	0.89	6.9	1835.9	0.5447	1.58
0.60	1.52	0.40	0.53	0.74	1.00	0.36	1.77	0.95	1.09	50.0	56.9	0.93	6.9	1835.2	0.5449	1.94
0.53	1.56	0.33	0.47	0.95	1.08	0.30	1.91	0.91	1.02	50.0	56.9	0.94	6.9	1834.1	0.5452	2.01
0.57	1.56	0.41	0.53	0.93	1.08	0.38	2.11	0.99	1.09	50.0	56.9	1.00	7.0	1831.2	0.5461	2.10

********RUN NO15.********

VOLTS11.90 AMPS 185.

FERRIC OXIDE CONC (PPM) 2400.

FLOW RATE 0.1300 KGS.M/SEC

PH:6.7 DISS.O2 CONC (PPM) 5.4

HEAT FLOW SUPPLIED 2201.5 WATTS
HEAT FLUX SUPPLIED 94368. WATTS/SQ.M

TOR=TINLET 50.8 DEG C
DENSITY: 986.3KGS./CU.M
T OUTLET 54.7 DEG C

AVG TEMP 52.8 DEG C
KINEMATIC
VISCOSITYX100 0.000053 SQ.M/SEC

FLUID VELOCITY 1.407 M/SEC
REYNOLDS NO 25076.9
PRANDTL NO 3.81

HEAT SUPP 2201.5 WATTS
HEAT TRANS 2116.4 WATTS
HEAT LOST 85.1 WATTS
PERCENT HEAT LOST 3.86
HEAT FLUX TRANS 90722WATTS/SQ.M

NUSSELT NO 136.7
RFILM 0.140
RWALL 0.059
RTOTAL 0.198 SQ.M-DEG.C/WATTS

LOCALIZED WALL TEMPERATURES (DEG.C)

T101 DEG.C	T102 DEG.C	T103 DEG.C	T104 DEG.C	T105 DEG.C	T106 DEG.C	T107 DEG.C	T108 DEG.C	T109 DEG.C	T110 DEG.C	TIN DEG.C	TOUT DEG.C	TM DEG.C	DELTA DEG.C	H	R X1000	TIME HOURS
86.0	109.4	108.1	108.8	109.0	110.0	110.9	117.1	117.6	118.9	50.8	54.7	111.4	3.9	1352.0	0.7397	0.00
86.0	109.3	108.2	108.8	109.1	110.0	110.9	117.2	117.6	118.9	50.9	54.7	111.4	3.8	1351.5	0.7399	0.10
86.0	109.3	108.1	108.7	109.0	110.0	110.9	117.2	117.7	118.9	50.9	54.7	111.4	3.8	1352.2	0.7395	0.13
86.1	109.4	108.2	108.9	109.1	110.1	110.9	117.2	117.7	118.9	50.9	54.7	111.4	3.7	1350.3	0.7406	0.15
86.1	109.6	108.4	109.0	109.3	110.2	111.1	117.4	117.9	119.1	50.9	54.7	111.6	3.8	1345.4	0.7427	0.48
86.1	109.7	108.4	109.1	109.4	110.2	111.2	117.5	117.9	119.1	50.9	54.7	111.7	3.8	1344.6	0.7437	0.50
86.2	109.7	108.4	109.1	109.5	110.4	111.3	117.5	118.0	119.3	50.9	54.7	111.8	3.8	1343.3	0.7444	0.58
86.2	109.8	108.6	109.2	109.5	110.4	111.4	117.6	118.1	119.3	50.9	54.7	111.8	3.8	1341.3	0.7456	0.60
86.2	109.8	108.6	109.2	109.5	110.4	111.4	117.6	118.1	119.3	50.9	54.7	111.8	3.8	1341.5	0.7454	0.71
86.2	110.1	108.8	109.4	109.7	110.5	111.6	117.7	118.2	119.5	50.9	54.7	112.0	3.8	1337.9	0.7474	0.95
86.2	110.0	108.7	109.3	109.6	110.4	111.5	117.5	118.2	119.4	50.9	54.7	111.9	3.9	1340.0	0.7463	1.00
86.3	110.2	109.1	109.6	110.0	110.6	111.8	117.9	118.4	119.7	50.8	54.7	112.2	3.9	1331.8	0.7509	1.28
86.3	110.3	108.9	109.6	109.9	110.7	111.7	118.3	118.6	119.8	50.9	54.6	112.3	3.8	1331.0	0.7513	1.40
86.2	110.5	108.9	109.4	109.8	110.7	111.9	117.9	118.5	119.9	50.8	54.6	112.2	3.8	1331.5	0.7510	1.83
86.2	110.5	109.0	109.4	109.8	110.7	111.9	118.0	118.4	119.9	50.9	54.7	112.2	3.9	1331.6	0.7510	1.90
86.2	110.5	109.1	109.4	109.9	110.7	112.1	118.1	118.5	120.0	50.8	54.7	112.3	3.9	1330.4	0.7516	1.91
86.3	110.6	109.1	109.4	109.9	110.8	112.1	118.2	118.5	120.1	50.8	54.7	112.3	3.9	1330.0	0.7519	1.93
86.3	110.6	109.1	109.5	109.9	110.8	112.1	118.3	118.6	120.1	50.9	54.7	112.4	3.8	1329.9	0.7519	2.07
86.3	110.6	109.2	109.5	110.0	110.8	112.1	118.2	118.6	120.2	50.9	54.7	112.4	3.9	1329.4	0.7522	2.10
86.3	110.6	109.1	109.5	109.9	110.8	112.2	118.2	118.6	120.1	50.9	54.7	112.4	3.8	1329.9	0.751[illegible]	2.13
86.3	110.5	109.1	109.4	109.9	110.7	112.1	118.1	118.5	120.1	50.9	54.7	112.3	3.8	1330.9	0.7514	2.18
86.2	110.5	109.1	109.2	109.8	110.5	112.0	118.0	118.2	120.0	50.9	54.7	112.2	3.8	1334.4	0.7494	2.40
86.1	110.7	109.2	109.3	109.9	110.5	112.1	118.2	118.2	120.2	50.8	54.7	112.2	3.9	1332.3	0.7506	2.77
86.2	110.7	109.2	109.4	109.9	110.6	112.1	118.2	118.3	120.2	50.9	54.7	112.3	3.8	1330.7	0.7515	2.78
86.3	110.7	109.1	109.4	109.9	110.7	112.1	118.1	118.4	120.2	50.9	54.7	112.3	3.8	1331.6	0.7510	2.80
86.3	110.6	109.2	109.3	109.9	110.7	112.1	118.2	118.4	120.2	50.9	54.7	112.3	3.8	1331.5	0.7510	3.03
86.3	110.7	109.3	109.4	109.9	110.8	112.2	118.2	118.5	120.2	50.9	54.8	112.4	3.9	1329.8	0.7523	3.05
86.3	110.7	109.3	109.5	110.0	110.8	112.3	118.2	118.5	120.3	50.9	54.8	112.4	3.9	1328.6	0.7527	3.07
86.3	110.8	109.3	109.6	110.0	110.9	112.3	118.3	118.6	120.3	50.8	54.7	112.5	3.9	1326.5	0.7537	3.20
86.3	110.7	109.2	109.5	109.9	110.8	112.2	118.2	118.5	120.2	50.8	54.7	112.4	3.9	1329.3	0.7523	3.25
86.3	110.8	109.3	109.6	110.0	110.9	112.3	118.3	118.6	120.3	50.8	54.8	112.5	3.9	1326.7	0.7538	3.40
86.2	110.5	109.1	109.5	109.9	110.7	112.0	118.1	118.5	120.0	50.9	54.7	112.3	3.9	1331.2	0.7512	3.43
86.2	110.4	109.1	109.4	109.8	110.6	111.9	118.1	118.4	120.0	50.8	54.7	112.2	3.9	1332.3	0.7506	3.45
86.2	110.3	109.1	109.4	109.7	110.6	111.9	118.0	118.4	120.0	50.9	54.7	112.2	3.8	1333.4	0.7500	3.64
86.3	110.4	109.1	109.4	110.0	110.6	111.9	117.9	118.5	120.0	50.9	54.7	112.2	3.8	1332.3	0.7506	4.15
86.3	110.6	109.2	109.6	110.0	110.7	112.0	118.2	118.6	120.1	50.9	54.7	112.4	3.9	1330.0	0.7519	4.35
86.3	110.5	109.1	109.6	110.0	110.7	112.0	118.1	118.6	120.1	50.9	54.7	112.3	3.9	1331.0	0.7513	4.39
86.3	110.5	109.1	109.6	110.0	110.7	112.0	118.2	118.6	120.1	50.9	54.6	112.3	3.9	1331.4	0.7511	4.50
86.3	110.6	109.2	109.6	110.0	110.7	112.0	118.1	118.6	120.1	50.9	54.7	112.4	3.8	1330.5	0.7516	4.61

LOCALIZED FOULING RESISTANCE (SQ.M-DEG.C/WATTS)X100.000

T101	T102	T103	T104	T105	T106	T107	T108	T109	T110	TIN DEG.C	TOUT DEG.C	RFM	DELTA DEG.C	H	RTOT X1000	TIME HOURS
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	50.8	54.7	0.00	3.9	1352.0	0.7397	0.00
0.07	0.00	0.09	0.03	0.04	0.05	0.04	0.08	0.03	0.04	50.9	54.7	0.04	3.8	1351.5	0.7399	0.10
0.03	0.00	0.03	0.00	0.00	0.02	0.01	0.05	0.04	0.00	50.9	54.7	0.01	3.8	1352.2	0.7395	0.13
0.13	0.01	0.14	0.09	0.11	0.09	0.10	0.11	0.11	0.06	50.9	54.7	0.09	3.7	1350.3	0.7406	0.15
0.12	0.30	0.30	0.24	0.27	0.21	0.33	0.28	0.27	0.25	50.9	54.7	0.28	3.8	1345.4	0.7427	0.48
0.13	0.36	0.39	0.34	0.35	0.25	0.37	0.44	0.33	0.29	50.9	54.7	0.35	3.8	1344.6	0.7437	0.50
0.22	0.41	0.54	0.40	0.45	0.38	0.52	0.39	0.46	0.45	50.9	54.7	0.45	3.8	1343.3	0.7444	0.58
0.26	0.50	0.62	0.49	0.56	0.45	0.61	0.51	0.52	0.49	50.9	54.7	0.53	3.8	1341.3	0.7456	0.60
0.26	0.58	0.59	0.48	0.54	0.45	0.57	0.50	0.51	0.51	50.9	54.7	0.52	3.8	1341.5	0.7454	0.71
0.26	0.84	0.76	0.66	0.72	0.56	0.78	0.68	0.67	0.70	50.9	54.7	0.71	3.8	1337.9	0.7474	0.95
0.19	0.66	0.69	0.60	0.66	0.43	0.67	0.45	0.60	0.61	50.9	54.7	0.59	3.9	1340.0	0.7463	1.00
0.35	0.91	1.14	0.92	1.06	0.67	1.04	0.83	0.59	0.90	50.8	54.7	0.93	3.9	1331.8	0.7509	1.28
0.30	1.07	0.96	0.91	0.96	0.62	0.97	1.31	1.09	1.06	50.9	54.6	1.01	3.8	1331.0	0.7513	1.40
0.22	1.29	0.36	0.73	0.53	0.78	1.17	0.79	0.79	1.17	50.8	54.6	0.94	3.8	1331.5	0.7510	1.83
0.26	1.24	1.00	0.68	0.80	0.74	1.20	1.00	0.69	1.16	50.8	54.7	0.94	3.9	1331.6	0.7510	1.90
0.28	1.29	1.13	0.75	0.92	0.80	1.33	1.08	0.98	1.26	50.8	54.7	1.04	3.9	1330.4	0.7516	1.91
0.31	1.32	1.16	0.72	0.91	0.84	1.36	1.22	1.32	1.35	50.8	54.7	1.07	3.9	1330.0	0.7519	1.93
0.37	1.37	1.17	0.79	0.96	0.91	1.40	1.36	1.12	1.40	50.9	54.7	1.13	3.8	1329.9	0.7519	2.07
0.39	1.38	1.26	0.81	1.01	0.89	1.42	1.17	1.12	1.47	50.9	54.7	1.13	3.9	1329.4	0.7522	2.10
0.38	1.34	1.16	0.82	0.96	0.91	1.43	1.16	1.11	1.40	50.9	54.7	1.11	3.8	1329.9	0.7519	2.13
0.35	1.29	1.16	0.71	0.91	0.82	1.33	1.11	0.99	1.37	50.9	54.7	1.04	3.8	1330.8	0.7514	2.19
0.22	1.21	1.15	0.51	0.80	0.51	1.27	0.99	0.61	1.27	50.9	54.7	0.88	3.8	1334.4	0.7494	2.40
0.18	1.46	1.26	0.61	0.92	0.50	1.33	1.20	0.62	1.49	50.8	54.7	0.99	3.9	1332.3	0.7506	2.77
0.26	1.46	1.20	0.68	0.93	0.67	1.42	1.22	0.79	1.48	50.9	54.7	1.03	3.8	1330.7	0.7515	2.78
0.31	1.45	1.18	0.71	0.90	0.74	1.40	1.11	0.64	1.45	50.9	54.7	1.04	3.8	1331.6	0.7510	2.80
0.31	1.38	1.21	0.66	0.91	0.74	1.37	1.14	0.83	1.43	50.9	54.7	1.03	3.8	1331.5	0.7510	3.03
0.38	1.47	1.29	0.77	0.98	0.84	1.50	1.18	0.93	1.51	50.9	54.8	1.12	3.9	1329.8	0.7523	3.05
0.39	1.52	1.37	0.80	1.02	0.89	1.54	1.23	0.99	1.56	50.8	54.8	1.17	3.9	1328.6	0.7527	3.07
0.38	1.57	1.39	0.93	1.09	0.95	1.63	1.31	1.37	1.62	50.8	54.7	1.24	3.9	1326.5	0.7537	3.20
0.33	1.47	1.22	0.80	0.96	0.87	1.46	1.18	1.02	1.51	50.8	54.7	1.12	3.9	1329.3	0.7523	3.25
0.39	1.60	1.39	0.91	1.11	0.96	1.63	1.31	1.10	1.64	50.8	54.8	1.25	3.9	1326.7	0.7538	3.40
0.28	1.29	1.18	0.84	0.88	0.76	1.28	1.10	0.96	1.29	50.9	54.7	1.03	3.9	1331.2	0.7512	3.43
0.25	1.20	1.08	0.76	0.81	0.69	1.19	1.06	0.90	1.25	50.8	54.7	0.94	3.9	1332.3	0.7506	3.45
0.28	1.09	1.07	0.72	0.79	0.71	1.20	1.01	0.87	1.23	50.9	54.7	0.93	3.8	1333.4	0.7500	3.64
0.34	1.11	1.13	0.92	1.01	0.67	1.19	0.84	0.37	1.27	50.9	54.7	0.78	3.8	1332.3	0.7506	4.15
0.34	1.35	1.19	0.97	1.09	0.74	1.25	1.14	1.05	1.33	50.9	54.7	1.10	3.9	1330.0	0.7519	4.35
0.33	1.29	1.12	0.94	1.06	0.74	1.25	1.05	1.08	1.31	50.9	54.7	1.06	3.9	1331.0	0.7513	4.39
0.35	1.26	1.16	0.98	1.07	0.76	1.25	1.14	1.11	1.35	50.9	54.6	1.03	3.9	1331.4	0.7511	4.50
0.39	1.33	1.20	0.99	1.10	0.79	1.29	1.02	1.11	1.37	50.9	54.7	1.13	3.8	1330.5	0.7516	4.61

*******RUN NO16.*******

VOLTS12.70 AMPS 213.

FERRIC OXIDE CONC (PPM) 2400.

FLOW RATE 0.0805 KGS.M/SEC

PH:6.3 DISS.O2 CONC (PPM) 5.2

HEAT FLOW SUPPLIED 2705.1 WATTS
HEAT FLUX SUPPLIED 115954. WATTS/SQ.M

TOP=TINLET 50.0 DEG C
DENSITY: 985.7KGS./CU.M
T OUTLET 57.7 DEG C

AVG TEMP 53.8 DEG C
KINEMATIC
VISCOSITYX100 0.000052 SQ.M/SEC

FLUID VELOCITY 0.872 M/SEC
REYNOLDS NO 18315.6
PRANDTL NO 3.74

HEAT SUPP 2705.1 WATTS
HEAT TRANS 2595.5 WATTS
HEAT LOST 109.6 WATTS
PERCENT HEAT LOST 4.05
HEAT FLUX TRANS 111257WATTS/SQ.M

NUSSELT NO 95.5
RFILM 0.199
RWALL 0.058
RTOTAL 0.258 SQ.M-DEG.C/WATTS

STIMATES OF ROOT MEAN SQUARE STATISTICAL ERROR IN THERA RAMETER
0.70049 2.76477
STIMATES OF ROOT MEAN SQUARE TOTAL ERROR IN THE PARAMET ERS
0.07461 0.27056
STIMATE OF RO,RINF,AND B IN RF=RINF((1.-EXP(-B*TIME)
0.00000 0.72584 5.86979

TIME HURS	CALC. RESISTANCE ((SQ.M-DEGC/WATTS)X100,000)	FITTED VALUE
0.00	0.00	0.00
0.13	0.26	0.37
0.20	0.45	0.50
0.25	0.63	0.56
0.40	0.84	0.66
0.60	0.68	0.70
0.79	0.73	0.72
1.01	0.71	0.72
1.26	0.62	0.73

LOCALIZED WALL TEMPERATURES (DEG.C)

T101 DEG.C	T102 DEG.C	T103 DEG.C	T104 DEG.C	T105 DEG.C	T106 DEG.C	T107 DEG.C	T108 DEG.C	T109 DEG.C	T110 DEG.C	TIN DEG.C	TOUT DEG.C	TM DEG.C	DELTA DEG.C	H	R X1000	TIME HOURS
86.6	110.2	108.6	109.4	109.7	111.5	111.7	119.0	119.4	120.7	50.0	57.7	112.4	7.6	1657.3	0.6034	0.00
86.6	110.6	109.0	109.7	110.1	111.6	112.1	119.3	119.5	121.0	50.0	57.7	112.7	7.7	1648.6	0.6066	0.13
86.7	110.8	109.1	109.9	110.3	111.8	112.3	119.6	119.8	121.2	50.0	57.7	112.9	7.7	1643.2	0.6086	0.20
86.8	110.9	109.3	110.0	110.5	112.0	112.4	119.9	120.1	121.5	50.0	57.7	113.1	7.7	1637.9	0.6105	0.25
86.9	111.3	109.6	110.2	110.7	112.2	112.7	120.1	120.3	121.8	50.0	57.8	113.4	7.8	1632.1	0.6127	0.40
86.7	111.1	109.4	110.1	110.5	112.0	112.5	120.0	120.1	121.7	50.0	57.7	113.2	7.7	1636.2	0.6112	0.60
86.9	111.1	109.6	110.2	110.6	112.0	112.6	119.9	120.2	121.7	50.0	57.7	113.3	7.7	1635.1	0.6116	0.79
86.8	111.2	109.6	110.2	110.6	111.9	112.6	119.8	120.1	121.8	50.0	57.7	113.2	7.8	1635.6	0.6114	1.01
86.7	111.1	109.4	110.0	110.4	111.9	112.4	119.8	120.0	121.8	50.0	57.7	113.1	7.7	1639.4	0.6100	1.26

LOCALIZED FOULING RESISTANCE (SQ.M-DEG.C/WATTS)X100,000

T101	T102	T103	T104	T105	T106	T107	T108	T109	T110	TIN DEG.C	TOUT DEG.C	REM	DELTA DEG.C	H	RTOT X1000	TIME HOURS
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	50.0	57.7	0.00	7.6	1657.3	0.6034	0.00
0.03	0.29	0.37	0.24	0.31	0.06	0.37	0.32	0.08	0.32	50.0	57.7	0.26	7.7	1648.6	0.6066	0.13
0.10	0.50	0.49	0.42	0.47	0.24	0.52	0.59	0.34	0.53	50.0	57.7	0.45	7.7	1643.2	0.6086	0.20
0.23	0.65	0.67	0.50	0.67	0.45	0.64	0.82	0.50	0.73	50.0	57.7	0.63	7.7	1637.9	0.6105	0.25
0.27	0.96	0.92	0.76	0.86	0.58	0.99	1.00	0.79	1.06	50.0	57.8	0.84	7.8	1632.1	0.6127	0.40
0.16	0.77	0.73	0.59	0.69	0.43	0.68	0.91	0.66	0.72	50.0	57.7	0.60	7.7	1636.2	0.6112	0.60
0.26	0.75	0.87	0.58	0.80	0.46	0.77	0.86	0.67	0.91	50.0	57.7	0.73	7.7	1635.1	0.6116	0.79
0.19	0.86	0.92	0.69	0.78	0.36	0.80	0.71	0.69	1.02	50.0	57.7	0.71	7.8	1635.6	0.6114	1.01
0.14	0.77	0.75	0.51	0.63	0.31	0.62	0.79	0.56	1.00	50.0	57.7	0.62	7.7	1639.4	0.6100	1.26

*******RUN NO17.*******

VOLTS11.70 AMPS 196.

FERRIC OXIDE CONC (PPM) 2400.

FLOW RATE 0.0799 KGS.M/SEC

PH:6.2 DISS.O2 CONC (PPM) 5.1

HEAT FLOW SUPPLIED 2176.2 WATTS
HEAT FLUX SUPPLIED 93293. WATTS/SQ.M

TOR=TINLET 50.0 DEG C
DENSITY: 986.1KGS./CU.M
T OUTLET 55.4 DEG C

AVG TEMP 53.2 DEG C
KINEMATIC
VISCOSITYX100 0.000053 SQ.M/SEC

FLUID VELOCITY 0.855 M/SEC
REYNOLDS NO 17790.5
PRANDTL NO 3.78

HEAT SUPP 2176.2 WATTS
HEAT TRANS 2127.2 WATTS
HEAT LOST 49.0 WATTS
PERCENT HEAT LOST 2.25
HEAT FLUX TRANS 91183WATTS/SQ.M

NUSSELT NO 93.1
RFILM 0.205
RWALL 0.058
RTOTAL 0.263 SQ.M-DEG.C/WATTS

STIMATES OF ROOT MEAN SQUARE STATISTICAL ERROR IN THEPA RAMETER
0.32676 2.41202
STIMATES OF ROOT MEAN SQUARE TOTAL ERROR IN THE PARAMET IRS
0.12011 0.35041
STIMATE OF RO,RINF,AND B IN RF=RINF((1.-EXP(-B*TIME)
0.00000 1.07102 2.15530

TIME HURS	CALC. RESISTANCE ((SQ.M-DEGC/WATTS)X100,000)	FITTED VALUE
0.00	0.00	0.00
0.09	0.43	0.17
0.33	0.65	0.53
0.51	0.50	0.71
0.70	0.83	0.83
1.09	0.96	0.97
1.33	1.04	1.01
1.85	1.09	1.05

LOCALIZED WALL TEMPERATURES (DEG.C)

T101 DEG.C	T102 DEG.C	T103 DEG.C	T104 DEG.C	T105 DEG.C	T106 DEG.C	T107 DEG.C	T108 DEG.C	T109 DEG.C	T110 DEG.C	TIN DEG.C	TOUT DEG.C	TM DEG.C	DELTA DEG.C	H	R X1000	TIME HOURS
77.2	92.8	91.2	90.6	90.3	93.4	94.8	99.2	99.1	99.6	49.9	56.3	93.9	6.4	1954.7	0.5116	0.00
77.3	93.2	91.6	91.2	90.8	93.9	95.1	99.5	99.4	100.3	49.8	56.4	94.3	6.6	1934.2	0.5170	0.08
77.4	93.4	91.9	91.5	91.2	93.6	95.3	99.7	99.7	100.5	50.0	56.4	94.5	6.4	1931.8	0.5176	0.33
77.3	93.4	91.9	91.2	91.1	93.4	95.2	99.5	99.3	100.5	49.9	56.4	94.4	6.5	1935.6	0.5166	0.51
77.4	93.8	92.2	91.5	91.5	93.5	95.6	100.0	99.6	100.7	49.9	56.4	94.7	6.4	1920.4	0.5207	0.70
77.3	93.8	92.6	92.1	91.8	93.2	95.4	99.9	99.7	101.1	50.1	56.4	94.8	6.3	1919.7	0.5209	1.09
77.3	93.9	92.6	92.1	91.9	93.6	95.4	99.7	99.9	101.1	49.9	56.3	94.9	6.5	1909.3	0.5238	1.33
77.2	93.9	92.8	92.2	91.9	93.4	95.5	99.9	99.7	101.2	50.0	56.4	94.9	6.4	1912.8	0.5228	1.85

LOCALIZED FOULING RESISTANCE (SQ.M-DEG.C/WATTS)X100,000

T101	T102	T103	T104	T105	T106	T107	T108	T109	T110	TIN DEG.C	TOUT DEG.C	RFM	DELTA DEG.C	H	RTOT X1000	TIME HOURS
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	49.9	56.3	0.00	6.4	1951.7	0.5116	0.00
0.04	0.33	0.40	0.66	0.59	0.42	0.24	0.32	0.35	0.69	49.8	56.4	0.43	6.6	1934.2	0.5170	0.08
0.10	0.64	0.74	1.00	0.99	0.13	0.46	0.57	0.64	0.90	50.0	56.4	0.63	6.4	1931.8	0.5176	0.33
0.09	0.68	0.72	0.70	0.91	0.00	0.41	0.39	0.22	0.93	49.9	56.4	0.57	6.5	1935.6	0.5156	0.51
0.16	1.07	1.04	1.02	1.29	0.10	0.77	0.99	0.48	1.33	49.9	56.4	0.83	6.4	1920.4	0.5207	0.70
0.12	1.11	1.44	1.66	1.67	0.00	0.59	0.76	0.61	1.60	50.1	56.4	0.96	6.3	1919.7	0.5209	1.09
0.12	1.17	1.53	1.79	1.79	0.15	0.63	0.58	0.84	1.67	49.9	56.3	1.04	6.5	1909.3	0.5238	1.33
0.00	1.25	1.67	1.81	1.77	0.00	0.72	0.72	0.82	1.68	50.0	56.4	1.09	6.4	1912.8	0.5228	1.85

*******RUN NO18.*******

VOLTS12.80   AMPS 225.

FERRIC OXIDE CONC (PPM)   2400.

FLOW RATE 0.1270 KGS.M/SEC

PH:6.3   DISS.O2 CONC (PPM) 5.2

HEAT FLOW SUPPLIED 2890.0   WATTS
HEAT FLUX SUPPLIED   123451. WATTS/SQ.M

TOR=TINLET 50.0   DEG C
DENSITY: 986.4KGS./CU.M
T OUTLET 55.3   DEG C

AVG TEMP 52.7   DEG C
KINEMATIC
VISCOSITYX100 0.000053   SQ.M/SEC

FLUID VELOCITY 1.375   M/SEC
REYNOLDS NO 28346.7
PRANDTL NO   3.82

HEAT SUPP   2890.0   WATTS
HEAT TRANS   2846.1   WATTS
HEAT LOST   33.9   WATTS
PERCENT HEAT LOST   1.10
HEAT FLUX TRANS 121928WATTS/SQ.M

NUSSELT NO   135.2
RFILM   0.141
RWALL   0.059
RTOTAL   0.270   SQ.M-DEG.C/WATTS

STIMATES OF ROOT MEAN SQUARE STATISTICAL ERROR IN THEPA RAMETER
0.01029   4.15406
STIMATES OF ROOT MEAN SQUARE TOTAL ERROR IN THE PARAMET IRS
0.21991   0.22776
STIMATE OF RO,RINF,AND B IN RF=RINF((1.-EXP(-B*TIME)
0.00000   0.47252   4.01921

TIME HURS	CALC. RESISTANCE ((SQ.M-DEGC/WATTS)X100.000)	FITTED VALUE
0.00	0.00	0.00
0.10	0.11	0.15
0.17	0.21	0.23
0.37	0.42	0.37
0.57	0.44	0.42
0.97	0.45	0.45
1.11	0.48	0.47
1.31	0.52	0.47
1.41	0.45	0.47
1.75	0.35	0.47
1.91	0.53	0.47

LOCALIZED WALL TEMPERATURES (DEG.C)

T101 DEG.C	T102 DEG.C	T103 DEG.C	T104 DEG.C	T105 DEG.C	T106 DEG.C	T107 DEG.C	T108 DEG.C	T109 DEG.C	T110 DEG.C	TIN DEG.C	TOUT DEG.C	TM DEG.C	DELTA DEG.C	H	R X1000	TIME HOURS
84.8	105.7	103.9	105.4	105.1	108.8	107.3	116.5	115.7	117.8	50.0	55.3	108.7	5.3	1905.2	0.5249	0.00
84.7	106.3	103.9	105.3	105.1	108.9	107.5	116.8	116.7	118.0	50.0	55.3	108.8	5.3	1901.0	0.5250	0.10
84.9	106.4	104.0	105.4	105.2	108.9	107.6	117.0	116.9	118.3	50.0	55.3	108.9	5.3	1897.1	0.5271	0.17
84.7	106.8	104.4	105.6	105.5	108.9	108.0	117.2	116.9	118.8	49.9	55.4	109.2	5.4	1889.5	0.5292	0.37
84.9	106.8	104.3	105.6	105.5	109.0	108.1	117.4	116.9	118.6	50.0	55.4	109.2	5.5	1889.0	0.5294	0.57
84.7	105.8	104.4	105.6	105.5	108.9	108.0	117.4	117.0	118.7	50.0	55.4	109.2	5.4	1888.3	0.5296	0.97
84.8	106.8	104.5	105.7	105.5	109.0	108.1	117.5	117.0	118.7	50.0	55.4	109.3	5.5	1887.8	0.5297	1.11
84.8	106.9	104.6	105.7	105.6	109.0	108.2	117.5	117.0	118.7	50.0	55.4	109.3	5.4	1886.0	0.5302	1.31
84.7	106.8	104.5	105.6	105.5	108.9	108.1	117.5	116.9	118.9	50.0	55.3	109.2	5.3	1887.7	0.5298	1.41
84.7	106.7	104.4	105.5	105.4	108.7	108.0	117.2	116.8	118.7	50.0	55.4	109.1	5.4	1892.8	0.5283	1.75
84.8	107.0	104.6	105.7	105.6	108.9	108.2	117.6	117.0	118.8	49.9	55.4	109.3	5.5	1885.4	0.5304	1.91

LOCALIZED FOULING RESISTANCE (SQ.M-DEG.C/WATTS)X100.000

T101	T102	T103	T104	T105	T106	T107	T108	T109	T110	TIN DEG.C	TOUT DEG.C	REM	DELTA DEG.C	H	RTOT X1000	TIME HOURS
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	50.0	55.3	0.00	5.3	1905.2	0.5249	0.00
0.00	0.48	0.00	0.00	0.00	0.05	0.12	0.21	0.04	0.10	50.0	55.3	0.11	5.3	1901.0	0.5250	0.10
0.01	0.61	0.13	0.03	0.07	0.05	0.26	0.35	0.17	0.44	50.0	55.3	0.21	5.3	1897.1	0.5271	0.17
0.00	0.91	0.44	0.12	0.30	0.09	0.60	0.57	0.23	0.80	49.9	55.4	0.42	5.4	1889.5	0.5292	0.37
0.05	0.92	0.38	0.20	0.29	0.12	0.61	0.74	0.24	0.65	50.0	55.4	0.44	5.5	1889.0	0.5294	0.57
0.00	0.91	0.44	0.23	0.32	0.11	0.60	0.73	0.28	0.78	50.0	55.4	0.45	5.4	1888.3	0.5296	0.97
0.02	0.93	0.48	0.27	0.35	0.12	0.64	0.77	0.29	0.73	50.0	55.4	0.48	5.5	1887.8	0.5297	1.11
0.01	1.01	0.56	0.29	0.41	0.13	0.72	0.78	0.25	0.77	50.0	55.4	0.52	5.4	1886.0	0.5302	1.31
0.00	0.93	0.49	0.22	0.33	0.04	0.63	0.76	0.24	0.86	50.0	55.3	0.45	5.3	1887.7	0.5298	1.41
0.00	0.83	0.46	0.12	0.25	0.00	0.57	0.55	0.11	0.73	50.0	55.4	0.35	5.4	1892.8	0.5283	1.75
0.07	1.02	0.58	0.29	0.41	0.09	0.69	0.84	0.27	0.83	49.9	55.4	0.53	5.5	1885.4	0.5304	1.91

*******RUN NO19.*******

VOLTS12.80 AMPS 220.

FERRIC OXIDE CONC (PPM) 2400.

FLOW RATE 0.1000 KGS.M/SEC

PH:6.1 DISS.O2 CONC (PPM) 5.2

HEAT FLOW SUPPLIED 2816.0 WATTS
HEAT FLUX SUPPLIED 120798. WATTS/SQ.M

TOR=TINLET 50.0 DEG C
DENSITY: 986.0KGS./CU.M
T OUTLET 56.7 DEG C

AVG TEMP 53.3 DEG C
KINEMATIC
VISCOSITYX100 0.000052 SQ.M/SEC

FLUID VELOCITY 1.083 M/SEC
REYNOLDS NO 22566.3
PRANDTL NO 3.77

HEAT SUPP 2816.0 WATTS
HEAT TRANS 2784.0 WATTS
HEAT LOST 32.0 WATTS
PERCENT HEAT LOST 1.14
HEAT FLUX TRANS 119336WATTS/SQ.M

NUSSELT NO 112.8
RFILM 0.162
RWALL 0.058
RTOTAL 0.227 SQ.M-DEG.C/WATTS

STIMATES OF ROOT MEAN SQUARE STATISTICAL ERROR IN THEPA RAMET
0.05310 3.69819
STIMATES OF ROOT MEAN SQUARE TOTAL ERROR IN THE PARAMET ERS
0.07685 0.33314
STIMATE OF RO,RINF,AND B IN RF=RINF((1.-EXP(-B*TIME)
0.00000 0.55043 4.93732

TIME HURS	CALC. RESISTANCE ((SQ.M-DEGC/WATTS)X100,000)	FITTED VALUE
0.00	0.00	0.00
0.09	0.31	0.29
0.18	0.36	0.32
0.37	0.44	0.46
0.50	0.31	0.50
0.61	0.52	0.52
1.15	0.56	0.55
1.28	0.62	0.55
1.49	0.64	0.55
1.71	0.51	0.55

LOCALIZED WALL TEMPERATURES (DEG.C)

TI01 DEG.C	TI02 DEG.C	TI03 DEG.C	TI04 DEG.C	TI05 DEG.C	TI06 DEG.C	TI07 DEG.C	TI08 DEG.C	TI09 DEG.C	TI10 DEG.C	TIN DEG.C	TOUT DEG.C	TM DEG.C	DELTA DEG.C	H	R X1000	TIME HOURS
86.1	110.0	107.8	108.5	108.6	111.1	111.4	120.0	119.0	122.3	50.1	56.6	112.0	6.6	1776.7	0.5629	0.00
86.4	110.5	108.1	108.7	109.0	111.3	111.8	120.4	119.5	122.5	50.0	56.6	112.4	6.6	1766.0	0.5652	0.09
86.4	110.9	108.2	109.7	109.0	111.3	111.9	120.4	119.5	122.7	49.9	56.7	112.5	6.8	1764.2	0.5658	0.18
86.5	111.0	108.3	108.8	109.1	111.4	111.9	120.7	119.6	122.8	50.0	56.7	112.6	6.7	1761.1	0.5678	0.37
86.4	110.7	108.1	108.6	108.9	111.2	111.7	120.4	119.6	122.7	50.0	56.6	112.4	6.6	1766.0	0.5653	0.50
86.5	111.0	108.5	108.0	109.2	111.4	112.0	120.6	119.7	122.0	50.0	56.7	112.7	6.7	1759.4	0.5684	0.61
86.5	111.2	108.6	109.9	109.0	111.4	112.2	120.7	119.7	122.9	50.0	56.8	112.7	6.8	1759.5	0.5683	1.15
86.5	111.2	108.6	109.0	109.4	111.4	112.2	120.7	119.8	123.1	50.0	56.7	112.8	6.7	1757.2	0.5691	1.28
86.6	111.2	108.6	109.0	109.4	111.5	112.2	120.8	119.8	123.1	49.9	56.7	112.8	6.8	1755.1	0.5690	1.49
86.7	111.0	108.5	108.9	109.3	111.4	112.0	120.5	119.7	123.0	50.0	56.7	112.7	6.7	1759.7	0.5693	1.71

LOCALIZED FOULING RESISTANCE (SQ.M-DEG.C/WATTS)X100,000

TI01	TI02	TI03	TI04	TI05	TI06	TI07	TI08	TI09	TI10	TIN DEG.C	TOUT DEG.C	RFM	DELTA DEG.C	H	RTOT X1000	TIME HOURS
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	50.1	56.6	0.00	6.6	1776.7	0.5629	0.00
0.26	0.46	0.26	0.23	0.26	0.22	0.29	0.20	0.44	0.16	50.0	56.6	0.31	6.6	1766.0	0.5662	0.09
0.24	0.75	0.31	0.23	0.30	0.20	0.35	0.31	0.43	0.35	49.9	56.7	0.36	6.8	1764.2	0.5668	0.18
0.30	0.83	0.37	0.27	0.36	0.27	0.37	0.56	0.51	0.42	50.0	56.7	0.44	6.7	1761.1	0.5678	0.37
0.26	0.66	0.26	0.15	0.25	0.16	0.24	0.31	0.47	0.38	50.0	56.6	0.31	6.6	1766.0	0.5663	0.50
0.35	0.91	0.55	0.37	0.50	0.26	0.51	0.49	0.57	0.56	50.0	56.7	0.52	6.7	1759.4	0.5684	0.61
0.37	1.03	0.69	0.43	0.33	0.29	0.63	0.56	0.69	0.42	50.0	56.8	0.56	6.8	1759.5	0.5683	1.15
0.35	1.07	0.66	0.43	0.62	0.28	0.63	0.51	0.69	0.70	50.0	56.7	0.62	6.7	1757.2	0.5691	1.28
0.41	1.01	0.67	0.46	0.64	0.37	0.63	0.63	0.68	0.68	49.9	56.7	0.64	6.8	1755.1	0.5690	1.49
0.40	0.87	0.56	0.33	0.52	0.27	0.48	0.43	0.63	0.63	50.0	56.7	0.51	6.7	1759.7	0.5693	1.71

********RUN NU20.********

VOLTS12.80 AMPS 220.

FERRIC OXIDE CONC (PPM) 2400.

FLOW RATE 0.0750 KGS.M/SEC

PH:6.1 DISS.O2 CONC (PPM) 5.2

HEAT FLOW SUPPLIED 2816.0 WATTS
HEAT FLUX SUPPLIED 120708. WATTS/SQ.M

TOR=TINLET 49.9 DEG C
DENSITY: 985.5KGS./CU.M
T OUTLET 58.5 DEG C

AVG TEMP 54.2 DEG C
KINEMATIC
VISCOSITYX100 0.000052 SQ.M/SEC

FLUID VELOCITY 0.813 M/SEC
REYNOLDS NO 17173.9
PRANDTL NO 3.71

HEAT SUPP 2816.0 WATTS
HEAT TRANS 2690.1 WATTS
HEAT LOST 125.9 WATTS
PERCENT HEAT LOST 4.47
HEAT FLUX TRANS 115309WATTS/SQ.M

NUSSELT NO 90.8
RFILM 0.210
RWALL 0.058
RTOTAL 0.268 SQ.M-DEG.C/WATTS

STIMATES OF ROOT MEAN SQUARE STATISTICAL ERROR IN THEPA RAMET
0.88942 2.93631
STIMATES OF ROOT MEAN SQUARE TOTAL ERROR IN THE PARAMET ERS
0.08832 0.29158
STIMATE OF RO,RINF,AND B IN RF=RINF*(1.-EXP(-B*TIME)
0.00000 0.61677 1.97676

TIME HOURS	CALC. RESISTANCE	FITTED VALUE
	((SQ.M-DEGC/WATTS)X100,000)	
0.00	0.00	0.00
0.29	0.10	0.27
0.40	0.26	0.34
0.49	0.43	0.38
0.57	0.38	0.42
0.87	0.60	0.51
0.90	0.74	0.51
1.23	0.60	0.56
1.33	0.54	0.57
1.40	0.46	0.58
1.60	0.61	0.59
1.85	0.56	0.60
2.11	0.60	0.61
2.18	0.58	0.61

LOCALIZED WALL TEMPERATURES (DEG.C)

T101 DEG.C	T102 DEG.C	T103 DEG.C	T104 DEG.C	T105 DEG.C	T106 DEG.C	T107 DEG.C	T108 DEG.C	T109 DEG.C	T110 DEG.C	TIN DEG.C	TOUT DEG.C	TM DEG.C	DELTA DEG.C	H	H X1000	TIME HOURS
88.2	115.0	112.7	112.6	113.3	114.9	116.3	123.8	123.7	127.2	49.9	58.4	116.5	8.5	1615.4	0.6190	0.00
88.4	115.3	112.9	112.7	113.5	115.0	116.4	123.9	123.7	127.3	50.0	58.4	116.7	8.4	1614.5	0.6194	0.29
88.5	115.5	113.1	112.8	113.7	115.1	116.6	124.0	124.0	127.7	50.0	58.4	116.8	8.5	1608.7	0.6216	0.40
88.5	115.7	113.2	113.0	113.9	115.3	116.8	124.3	124.2	127.9	50.0	58.5	117.0	8.6	1604.7	0.6232	0.49
88.5	115.7	113.2	112.9	113.8	115.2	116.7	124.2	124.2	127.9	50.0	58.5	117.0	8.6	1607.0	0.6223	0.57
88.7	116.0	113.5	113.2	114.1	115.4	117.0	124.4	124.3	128.1	49.9	58.5	117.2	8.6	1599.9	0.6230	0.87
88.7	116.2	113.7	113.3	114.3	115.5	117.2	124.7	124.5	128.2	49.9	58.5	117.4	8.6	1594.8	0.6270	0.90
88.6	116.0	113.5	113.1	114.1	115.3	117.0	124.5	124.3	128.0	49.9	58.5	117.2	8.6	1599.2	0.6253	1.23
88.7	115.9	113.4	113.1	114.0	115.4	117.0	124.3	124.3	128.0	50.0	58.6	117.2	8.6	1603.1	0.6238	1.33
88.5	115.8	113.3	113.0	113.9	115.3	116.8	124.4	124.3	127.9	50.0	58.5	117.1	8.5	1603.9	0.6235	1.40
88.6	116.0	113.5	113.1	114.1	115.4	117.1	124.4	124.4	128.1	49.9	58.5	117.2	8.6	1599.4	0.6252	1.60
88.5	116.0	113.4	113.1	114.0	115.3	117.0	124.5	124.4	128.1	50.0	58.6	117.2	8.6	1602.0	0.6242	1.85
88.5	116.0	113.4	113.1	114.0	115.3	117.0	124.5	124.4	128.1	49.9	58.5	117.2	8.6	1598.9	0.6254	2.11
88.5	116.0	113.4	113.1	114.0	115.3	117.0	124.6	124.4	128.1	49.9	58.6	117.2	8.6	1601.1	0.6246	2.18

LOCALIZED FOULING RESISTANCE (SQ.M-DEG.C/WATTS)X100,000

T101	T102	T103	T104	T105	T106	T107	T108	T109	T110	TIN DEG.C	TOUT DEG.C	RFM	DELTA DEG.C	H	RTOT X1000	TIME HOURS
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	49.9	58.4	0.00	8.5	1615.4	0.6190	0.00
0.14	0.29	0.12	0.05	0.13	0.06	0.11	0.05	0.01	0.05	50.0	58.4	0.10	8.4	1614.5	0.6194	0.29
0.22	0.44	0.28	0.19	0.28	0.16	0.26	0.17	0.27	0.40	50.0	58.4	0.26	8.5	1608.7	0.6216	0.40
0.27	0.66	0.43	0.35	0.45	0.28	0.40	0.43	0.44	0.55	50.0	58.5	0.43	8.6	1604.7	0.6232	0.49
0.22	0.64	0.40	0.30	0.37	0.22	0.37	0.35	0.40	0.38	50.0	58.5	0.38	8.6	1607.0	0.6223	0.57
0.39	0.99	0.66	0.51	0.65	0.42	0.64	0.55	0.53	0.75	49.9	58.5	0.62	8.6	1599.9	0.6250	0.87
0.42	1.03	0.80	0.65	0.78	0.50	0.76	0.75	0.68	0.85	49.9	58.5	0.74	8.6	1594.8	0.6270	0.90
0.33	0.85	0.65	0.48	0.66	0.34	0.64	0.63	0.53	0.65	49.9	58.5	0.60	8.6	1599.2	0.6253	1.23
0.39	0.81	0.58	0.45	0.55	0.35	0.62	0.41	0.55	0.72	50.0	58.6	0.54	8.6	1603.1	0.6238	1.33
0.29	0.74	0.45	0.34	0.46	0.29	0.43	0.48	0.52	0.64	50.0	58.5	0.46	8.5	1603.9	0.6235	1.40
0.36	0.88	0.69	0.49	0.67	0.37	0.68	0.51	0.57	0.76	49.9	58.5	0.61	8.6	1599.4	0.6252	1.60
0.29	0.86	0.57	0.42	0.53	0.32	0.58	0.64	0.59	0.79	50.0	58.6	0.56	8.6	1602.0	0.6242	1.85
0.29	0.91	0.61	0.47	0.60	0.34	0.61	0.65	0.62	0.81	49.9	58.5	0.60	8.6	1598.9	0.6254	2.11
0.28	0.89	0.54	0.44	0.54	0.32	0.58	0.73	0.61	0.75	49.9	58.6	0.58	8.6	1601.1	0.6246	2.18

*******RUN NO21.*******

VOLTS12.80 AMPS 220.

FERRIC OXIDE CONC (PPM) 2400.

FLOW RATE 0.0550 KGS.M/SEC

PH:6.2 DISS.O2 CONC (PPM) 5.2

HEAT FLOW SUPPLIED 2816.0 WATTS
HEAT FLUX SUPPLIED 120708. WATTS/SQ.M

TDR=TINLET 50.0 DEG C
DENSITY: 984.5KGS./CU.M
T OUTLET 61.8 DEG C

AVG TEMP 55.9 DEG C
KINEMATIC
VISCOSITYX100 0.000050 SQ.M/SEC

FLUID VELOCITY 0.597 M/SEC
REYNOLDS NO 12932.5
PRANDTL NO 3.60

HEAT SUPP 2816.0 WATTS
HEAT TRANS 2728.7 WATTS
HEAT LOST 87.3 WATTS
PERCENT HEAT LOST 3.10
HEAT FLUX TRANS 116967WATTS/SQ.M

NUSSELT NO 72.5
RFILM 0.262
RWALL 0.058
RTOTAL 0.319 SQ.M-DEG.C/WATTS

STIMATES OF ROOT MEAN SQUARE STATISTICAL ERROR IN THEPA PAMETI
1.30315. 4.23536
STIMATES OF ROOT MEAN SQUARE TOTAL ERROR IN THE PARAMET IRS
0.09293 0.30202
STIMATE OF RO,RINF,AND B IN RF=RINF((1.-EXP(-B*TIME)
0.00000 0.50041 2.02053

TIME HURS	CALC. RESISTANCE ((SQ.M-DEGC/WATTS)X100.000)	FITTED VALUE
0.00	0.00	0.00
0.07	0.16	0.07
0.21	0.19	0.17
0.29	0.28	0.22
0.50	0.29	0.32
0.85	0.36	0.41
1.35	0.38	0.47
1.61	0.55	0.48
1.85	0.44	0.49
2.26	0.58	0.50

LOCALIZED WALL TEMPERATURES (DEG.C)

T101 DEG.C	T102 DEG.C	T103 DEG.C	T104 DEG.C	T105 DEG.C	T106 DEG.C	T107 DEG.C	T108 DEG.C	T109 DEG.C	T110 DEG.C	TIN DEG.C	TOUT DEG.C	TM DEG.C	DELTA DEG.C	H	R X1000	TIME HOURS
92.3	124.2	122.1	120.4	122.4	121.4	125.8	132.2	131.6	135.5	49.9	61.8	125.0	11.8	1477.3	0.6769	0.00
92.4	124.6	122.3	120.7	122.6	121.8	126.1	132.0	131.8	136.1	50.0	61.8	125.2	11.7	1473.5	0.6785	0.07
92.4	124.9	122.3	120.7	122.7	121.6	126.0	132.2	131.7	136.2	49.9	61.9	125.3	12.0	1474.2	0.6783	0.21
92.5	125.0	122.4	120.8	122.8	121.7	126.1	132.3	131.8	136.3	49.9	61.9	125.4	12.0	1471.7	0.6795	0.29
92.4	124.9	122.3	120.8	122.7	121.7	126.0	132.5	131.9	136.4	50.0	61.8	125.4	11.9	1471.7	0.6795	0.50
92.4	125.0	122.4	120.8	122.9	121.7	126.1	132.6	131.9	136.5	49.9	61.8	125.5	11.9	1469.6	0.6805	0.85
92.6	125.0	122.5	121.0	122.9	121.7	126.3	132.3	132.1	136.5	49.9	62.0	125.5	12.1	1469.6	0.6804	1.35
92.6	125.4	122.9	121.1	123.2	121.9	126.7	132.3	132.0	136.7	50.0	62.0	125.7	11.9	1466.7	0.6818	1.61
92.4	125.1	122.4	120.9	123.0	121.9	126.3	132.7	131.9	136.5	49.9	61.8	125.5	12.0	1466.5	0.6819	1.85
92.5	125.0	123.0	121.5	122.9	121.8	126.6	133.0	131.8	136.3	50.0	61.7	125.7	11.8	1462.6	0.6837	2.26

LOCALIZED FOULING RESISTANCE (SQ.M-DEG.C/WATTS)X100,000

T101	T102	T103	T104	T105	T106	T107	T108	T109	T110	TIN DEG.C	TOUT DEG.C	RFM .	DELTA DEG.C	H	RTOT X1000	TIME HOURS
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	49.9	61.8	0.00	11.8	1477.3	0.6769	0.00
0.06	0.30	0.12	0.23	0.19	0.27	0.23	0.00	0.12	0.49	50.0	61.8	0.16	11.7	1473.8	0.6785	0.07
0.13	0.55	0.13	0.24	0.24	0.16	0.17	0.00	0.06	0.61	49.9	61.9	0.19	12.0	1474.2	0.6783	0.21
0.15	0.62	0.24	0.33	0.37	0.20	0.28	0.06	0.17	0.66	49.9	61.9	0.28	12.0	1471.7	0.6795	0.29
0.09	0.60	0.18	0.28	0.29	0.25	0.22	0.23	0.24	0.74	50.0	61.8	0.29	11.9	1471.7	0.6795	0.50
0.10	0.68	0.28	0.34	0.40	0.25	0.29	0.33	0.26	0.83	49.9	61.8	0.36	11.9	1469.6	0.6805	0.85
0.28	0.66	0.34	0.47	0.44	0.20	0.47	0.09	0.37	0.84	49.9	62.0	0.38	12.1	1469.6	0.6804	1.35
0.29	0.99	0.64	0.59	0.71	0.35	0.75	0.04	0.34	0.96	50.0	62.0	0.55	11.9	1466.7	0.6818	1.61
0.11	0.75	0.28	0.37	0.55	0.40	0.45	0.43	0.26	0.87	49.9	61.8	0.44	12.0	1466.5	0.6819	1.85
0.15	0.65	0.79	0.91	0.40	0.33	0.71	0.71	0.16	0.65	50.0	61.7	0.58	11.8	1462.6	0.6837	2.26

*******RUN NO22.*******

VOLTS11.90 AMPS 190.

FERRIC OXIDE CONC (PPM) 2400.

FLOW RATE 0.1350 KGS.M/SEC

PH:6.2 DISS.O2 CONC (PPM) 5.2

HEAT FLOW SUPPLIED 2261.0 WATTS
HEAT FLUX SUPPLIED 96918. WATTS/SQ.M

TOP=TINLET 50.0 DEG C
DENSITY: 986.9KGS./CU.M
T OUTLET 53.7 DEG C

AVG TEMP 51.8 DEG C
KINEMATIC
VISCOSITYX100 0.000054 SQ.M/SEC

FLUID VELOCITY 1.461 M/SEC
REYNOLDS NO 29737.4
PRANDTL NO 3.87

HEAT SUPP 2261.0 WATTS
HEAT TRANS 2131.7 WATTS
HEAT LOST 129.3 WATTS
PERCENT HEAT LOST 5.72
HEAT FLUX TRANS 91377WATTS/SQ.M

NUSSELT NO 139.9
RFILM 0.137
RWALL 0.059
RTOTAL 0.195 SQ.M-DEG.C/WATTS

STIMATES OF ROOT MEAN SQUARE STATISTICAL ERROR IN THEPA
1.35356 4.68391
STIMATES OF ROOT MEAN SQUARE TOTAL ERROR IN THE PARAMET
0.09900 0.31075
STIMATE OF RO.RINF.AND B IN RF=RINF((1.-EXP(-B*TIME)
0.00000 0.44220 2.09738

TIME HURS	CALC. RESISTANCE ((SQ.M-DEGC/WATTS)X100.000)	FITTED VALUE
0.00	0.00	0.00
0.07	0.17	0.06
0.21	0.19	0.16
0.40	0.23	0.25
0.61	0.18	0.32
0.75	0.44	0.35
1.11	0.44	0.40
1.25	0.40	0.41
1.40	0.39	0.42
1.75	0.44	0.43
1.93	0.43	0.43
2.01	0.44	0.44

LOCALIZED WALL TEMPERATURES (DEG.C)

T101 DEG.C	T102 DEG.C	T103 DEG.C	T104 DEG.C	T105 DEG.C	T106 DEG.C	T107 DEG.C	T108 DEG.C	T109 DEG.C	T110 DEG.C	TIN DEG.C	TOUT DEG.C	TM DEG.C	DELTA DEG.C	H	R X1000	TIME HOURS
77.1	93.9	92.2	93.0	92.9	95.4	94.8	102.8	102.1	105.3	50.0	53.7	95.9	3.7	1817.5	0.5502	0.00
77.2	94.0	92.3	93.2	93.0	95.5	95.1	102.9	102.3	105.4	50.0	53.7	96.0	3.8	1811.3	0.5521	0.07
77.2	94.0	92.4	93.3	93.1	95.5	95.1	102.9	102.2	105.4	49.9	53.7	96.1	3.8	1808.6	0.5529	0.21
77.2	94.0	92.5	93.3	93.1	95.5	95.2	102.9	102.3	105.4	50.0	53.8	96.1	3.8	1809.5	0.5526	0.40
77.2	94.0	92.4	93.2	93.1	95.5	95.1	102.9	102.2	105.4	50.0	53.7	96.1	3.8	1811.1	0.5522	0.61
77.3	94.3	92.6	93.5	93.2	95.7	95.3	103.3	102.5	105.7	50.0	53.7	96.3	3.8	1801.0	0.5552	0.75
77.3	94.3	92.6	93.5	93.2	95.7	95.3	103.3	102.5	105.7	50.0	53.7	96.3	3.8	1801.4	0.5551	1.11
77.3	94.2	92.6	93.4	93.2	95.7	95.2	103.2	102.5	105.7	49.9	53.7	96.3	3.8	1801.6	0.5551	1.25
77.2	94.3	92.5	93.5	93.2	95.7	95.2	103.0	102.6	105.7	49.9	53.7	96.2	3.8	1801.8	0.5550	1.40
77.3	94.3	92.6	93.5	93.3	95.7	95.2	103.0	102.6	105.8	50.0	53.8	96.3	3.8	1802.1	0.5549	1.75
77.3	94.3	92.6	93.5	93.3	95.7	95.2	103.0	102.6	105.7	50.0	53.8	96.3	3.8	1802.0	0.5549	1.93
77.3	94.3	92.6	93.5	93.3	95.7	95.2	103.1	102.6	105.7	50.0	53.8	96.3	3.8	1803.7	0.5544	2.01

LOCALIZED FOULING RESISTANCE (SQ.M-DEG.C/WATTS)X100.000

T101	T102	T103	T104	T105	T106	T107	T108	T109	T110	TIN DEG.C	TOUT DEG.C	REM	DELTA DEG.C	H	RTOT X1000	TIME HOURS
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	50.0	53.7	0.00	3.7	1817.5	0.5502	0.00
0.06	0.09	0.11	0.27	0.17	0.13	0.26	0.13	0.18	0.00	50.0	53.7	0.17	3.8	1811.3	0.5521	0.07
0.08	0.09	0.20	0.32	0.22	0.13	0.32	0.10	0.13	0.05	49.9	53.7	0.19	3.8	1808.6	0.5529	0.21
0.10	0.11	0.26	0.36	0.30	0.15	0.36	0.12	0.17	0.10	50.0	53.8	0.23	3.8	1809.5	0.5526	0.40
0.07	0.17	0.18	0.27	0.20	0.12	0.29	0.13	0.08	0.05	50.0	53.7	0.18	3.8	1811.1	0.5522	0.61
0.19	0.45	0.36	0.50	0.40	0.37	0.52	0.51	0.42	0.41	50.0	53.7	0.44	3.8	1801.0	0.5552	0.75
0.15	0.44	0.39	0.53	0.42	0.37	0.50	0.50	0.40	0.41	50.0	53.7	0.44	3.8	1801.4	0.5551	1.11
0.14	0.39	0.35	0.49	0.39	0.35	0.45	0.40	0.39	0.39	49.9	53.7	0.40	3.8	1801.6	0.5551	1.25
0.10	0.42	0.31	0.51	0.36	0.36	0.38	0.25	0.52	0.41	49.9	53.7	0.39	3.8	1801.8	0.5550	1.40
0.17	0.49	0.37	0.55	0.44	0.41	0.45	0.25	0.56	0.45	50.0	53.8	0.44	3.8	1802.1	0.5549	1.75
0.15	0.47	0.36	0.56	0.43	0.39	0.44	0.24	0.55	0.44	50.0	53.8	0.43	3.8	1802.0	0.5549	1.93
0.21	0.47	0.37	0.56	0.42	0.41	0.44	0.31	0.55	0.44	50.0	53.8	0.44	3.8	1803.7	0.5544	2.01

*******RUN NU23.*******

VOLTS11.90 AMPS 191.

FERRIC OXIDE CONC (PPM) 2400.

FLOW RATE 0.0900 KGS.M/SEC

PH:6.1 DISS.O2 CONC (PPM) 5.2

HEAT FLOW SUPPLIED 2272.9 WATTS
HEAT FLUX SUPPLIED 97428. WATTS/SQ.M

TOR=TINLET 50.0 DEG C
DENSITY: 986.2KGS./CU.M
T OUTLET 56.0 DEG C

AVG TEMP 53.0 DEG C
KINEMATIC
VISCOSITYX100 0.000053 SQ.M/SEC

FLUID VELOCITY 0.974 M/SEC
REYNOLDS NO 20192.9
PRANDTL NO 3.79

HEAT SUPP 2272.9 WATTS
HEAT TRANS 2265.1 WATTS
HEAT LOST 7.8 WATTS
PERCENT HEAT LOST 0.34
HEAT FLUX TRANS 97094WATTS/SQ.M

NUSSELT NO 103.0
RFILM 0.105
RWALL 0.058
RTOTAL 0.244 SQ.M-DEG.C/WATTS

STIMATES OF ROOT MEAN SQUARE STATISTICAL ERROR IN THEPA RAMETER
0.40368 2.86433
STIMATES OF ROOT MEAN SQUARE TOTAL ERROR IN THE PARAMET IRS
0.06347 0.37504
STIMATE OF RO,RINF,AND B IN RF=RINF((1.-EXP(-B*TIME)
0.00000 0.74125 7.70850

TIME HURS	CALC. RESISTANCE	FITTED VALUE ((SQ.M-DEGC/WATTS)X100,000)
0.00	0.00	0.00
0.07	0.51	0.31
0.17	0.49	0.54
0.33	0.55	0.68
0.55	0.52	0.73
0.63	0.59	0.74
0.90	0.77	0.74
1.25	0.81	0.74
1.41	0.87	0.74
1.61	0.79	0.74
1.71	0.88	0.74
1.83	0.76	0.74

LOCALIZED WALL TEMPERATURES (DEG.C)

T101 DEG.C	T102 DEG.C	T103 DEG.C	T104 DEG.C	T105 DEG.C	T106 DEG.C	T107 DEG.C	T108 DEG.C	T109 DEG.C	T110 DEG.C	TIN DEG.C	TOUT DEG.C	TM DEG.C	DELTA DEG.C	H	R X1000	TIME HOURS
80.1	100.0	98.5	99.0	98.9	100.1	101.3	107.7	107.3	110.7	49.9	55.9	101.6	6.0	1743.1	0.5737	0.00
80.3	100.3	98.9	99.4	99.4	100.6	101.7	108.5	108.0	111.6	50.0	55.9	102.1	6.0	1726.3	0.5793	0.07
80.3	100.5	98.9	99.4	99.4	100.6	101.7	108.4	108.0	111.7	50.0	55.9	102.1	5.9	1728.0	0.5787	0.17
80.3	100.7	99.0	99.4	99.5	100.6	101.8	108.3	108.0	111.8	49.9	56.0	102.2	6.1	1726.6	0.5792	0.33
80.3	100.4	99.0	99.4	99.5	100.6	101.7	108.3	108.0	111.7	50.0	56.0	102.1	6.0	1727.2	0.5790	0.55
80.4	100.7	99.1	99.5	99.5	100.7	101.8	108.3	108.0	111.9	49.9	55.9	102.2	6.0	1723.8	0.5801	0.63
80.5	100.9	99.2	99.6	99.7	100.8	102.0	108.4	108.2	112.1	50.0	56.0	102.4	6.0	1719.0	0.5817	0.90
80.5	100.9	99.3	99.7	99.7	100.9	102.0	108.5	108.2	112.1	50.0	56.0	102.4	6.0	1718.2	0.5820	1.25
80.4	101.0	99.3	99.7	99.7	100.9	102.1	108.7	108.4	112.3	50.0	56.0	102.5	6.0	1716.9	0.5824	1.41
80.4	100.9	99.2	99.6	99.7	100.8	102.0	108.5	108.3	112.1	50.0	56.0	102.4	6.0	1718.3	0.5820	1.51
80.5	101.0	99.3	99.7	99.8	100.8	102.1	108.7	108.2	112.1	50.0	56.1	102.5	6.1	1717.1	0.5824	1.71
80.4	100.9	99.2	99.6	99.7	100.8	101.9	108.5	108.2	112.0	50.0	56.0	102.4	6.0	1718.7	0.5818	1.83

LOCALIZED FOULING RESISTANCE (SQ.M-DEG.C/WATTS)X100,000

T101	T102	T103	T104	T105	T106	T107	T108	T109	T110	TIN DEG.C	TOUT DEG.C	REM	DELTA DEG.C	H	RTOT X1000	TIME HOURS
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	49.9	55.9	0.00	6.0	1743.1	0.5737	0.00
0.21	0.36	0.41	0.44	0.51	0.46	0.45	0.76	0.72	0.87	50.0	55.9	0.51	6.0	1726.3	0.5793	0.07
0.23	0.53	0.37	0.36	0.46	0.47	0.38	0.64	0.71	1.00	50.0	55.9	0.49	5.9	1728.0	0.5787	0.17
0.25	0.69	0.50	0.43	0.53	0.46	0.50	0.55	0.71	1.08	49.9	56.0	0.55	6.1	1726.6	0.5792	0.33
0.26	0.44	0.49	0.41	0.57	0.49	0.44	0.57	0.74	1.01	50.0	56.0	0.52	6.0	1727.2	0.5790	0.55
0.32	0.70	0.54	0.48	0.60	0.54	0.49	0.57	0.78	1.17	49.9	55.9	0.59	6.0	1723.8	0.5801	0.63
0.44	0.93	0.71	0.65	0.79	0.72	0.68	0.69	1.00	1.42	50.0	56.0	0.77	6.0	1719.0	0.5817	0.90
0.41	0.95	0.80	0.67	0.84	0.70	0.74	0.80	1.00	1.44	50.0	56.0	0.81	6.0	1718.2	0.5820	1.25
0.39	1.06	0.77	0.67	0.84	0.76	0.77	0.95	1.12	1.57	50.0	56.0	0.87	6.0	1716.9	0.5824	1.41
0.34	0.97	0.69	0.60	0.80	0.71	0.72	0.77	1.02	1.45	50.0	56.0	0.79	6.0	1718.3	0.5820	1.61
0.41	1.06	0.83	0.71	0.90	0.74	0.81	1.00	0.97	1.39	50.0	56.1	0.88	6.1	1717.1	0.5824	1.71
0.36	0.96	0.71	0.61	0.77	0.64	0.64	0.82	0.96	1.36	50.0	56.0	0.76	6.0	1718.7	0.5818	1.83

*******RUN NO24.*******

VOLTS11.90 AMPS 190.

FERRIC OXIDE CONC (PPM) 2400.

FLOW RATE 0.0700 KGS.M/SEC

PH:6.1 DISS.O2 CONC (PPM) 5.2

HEAT FLOW SUPPLIED 2261.0 WATTS
HEAT FLUX SUPPLIED 96918. WATTS/SQ.M

TOR=TINLET 50.0 DEG C
DENSITY: 985.9KGS./CU.M
T OUTLET 57.1 DEG C

AVG TEMP 53.5 DEG C
KINEMATIC
VISCOSITYX100 0.000052 SQ.M/SEC

FLUID VELOCITY 0.753 M/SEC
REYNOLDS NO 15842.6
PRANDTL NO 3.76

HEAT SUPP 2261.0 WATTS
HEAT TRANS 2079.0 WATTS
HEAT LOST 182.0 WATTS
PERCENT HEAT LOST 8.05
HEAT FLUX TRANS 89116WATTS/SQ.M

NUSSELT NO 84.9
RFILM 0.224
RWALL 0.058
RTOTAL 0.283 SQ.M-DEG.C/WATTS

STIMATES OF ROOT MEAN SQUARE STATISTICAL ERROR IN THEPA RAMETEP
0.71179 2.40586
STIMATES OF ROOT MEAN SQUARE TOTAL ERROR IN THE PARAMET IRS
0.09765 0.29543
STIMATE OF RO,RINF,AND B IN RF=RINF((1.-EXP(-B*TIME)
0.00000 0.02288 2.23292

TIME HURS	CALC. RESISTANCE ((SQ.M-DEGC/WATTS)X100,000)	FITTED VALUE
0.00	0.00	0.00
0.11	0.39	0.18
0.27	0.29	0.37
0.49	0.63	0.55
0.59	0.62	0.60
0.69	0.49	0.65
1.00	0.64	0.73
1.21	0.91	0.77
1.37	0.91	0.78
1.50	0.69	0.79
1.87	0.74	0.81
2.20	0.88	0.82

LOCALIZED WALL TEMPERATURES (DEG.C)

T101 DEG.C	T102 DEG.C	T103 DEG.C	T104 DEG.C	T105 DEG.C	T106 DEG.C	T107 DEG.C	T108 DEG.C	T109 DEG.C	T110 DEG.C	TIN DEG.C	TOUT DEG.C	TM DEG.C	DELTA DEG.C	H	R X1000	TIME HOURS
81.7	102.4	101.8	101.9	102.2	102.1	104.8	110.3	109.8	113.6	50.0	57.1	104.4	7.1	1529.2	0.6539	0.00
81.7	103.7	102.0	102.0	102.4	102.3	105.0	110.6	110.0	114.7	49.9	57.0	104.8	7.1	1517.3	0.6591	0.11
81.9	103.8	101.9	101.9	102.3	102.3	104.8	110.5	110.0	114.7	50.0	57.1	104.7	7.1	1524.2	0.6561	0.27
82.0	104.0	102.2	102.2	102.6	102.5	105.2	110.8	110.3	115.0	50.0	57.1	105.0	7.1	1514.2	0.6604	0.49
82.0	104.0	102.1	102.1	102.6	102.6	105.1	110.8	110.4	115.0	50.0	57.1	105.0	7.1	1514.9	0.6601	0.59
82.0	103.9	102.0	102.0	102.4	102.5	104.9	110.7	110.3	114.9	50.0	57.0	104.8	7.0	1517.2	0.6591	0.69
81.9	103.9	102.1	102.1	102.5	102.6	105.0	111.2	110.4	115.0	50.0	57.0	105.0	7.1	1513.6	0.6607	1.00
82.1	104.3	102.4	102.4	102.8	102.7	105.4	111.3	110.6	115.3	50.0	57.1	105.2	7.2	1507.2	0.6635	1.21
82.0	104.3	102.4	102.3	102.7	102.7	105.3	111.5	110.6	115.4	49.9	57.1	105.2	7.1	1506.7	0.6637	1.37
82.0	104.0	102.1	102.1	102.5	102.6	105.0	111.3	110.6	115.1	50.1	57.1	105.0	7.0	1514.3	0.6604	1.50
82.0	104.1	102.2	102.2	102.6	102.6	105.1	111.3	110.5	115.1	50.0	57.1	105.1	7.1	1512.4	0.6612	1.87
82.1	104.2	102.4	102.3	102.8	102.8	105.3	111.2	110.6	115.3	50.0	57.1	105.2	7.1	1507.6	0.6633	2.20

LOCALIZED FOULING RESISTANCE (SQ.M-DEG.C/WATTS)X100,000

T101	T102	T103	T104	T105	T106	T107	T108	T109	T110	TIN DEG.C	TOUT DEG.C	REM	DELTA DEG.C	H	RTOT X1000	TIME HOURS
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	50.0	57.1	0.00	7.1	1529.2	0.6539	0.00
0.02	1.51	0.20	0.14	0.18	0.20	0.27	0.31	0.30	1.17	49.9	57.0	0.37	7.1	1517.3	0.6591	0.11
0.17	1.56	0.04	0.01	0.03	0.16	0.06	0.19	0.25	1.15	50.0	57.1	0.20	7.1	1524.2	0.6551	0.27
0.36	1.79	0.43	0.34	0.47	0.44	0.46	0.52	0.58	1.48	50.0	57.1	0.53	7.1	1514.2	0.6604	0.49
0.32	1.83	0.34	0.32	0.41	0.50	0.36	0.50	0.65	1.56	50.0	57.1	0.52	7.1	1514.9	0.6601	0.59
0.28	1.70	0.17	0.19	0.21	0.40	0.16	0.45	0.60	1.43	50.0	57.0	0.49	7.0	1517.2	0.6591	0.69
0.26	1.76	0.24	0.28	0.29	0.50	0.28	1.03	0.71	1.50	50.0	57.0	0.64	7.1	1513.6	0.6607	1.00
0.44	2.12	0.64	0.55	0.63	0.69	0.69	1.07	0.90	1.85	50.0	57.1	0.91	7.2	1507.2	0.6635	1.21
0.37	2.15	0.61	0.50	0.58	0.67	0.60	1.33	0.90	1.93	49.9	57.1	0.91	7.1	1506.7	0.6637	1.37
0.32	1.86	0.27	0.28	0.33	0.49	0.30	1.09	0.88	1.62	50.1	57.1	0.69	7.0	1514.3	0.6604	1.50
0.33	1.92	0.38	0.35	0.40	0.56	0.39	1.09	0.82	1.67	50.0	57.1	0.74	7.1	1512.4	0.6612	1.87
0.43	2.02	0.60	0.54	0.61	0.71	0.37	1.03	0.96	1.80	50.0	57.1	0.08	7.1	1507.6	0.6633	2.20

```
*******RUN NO25.*******

VOLTS11.90          AMPS 191.

FERRIC OXIDE CONC (PPM)    2400.

FLOW RATE 0.0510  KGS.M/SEC

PH:6.2              DISS.O2 CONC (PPM)   5.2

HEAT FLOW SUPPLIED  2272.9     WATTS
HEAT FLUX SUPPLIED    97428.  WATTS/SQ.M

TOR=TINLET 50.2                        DEG C
DENSITY: 984.9KGS./CU.M
                    T OUTLET 60.4      DEG C

AVG TEMP 55.3      DEG C
KINEMATIC
VISCOSITYX100 0.000051                  SQ.M/SEC

FLUID VELOCITY 0.553   M/SEC
REYNOLDS NO  11874.2
PRANDTL NO    3.64

HEAT SUPP      2272.9     WATTS
HEAT TRANS      2168.4    WATTS
HEAT LOST       104.5     WATTS
PERCENT HEAT LOST     4.60
HEAT FLUX TRANS   92950WATTS/SQ.M


NUSSELT NO      67.4
RFILM      0.202
RWALL      0.058
RTOTAL      0.340      SQ.M-DEG.C/WATTS
```

```
STIMATES OF ROOT MEAN SQUARE STATISTICAL ERROR IN THEPA  RAMETER
    1.20159              3.59102
STIMATES OF ROOT MEAN SQUARE TOTAL ERROR IN THE PARAMET  IRS
    0.13036              0.18995
STIMATE OF RO,RINF,AND B IN RF=RINF((1.-EXP(-B*TIME)
    0.00000              0.66975              2.10640
    TIME          CALC. RESISTANCE    FITTED VALUE
    HURS           ((SQ.M-DEGC/WATTS)X100,000)
```

TIME HURS	CALC. RESISTANCE	FITTED VALUE
0.00	0.00	0.00
0.13	0.29	0.16
0.28	0.39	0.30
0.48	0.51	0.43
0.73	0.35	0.53
0.85	0.46	0.55
0.95	0.48	0.58
1.31	0.67	0.63
1.51	0.69	0.64
1.75	0.74	0.65

LOCALIZED WALL TEMPERATURES (DEG.C)

T101 DEG.C	T102 DEG.C	T103 DEG.C	T104 DEG.C	T105 DEG.C	T106 DEG.C	T107 DEG.C	T108 DEG.C	T109 DEG.C	T110 DEG.C	TIN DEG.C	TOUT DEG.C	TM DEG.C	DELTA DEG.C	H	R X1000	TIME HOURS
85.0	112.5	110.7	109.4	110.7	109.2	113.6	117.8	116.8	122.1	50.2	60.3	112.6	10.1	1415.6	0.7061	0.00
86.0	112.9	111.0	109.7	111.1	109.4	113.9	118.1	117.0	122.2	50.3	60.4	112.9	10.1	1409.6	0.7094	0.13
86.0	113.0	111.2	109.9	111.2	109.5	114.0	118.1	117.0	122.3	50.2	60.4	113.0	10.2	1406.3	0.7111	0.28
86.1	113.1	111.3	109.9	111.3	109.6	114.1	118.3	117.1	122.4	50.2	60.4	113.1	10.2	1403.3	0.7126	0.48
86.0	113.1	111.3	109.7	111.1	109.5	113.9	117.9	117.0	122.4	50.2	60.4	112.9	10.2	1408.0	0.7102	0.73
86.1	113.1	111.4	109.9	111.3	109.5	114.0	118.0	117.1	122.5	50.2	60.3	113.0	10.1	1404.8	0.7119	0.85
86.2	113.2	111.4	109.9	111.4	109.5	114.1	118.0	116.9	122.3	50.2	60.5	113.1	10.2	1406.0	0.7113	0.95
86.1	113.4	111.5	109.9	111.6	109.6	114.3	118.5	117.1	122.6	50.1	60.4	113.2	10.2	1399.4	0.7116	1.31
86.2	113.4	111.5	110.0	111.8	109.6	114.2	118.4	117.1	122.7	50.1	60.4	113.3	10.2	1398.8	0.7149	1.51
86.3	113.4	111.6	110.1	111.8	109.6	114.3	118.4	117.1	122.8	50.2	60.4	113.3	10.1	1399.0	0.7148	1.75

LOCALIZED FOULING RESISTANCE (SQ.M-DEG.C/WATTS)X100,000

T101	T102	T103	T104	T105	T106	T107	T108	T109	T110	TIN DEG.C	TOUT DEG.C	RFM	DELTA DEG.C	H	RTOT X1000	TIME HOURS
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	50.2	60.3	0.00	10.1	1415.6	0.7064	0.00
0.15	0.42	0.37	0.24	0.35	0.19	0.29	0.29	0.19	0.19	50.3	60.4	0.29	10.1	1409.6	0.7094	0.13
0.20	0.54	0.59	0.40	0.49	0.25	0.43	0.23	0.21	0.23	50.2	60.4	0.39	10.2	1406.3	0.7111	0.28
0.25	0.63	0.70	0.46	0.65	0.34	0.50	0.51	0.28	0.31	50.2	60.4	0.51	10.2	1403.3	0.7126	0.48
0.19	0.62	0.71	0.22	0.37	0.25	0.37	0.05	0.21	0.34	50.2	60.4	0.35	10.2	1408.0	0.7102	0.73
0.15	0.64	0.73	0.43	0.63	0.27	0.46	0.18	0.37	0.43	50.2	60.3	0.46	10.1	1404.8	0.7119	0.05
0.36	0.72	0.80	0.43	0.71	0.30	0.54	0.20	0.16	0.29	50.2	60.5	0.48	10.2	1406.0	0.7113	0.95
0.11	0.95	0.88	0.47	0.93	0.36	0.78	0.70	0.29	0.55	50.1	60.4	0.67	10.2	1399.4	0.7116	1.31
0.36	0.95	0.99	0.61	1.12	0.35	0.67	0.62	0.34	0.70	50.1	60.4	0.67	10.2	1398.8	0.7149	1.51
0.48	0.98	0.97	0.67	1.19	0.39	0.78	0.64	0.28	0.77	50.2	60.4	0.74	10.1	1399.0	0.7148	1.75

*******RUN N026.*******

VOLTS12.80 AMPS 220.

FERRIC OXIDE CONC (PPM) 2400.

FLOW RATE 0.0693 KGS.M/SEC

PH:6.2 DISS.O2 CONC (PPM) 5.2

HEAT FLOW SUPPLIED 2816.0 WATTS
HEAT FLUX SUPPLIED 120700. WATTS/SQ.M

TOR=TINLET 50.2 DEG C
DENSITY: 985.0KGS./CU.M
T OUTLET 59.6 DEG C

AVG TEMP 54.9 DEG C
KINEMATIC
VISCOSITYX100 0.000051 SQ.M/SEC

FLUID VELOCITY 0.753 M/SEC
REYNOLDS NO 16094.2
PRANDTL NO 3.66

HEAT SUPP 2816.0 WATTS
HEAT TRANS 2732.2 WATTS
HEAT LOST 83.8 WATTS
PERCENT HEAT LOST 2.98
HEAT FLUX TRANS 117115WATTS/SQ.M

NUSSELT NO 86.1
RFILM 0.221
RWALL 0.058
RTOTAL 0.279 SQ.M-DEG.C/WATTS

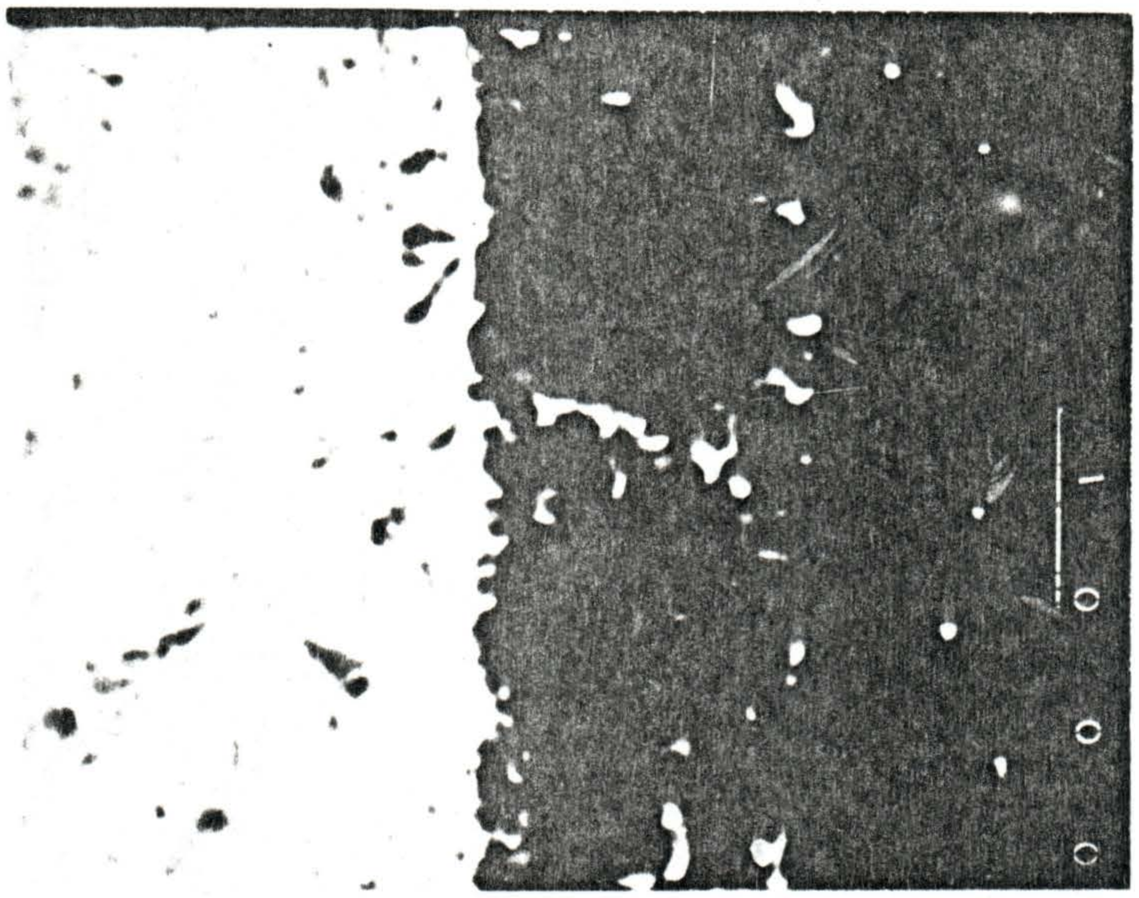
LOCALIZED FOULING RESISTANCE (SQ.M-DEG.C/WATTS)X100,000

T101	T102	T103	T104	T105	T106	T107	T108	T109	T110	TIN DEG.C	TOUT DEG.C	RFM	DELTA DEG.C	H	RTOT X1000	TIME HOURS
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	50.2	59.6	0.00	9.4	1585.0	0.6306	0.00
0.08	0.12	0.16	0.10	0.15	0.04	0.16	0.13	0.04	0.08	50.2	59.6	0.11	9.4	1582.1	0.6321	0.15
0.22	0.42	0.41	0.31	0.40	0.30	0.41	0.64	0.32	0.39	50.3	59.6	0.40	9.3	1574.0	0.6353	0.37
0.26	0.53	0.50	0.39	0.48	0.34	0.48	0.70	0.37	0.50	50.3	59.6	0.47	9.3	1572.3	0.6350	0.50
0.23	0.66	0.65	0.49	0.61	0.35	0.62	0.84	0.43	0.61	50.2	59.6	0.50	9.4	1568.8	0.6374	0.67
0.26	0.73	0.65	0.51	0.63	0.37	0.70	0.71	0.45	0.66	50.3	59.7	0.62	9.4	1569.0	0.6374	0.83
0.31	0.73	0.70	0.55	0.69	0.44	0.75	0.95	0.54	0.67	50.3	59.6	0.67	9.4	1567.4	0.6330	1.11
0.30	0.79	0.73	0.60	0.72	0.49	0.77	1.04	0.61	0.74	50.2	59.6	0.72	9.4	1564.3	0.6393	1.21
0.34	0.86	0.79	0.65	0.79	0.49	0.83	1.11	0.65	0.80	50.3	59.7	0.77	9.4	1565.6	0.6397	1.46
0.33	0.93	0.85	0.70	0.92	0.54	0.97	1.11	0.68	0.84	50.2	59.7	0.83	9.5	1563.0	0.6398	2.05
0.42	1.01	0.99	0.81	0.98	0.64	1.02	1.30	0.75	0.91	50.3	59.7	0.94	9.4	1561.5	0.6404	2.15
0.43	1.07	1.01	0.82	0.99	0.64	1.07	1.31	0.89	0.98	50.3	59.8	0.96	9.5	1560.7	0.6407	2.25
0.59	1.23	1.29	1.04	1.25	0.83	1.32	1.48	0.94	1.16	50.3	59.7	1.17	9.4	1554.3	0.6434	2.27
0.45	1.10	1.06	0.83	1.00	0.64	1.12	1.33	0.83	1.00	50.2	59.9	0.99	9.5	1559.6	0.6412	2.37
0.47	1.12	1.15	0.89	1.09	0.68	1.23	1.19	0.84	1.05	50.2	59.7	1.03	9.5	1557.5	0.6421	2.49
0.45	1.17	1.11	0.91	1.05	0.72	1.18	1.30	0.90	1.07	50.3	59.8	1.04	9.5	1558.1	0.6418	2.50
0.40	1.06	0.97	0.77	0.93	0.61	1.05	1.28	0.77	1.02	50.3	59.7	0.93	9.4	1561.2	0.6405	2.70
0.33	1.01	0.84	0.65	0.82	0.51	0.94	1.20	0.63	0.93	50.3	59.7	0.82	9.4	1563.9	0.6394	3.01

LOCALIZED WALL TEMPERATURES (DEG.C)

T101 DEG.C	T102 DEG.C	T103 DEG.C	T104 DEG.C	T105 DEG.C	T106 DEG.C	T107 DEG.C	T108 DEG.C	T109 DEG.C	T110 DEG.C	TIN DEG.C	TOUT DEG.C	TM DEG.C	DELTA DEG.C	H	R X1000	TIME HOURS
90.0	118.8	115.7	115.6	116.2	117.6	119.2	126.6	125.9	129.5	50.2	59.6	119.5	9.4	1585.0	0.6306	0.00
90.0	118.9	115.9	115.7	116.4	117.7	119.4	126.8	125.9	127.5	50.2	59.6	119.6	9.4	1582.1	0.6321	0.15
90.2	119.3	116.2	116.0	116.7	118.0	119.7	127.4	126.3	129.9	50.3	59.6	119.9	9.3	1574.0	0.6333	0.37
90.3	119.4	116.3	116.0	116.9	118.0	119.8	127.4	126.3	130.0	50.3	59.6	120.0	9.3	1572.3	0.6350	0.50
90.2	119.6	116.5	116.2	116.9	119.0	120.0	127.6	126.4	130.2	50.2	59.6	120.1	9.4	1568.8	0.6374	0.57
90.3	119.6	116.5	116.2	117.0	119.1	120.1	127.7	126.4	130.2	50.3	59.7	120.2	9.4	1569.0	0.6374	0.83
90.3	119.7	116.5	116.2	117.0	118.1	120.1	127.7	126.5	130.2	50.3	59.6	120.2	9.4	1567.4	0.6330	1.11
90.3	119.7	116.6	116.3	117.1	118.2	120.1	127.8	126.6	130.3	50.2	59.6	120.3	9.4	1564.3	0.6393	1.21
90.4	119.8	116.7	116.3	117.1	119.2	120.2	127.9	126.7	130.4	50.3	59.7	120.4	9.4	1565.6	0.6397	1.46
90.4	119.9	116.7	116.4	117.2	119.3	120.4	127.9	126.7	130.4	50.2	59.7	120.4	9.5	1563.0	0.6398	2.05
90.4	120.0	116.9	116.5	117.4	119.4	120.4	128.1	126.8	130.5	50.3	59.7	120.5	9.4	1561.5	0.6404	2.15
90.5	120.1	116.9	116.5	117.4	118.4	120.5	128.2	126.8	130.6	50.3	59.8	120.6	9.5	1560.7	0.6407	2.25
90.6	120.2	117.2	116.9	117.7	119.6	120.9	128.4	127.0	130.8	50.3	59.7	120.8	9.4	1554.3	0.6434	2.27
90.5	120.1	117.0	116.6	117.4	118.4	120.6	128.2	126.9	130.6	50.2	59.8	120.6	9.5	1559.6	0.6412	2.37
90.5	120.1	117.1	116.8	117.5	118.4	120.7	128.0	126.9	130.7	50.2	59.7	120.7	9.5	1557.5	0.6421	2.45
90.5	120.2	117.0	116.7	117.5	118.5	120.6	128.1	126.9	130.7	50.3	59.8	120.7	9.5	1558.1	0.6418	2.50
90.4	120.0	116.9	116.5	117.3	118.3	120.5	128.1	126.8	130.7	50.3	59.7	120.6	9.4	1561.2	0.6405	2.70
90.3	120.0	116.7	116.3	117.2	118.2	120.3	128.0	126.6	130.5	50.3	59.7	120.4	9.4	1563.9	0.6394	3.01

ELECTRON MICROPROBE RESULTS



A) Absorbed Electron Image

This image was taken using inversed electron current. This is similar to the image produced below using back scattered electrons. Contrast between the different areas clearly defines the three regions.

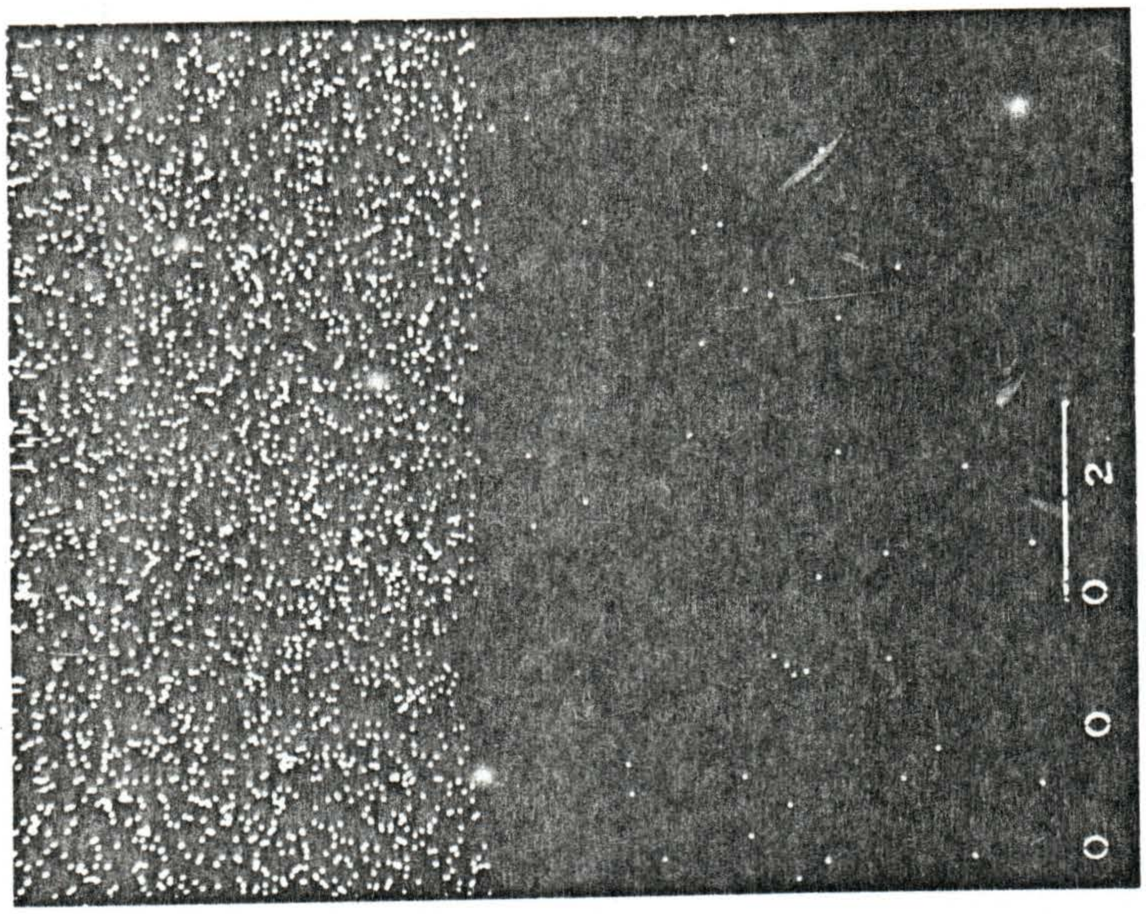
1) The Pipe Wall
2) Fouling Deposit and
3) Mounting Resin

1) Pipe wall   2) Deposit   3) Plastic

B) Secondary Electron Image

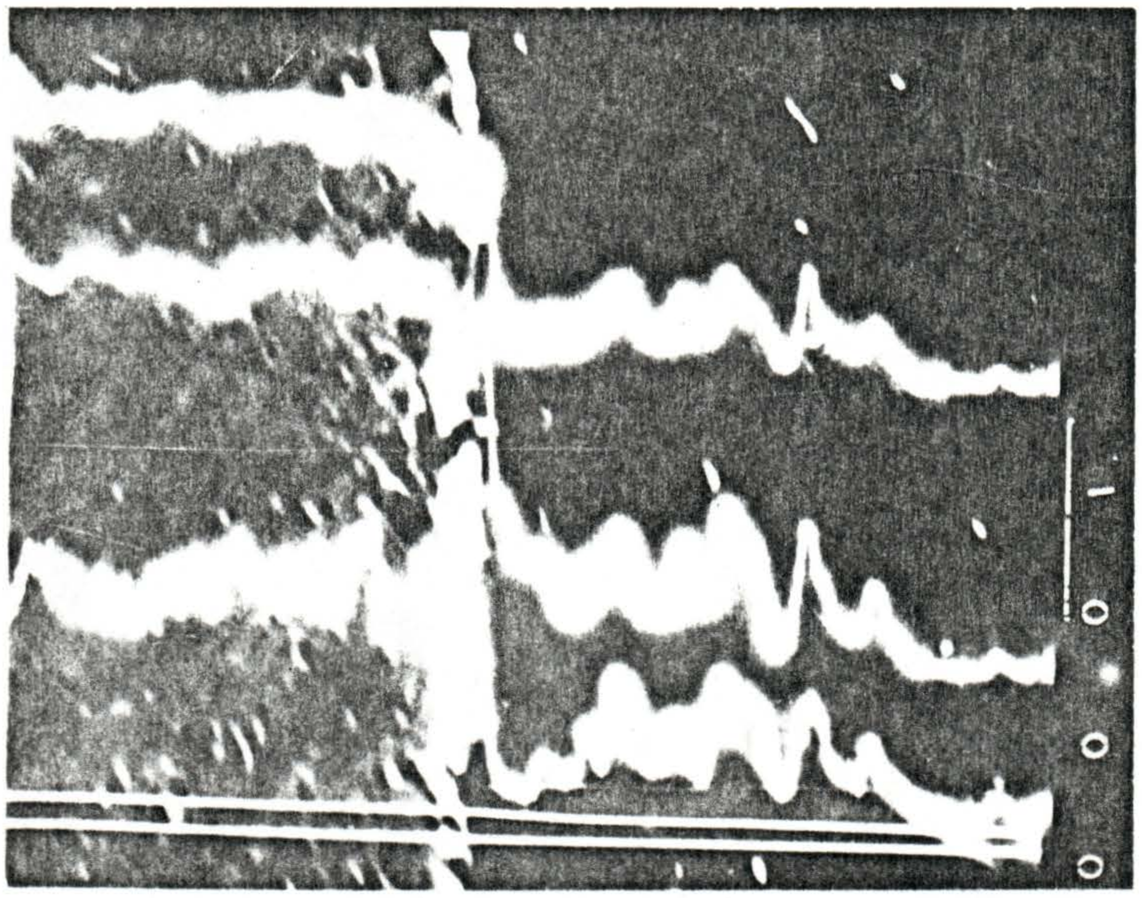
Secondary electron image of the fouled tube sample. Note the lack of contrast between the three areas compared to the absorbed election image above.

1) Pipe wall   2) Deposit   3) Plastic



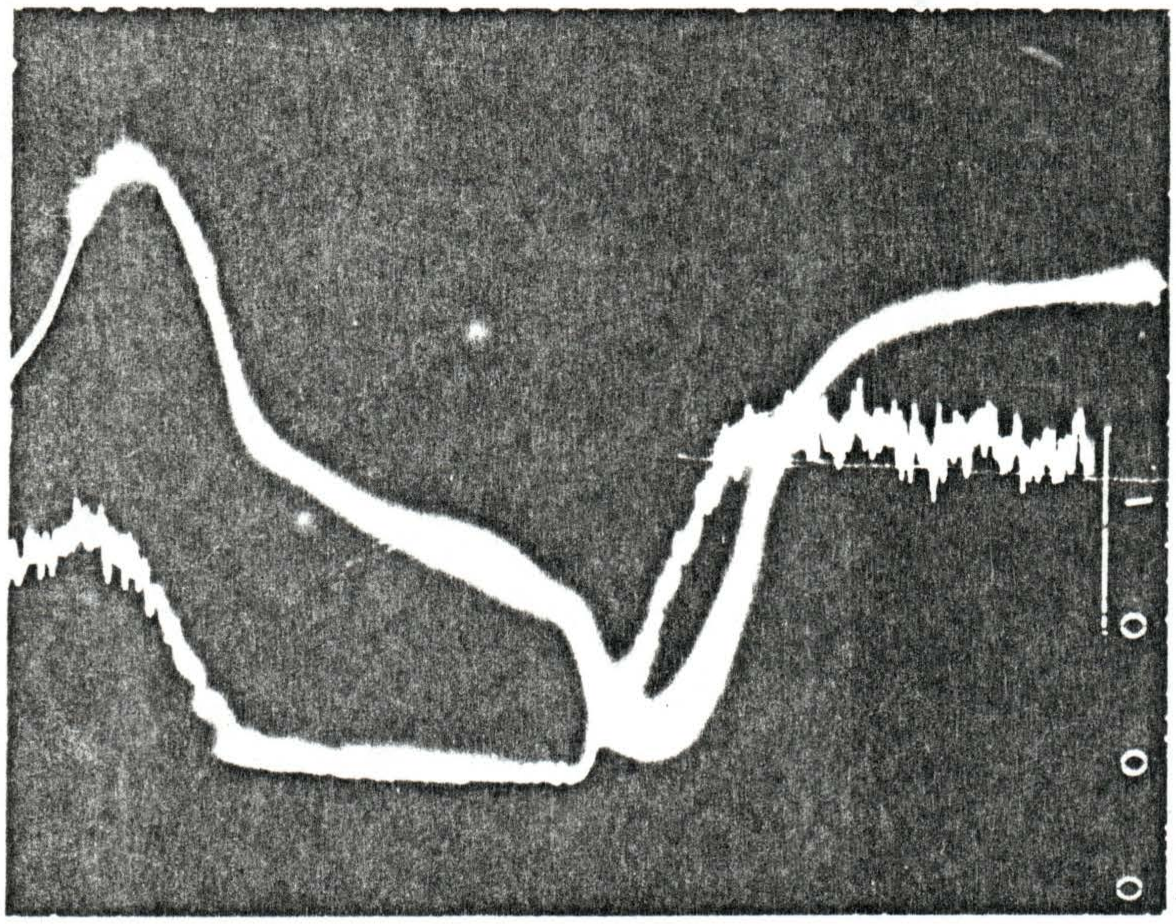
C) X-Ray Intensity Distribution

X-ray Scan for Chromium over the deposit area. Image shows absence of Chromium in this particular location.



D) X-Ray Line Scan

Image is a multiple exposure of line scans for Fe, Cr and Ni across the three regions. Relative compositions can be roughly determined. Note the smaller drop off for Fe going from metal to deposit than for Cr and Ni.



E) X-Ray and Backscatter Line Scan

This is a double exposure of the line scans over the same area as the previous image. The topography scan is a type of backscatter image where the signal is dependent upon changes in topology.

COULTER COUNTER® Model T & T_A Worksheet

SAMPLE Ferric Oxide (Aqueous Suspension)								
ELECTROLYTE	DISPERSANT							
EQUIPMENT SERIAL	Aper. Dia.	Ser. No.	CALIBRATION DATA	Part. Dia.	W	± I A	A	
ORGANIZATION	100μ		Polystyrene	9.69	9		190	
OPERATOR DATE								
Samples of fouling fluid taken before								
and after a fouling run.								

$$k = d\sqrt[3]{\frac{2^{w}}{A}}$$

FOR MODEL T

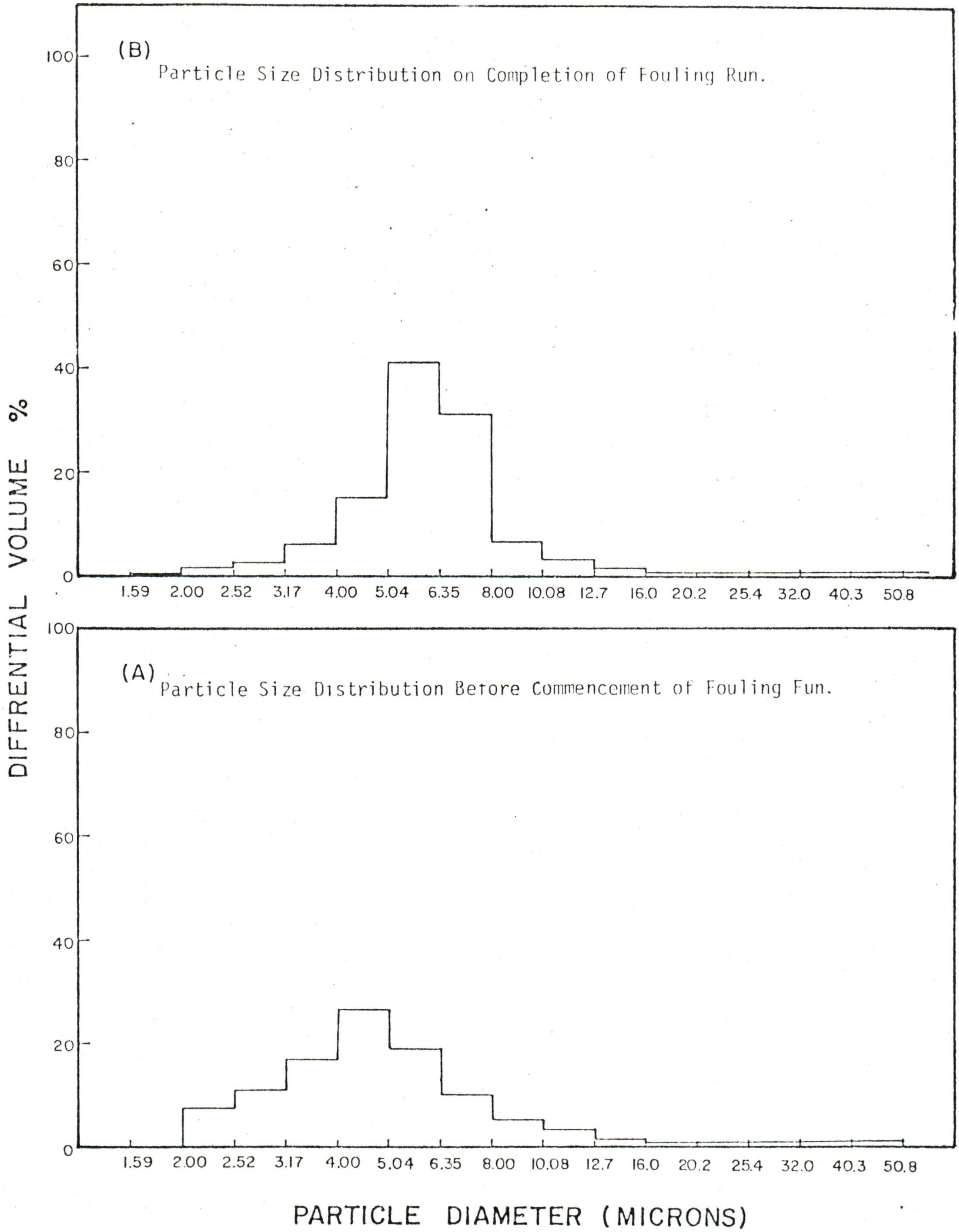
± I A	4.2	4.2
CALIB. A	190	322
APERTURE DIA.	100	100

$\frac{A_2}{A_1} \cdot (\frac{d_2}{d_1})^3\ 2^{(W_2\ W_1)}$ For Model T

$\frac{A_2}{A_1}\ (\frac{d_1}{d_2})^3\ 2^{(W_2\ W_1)}$ For Model T_A

SAMPLE DATA

Geometric Mean μ^3	Volume μ^3	Diameter μ	Channel (W)	DIFFERENTIAL VOL. % A (BEFORE)	B (AFTER)
.00575	.004091	.198			
.0115	.008181	.250			
.0231	.01636	.315			
.0462	.03272	.397			
.0925	.06545	.500			
.1851	.1309	.630			
.3702	.2618	.794			
.7405	.5236	1.00			
1.481	1.047	1.26			
2.962	2.094	1.59	1	0	0.4
5.924	4.189	2.00	2	7.5	1.5
11.85	8.378	2.52	3	11.1	2.4
23.70	16.76	3.17	4	16.8	5.8
47.39	33.51	4.00	5	25.6	15.1
94.78	67.02	5.04	6	19.1	40.6
189.6	134.0	6.35	7	10.0	31.4
379.1	268.1	8.00	8	4.8	6.5
758.3	536.2	10.08	9	2.7	3.0
1516.	1072.	12.7	10	1.2	1.2
3033.	2145.	16.0	11	.50	0.6
6066.	4289.	20.2	12	.20	0.5
12.13×10^3	8579.	25.4	13	.10	0.5
24.27×10^3	17.16×10^3	32.0	14	.05	0.5
48.54×10^3	34.31×10^3	40.3	15	.05	0.6
97.18×10^3	68.63×10^3	50.8	16	.05	0.5
194.4×10^3	137.3×10^3	64.0			
388.7×10^3	274.5×10^3	80.6			
777.4×10^3	549.0×10^3	101.6			
1.555×10^6	1.098×10^6	128.			
3.109×10^6	2.196×10^6	161.			
6.219×10^6	4.392×10^6	203.			
12.44×10^6	8.784×10^6	256.			
24.88×10^6	17.57×10^6	322.			
49.75×10^6	35.14×10^6	406.			
99.50×10^6	70.27×10^6	512.			
199.0×10^6	140.6×10^6	645.			
398.0×10^6	281.1×10^6	812.			
796.0×10^6	562.2×10^6	1024.			


(B)
Particle Size Distribution on Completion of Fouling Run.
(A)
Particle Size Distribution Before Commencement of Fouling Fun.
DIFFRENTIAL VOLUME %
0
20
40
60
80
100
1.59 2.00 2.52 3.17 4.00 5.04 6.35 8.00 10.08 12.7 16.0 20.2 25.4 32.0 40.3 50.8
PARTICLE DIAMETER (MICRONS)

COULTER COUNTER® Model T & T_A Worksheet

SAMPLE Ferric Oxide (Aqueous Suspension)

ELECTROLYTE | DISPERSANT

EQUIPMENT	SERIAL	Aper. Dia.	Ser. No.	CALIBRATION DATA	Part. Dia.	W	± I A	A
ORGANIZATION		100μ		Polystyrene	9.69	9		190
OPERATOR	DATE							
Samples of fouling fluid taken every								
½ hr. during a run.								

$$k = d\sqrt[3]{\frac{2^w}{A}}$$

FOR MODEL T

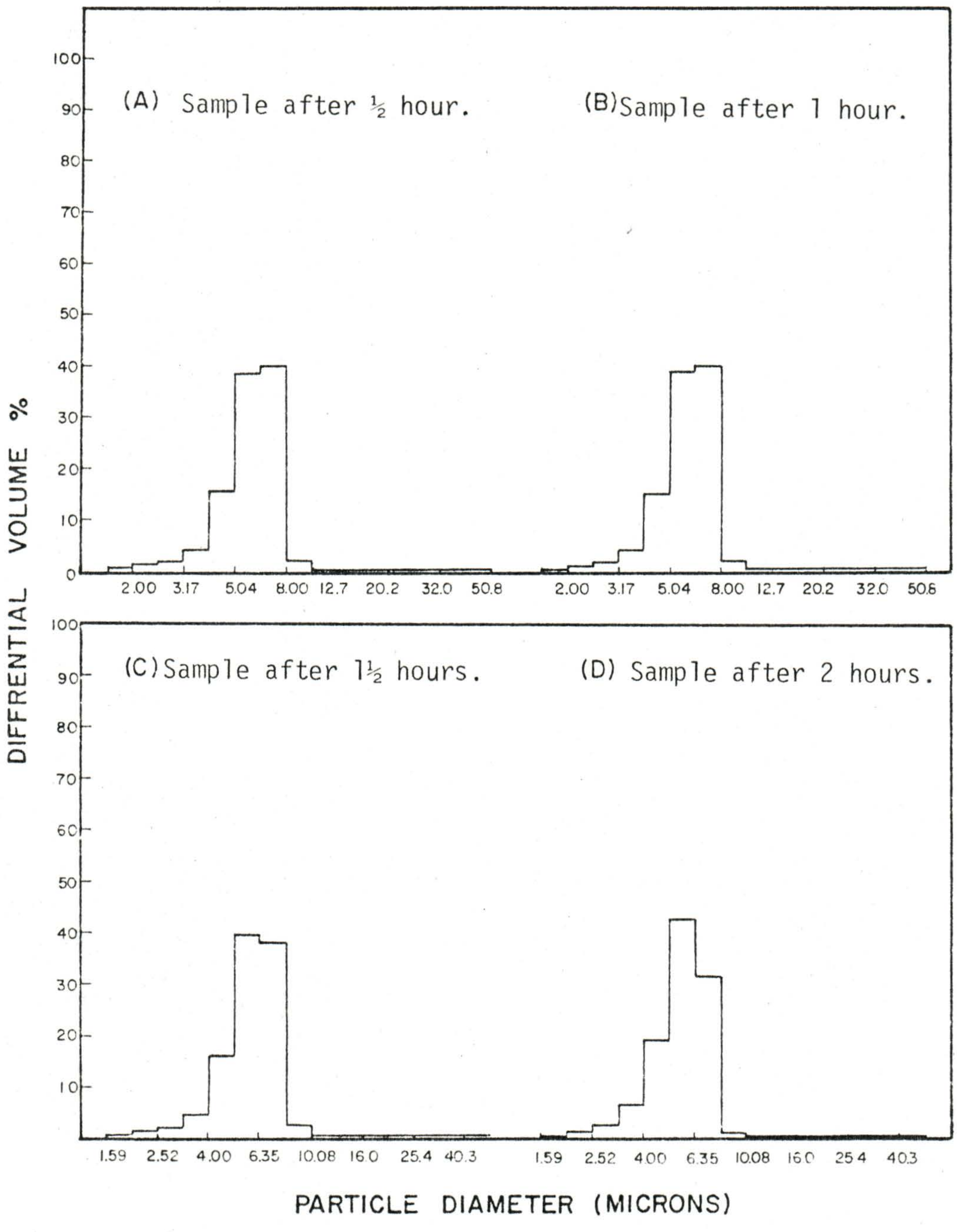
± I A	4.2	4.2		
CALIB. A	190	322		
APERTURE DIA.	100	100		

$\frac{A_2}{A_1}\left(\frac{d_2}{d_1}\right)^3 2^{(W_2-W_1)}$ For Model T

$\frac{A_2}{A_1}\left(\frac{d_1}{d_2}\right)^3 2^{(W_2-W_1)}$ For Model T_A

SAMPLE DATA

Geometric Mean μ^3	Volume μ^3	Diameter μ	Channel (W)				DIFFERENTIAL VOL. % A	B	C	D	
.00575	.004091	.198									
.0115	.008181	.250									
.0231	.01636	.315									
.0462	.03272	.397									
.0925	.06545	.500									
.1851	.1309	.630									
.3702	.2618	.794									
.7405	.5236	1.00									
1.481	1.047	1.26									
2.962	2.094	1.59	1				0.4	0.4	0.4	0.4	
5.924	4.189	2.00	2				1.2	1.3	1.2	1.5	
11.85	8.378	2.52	3				1.9	1.7	2.0	2.4	
23.70	16.76	3.17	4				4.2	4.5	4.4	5.8	
47.39	33.51	4.00	5				15.6	15.9	15.8	17.1	
94.78	67.02	5.04	6				38.5	39.1	39.5	42.6	
189.6	134.0	6.35	7				39.8	39.0	38.8	31.4	
379.1	268.1	8.00	8				2.4	2.2	2.4	4.5	
758.3	536.2	10.08	9				0.5	0.5	0.5	1.0	
1516.	1072.	12.7	10				0.5	0.5	0.5	0.6	
3033.	2145.	16.0	11				0.5	0.5	0.5	0.5	
6066.	4289.	20.2	12				0.5	0.5	0.5	0.5	
12.13×10^3	8579.	25.4	13				0.4	0.5	0.5	0.6	
24.27×10^3	17.16×10^3	32.0	14				0.4	0.5	0.5	0.6	
48.54×10^3	34.31×10^3	40.3	15				0.4	0.5	0.5	0.5	
97.18×10^3	68.63×10^3	50.8	16				0.4	0.5	0.5	0.5	
194.4×10^3	137.3×10^3	64.0									
388.7×10^3	274.5×10^3	80.6									
777.4×10^3	549.0×10^3	101.6									
1.555×10^6	1.098×10^6	128.									
3.109×10^6	2.196×10^6	161.									
6.219×10^6	4.392×10^6	203.									
12.44×10^6	8.784×10^6	256.									
24.88×10^6	17.57×10^6	322.									
49.75×10^6	35.14×10^6	406.									
99.50×10^6	70.27×10^6	512.									
199.0×10^6	140.6×10^6	645.									
398.0×10^6	281.1×10^6	812.									
796.0×10^6	562.2×10^6	1024.									



Particle Size Distribution of Ferric Oxide in Fouling Fluid Sample During a Run.