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EFFECTS OF THE COOLING SYSTEM PARAMETERS ON HEAT TRANSFER AND PERFORMANCE OF THE PAFC STACK DURING TRANSIENT OPERATION

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EFFECTS OF THE COOLING SYSTEM PARAMETERS ON HEAT TRANSFER AND PERFORMANCE OF THE PAFC STACK DURING TRANSIENT OPERATION

RABI M. J. RIDHA

ABSTRACT

An experimental investigation for the effects of transient operation of a phosphoric acid fuel-cell stack on heat transfer and temperature distribution in the electrodes has been conducted.

The proposed work utilized the experimental setup with modifications, which was designed and constructed under NASA Contract No. NCC-3-17(5). The experimental results obtained from this investigation and the mathematical model obtained under NASA Contract No. NCC3-17(4) after modifications, were utilized to develop mathematical models for transient heat transfer coefficient and temperature distribution in the electrode and to evaluate the performance of the cooling system under unsteady state conditions. The empirical formulas developed were then implemented to modifying the developed computer code.

Two incompressible coolants were used to study experimentally the effect of the thermophysical properties of the coolants on the transient heat transfer coefficient and the thermal contact resistance during start-up and shut-down processes. Coolant mass flow rates were verified from 16 to 88.2 Kg/hr during the transient process when the electrical

power supply was gradually increased or decreased in the range (0 to 3000 W/m^2). The effect of the thermal contact resistance with a range of stack pressure from 0 to 3500 KPa was studied.

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LIST OF SYMBOLS

A = Area

C_p = Heat Capacity

D = Diameter

E = Voltage

E.E. = Electrical energy rate per unit area

h = Heat transfer coefficient

K = Thermal conductivity

K_c = Cooling fluid thermal conductivity

$\dot{m}$ = Mass flow rate

Q = Heat transfer rate

Q/A = Heat flux

λ = Constant

θ = Constant

t = time

ΔT = Temperature differential

T_w = Wall temperature

T_∞ = Fluid temperature

$\frac{dT}{dx}$ = Temperature gradient

r = Thermal contact resistance, unless otherwise specified

T = Temperature

ρ = Density

Pr = Prandlt number

Re = Reynolds number

$\bar{V}$ = Overall heat transfer coefficient neglecting the thermal contact resistance

v = Velocity

$\dot{V}$ = Volumetric flow rate

ox = Length of element

η = Dynamic viscosity

γ = Kinematic viscosity

U = Overall heat transfer coefficient

u = Internal energy

α = Stack pressure constant

λ = Time constant

∂ = Flow constant

X = x-coordinate

Y = y-coordinate

P = Pressure

Nu = Nusselt number

Δx = Conduction thickness

CHAPTER I

INTRODUCTION

A phosphoric acid fuel cell power plant is an energy conversion system that can efficiently utilize different hydrogen rich fossil fuels, reduce emission of harmful chemicals, and offer a very economical co-generation system. Therefore, fuel cell system analysis efforts concerned with different systems design and operational criteria are essential for design optimization to improve system performance and cost effectiveness.

1.1 Fuel Cells

A fuel cell is defined as an electrochemical device which can continuously convert the chemical energy of hydrogen fuels and oxidant to electrical energy. Most of the available fuel cells today are primary electrochemical cells, and generate electrical energy in a similar way as the conventional primary cells, such as the very commonly used zinc-manganese dioxide battery. However it should be noticed that the process of galvanic oxidation that actually causes the production of electrical energy in fuel cells and, which resembles the process that produces energy in conventional primary storage batteries, is continuous. That is, mainly due to the fact that the construction of fuel cells permits continuous feed of reactants and continuous

product removal during the irreversible electrochemical oxidation process. Therefore, different design and engineering from that found in the conventional primary storage batteries are required in the case of fuel cells because of that continuous operation. In addition, the fuel cell chemical reactions always involve chemisorption and catalytic processes.

Basically the phosphoric-acid fuel cell system consists of two electrodes, cathode (positive electrode) and anode (negative electrode), separated by an electrolyte. The electrolyte will serve as a medium to transmit ions. Hydrogen, the fuel, is supplied to the anode while oxygen, the oxidant from air, is supplied to the cathode. Utilizing a catalyst on the anode causes the disassociation of the hydrogen molecules (H_2) into hydrogen ions and electrons. Then the hydrogen ions travel through the electrolyte to the cathode and react with electrons supplied by an external circuit load. The hydrogen atoms react with oxygen to form water. This process can be summarized for a H_2-O_2 fuel cell as follows (see Figure 1).

A. Anode Reaction:

$$H_2 \rightarrow 2H^+ + 2e-$$

B. Cathode Reaction:

$$1/2\ O_2 + 2H_2^+ + 2e- \rightarrow H_2O$$

C. The Control Volume Reaction:

$$H_2 + 1/2\ O_2 \rightarrow H_2O + Q + E.E.$$

where:

Q = thermal energy,

E.E. = electrical energy.

The anode reaction and the cathode reaction proceeds until a potential is established. This will bring the reaction into the equilibrium exhibited by the control volume reaction equation. Figure 2 shows the potential relations of a complete fuel cell. In general, the cell potential can be defined as:

$$\Delta E = E_{cathode} - E_{anode}$$

1.2 Fuel Cell Classification and Advantages of PAFC

There are several methods of classifying fuel cells, mainly according to their components and structure. An important classification of fuel cells is according to the used electrolyte. Essentially there are three types of fuel cells being developed to be a complete or a co-generation power plant; acid (A), molton carbonate (MC), and solid oxide fuel cells. These fuel cells are further distinguished by the temperature of operation classification.

Acid fuel cells utilize acid electrolytes because acids are tolerant to carbon dioxide which permits the use of hydrogen and oxygen with low purity. Phosphoric acid fuel cells are the most developed fuel cells, according to reference [1]. In addition, PFAC is economical to build and operate due to its simple design, (see Figure 3).

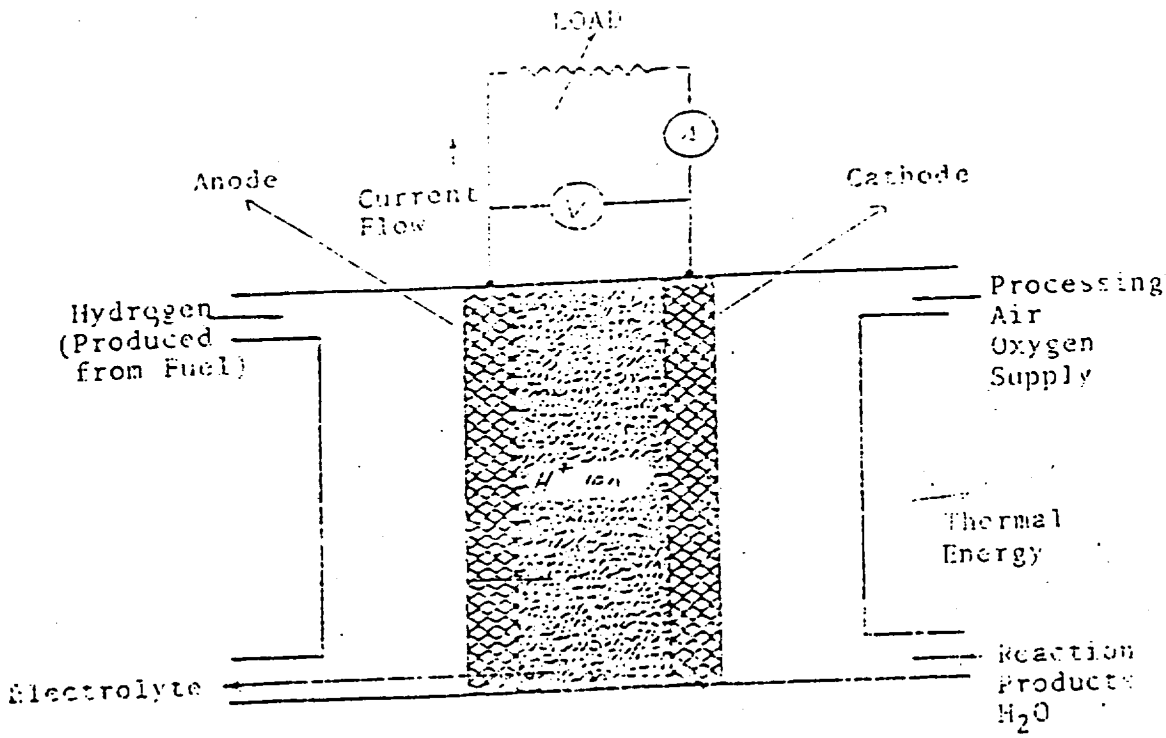


Figure 1. The Fuel Cell Concept.

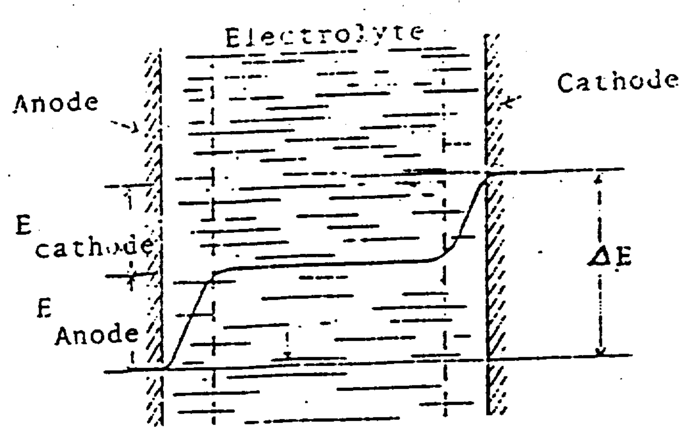


Figure 2. Potential of Fuel Cell

1.3 PAFC Systems

Figure 4 shows a diagram of a simple phosphoric acid fuel cell power plant. The plant consists of three major subsystems:

1.3.1 Fuel Processor: This subsystem consists of three components. The reformer which is a catalytic reactor with variable temperature that can reach 1200°C with a pressure of 10 atm. Double shift converters and heat exchangers will function in association with the reformer to consume fossil fuel such as natural gas, methanol and naphatha to produce hydrogen.

1.3.2 Fuel Cell Power Subsystem: Through this stage the Oxygen-Hydrogen reaction takes place and electrical energy, thermal energy and water will be the reaction products. The thermal energy generated is removed continuously by a cooling system to avoid the accumulation of heat which can cause high thermal stresses and electrode plate failures. This subsystem basically consists of several fuel-cell stacks. Cooling is provided to these models by arranging them in a sandwich configuration where the cooling plates surrounds a group

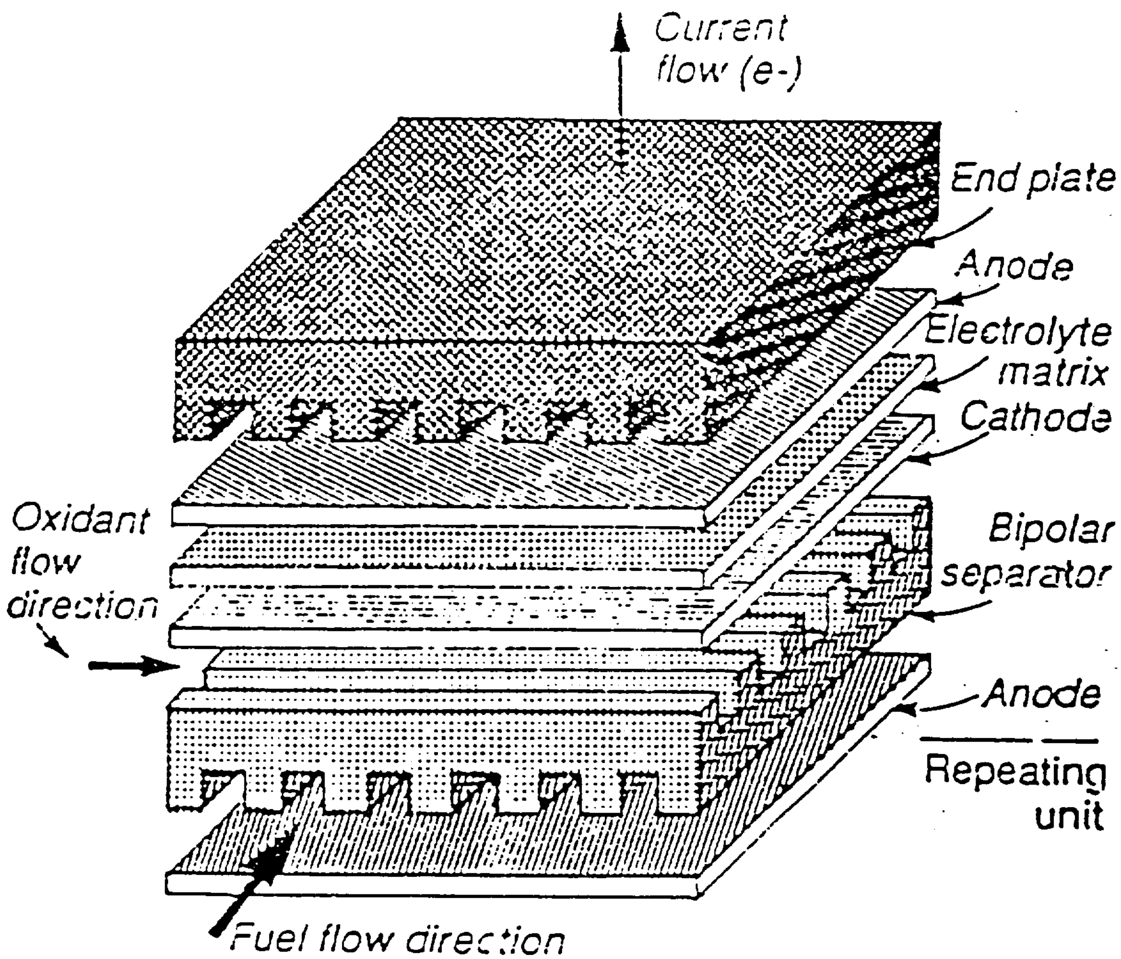


Figure 3. Principal of Operation of Fuel Cells in General. [Reference 16]

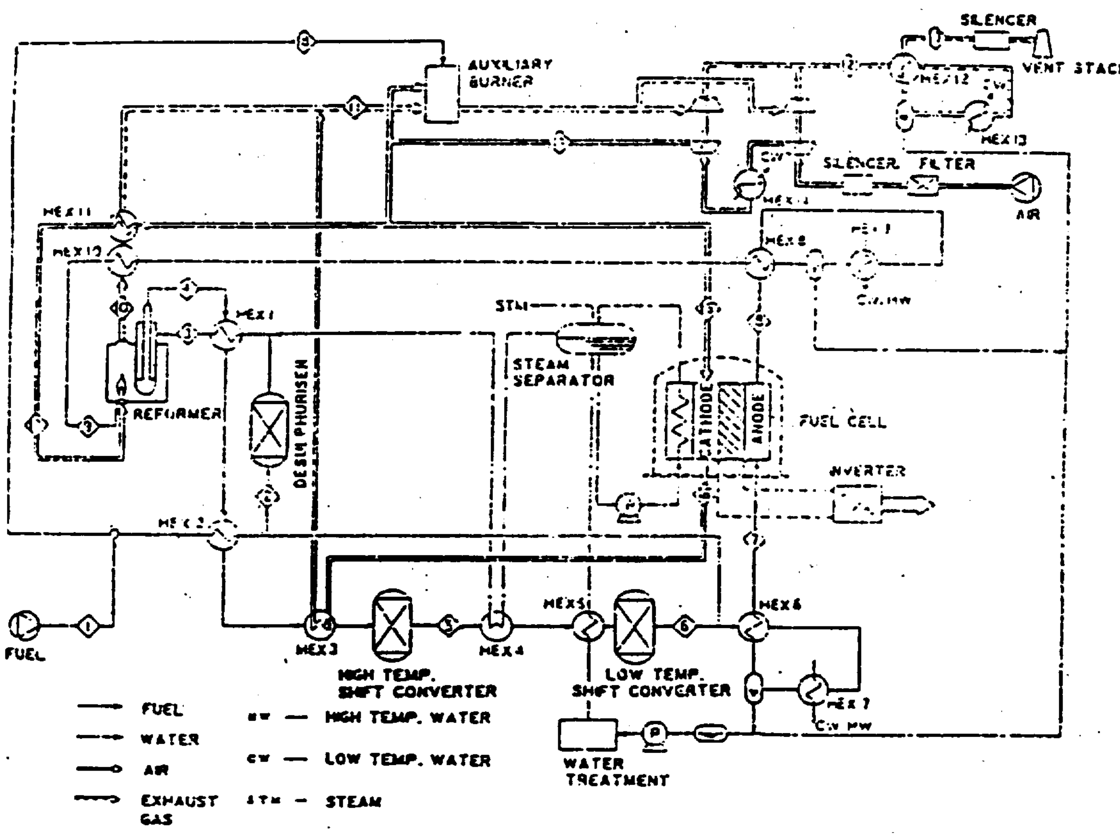


Figure 4. Process-Flow Chart for a (PAFC) Power Plant. [Reference 12]

than 8 hours. Plant control during COLD STARTUP will be manual.

1.4.2 WARM STARTUP

WARM STARTUP transient mode is defined as the plant transient from STANDBY to POWER. The plant will be designed for WARM STARTUP to the minimum POWER condition in a time interval of less than one hour. Plant control during WARM STARTUP will be either automatic or manual.

1.4.3 WARM SHUTDOWN

WARM SHUTDOWN transient mode is defined as the plant transient from POWER to STANDBY. The plant will be designed to complete a WARM SHUTDOWN from minimum power in a time interval of less than one hour. Plant control during WARM SHUTDOWN will be either automatic or manual.

1.4.4 COLD SHUTDOWN

COLD SHUTDOWN transient mode is defined as the plant transient from STANDBY to COLD STOP. The plant will be designed to complete a COLD SHUTDOWN in a time interval of less than 8 hours. Plant control during COLD SHUTDOWN will be manual only.

1.4.5 EMERGENCY SHUTDOWN

EMERGENCY SHUTDOWN transient mode is defined as the plant transient from a faulted condition during power operation to STANDBY. The plant will be designed to complete an EMERGENCY SHUTDOWN in a time interval of less than 1.5 hours; however, plant electrical power output will be disconnected from the utility transmission line in nearly 0.05 seconds. Plant control during EMERGENCY SHUTDOWN will be automatic only.

1.4.6 EMERGENCY STOP

EMERGENCY STOP is defined as the plant transient from a faulted condition during any plant operation or transient to COLD STOP. Plant control during EMERGENCY STOP will be automatic only.

The NASA Lewis Research Center, Fuel Cell Office,as the lead center for the PFAC Technology Program, has directed research and development efforts toward reducing cost, increasing life span, and improving performance and reliability of the fuel cell stack. In the technology area, some of the difficult problems that prevent the attainment of these goals are caused either by high temperatures at some regions of the electrode plate surface or by excessive temperature difference. While high temperature can cause corrosion of various components in the fuel cell module and excessive boiling and evaporation of the electrolyte, high temperature difference between various regions can produce thermal stresses that result in cracking or warping of the cathode and anode plates. These material problems can be especially compounded when the fuel-cell stack is subjected to sudden or gradual change of the electric output which is usually accompanied by a proportional change in the rate of flow of the heat generated. As a consequence, the fuel-cell module undergoes a finite volumetric expansion or reduction, depending on the change in the rate of heat generated. In turn, an increase or decrease of the volume of the stack will produce a proportional change in the clamping pressure which is used to hold the stack of fuel-cells and cooling plates together. However, the investigations, which were conducted under NASA Grant No. NCC 3-17(5) proved that a strong nonlinear functional relation exists between the clamped pressure and the overall heat transfer coefficient between the coolant and the electrode plates.

Thus, in addition to maintaining an almost uniform temperature on the electrode plates under steady state condition, the cooling system must make the necessary adjustments to cope with the compounded problem of changing the overall heat transfer coefficients and the rate of heat flow under unsteady state conditions. To achieve these tasks, accurate information concerning the nature of the functional relation between the stack clamped pressure and the overall heat transfer coefficient and the temperature distribution in the electrode plates, under unsteady state conditions, will be needed.

It should be noticed that previous work, under NASA Contract No. NCC 3-17(4), was directed to develop a computer model for the transient temperature distribution in the electrode plates and the fuel-cell stack. However, this contains various heat transfer coefficients that have not been experimentally determined and, thus, have not taken into consideration the effect of the thermal contact resistance which effect the performance of the (PAFC) performance dramatically.

CHAPTER II

LITERATURE REVIEW

Only limited information exists on phosphoric acid fuel cell temperature distribution, stack pressure effects, thermal stability and cooling requirement during transient operational conditions. Alkasab and Lu [1] studied the response of a phosphoric acid fuel-cell stack power plant. They developed a mathematical model to describe the mass and heat transfer rates. A Fortran computer code was developed utilizing the mathematical model to simulate the effect of the current density, cell-plate dimensions, and reactant flow rates, on the temperature distribution. Baker, et. al. [2,3] conducted intensive studies of electrochemical systems. A mathematical method was developed for both thick and thin stacks. The peak stack temperature was estimated for an isothermal wall case. Green's function was used to develop a formula to detect the non-uniformity of heat generation. Westinghouse [4,5] developed a simulation code which uses finite element analysis to calculate current-voltage characteristics, thermal energy generated and power as a function of the reactants' properties and the fuel-cell temperature distribution. Alkasab [6] et. al. investigated the performance of the PAFC model and succeeded in developing a thermodynamics model. Boyle [7] analyzed the heat transfer characteristics of the turbulent flow through serpentine passages. Buggy [8] conducted a feasibility study of using fuel-cells as commercial electric utilities. NASA [9,10] was heavily involved in several important researches concerning the performance of experimental PAFC under different transient operational conditions. In those studies, the efficiency of the cooling system was tested when separate gas, process gas and liquid cooling fluid are used. NASA [11] presented a comparison that considered the effect of different cooling systems on the performance, construction simplicity, reliability, thermal pollution, and cost of cooling subsystem and electrolyte cost. Two phase inter-cell cooling was tested by U.T.C. [12] for PAFC. The testing revealed the poor performance of that cooling system due to the need to protect the copper tubes in the corrosive acid environment which lead to dramatically reducing the convective and conductive heat transfer rates. Alkasab and Abdul-Aziz [13] conducted an experimental and analytical study of the effects of the cooling system perameters on the electrode heat transfer characteristics and investigated the stack pressure effect on the heat transferred by the coolant, the thermal efficiency, the thermal contact resistance and the effective temperature differential. The study revealed the dependence of the overall heat transfer coefficient and the thermal efficiency on the stack pressure for the different coolants and cooling system configuration used. Significant improvement in both the overall heat transfer coefficient and the thermal efficiency were noticed with higher stack pressure. Abelson [14] monitored the transient performance of a 200 kw PAFC plant and noticed that the equipment can respond rapidly to changes in the loads and efficiency is approximately constant as a function of demand in the interval 30% to 100% of the rated capacity.

Conway [15] considered PAFC researches in Europe and summarized the development achieved so far. The study concluded that PAFC as a co-generation system can be considered reliable for transient loading. Makansi [16] studied the feasibility of the concept of integrating power systems utilizing PAFC systems and PAFC units for residential applications. The results reported by the study predicts a steep decrease in the PAFC construction and operational costs of PAFC as a co-generation system using natural gas as a fuel. A time-dependent performance analysis of a 200 KW PAFC field test system at Hotel Plaza Oraka, Japan was presented by Singer et. al [12]. High efficiencies were noticed when the PAFC systems were compared to other co-generation systems especially when the combined cycle was used, i.e. the use of the generated heat. The transient efficiency change with a start-up process results are summarized in Figure 5.

Hart [51] presented a thermodynamic model to calculate the electrical and thermal energy generated due to the electrochemical reactions for different fuels and cell types.

White [36] studied the viscous laminar and turbulent internal flows. Karlekar and Desmond [37] analyzed heat transfer rates in different configurations of mixed and non-mixed heat exchangers and provided several mathematical models to calculate the effectiveness as a function of the heat exchanger design, flow rates and conductance of the components. Also, a complete convective and conductive heat transfer analysis was presented for different boundary conditions of flow over a flat plate and in tubes. In addition, several techniques to determine the heat transfer coefficient were discussed.

Several accurate methods are available currently to measure experimentally the convection heat transfer coefficient. One of the most accurate methods is to use electrically conducting wall coatings and sense the change in current intensity at different locations. Omega [66] employed carbon impregnated coating on plastic plates and gold vapor deposited on a polyester sheet. Bailey Control [67] utilized infra-red photos of the cooled plates to determine the transient heat transfer coefficient and temperature equilibrium. One of the less expensive and less accurate methods of measuring the local convective heat transfer coefficients is to employ electrically heated plates. The major source of error is the energy loss through radiation which is very difficult to evaluate as concluded by Hart [51]. In addition, electrically heated stainless steel foils with surface thermocouples were used to measure the transient change of local heat transfer coefficient in a wind tunnel by Boyle [7]. The major source of error again is the radiation heat transfer to the surroundings. An important experimental method used in heat exchangers to measure the heat transfer coefficient is to monitor the fluid temperature and volumetric flow rate and use this information to calculate the change in enthalpy. The only concern when using this method should be the possibility of disturbing the flow and accuracy of the flow meter used.

The imperfect contact between fuel-cell plates and cooling plates in the fuel-cell stack causes thermal resistance that depend upon the pressure imposed on the whole stack. This thermal resistance is called contact thermal resistance. As mentioned before, this parameter must be considered in the calculation of the fuel-cell heat transfer rate.

This important thermal resistance is due to the absence of perfect contact between any two conductive surfaces and the existence of air gaps. Therefore, not all the solid volume in contact is available and a undirectional heat flow away from the contact surfaces will exist.

The instantaneous thermal contact resistance parameter can be calculated using the Fourier equations away from the interference location. Alkasab and Abdul-Aziz [13] measured the steady-state temperature variation of the fuel cell plate at different thicknesses and at the fuel-cell plate cooling plate interferance. Brunont and Buckland [63] presented a study that demonstrates the effect of contact pressure and surface roughness on the value of the thermal contact resistance of cold rolled steel joints. The thermal contact resistance was found to decrease dramatically with reducing the surface roughness.

Pomerantrev [61] investigated the effect of thermal contact resistance on the heat flow and thermal stress in solids of revolution of arbitrary shapes. Barzely et. al. [64,65] analyzed the contribution of different metal combinations, using the same thicknesses, sample temperatures, heat flow direction and vertical pressure on the sample on the total value of the thermal contact resistance. The thermal contact resistance for a certain combination was found to increase with increasing the vertical pressure and depends heavily on the heat flow direction.

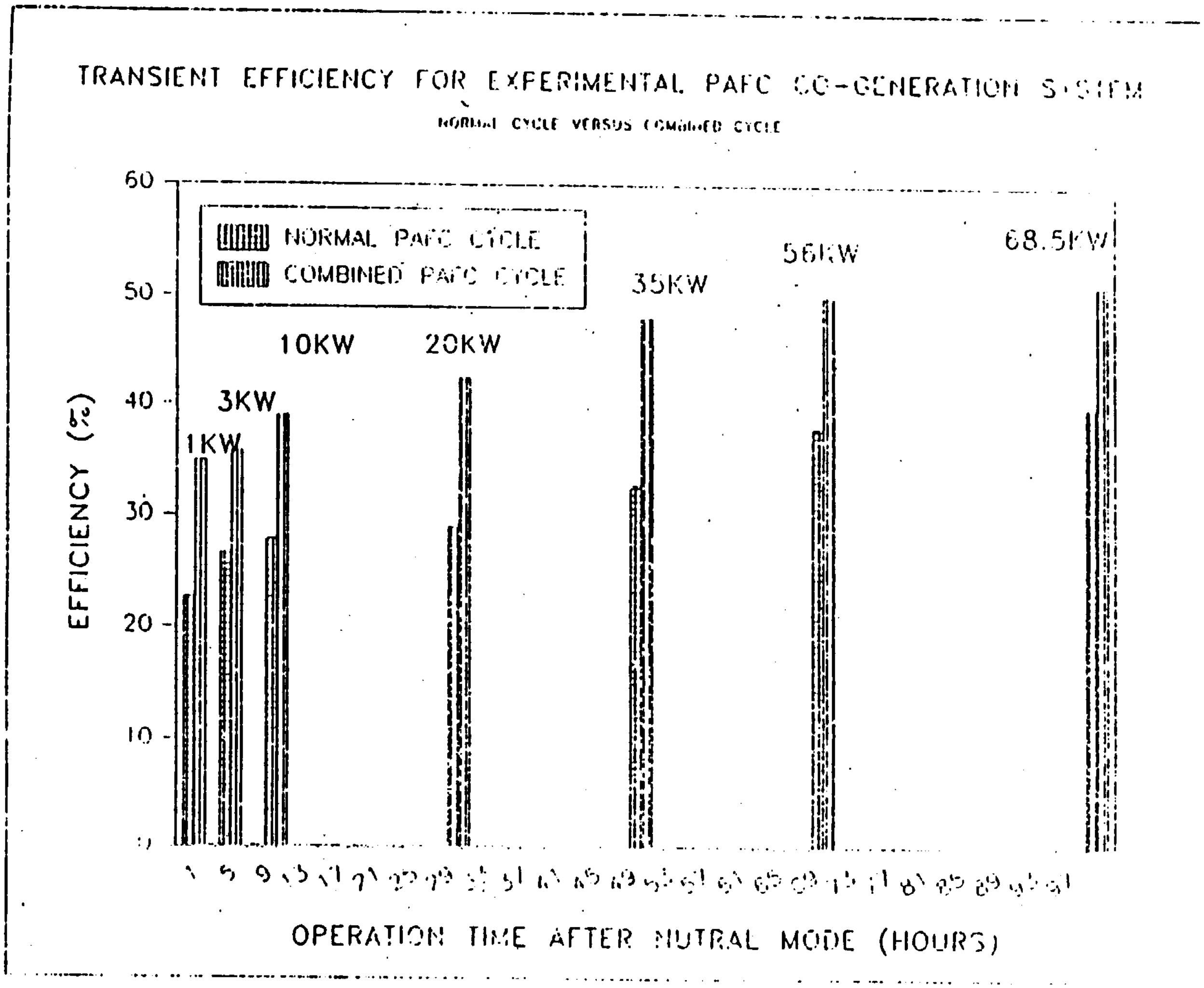


Figure 5. Transient Efficiency of an Experimental PAFC as a Co-generation System (Chart by Author).

CHAPTER III

EXPERIMENTAL SET-UP

In this chapter a summarized description of the experimental set-up used to generate the needed data and a brief procedural review will be presented.

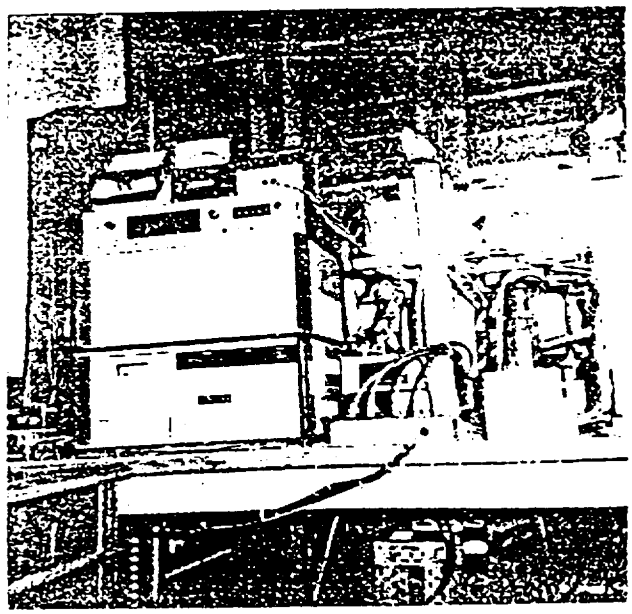
The experimental set-up, shown in Figure 6, consists of the following components:

1. Fuel-cell unit.
2. Special insulation
3. Power supply unit.
4. Cooling system.
5. Temperature measurement equipment.
6. Flow circulation and measurement equipment.
7. Data acquisition system.
8. Fuel cell stack pressure control and measurement equipment.

The experimental set-up components can be described as follows.

3.1 Fuel-Cell Unit

In order to simulate the heat generated by the chemical reaction inside the fuel cell during an actual transient operational condition of the PAFC, an electrical heat source, was placed inside the cell plate of the experimental



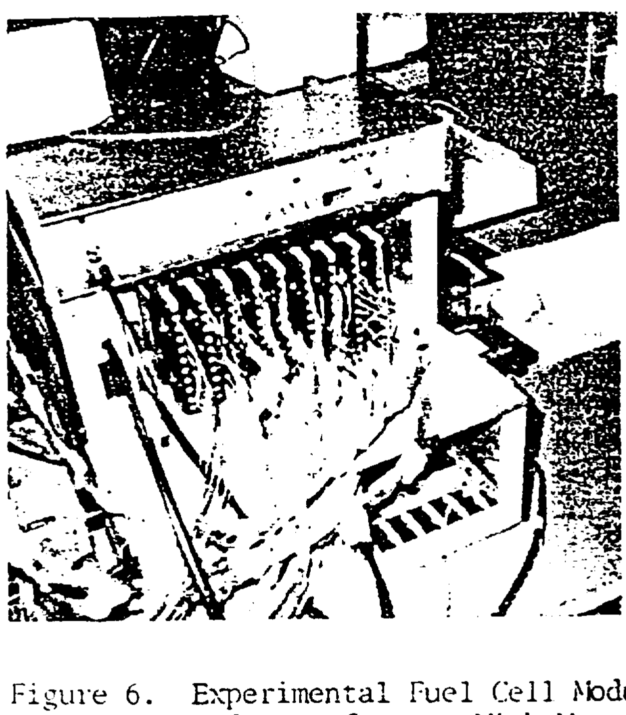


Figure 6. Experimental Fuel Cell Module and Interference With Measuring Equipment.

fuel cell model with the required power. The electrical heat source consists of four nickel-chromium alloy coils. The power provided to each coil can be controlled by changing the voltage across the coil.

The heating elements are sandwiched by the lower graphite plate, (o.3m x 0.41m x 9.5mm) and marinite plate from one side and the upper graphite plate (0.3m x 0.41m x 6.35mm) and a mica sheet from the other side. The marinite plate and the mica sheet were used basically to prevent any contact between the heating elements and the electrically conductive graphite plates. See Figure 7.

3.2 Power Supply Unit

The power supply unit has the ability to provide six independent variable subpower supplies. Also it can provide readings for the supplied voltage and amperage for each of those sources.

In order to measure accurately the voltage and amperage, a separate voltmeter and an ammeter were used at the interface of the power supply wires with the heating elements as shown in Figure 8. The energy level was simply calculated as follows:

$$P = I * E \quad (1)$$

$$E.E. = \frac{P}{A} \quad (2)$$

3.3 Special Insulation

The effect of heat losses from the control volume by

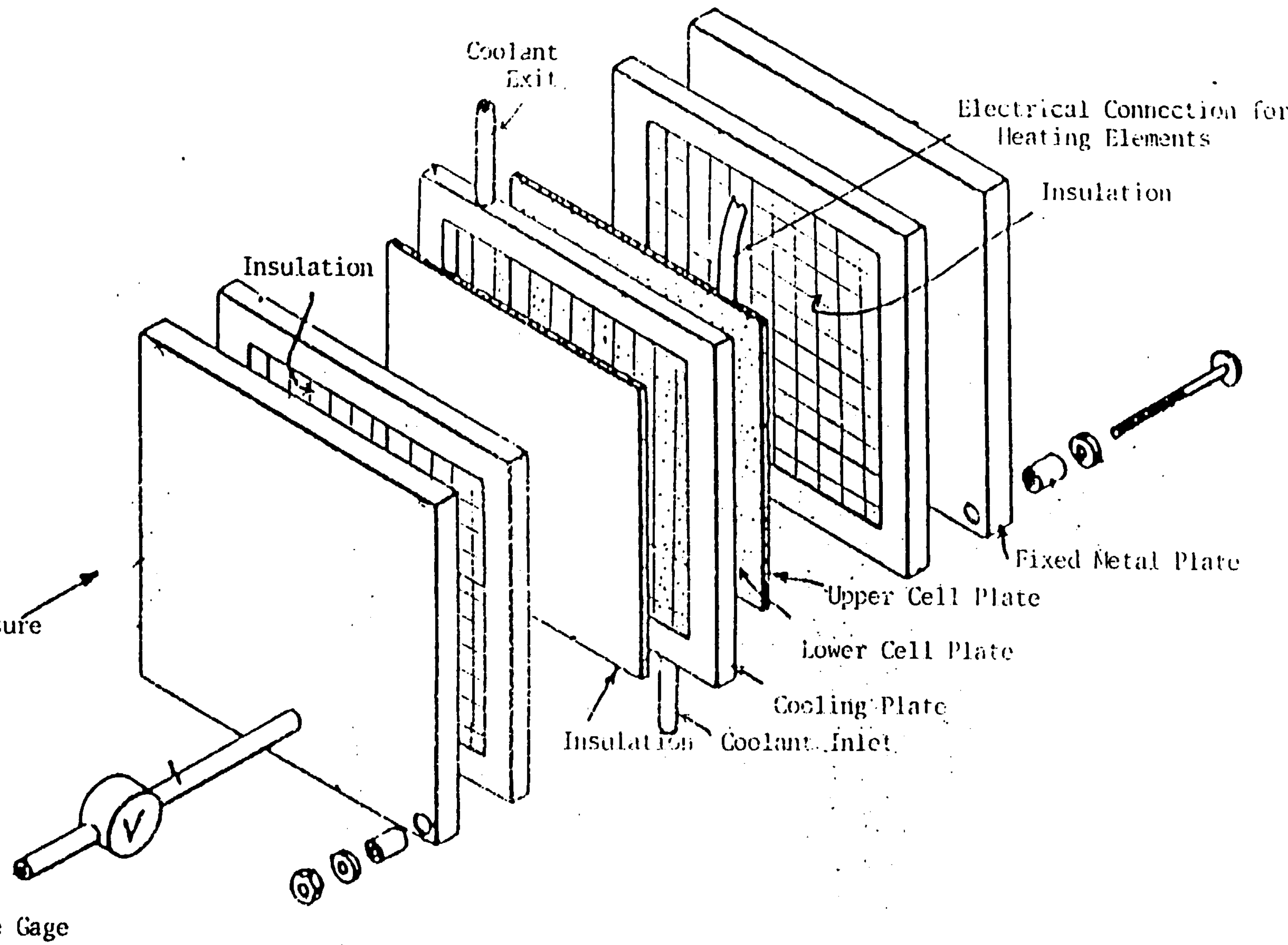
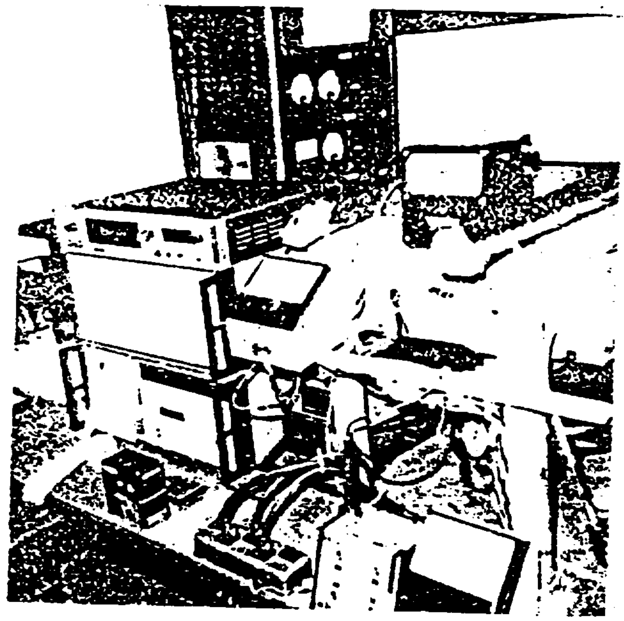


Figure 7 . Components of the Fuel Cell Module



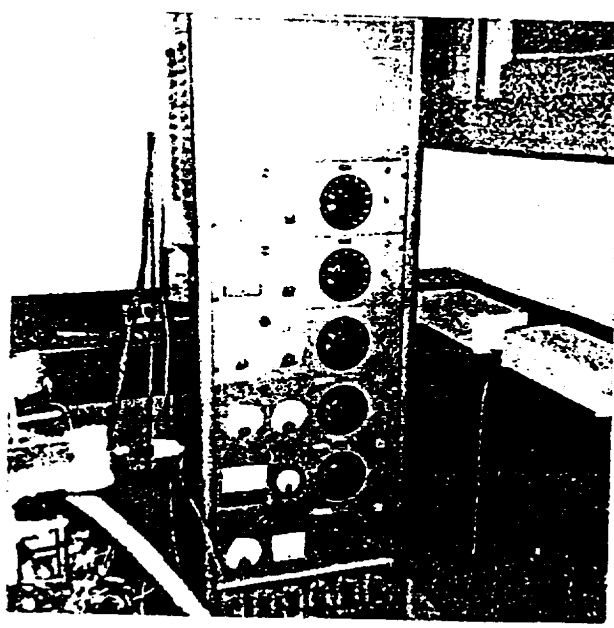


Figure 8. Power Supply to Fuel Cell Model.

radiation and convection was obvious on the accuracy of the gathered data. Therefore appropriate insulation was critically important to obtain acceptable results. Two Binder-Cement millboards were used above the upper graphite plate and below the cooling plate. Magnisa-85 insulation was used also to reduce heat losses above the upper millboard. Both of these insulations were used because of their ability to withstand high temperatures 300°C and above. Also all the clearences between the metal plates and the cell container walls were sealed by an insulation tape. In addition, insulation cement was used to seal any holes or clearence between the metal surfaces.

3.4 Cooling System

A serpentine cooling plate configuration was used for the removal of the generated heat, as shown in Figure 9. This configuration consists of a 9.5 mm in diameter copper tube sandwiched by the graphite plates. The required potential energy for the cooling fluid circulation was provided by a constant speed pump. A maximum flow rate of 5 gpm can be obtained. The complete water cooling system is shown in Figure 10 while the complete oil cooling system is shown in Figure 11. The different volumetric flow rates and in relation the different Reynolds number were provided by three adjustable valves that will extract some of the working fluid from the line entering the fuel-cell module.

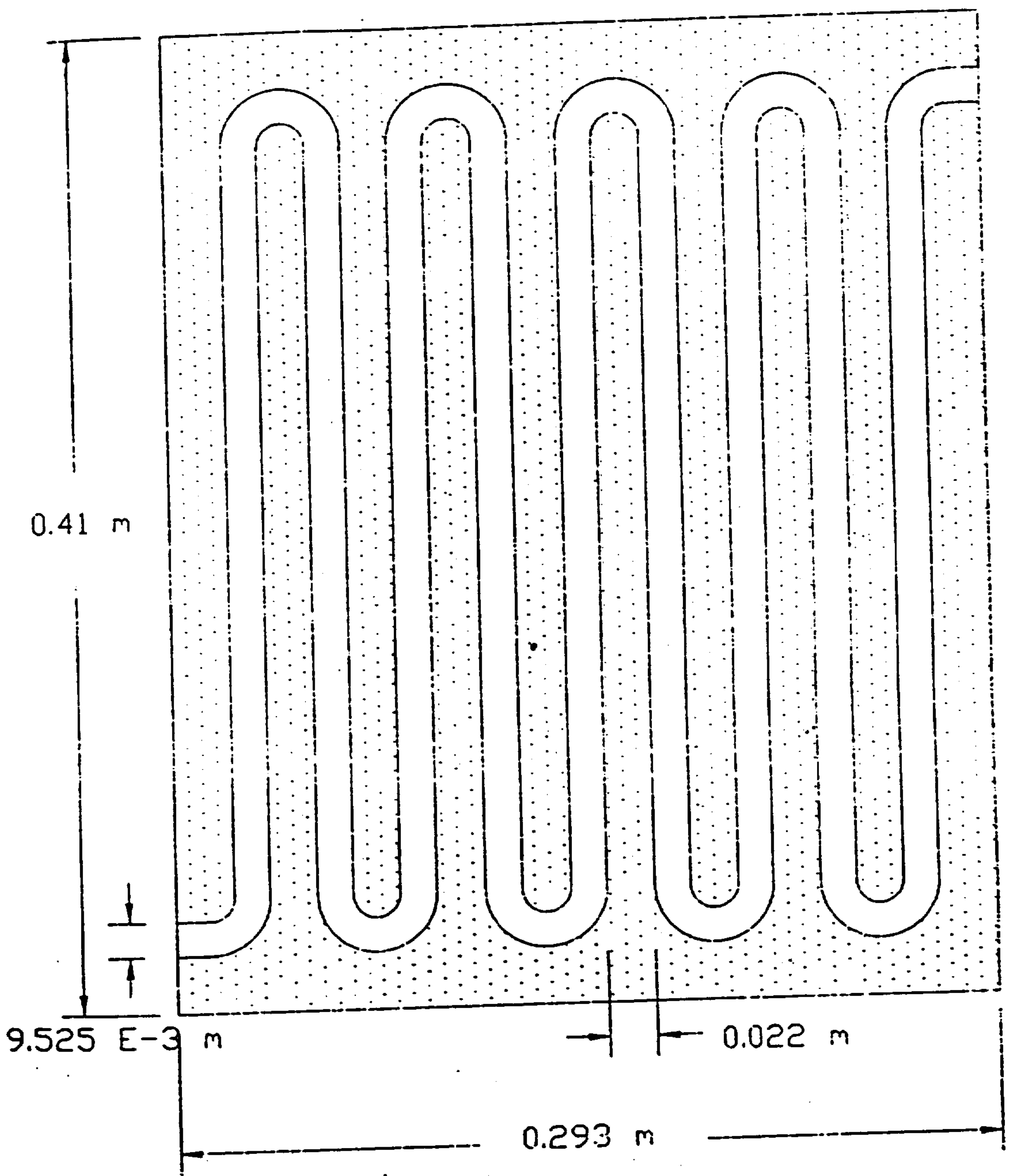


Figure 9. Serpentine Cooling Plate Dimensions

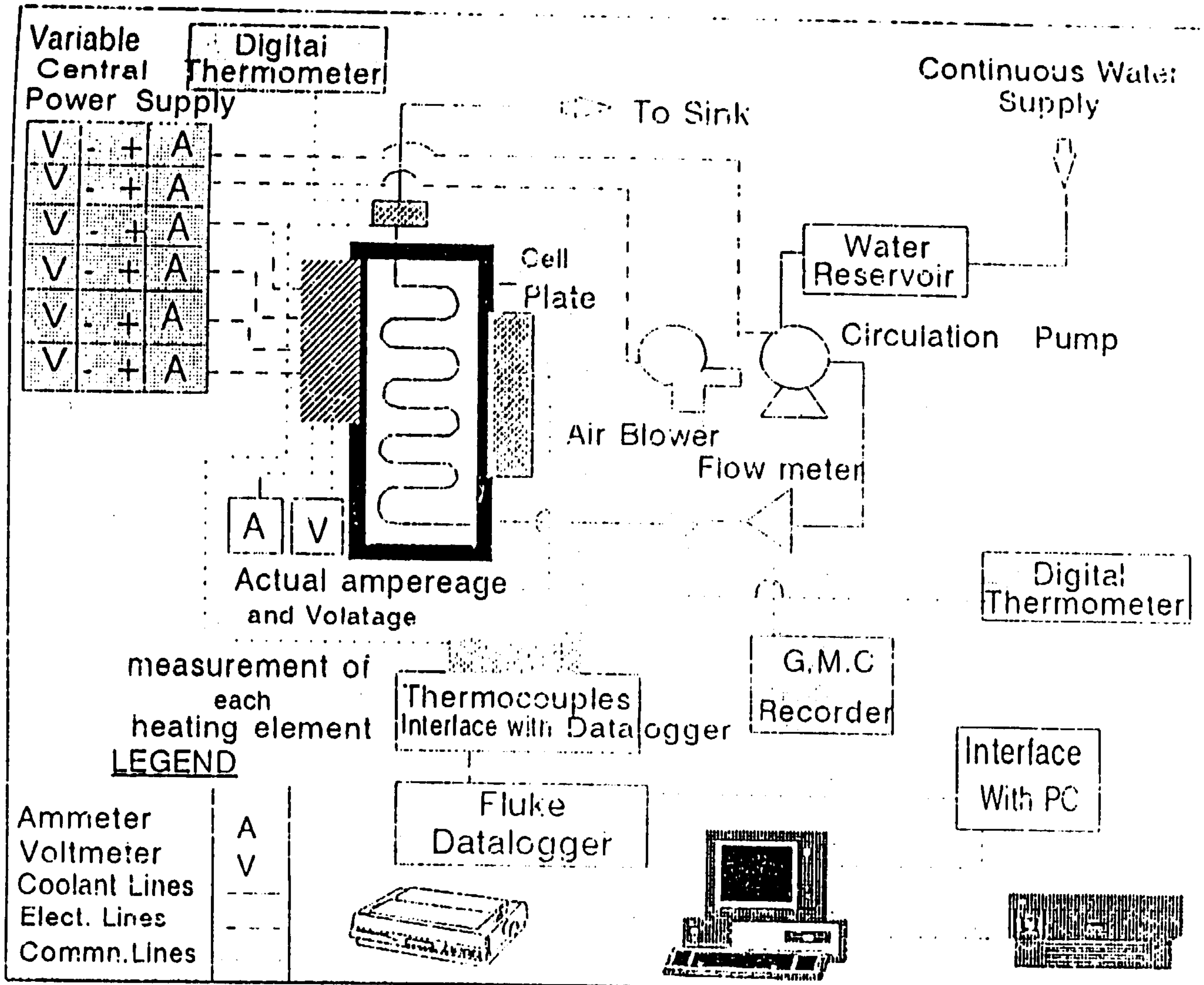


Figure 10. Layout of the Water Cooling System

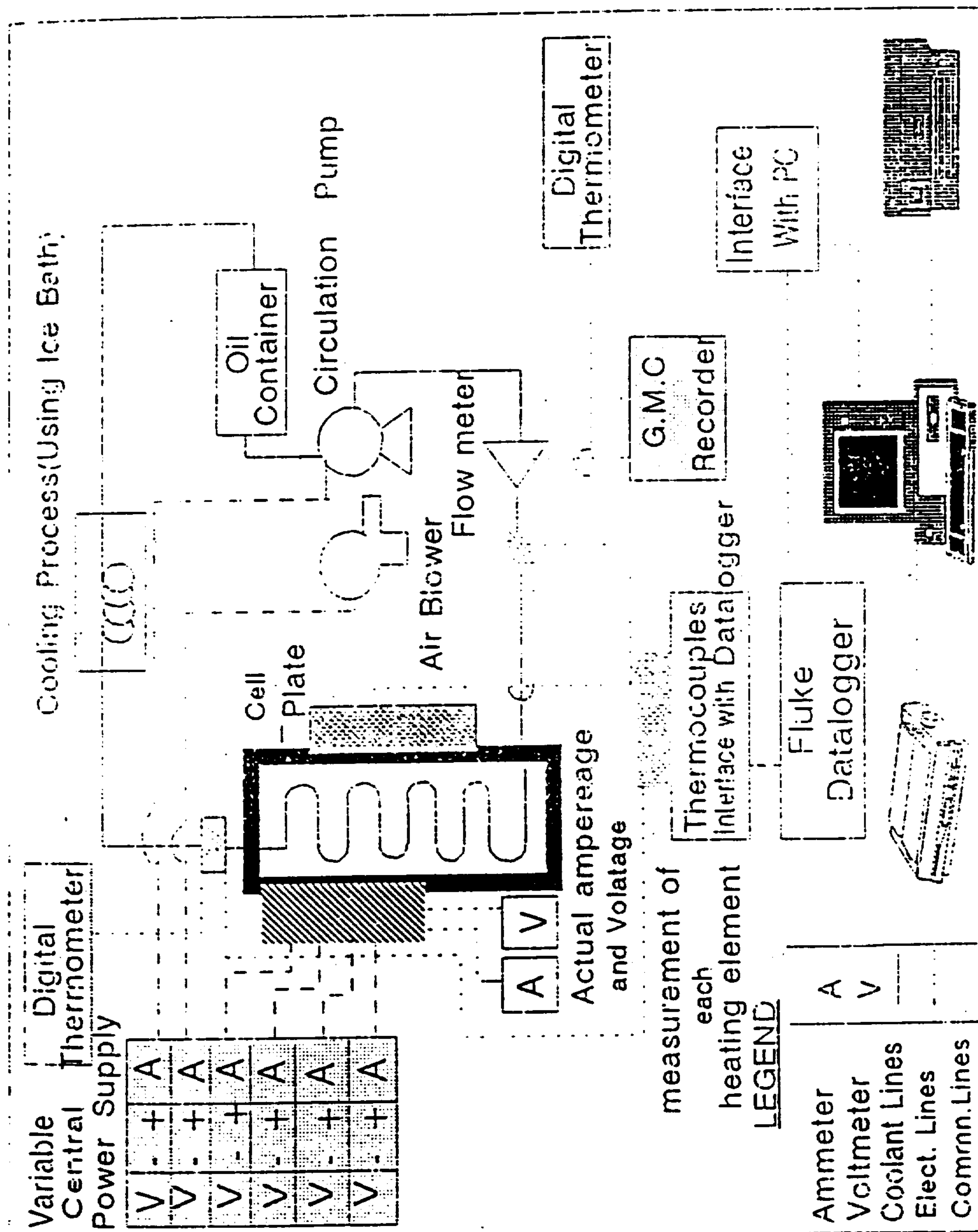


Figure 11. Layout of the Oil Cooling System

3.5 Temperature Measurement Equipment

0.25 mm diameter T-type thermocouples were used inside the fuel cell unit to monitor the temperature distribution. A Fluke (model 2201 A) scanner chassis and a Fluke (model 2200 B) data logger will serve as the data acquisition system. This reading can provide continuous logging of 100 temperature readings. The data logger was interfaced with a computer to monitor and record the following:

(a) The transient temperature distribution of the cell-plate.

(b) Temperature of the working fluid entering and leaving the fuel-cell module.

(c) Thermal contact resistance at the interface between the cell plate and the cooling plate.

3.6 Flow Measurement Equipment

The main flow rate can be read by using a flow meter and a turbine flow transducer. The second device has the ability to measure high temperature fluid flow, with high pressure with an accuracy of 0.4 gpm. This device was interfaced with the (MG Model 614A) counter to convert the frequency to digital readouts.

3.7. Data Acquisition System

An ARC (286 turbo) IBM compatible computer was used to monitor and record the time-dependent temperature profiles and the isotherm locations in conjunction with the coolant flow rate and power supplied to the heating element for the determined time intervals during a simulation of a start-up or a shut-down operation. This interface was used to produce the Figures of the instantaneous locations of the isotherms using a (h/p) plotter. Each isotherm was expressed with a certain color. The figures produced also contained the Reynolds number of the test, the electrical energy level, temperature tolerance of the isotherms shown, the time interval and type of the coolant working fluid. The time interval for recording and interpreting the experimental instantaneous data was approximately 3.5 seconds. This guaranteed an accurate input to the results' calculations.

3.8 Fuel Cell Stack Pressure Control and Measurement Equipment

The pressure applied on the PAFC was simulated by sandwiching the fuel cell plates and the cooling fluid plate between two metal plates and applying pressure on the bottom one while fixing the other using a four ton hydraulic jack, as shown in Figure 12.

3.9 Testing Procedure

Testing procedures for both incompressible fluids used was carried out as follows:

(A) **Water Coolant**: An open cooling system was used, a reservoir was filled continuously with water between 21°C and 25°C. Then the coolant was pumped through the fuel cell. At the beginning of the test (time = 0) the four heating elements were provided with 1500 W/m^2, the coolant circulation pump and

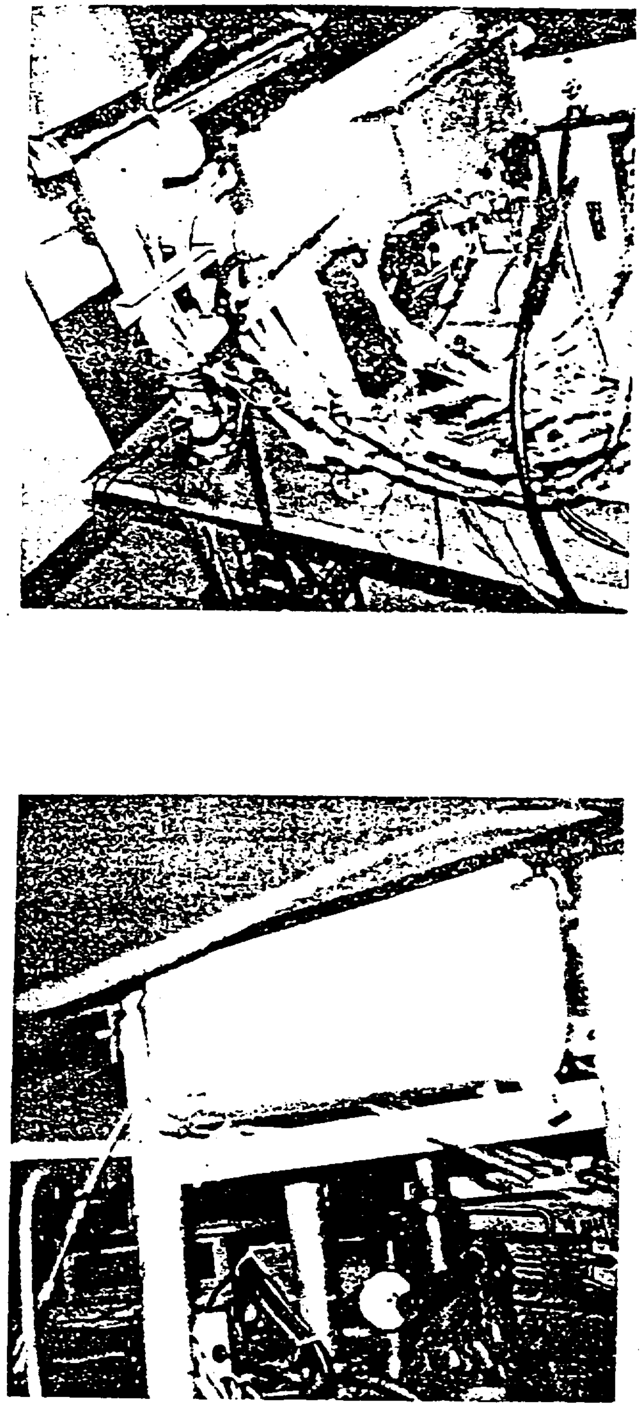


Figure 12. Fuel Cell Stack Pressurizing System.

valves, and the fuel cell stack pressure were adjusted for the test. An air blower was used to cool the circulation pump from overheating due to the long continuous runs. The power provided to the cell was gradually increased throughout the considered time intervals.

The temperature profile of the fuel cell was monitored and recorded continuously every one or five minutes. The figures produced provided instantaneous information about the fuel cell and the cooling system during the transient start-up process and through the shut-down process. Reynolds number for a whole test was kept constant throughout the two transient processes. Also, the pressure was kept constant during both processes. On the other hand, the power provided to the four heating elements were varied as follows to simulate the transient heat transfer process during start-up process and shut-down process. See Figure 13 and Figure 14.

1) Time intervals (1 through 2): the maximum power provided was 1500 W/m^2.
2) Time intervals (3 through 4): the maximum power provided was 2250 W/m^2.
3) Time interval (5 until reaching steady state): the maximum provided power was 3000 W/m^2.
4) Time intervals (steady state through 8): the minimum provided power was 2250 W/m^2.
5) Time intervals (9 through 10): the minimum provided power was 1500 W/m^2.

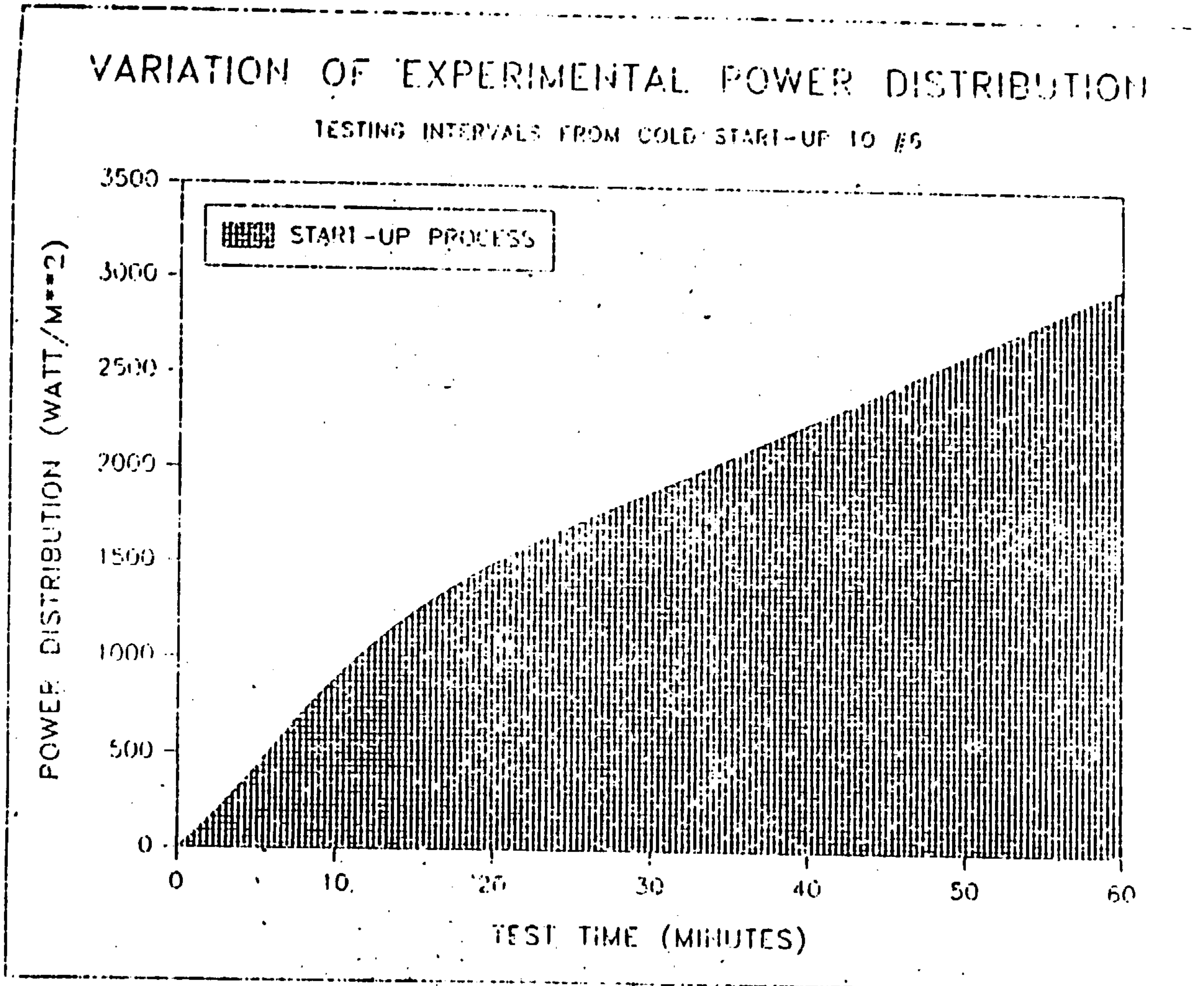


Figure 13. Experimental Power Distribution During the Considered Start-Up Processes.

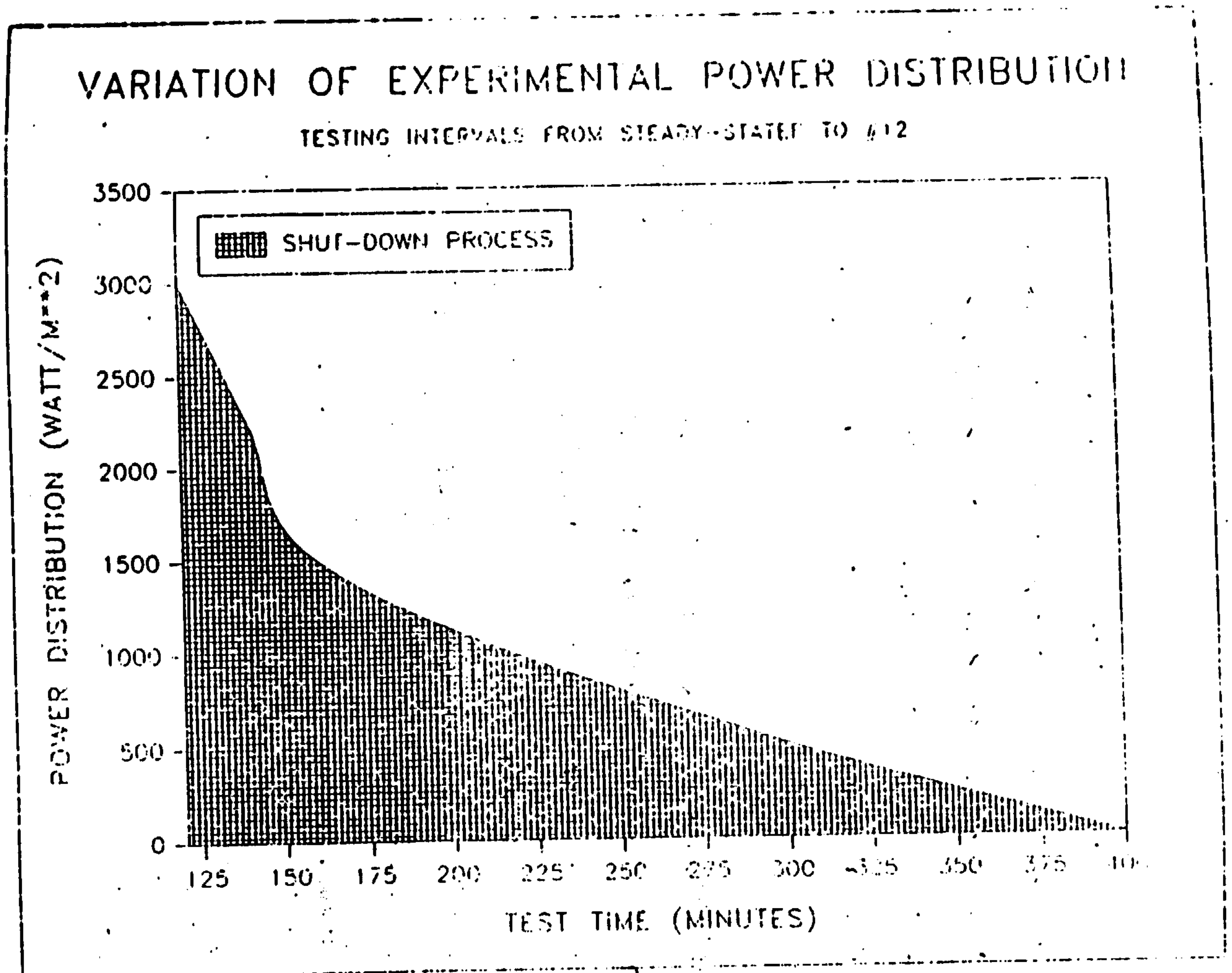


Figure 14. Experimental Power Distribution During the Considered Shut-Down Processes.

6) Time intervals (11 through 12): the minimum provided power was 0 W/m^2.

The mass flow rate was verified from 16 Kg/hr to 88.2 Kg/hr, while the stack pressure was varified from 0 KPA to 3500 KPA.

B) <u>Oil Coolant</u>: A closed cooling system with a secondary cooling system was used where the oil inlet temperature was kept approximately between (25°C and 26°C). The same testing procedure was followed. Also the same variation of stack pressure was used, but the Re number was increased from 15 to 80.

3.10 Interface Temperature Differential Measurements

The temperature differences due to imperfect surface contact were determined by twelve thermocouples located at and around the interface of the cell plate and the cooling plate as shown in Figure 15. Graphite powder was spread between the two plates to reduce air gaps and achieve better contact. The cooling plate thermocouples are attached to the cooling piping to measure the surface temperature.

3.11 Experimental Results Accuracy

Due to the instruments' accuracy and other factors there was an error percentage to be accounted for when representing the results. Accuracy is defined as the maximum amount by which a certain measurement differs from the true value, or

$$\text{Accuracy} = (M_m) - M_a$$

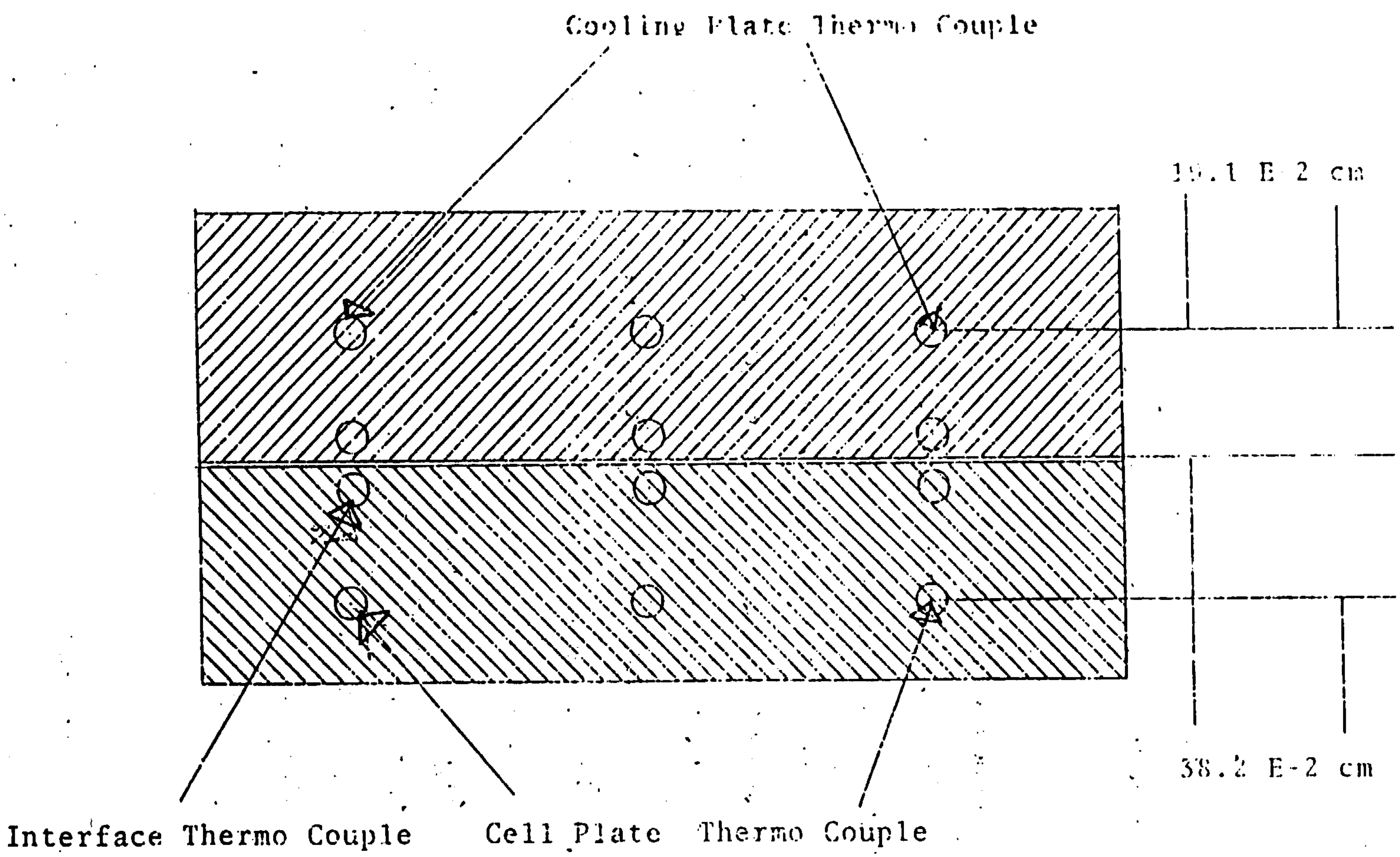


Figure 15. Location of Interferance Temperature Differential Thermocouple

Percent accuracy based on reading is

$$A = \frac{M_m - M_a}{M_a} * 100$$

where:

M_m = maximum or minimum measurement,

M_a = Actual value.

3.11.1 Instrumentation Error

The important instrumentation error can be summarized as follows.

3.11.1.1 Thermocouple Reading Accuracy

The thermocouple accuracy is considered the most important source of error that will affect the temperature distribution plots, the convection heat transfer coefficient, Nusselt number and overall heat transfer calculation. But this error has a significant effect on the effective temperature drop measurements which are used to determine the thermal contact resistance. The percentage of this error was determined by repeating certain tests with the same operation conditions, i.e. applied pressure, time interval versus supplied electrical energy for both incompressible coolants. The maximum error due to the thermocouples readings was found to be approximately 0.6 °C to 0°C, the manufacturer specfied that the error for T-type thermocouples are 0.75% or 1°C over zero °C.

3.11.1.2 Data Logger Readings Accuracy

Two factors affected remarkably the accuracy of the data logger reading.

(a) Data logger input.

The minimum error was 0.5% as specified by the manufacturer. Also, on one occasion the machine had to be calibrated again after an electronic failure due to an electrical surge.

(b) Specified recording time intervals.

Since all the tests considered are transient tests therefore the selected length of the time interval should be as short as possible to avoid any significant change in the internal energy and other time dependent thermodynamic properties of the system. The time interval for the data logger to monitor all the thermocouples including the working fluid inlet and outlet thermocouples was approximately 3.5 seconds. This time interval was found to be very accurate because the change in the coolant outlet temperature during this time interval was nearly zero.

3.11.1.3 Voltage and Amperage Readings

The accuracy of the ammeters and voltmeters mounted in the power supply unit was 4.0% while the digital multimeter accuracy was 2.1% as specified by the manufacturer. Actually the voltage and ampere readings were more accurate because the power unit readings were checked again by the cell instrumentation.

3.11.1.4 Pressure Gauge Readings

The pressure gauge accuracy was 0.1%. The maximum expected error when the highest applied pressure was used was ±35 KPa.

3.11.1.5 Volumetric Flow Rate Measurements

As mentioned before the combined accuracy of the flow instrumentation was found to be ± 0.4 gpm or maximum combined error of 2.3%.

3.11.2 Heat Exchange with the Surroundings

The unaccounted for heat transferred by radiation convection and conduction to the surroundings is very difficult to calculate. However if the rate of heat transfer was significantly high it could negatively affect the accuracy of the final results that depends on the evaluation of the transient thermal energy transferred by the cooling fluid. Several tests were carried out utilizing both working fluids under different operation conditions. The maximum heat transfer was found to be 17.5 watt where using 3000 w/m^2 and maintaining a steady state operating condition with minimum Re number and maximum pressure. This is 7.792% of the internal heat generator simulated by the supplied electrical power. Additional insulation was added as described by Chapter III to reduce the heat loss. The heat transfer rate to the surroundings was reduced to a maximum of 9.1 Watts which is 2.466% of the supplied power.

3.11.3 Human Error

The human error is an important factor in the accuracy of the final results. The effect of such error in this experiment was observed during the following.

(a) Voltage and amperage readings.

(b) Obtaining exactly the required stack pressure.

(c) Supplied power variation for the four electrical circuits used during a very short time interval.

(d) To maintain continuously throughout the testing time interval the exact volumetric flow rate.

(e) To maintain a constant room temperature during all the tests.

CHAPTER IV

MATHEMATICAL MODEL OF TRANSIENT HEAT TRANSFER IN THE FUEL-CELL STACK

The thermal energy generated in the fuel cell should be removed continuously to prevent accumulation of heat which could lead to thermal stress, lower efficiencies and even structural failure. Therefore, proper design of the cooling system is vital to the operation and performance of any fuel cell power system. In this chapter the effect of the expected transient operation conditions' effect on the cooling system performance were investigated with water and oil as coolants.

4.1 Transient Heat Transfer Analysis for the Cooling System

This section will summarize the formulation employed to generate the needed results utilizing the gathered experimental data during the transient process considered using incompressible cooling fluids.

4.1.1 Heat Transferred to the Cooling Fluid

Applying the first law of thermodynamics for the considered case, at any instant of time during the transient process, the energy balance equation for the cooling fluid can be written as follows; see Figure 16.a.

$$(\dot{Q}(t))_{c.s.} = \left|\frac{d\ E(t)}{dt}\right| + \left[\dot{m}_e(t)\ *\ H_e(t)\ -\ \dot{m}_i(t)\ *\ H_i(t)\right] \qquad (3)$$

But, $\dot{m}_e(t) = \dot{m}_i(t) = \dot{m}$ = constant for a given test

$$(\dot{Q}(t)_{c.s.} = \left|\frac{dE(t)}{dt}\right| + \dot{m}\ C_p\ (T_{be}(t) - T_{bi}(t)) \qquad (4)$$

Also

$$\frac{dE(t)}{dt} = \frac{m(t_2)*u(t_2)\ -\ m(t_1)*u(t_1)}{\Delta t} \qquad (5)$$

where:

$\dot{Q}_{c.s.}(t)$ = Heat transferred to the cooling fluid, as a function of time.

$\dot{m}_i(t)$ = Instantaneous mass flow rate entering the coolant channel, constant for a given test.

$m(t)$ = mass inside the cooling plate at time (t).

$H_i(t)$ = Instantaneous total enthalphy of the mass flow rate (i) entering the cell.

$\left(\frac{dE(t)}{dt}\right)$ = transient change of the control volume internal energy, which includes the cooling plate and the upper part of the cell plate.

$T_{bi}(t)$ = Cooling fluid bulk temperature entering the cell.

$T_{be}(t)$ = Cooling fluid bulk temperature leaving the cell.

$\dot{m}_e(t)$ = Instantaneous mass flow rate leaving the cell from location (e), constant for a given test.

$H_e(t)$ = Instantaneous total enthalpy of the mass flow rate (e) leaving the cell.

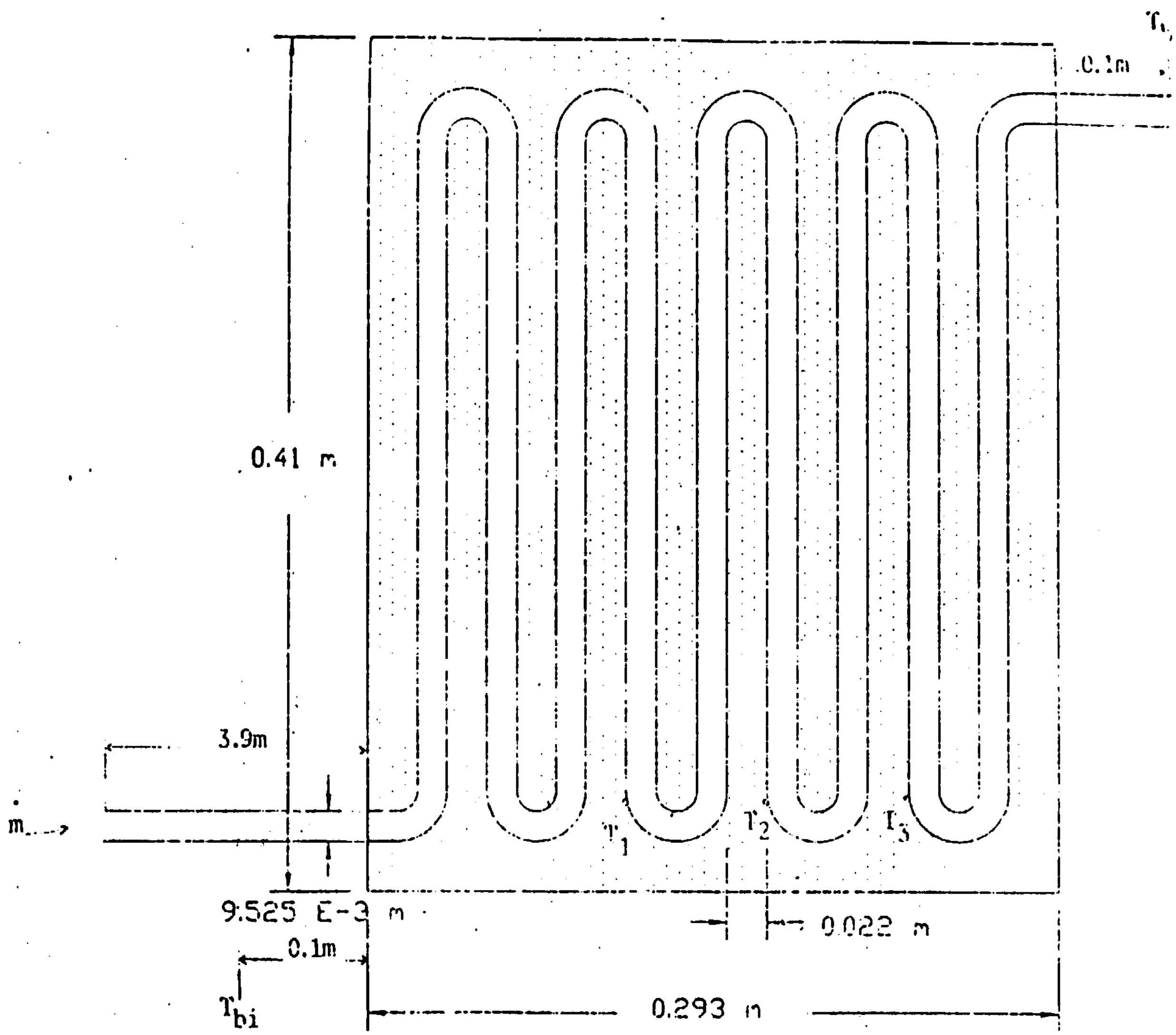


Figure 16. Heat Transfer Thermocouple Locations.

C_p = Specific heat at constant pressure.

u(t) = Cooling fluid internal energy at time (t) inside the control volume.

4.1.2 Transient Convective Heat Transfer Coefficients and Nusselt Number

The energy transferred to the cooling system can be utilized to accurately determine the transient local convective heat transfer coefficient as follows:

$$((\dot{Q}(t))_{c.s.} = h(t) * A_{c.s.} * [T_w(t) - T_\infty(t)] \qquad (5)$$

where:

h(t) = instantaneous convective heat transfer coefficient between tube surface and coolant.

$A_{c.s.}$ = available heat transfer surface area of the cooling channel.

$T_w(t)$ = instantaneous average wall surface temperature of the cooling plate. copper tube, obtained from the thermocouples welded to the coils.

$T_\infty(t)$ = instantaneous average bulk coolant temperature.

The instantaneous average wall surface temperature is the average of all the thermocouples' readings welded to the cooling coil for a certain measurement (see Figure 17.a).

The temperature variation of those thermocouples was found to be linear as a function of the coil length for any given test (refer to Appendix). The instantaneous average bulk temperature also called the mixed mean average temperature is basically the ratio of the total thermal energy crossing the tube in a unit time over the heat capacity of the fluid crossing the same section in a unit of time. This temperature was calculated utilizing the experimental data of selected laminar and turbulent cases for both fluids taking into consideration the change of the thermal diffusivity of the fluid ($\alpha = \frac{K_c}{\rho C_p}$). Also, for the laminar flow, the laminar entrance length was estimated using the average results of the Blasius, Sparrow and Schlichting equation in addition to the thermal entry length. The results of the average bulk temperature employing the forced convection of circular tubes equation provided by references [14] and [38] were compared to the average of the entrance and exit temperatures of the control volume. This comparison indicated that the difference was in the range of 1.5% to 3%. Therefore, the average bulk coolant temperature was used in the final calculations performed by the experimental monitoring system. The experimental convective heat transfer coefficient (h(t)) was calculated from equation (5), as follows:

$$h(t) = \frac{((Q(t))_{c.s.}}{A_{c.p.s.}(T_w(t) - T_\infty(t))} \quad (6)$$

Then the experimental transient Nusselt number was calculated as follows:

$$Nu(t) = \frac{h(t) * D}{K_c} \quad (7)$$

4.1.3 The Experimental Overall Heat Transfer Coefficient

The experimental transient overall heat transfer coefficient for the control volume defined in the previous section was determined as follows:

Since,

$$(\dot{Q}(t)_{c.s.} = U(t)*A*(T_e(t)-T_\infty(t))$$

Therefore:

$$U(t) = \frac{(Q(t))_{c.s.}}{A_c(T_e(t) - T_\infty(t)} \quad (8)$$

But it should be noticed that the transient overall heat transfer coefficient is considered: in the reciprocal of the sum of three resistances See Figure 17-b: the convection resistance, the conduction resistance, and the thermal contact resistance. U(t) can be expressed as follows:

$$U(t) = \frac{1}{\left[\left(\frac{X_1}{K}\right) + \left(\frac{1}{R_c(t))}\right) + \left(\frac{X_2}{K}\right) + \left(\frac{1}{h(t)}\right)\right]} \quad (9)$$

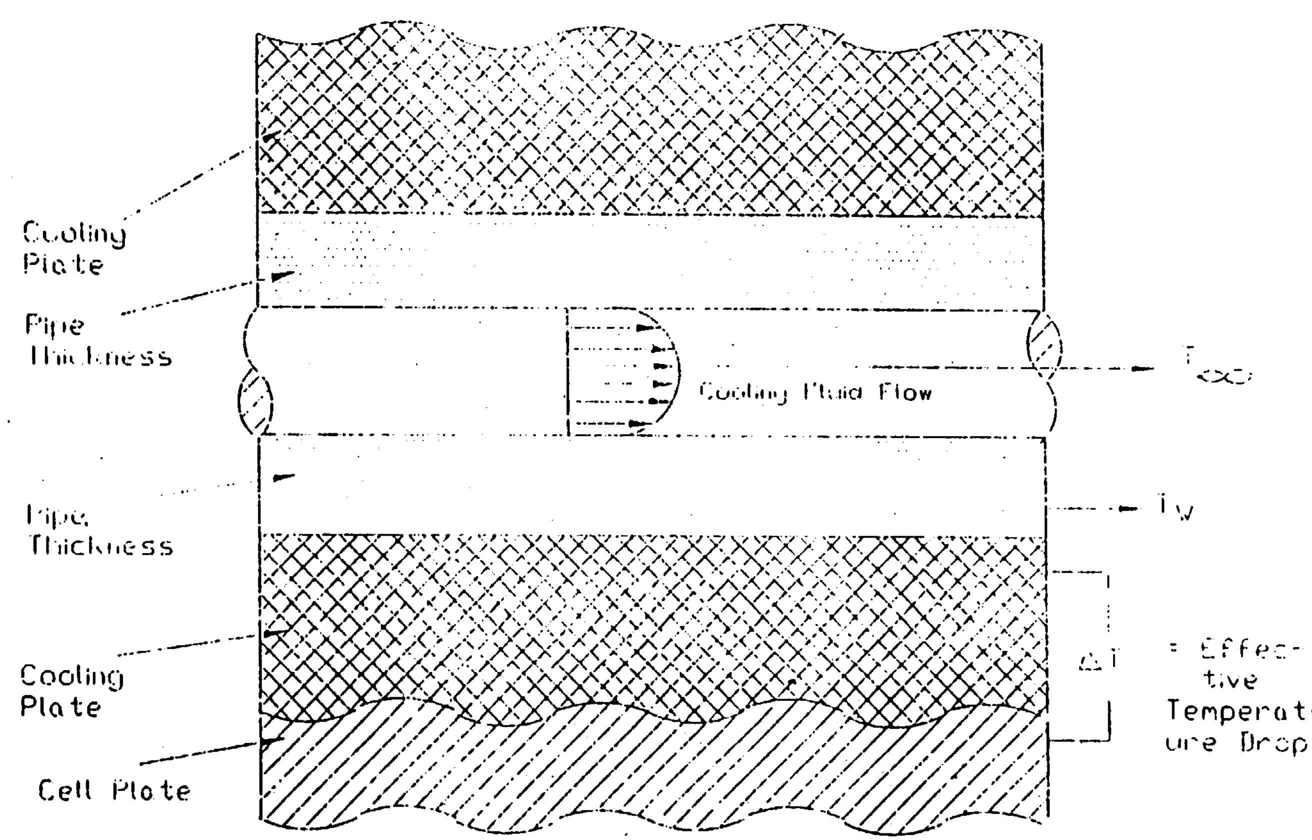


Figure 17-a. System Measured Temperature

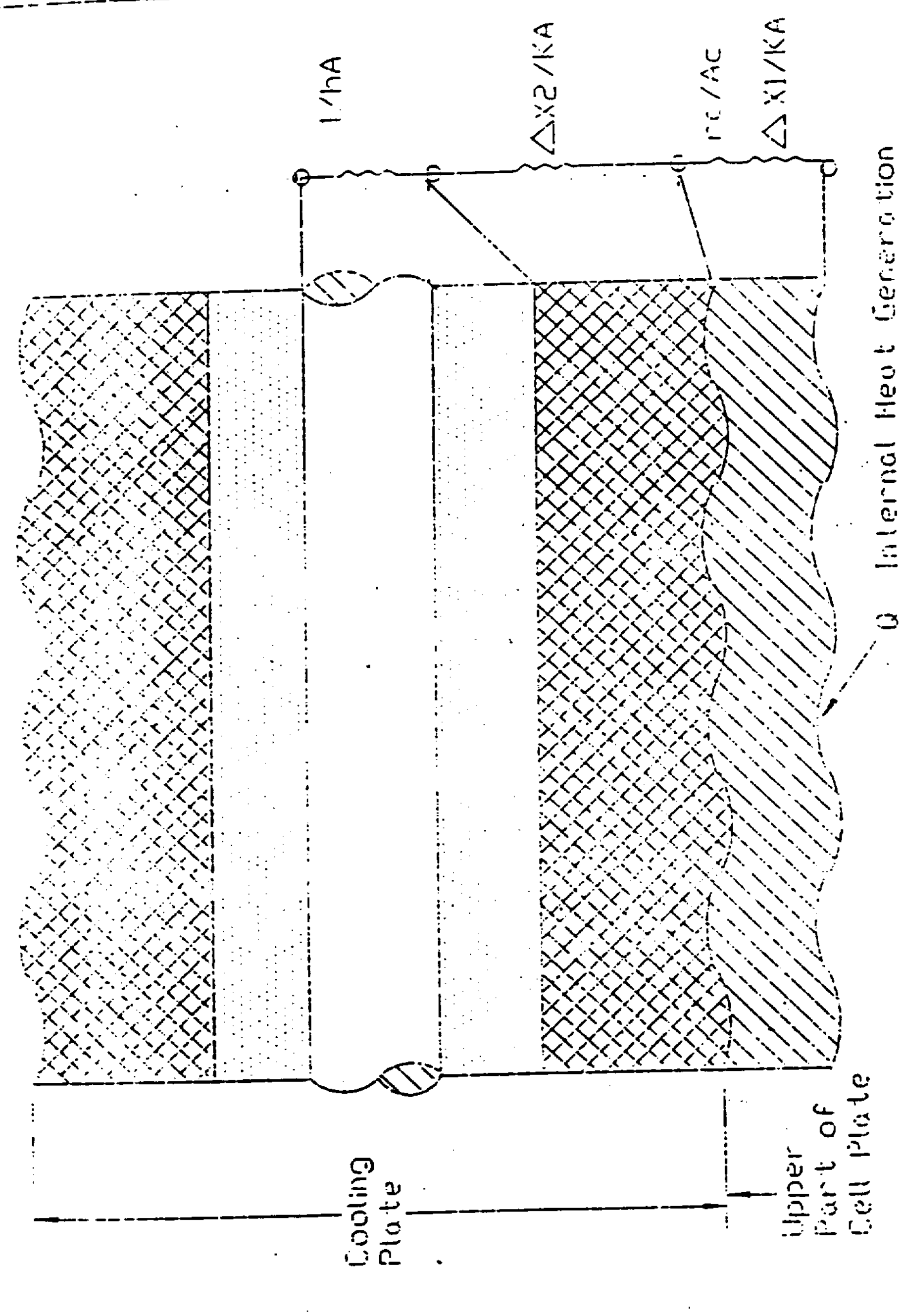


Figure 17-b. Thermal Resistance

The thermal contact resistance between the upper part of the cell plate and the cooling plate can be calculated as follows: (please refer to Figure 17.c).

$$Q = K_A \; A_c \; \frac{dT}{dx}\Big|_0^{L_1} = K_B \; A_c \; \frac{dT}{dx}\Big|_{L_1}^{L_2} \tag{10}$$

However, the instantaneous thermal conductance parameter (R) is defined as:

$$R_c(t) = \frac{q(t)}{\Delta T(t)}$$

when

q(t) = instantaneous heat flux (Q/A).

ΔT = effective temperature drop through the interference between the upper part of the cell plate and the cooling plate.

Substituting in equation (6):

$$R_c * \Delta T = K_A \frac{dT}{dx} = K_B \frac{dT}{dx}$$

or

$$R_c = \frac{K_A}{\Delta T} \frac{dT}{dx} = \frac{K_B}{\Delta T} \frac{dT}{dx} \tag{11}$$

The thermal contact resistance (r_c) is the inverse of (R_c):

$$r_c = \frac{1}{R_c} = \frac{\Delta T}{K_A \frac{dT}{dx}} = \frac{\Delta T}{K_B \frac{dT}{dx}} \tag{12}$$

Substituting equation (12) in equation (9), we will have the following:

$$U(t) = \frac{1}{\left[\left(\frac{x_1}{K}\right) + \left(\frac{\Delta T(t)}{K*(\frac{dT}{dx})} \right) + \left(\frac{x_2}{K}\right) + \left(\frac{1}{h(t)}\right) \right]} \tag{13}$$

where:

K_A = thermal conductance of the cell plate.

K_B = thermal conductance of the cooling plate.

u(t) = transient overall heat transfer coefficient of the control volume.

A_c = contact area between cooling plate and cell plate.

$T_e(t)$ = T.A. = transient average temperature of the electrode.

K = graphite conductivity (thermal).

x_1, x_2 = thickness in the X direction (please refer to Figure 17.c).

r_c = transient thermal contact resistance.

$\Delta T(t)$ = effective temperature drop.

4.2 Experimental Results

In this section the experimental results collected previously will be analyzed and interpreted to determine the effects of the stack pressure and the cooling systems flow characteristics on the fuel cell heat transfer characteristics. The experimental results will be further used to formulate the mathematical correlations to simulate and express the heat transfer characteristics of the examined fuel cell module during transient operation conditions, start-up and shut-down.

4.2.1 Start-Up Process

Referring to section (4.1) of this Chapter, The value of h(t), Nu(t) and U(t) were determined by applying equations (6), (7) and (13) using the data gathered from the experimental set up.

4.2.1.1. The Variation of the Transient Nusselt Number as a Function of the Cooling System Flow Characteristics

(a) Water Coolant (Re = 1250 to Re = 6167).

Experimental results demonstrated by Figure 18 indicates the dependence of the transient Nusselt number on the flow characteristics of the cooling system during a start-up process. Higher Nusselt numbers were calculated with higher flow rates.

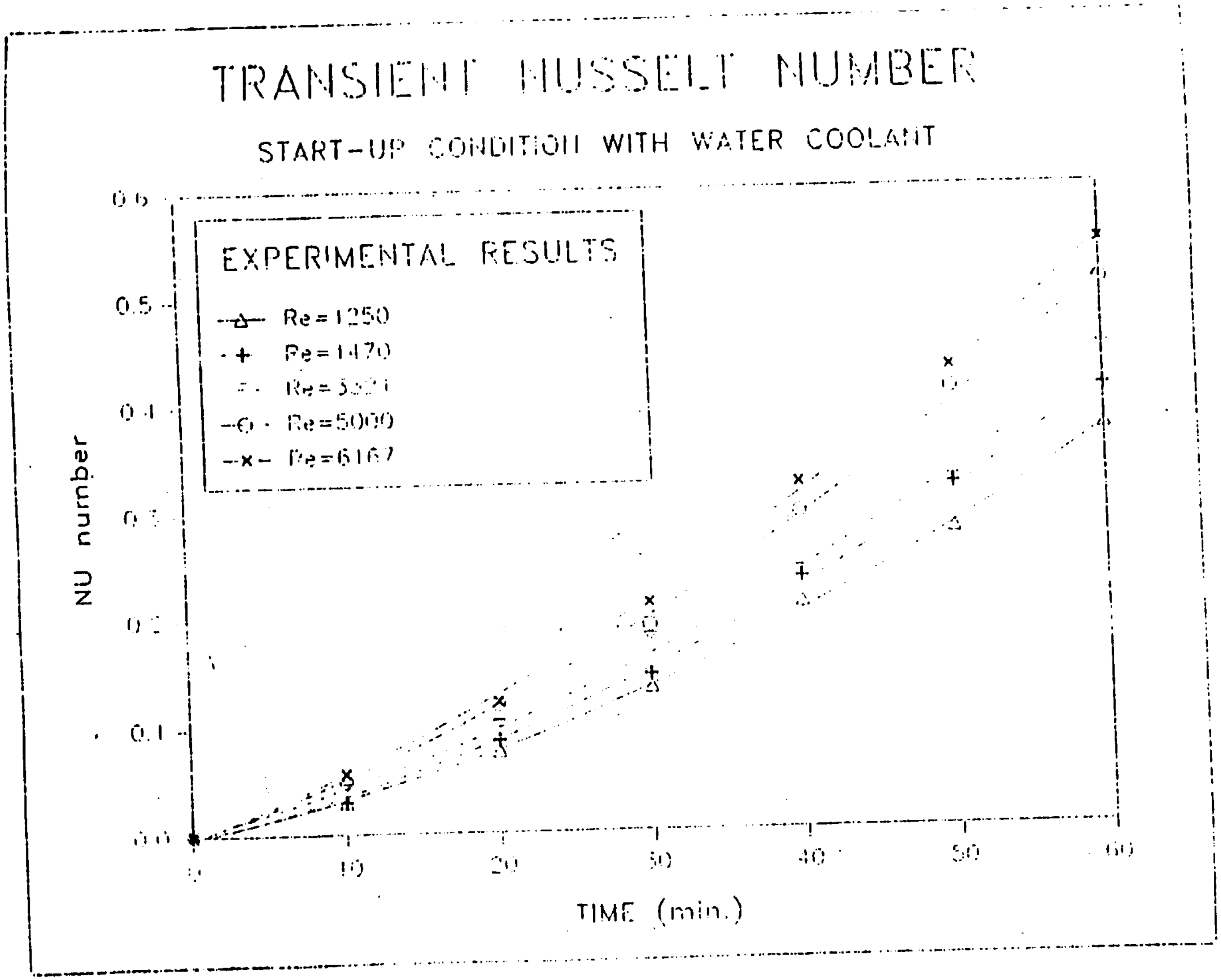


Figure 18. Experimental Transient Nuselt Number (Start-Up with Water Coolant).

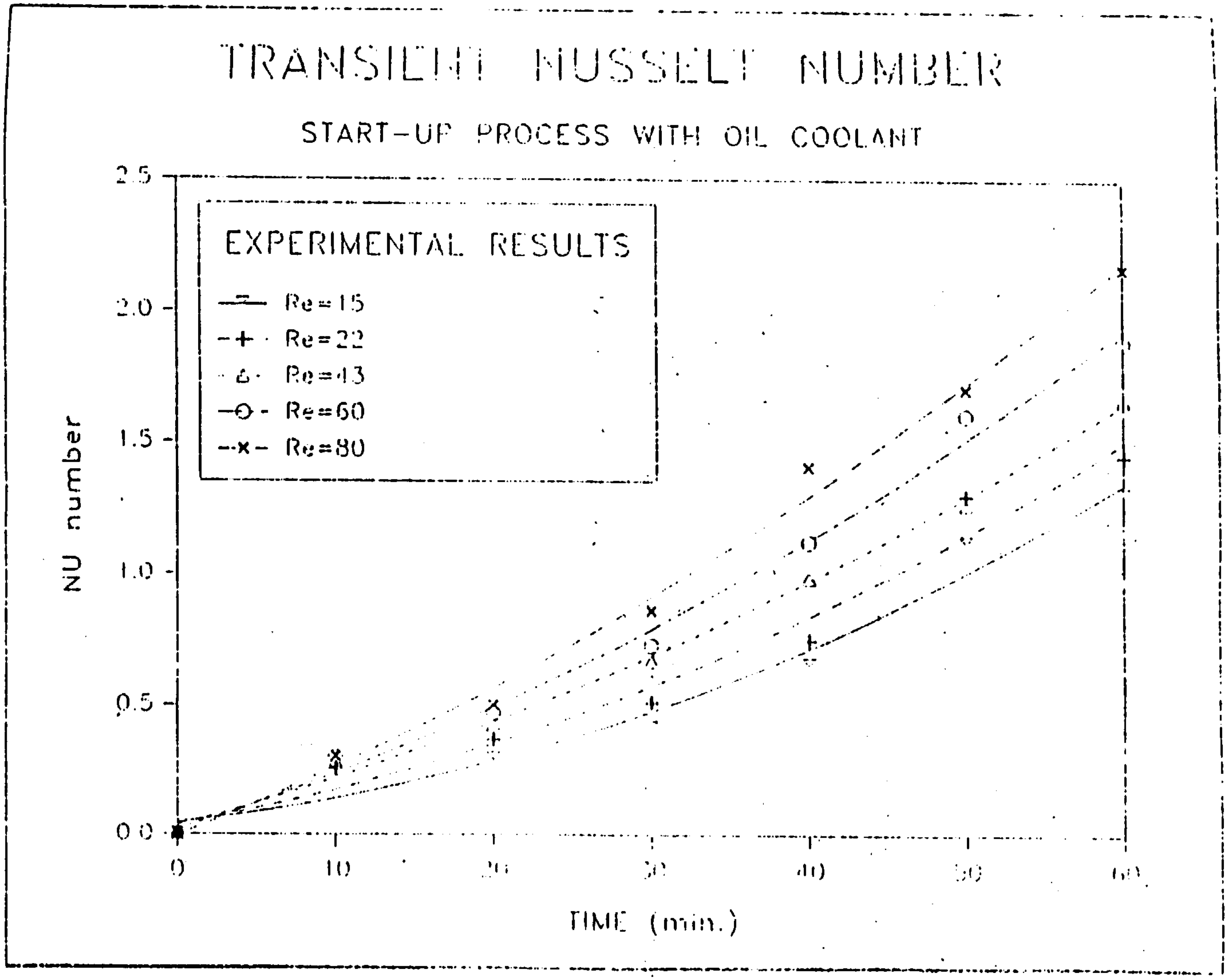


Figure 19. Experimental Transient Nusselt Number (Start-Up with Oil Coolant).

(b) Oil Coolant (Re=15 to Re=80).

Figure 19 demonstrates the variation of the Nu number during a start-up process using oil as a coolant.

4.2.1.2. Measurements of the Transient Thermal Contact Resistance

As described in Chapter III, the thermal contact resistance was actually measured utilizing 12 thermocouples planted around the interface area to measure the temperature differential. Equation (12) was then used to determine the value of r_c at any point in time. Figure 20 through Figure 22 shows the effect of the different considered stack pressures on the transient values of r_c. It should be noticed that a slight decrease in the rate of r_c was observed with a higher Re number.

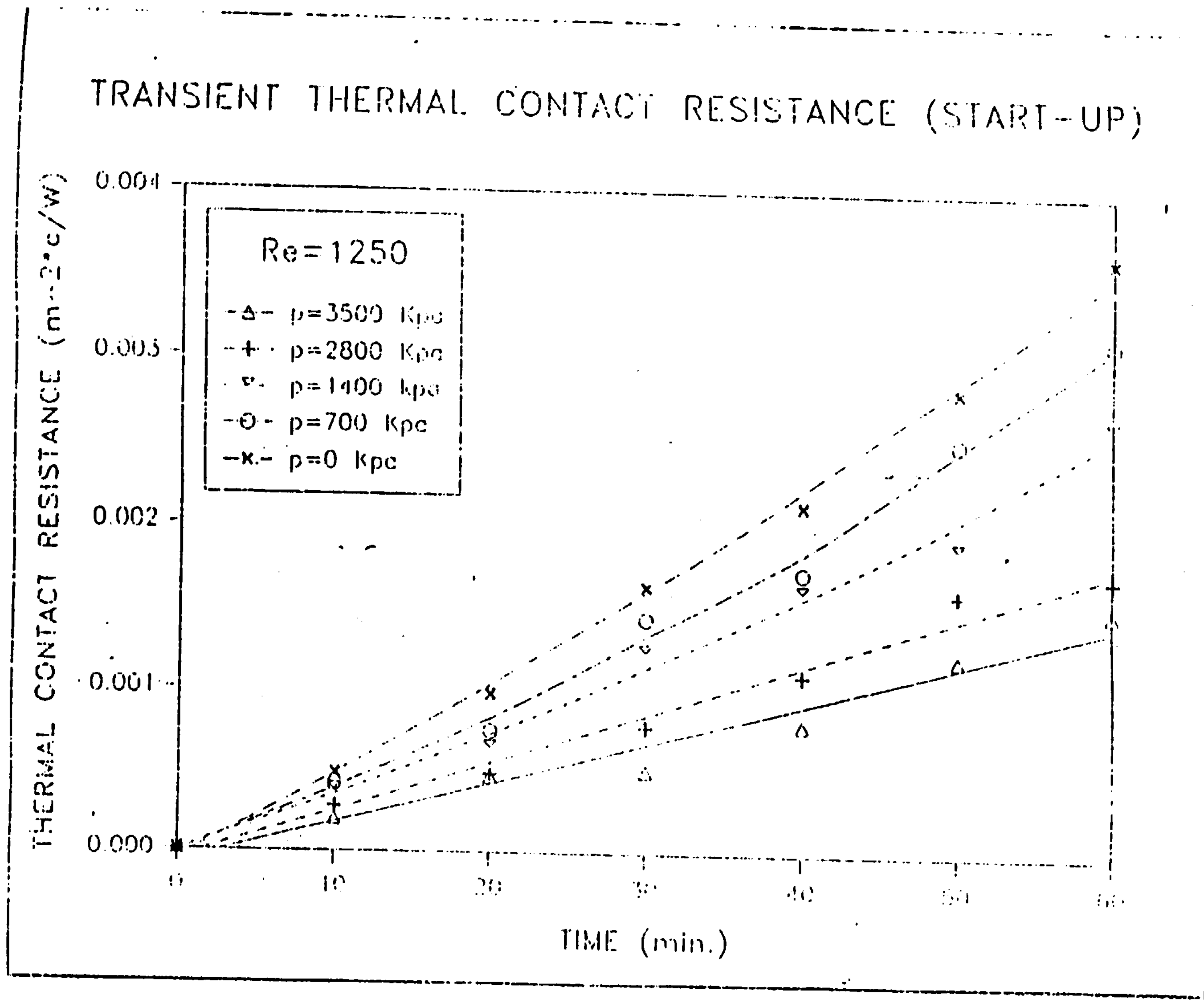


Figure 20. Experimental Transient Thermal Contact Resistance (Start-Up Condition with Water Coolant Re = 1250).

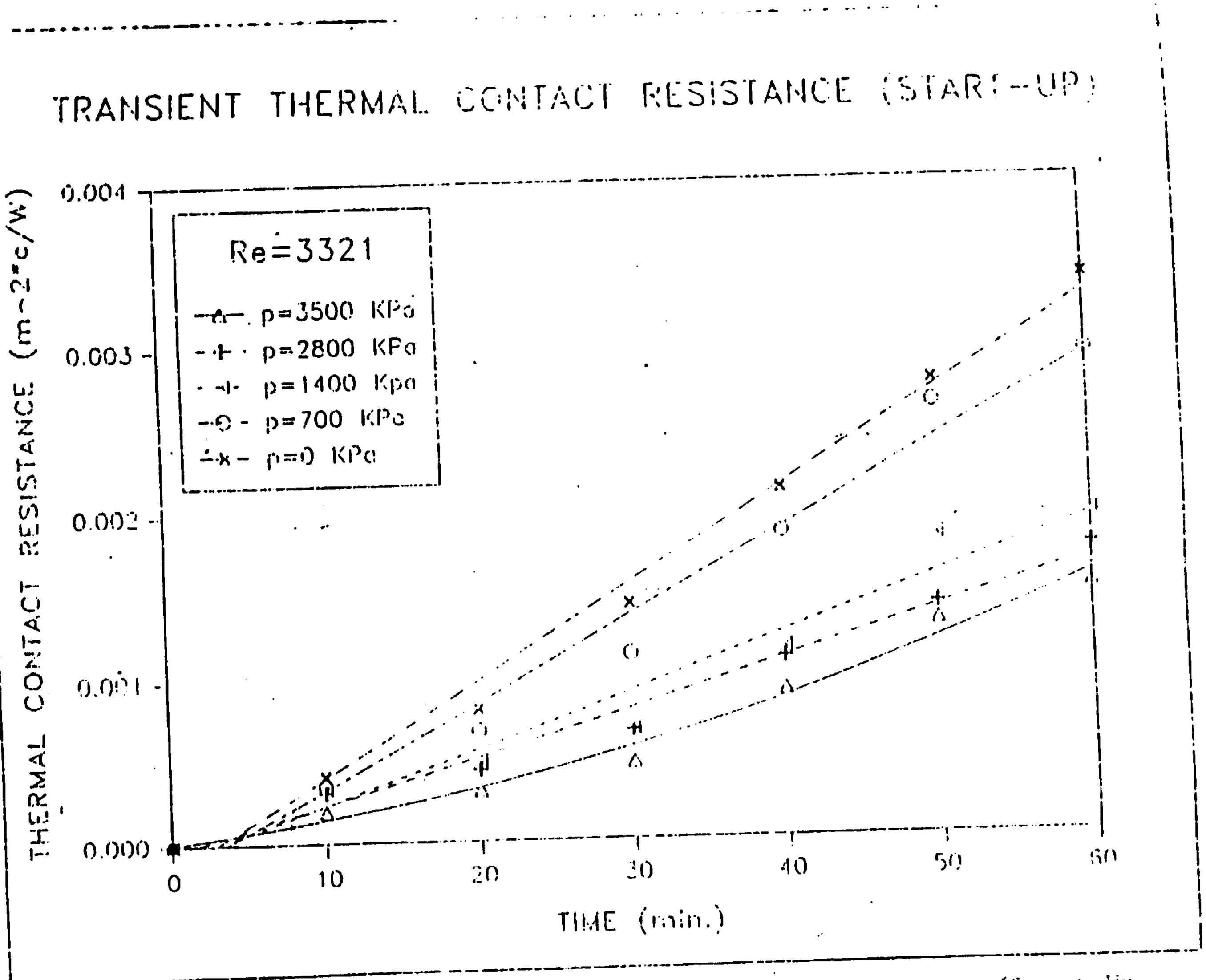


Figure 21. Experimental Transient Thermal Contact Resistance (Start-Up Condition with Water Coolant Re = 3321).

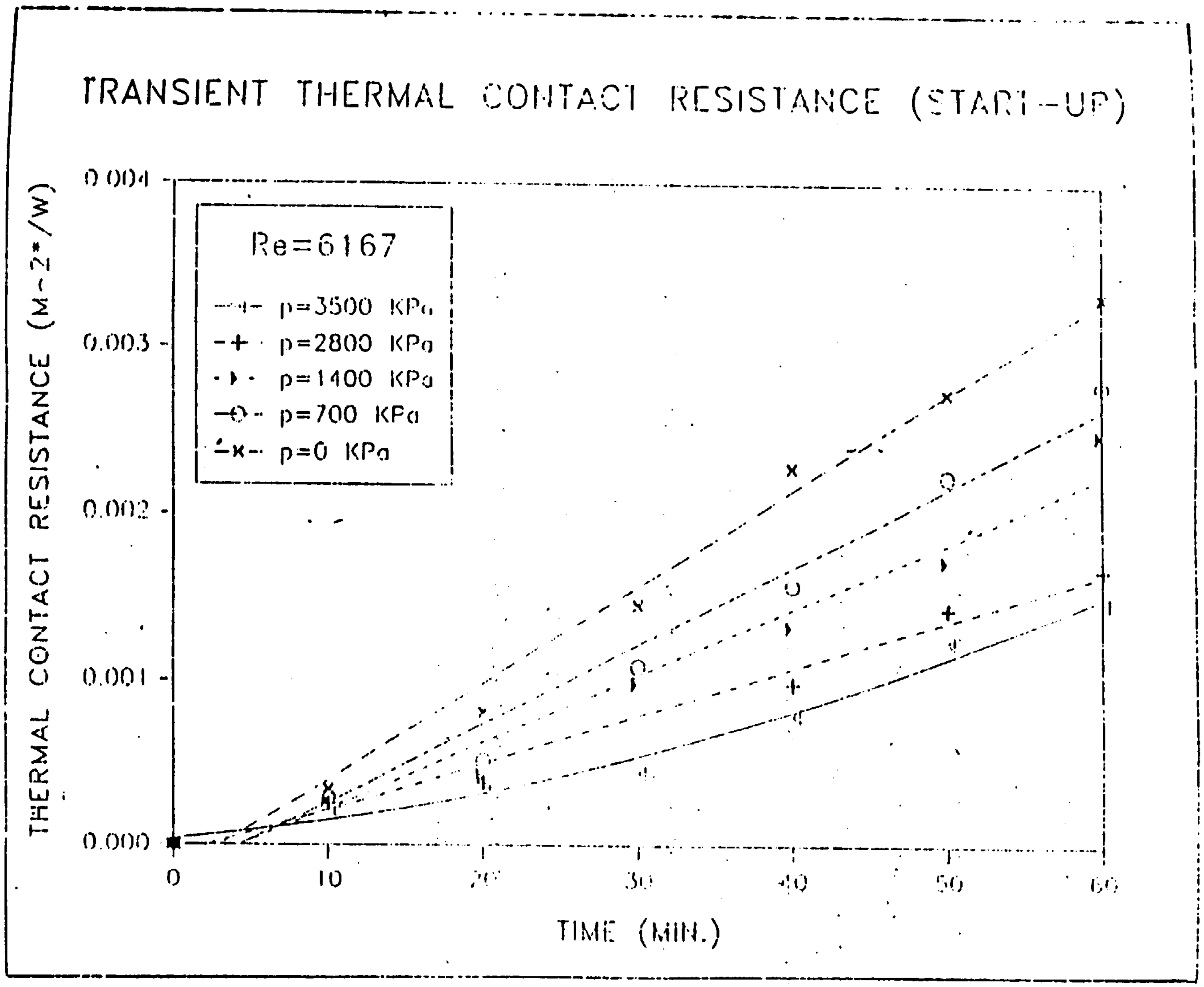


Figure 22. Experimental Transient Thermal Contact Resistance (Start-Up Condition with Water Coolant Re = 6167).

4.2.1.3 The Effect of the Stack Pressure and the Cooling System Flow Characteristics on the Transient Overall Heat Transfer Coefficient

(a) <u>Water Coolant (Re = 1250 to Re = 6167).</u>

Experimental results exhibited in Figure 23 through Figure 24 summarizes the experimental data gathered and the calculations from fifteen transient experimental tests which are part of the testing process that focused on investigating the heat transfer characteristics of the fuel cell during a start-up process. In each Figure the volumetric flow rate was kept constant for the five experimental runs to determine the overall heat transfer coefficient.

(b) <u>Oil Coolant (Re=15 to Re=80).</u>

Figure 26 through Figure 28 exhibits part of the experimental results during a start-up process using oil as a coolant.

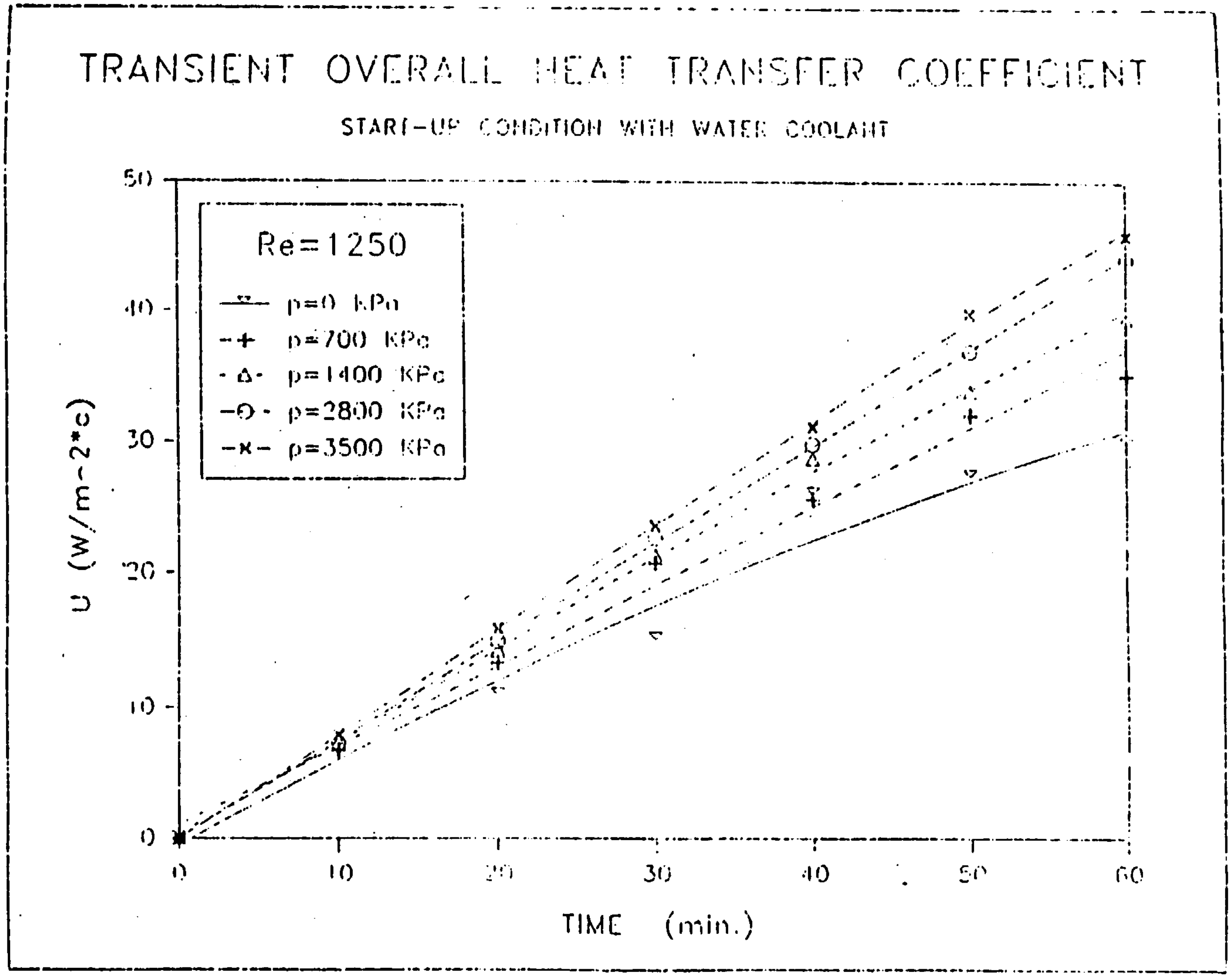


Figure 23. Experimental Transient Overall Heat Transfer Coefficient (Start-Up Condition with Water Coolant Re = 1250).

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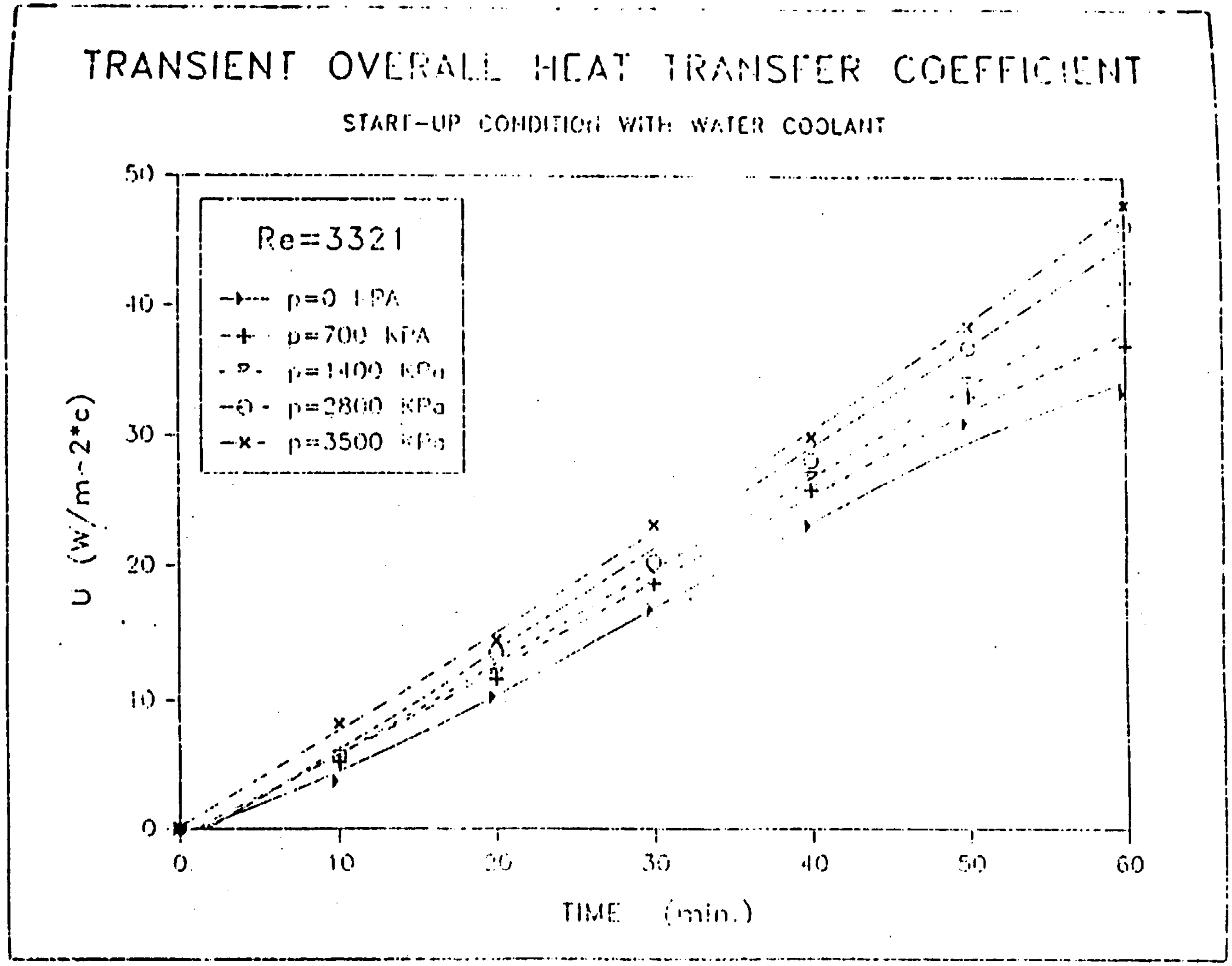

Figure 24. Experimental Transient Overall Heat Transfer Coefficient (Start-Up Condition with Water Coolant Re = 3321).

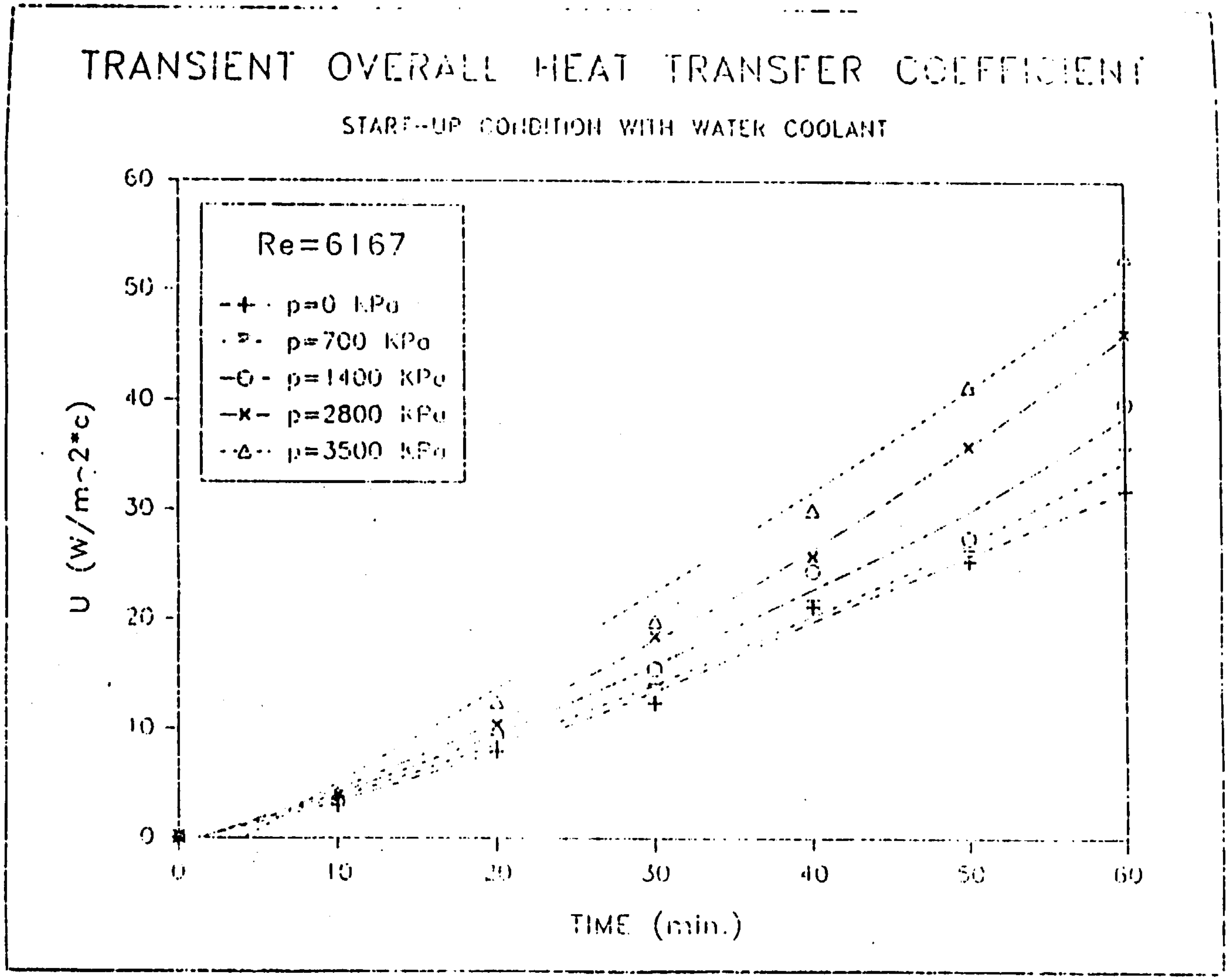

Figure 25. Experimental Transient Overall Heat Transfer Coefficient (Start-Up Condition with Water Coolant Re = 6167).

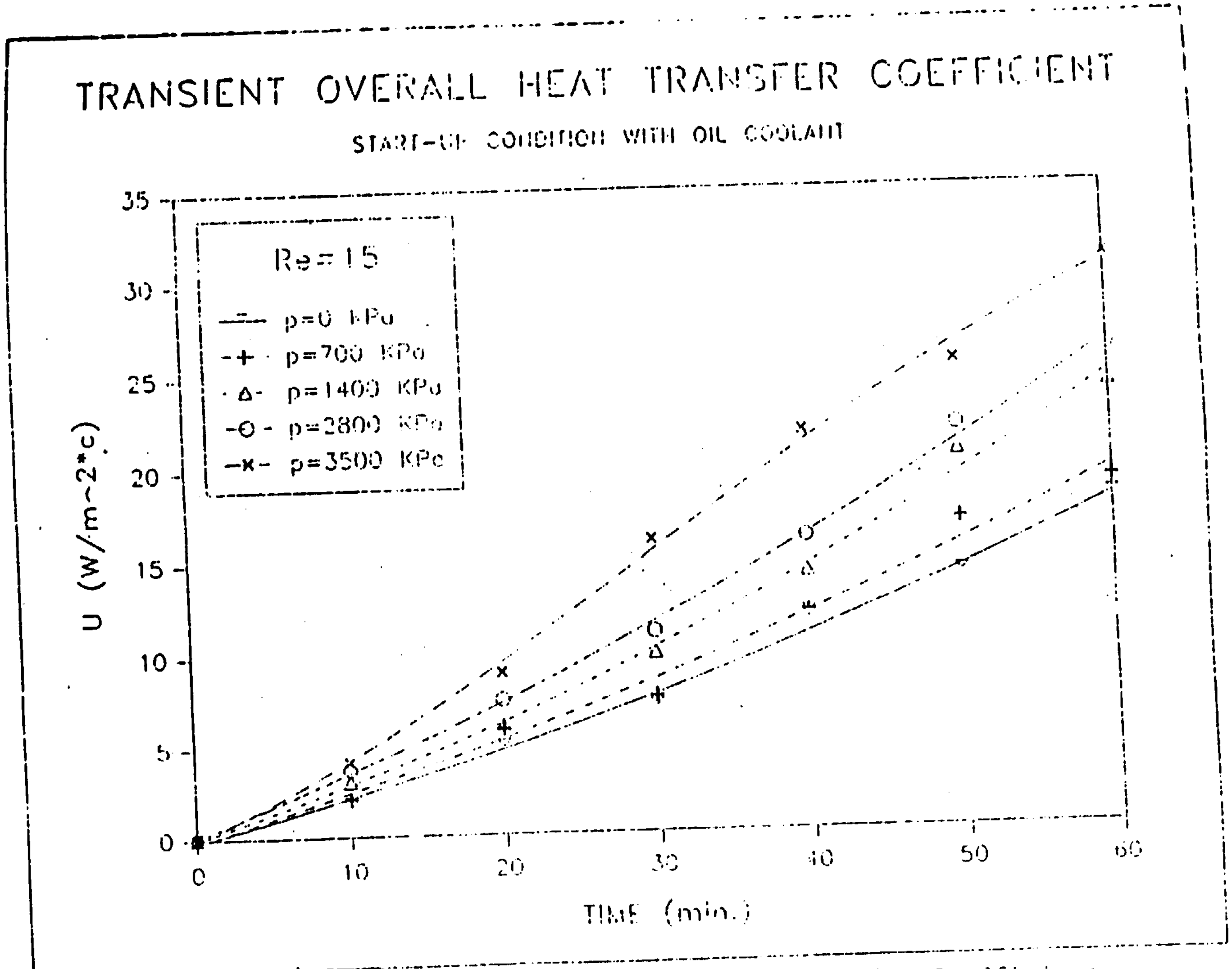

Figure 26. Experimental Transient Overall Heat Transfer Coefficient (Start-Up Condition with Oil Coolant Re = 15).

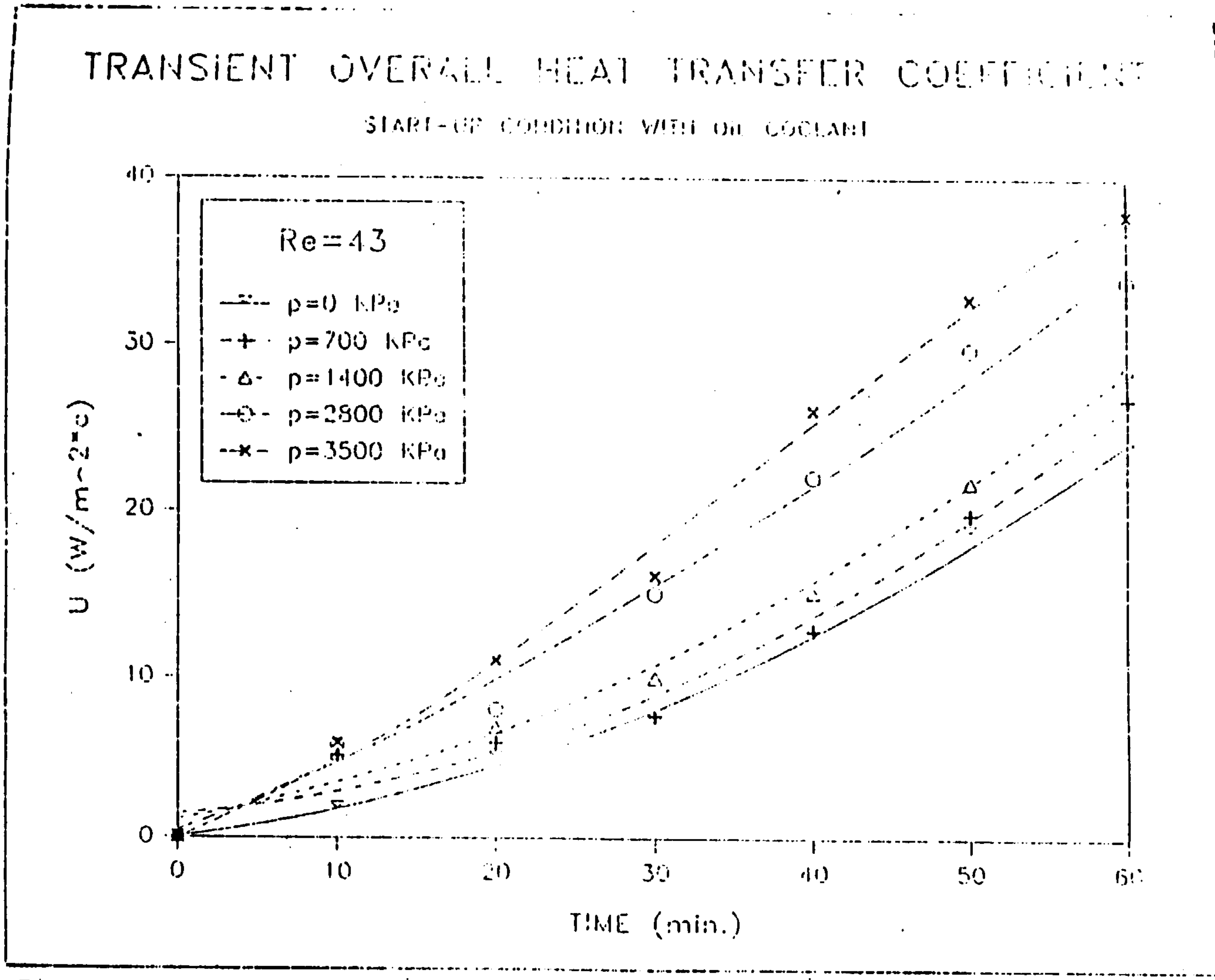

Figure 27. Experimental Transient Overall Heat Transfer Coefficient (Start-Up Condition with Oil Coolant Re = 43).

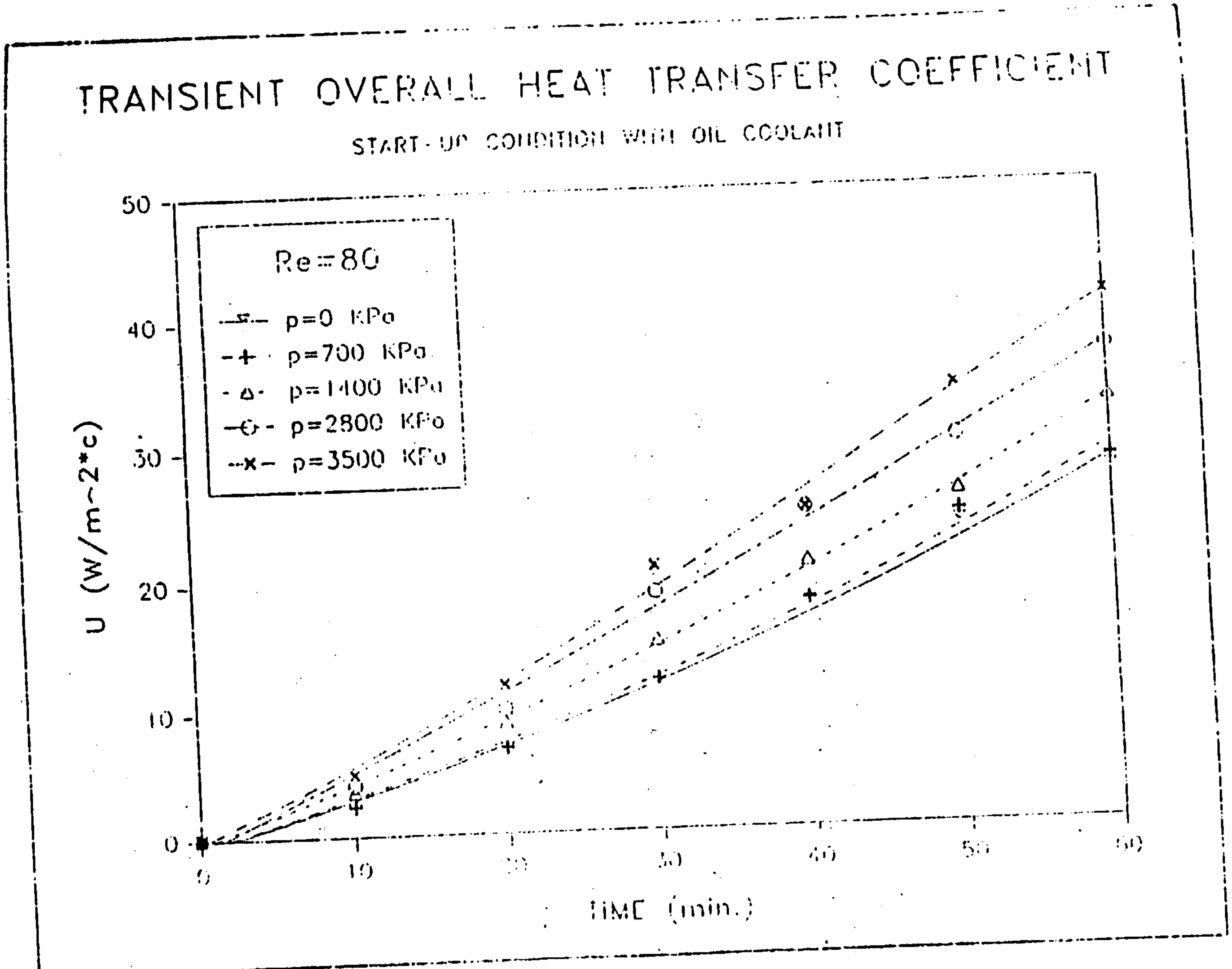

Figure 28. Experimental Transient Overall Heat Transfer Coefficient (Start-Up Condition with Oil Coolant Re = 80).

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4.2.2 Shut-Down Process

Referring to section (4.1.1 to (4.1.3)) of this Chapter, the values of h(t), Nu(t) and U(t) were determined using the same set of equations as in the previous section using the collected experimental data from the experimental set-up during a shut-down process.

4.2.2.1 The Variation of the Transient Nusselt Number as a Function of the Cooling System Flow Characteristics

(a) <u>Water Coolant (Re = 1250 to Re = 6167)</u>

Figure 29 summerizes the experimental results of the transient Nusselt number variation during shut-down process for different coolant flow rates.

(b) <u>Oil Coolant (Re=15 to Re=80)</u>

Refer to Figure 30, for the experimental results of the oil Nu number variation during a shut-down process.

4.2.2.2 Measurement of the Transient Thermal Contact Resistance

Figure 31 through 33 exhibits the transient thermal contact resistance measured during part of the shut-down processes and demonstrate the dependence of this thermal resistance mainly on the applied stack pressure for different coolant flow rates.

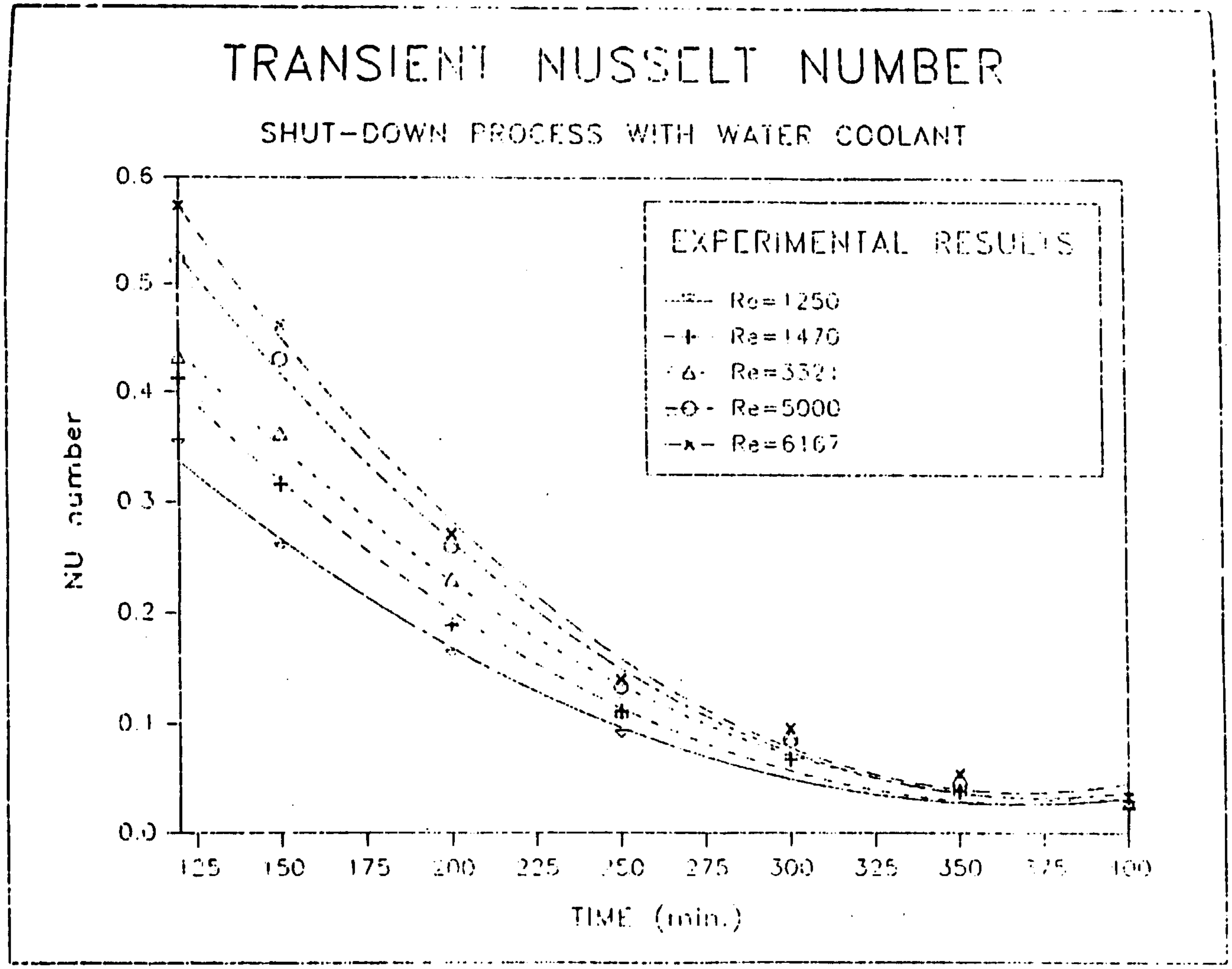

Figure 29. Experimental Transient Nusselt Number (Shut-Down Condition with Water Coolant).

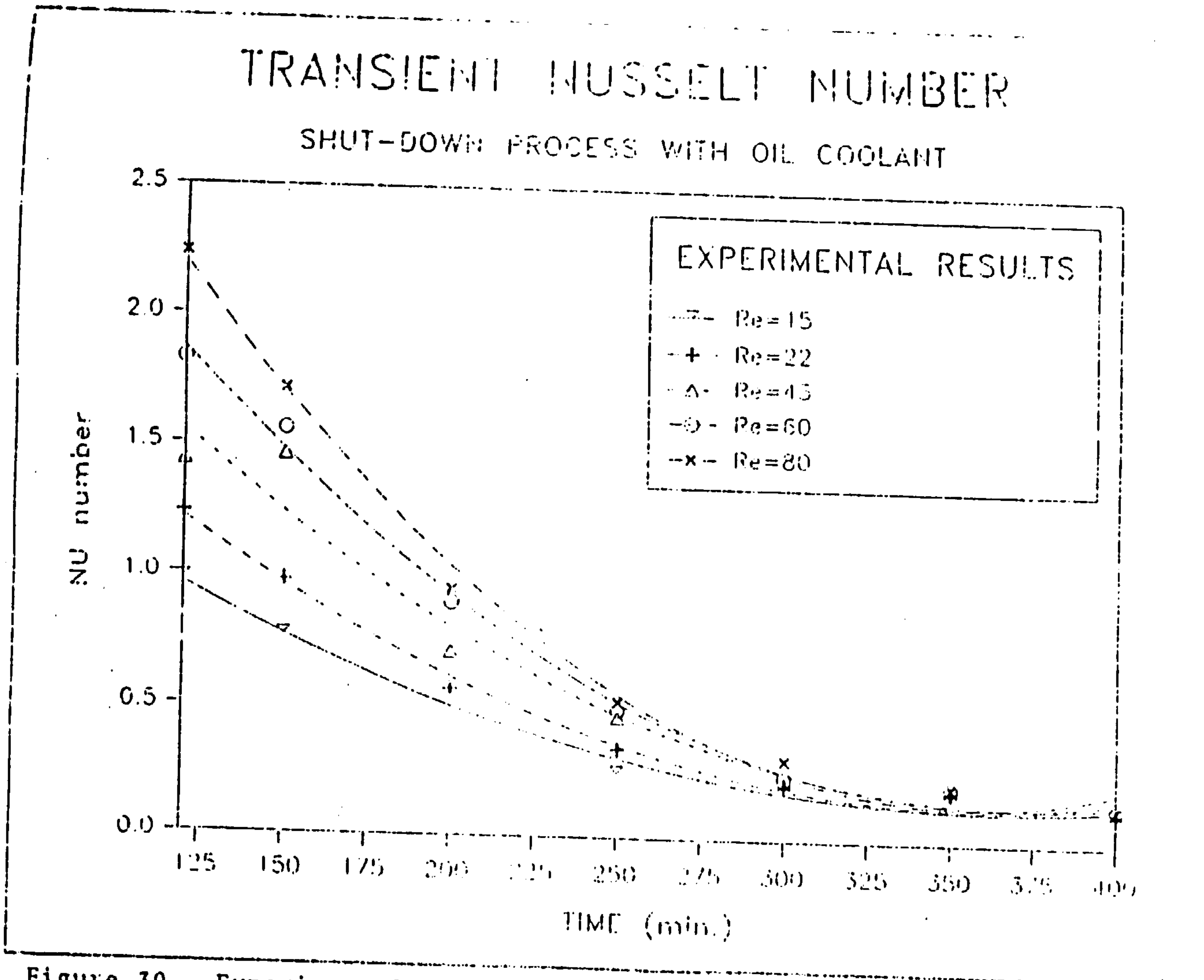

Figure 30. Experimental Transient Nusselt Number (Shut-Down Condition with Oil Coolant).

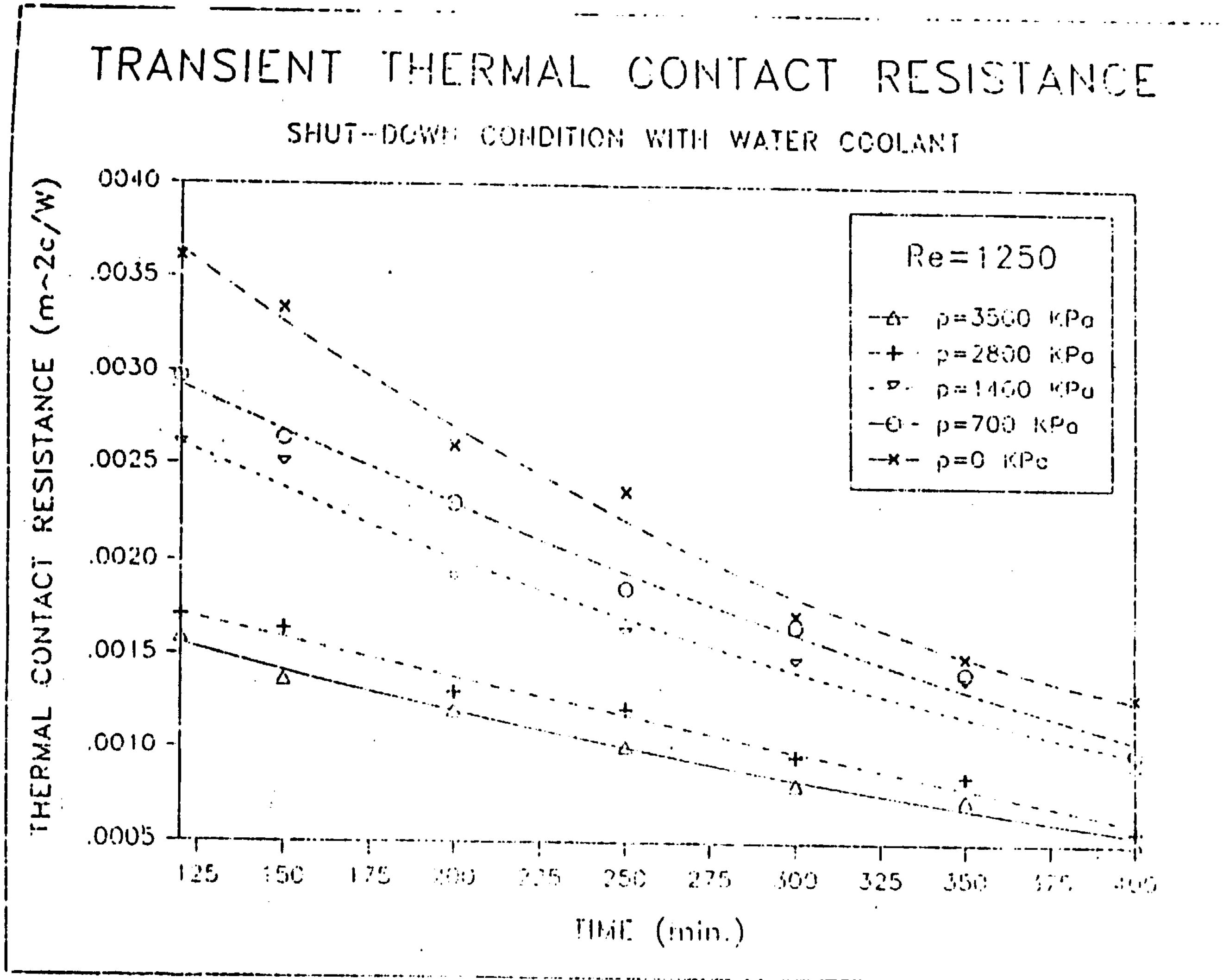

Figure 31. Experimental Transient Thermal Contact Resistance (Shut-Down Condition with Water Coolant, Re = 1250).

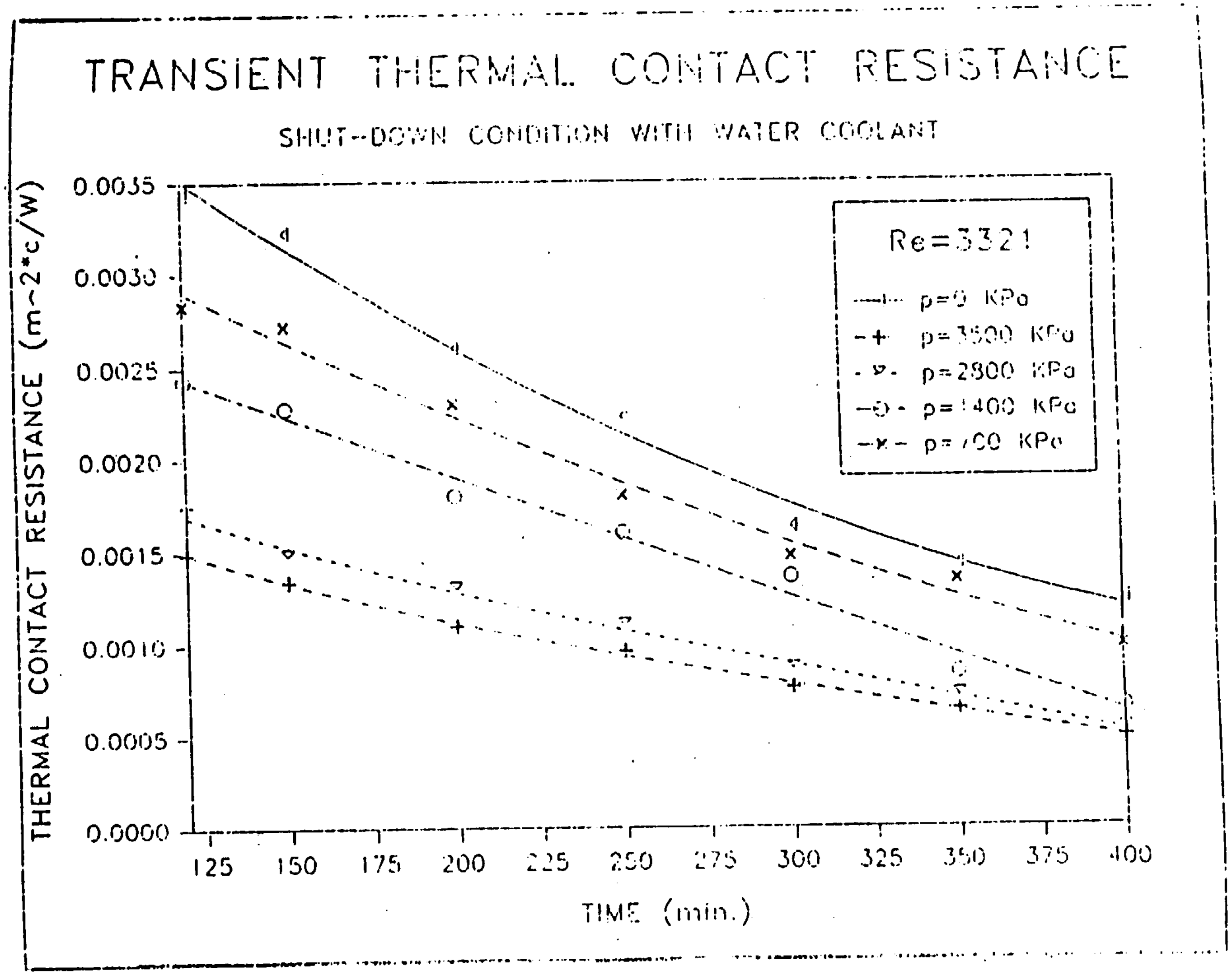

Figure 32. Experimental Transient Thermal Contact Resistance (Shut-Down Condition with Water Coolant, Re = 3321).

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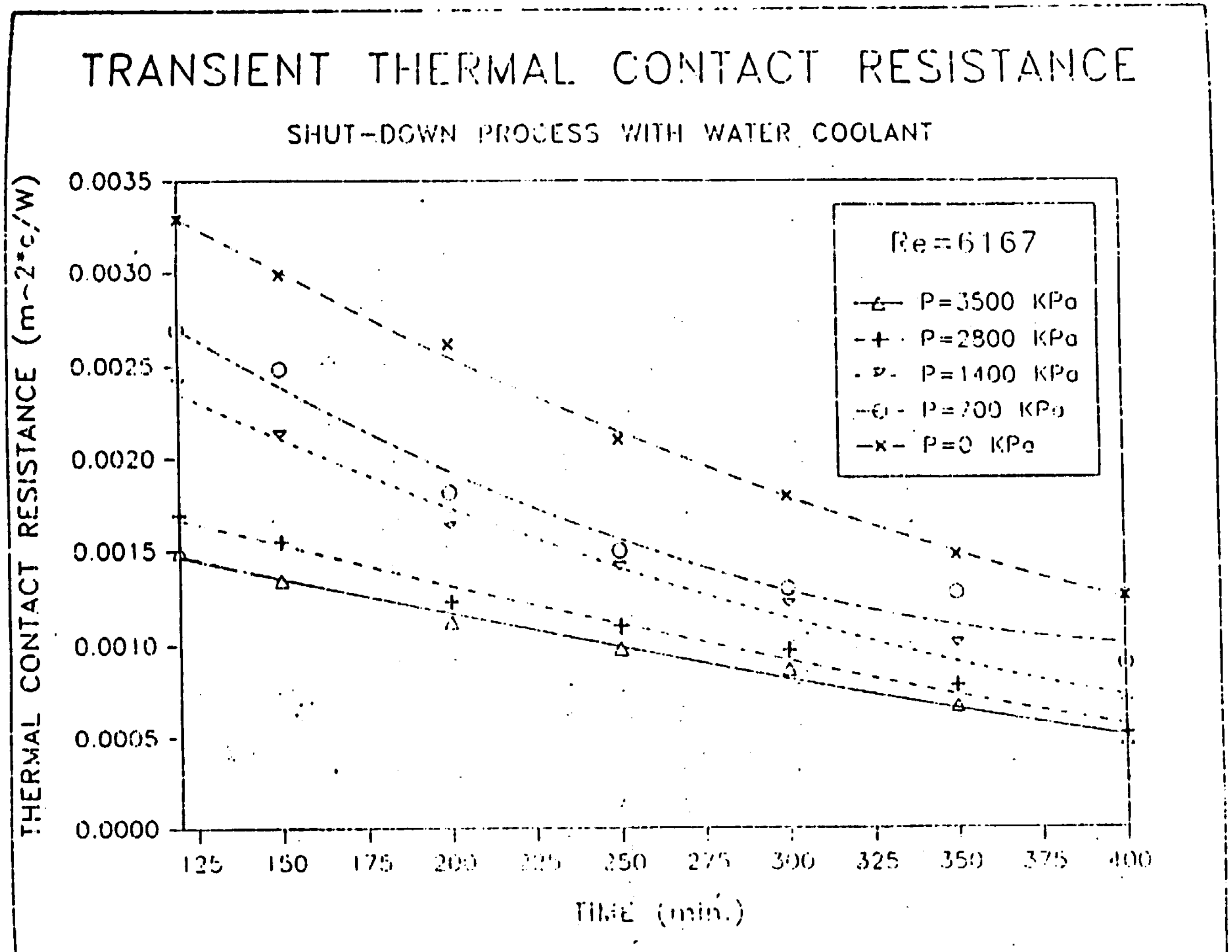

Figure 33. Experimental Transient Thermal Contact Resistance (Shut-Down Condition with Water Coolant, Re = 6167).

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4.2.2.3 The Effect of the Stack Clamping Pressure and the Cooling System Flow Characteristics on the Experimental Transient Overall Heat Transfer Coefficient

(a) Water Coolant (Re = 1250 to RE = 6167)

Figure 34 through Figure 36 shows the variation of the transient overall heat transfer coefficient as a function of the stack clamping pressure and Reynolds number during fifteen complete shut-down processes. During each process the fuel cell model was monitored up to 360 minutes starting at a steady state to accumulate the required experimental data.

(b) Oil Coolant (Re=15 to Re=80)

Refer to Figure 37 through Figure 39 for a summary of the experimental results when oil coolent is used during a shut-down process.

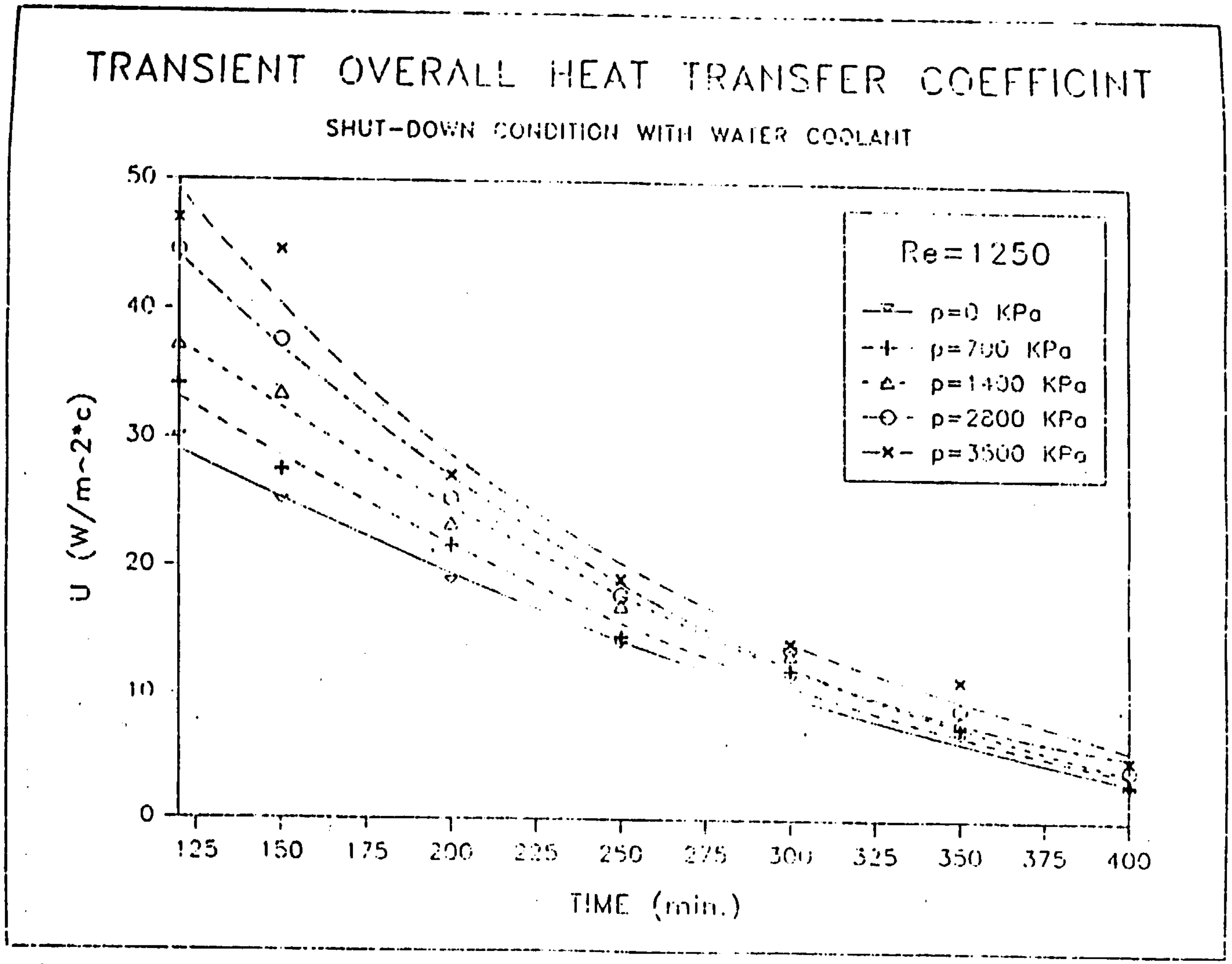

Figure 34. Experimental Transient Overall Heat Transfer Coefficient (Shut-Down Condition with Water Coolant, Re = 1250).

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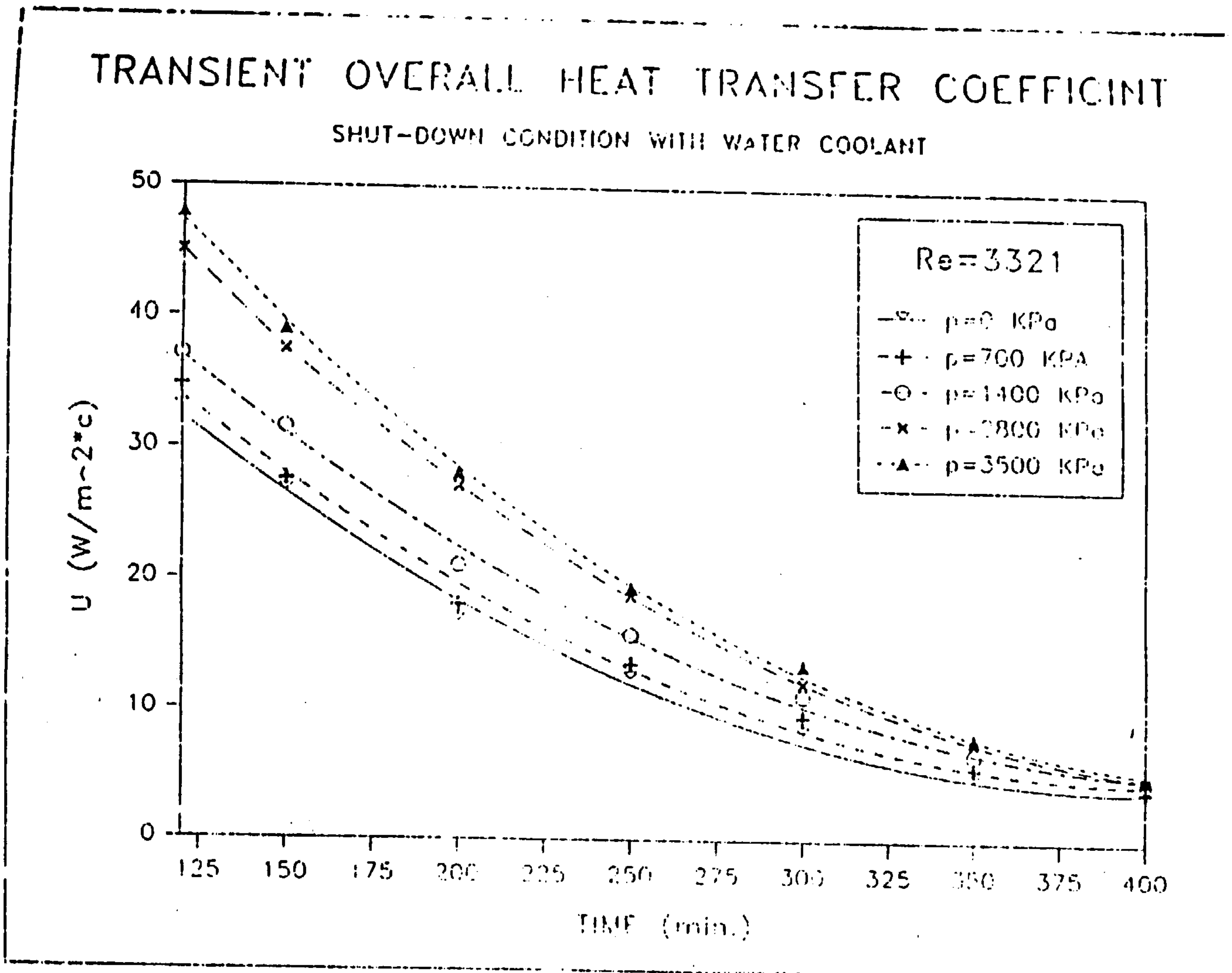

Figure 35. Experimental Transient Overall Heat Transfer Coefficient (Shut-Down Condition with Water Coolant, Re = 3321).

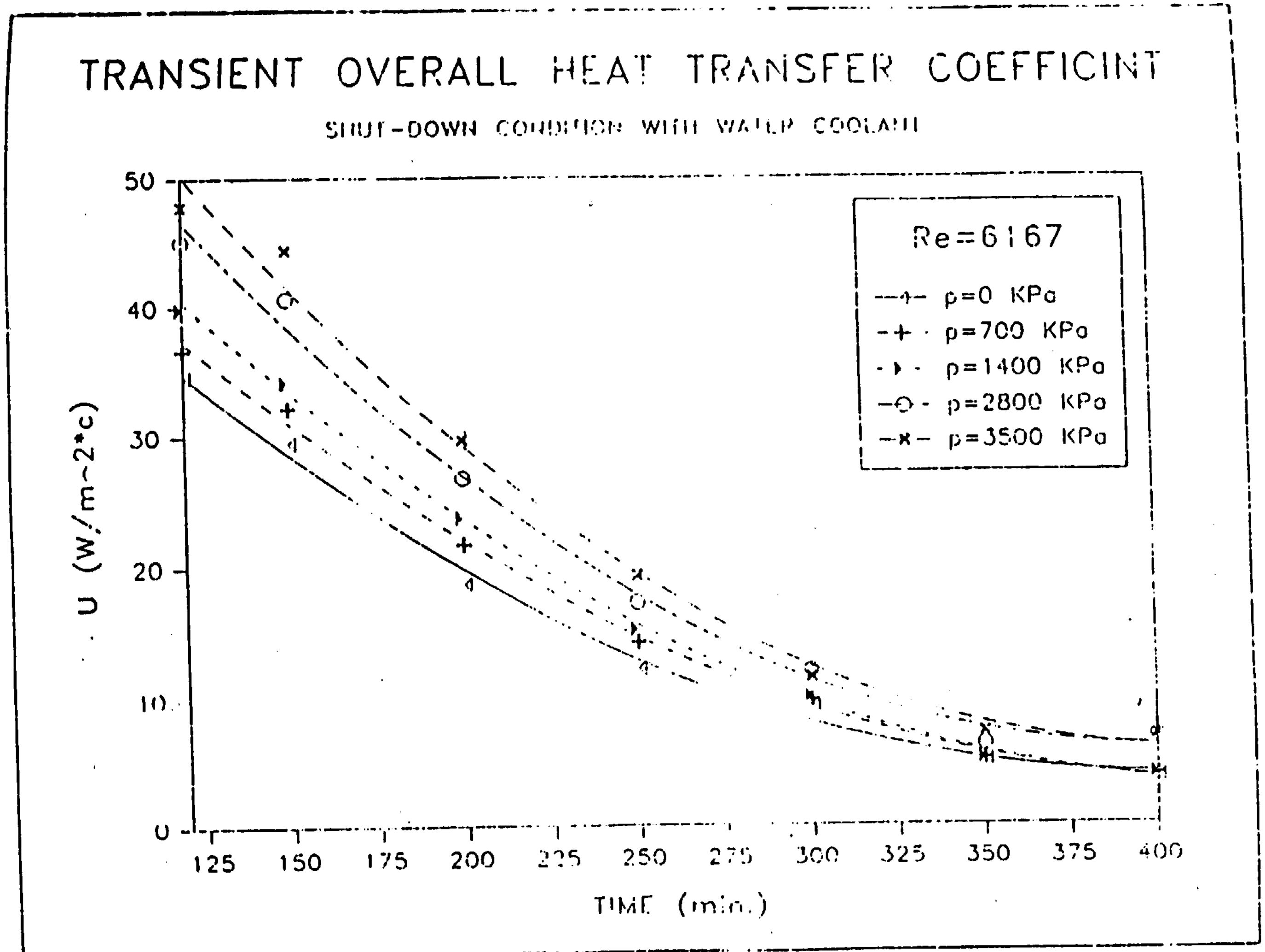

Figure 36. Experimental Transient Overall Heat Transfer Coefficient (Shut-Down Condition with Water Coolant, Re = 6167).

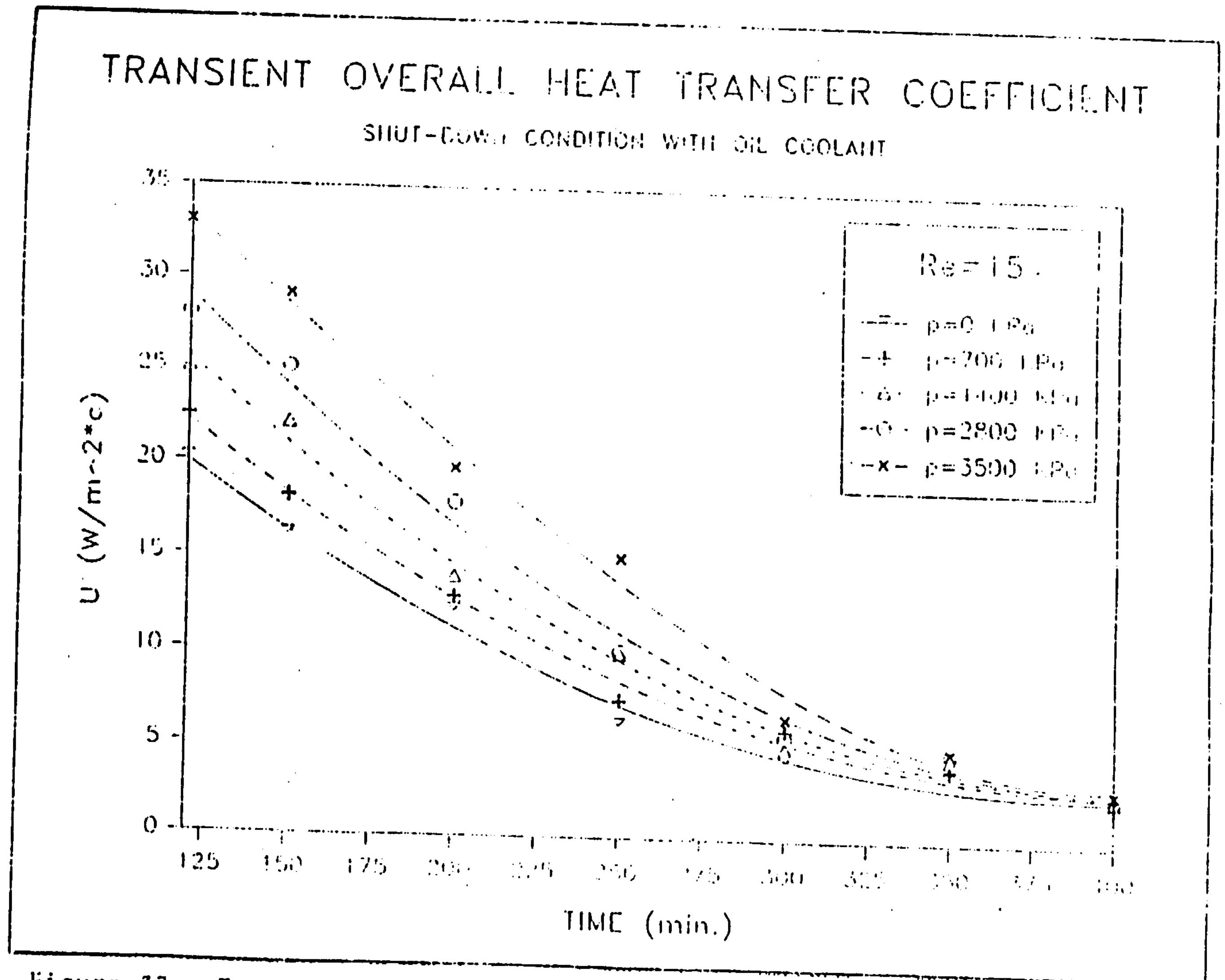

Figure 37. Experimental Transient Overall Heat Transfer Coefficient (Shut-Down Condition with Oil Coolant, Re = 15).

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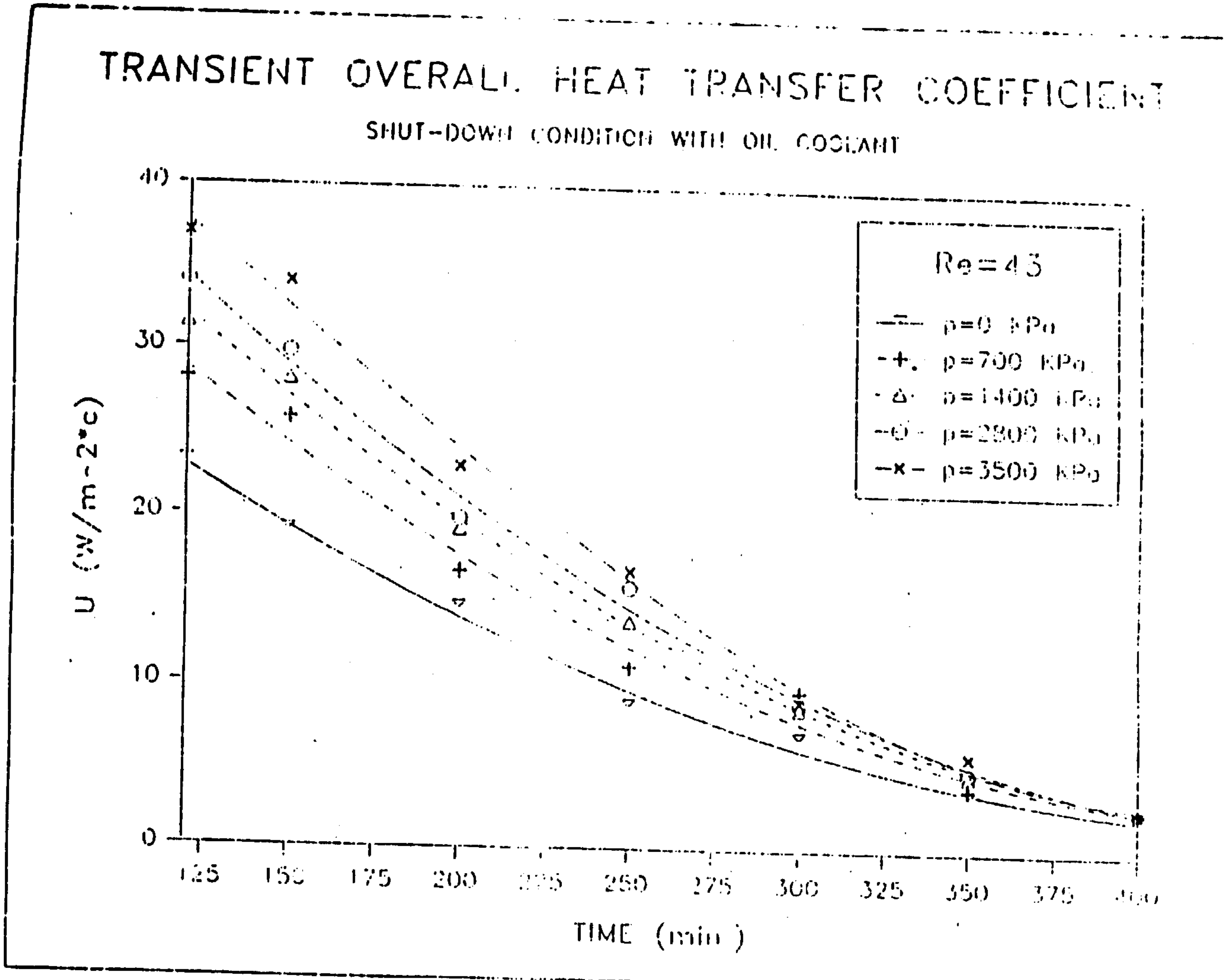

Figure 38. Experimental Transient Overall Heat Transfer Coefficient (Shut-Down Condition with Oil Coolant, Re = 43).

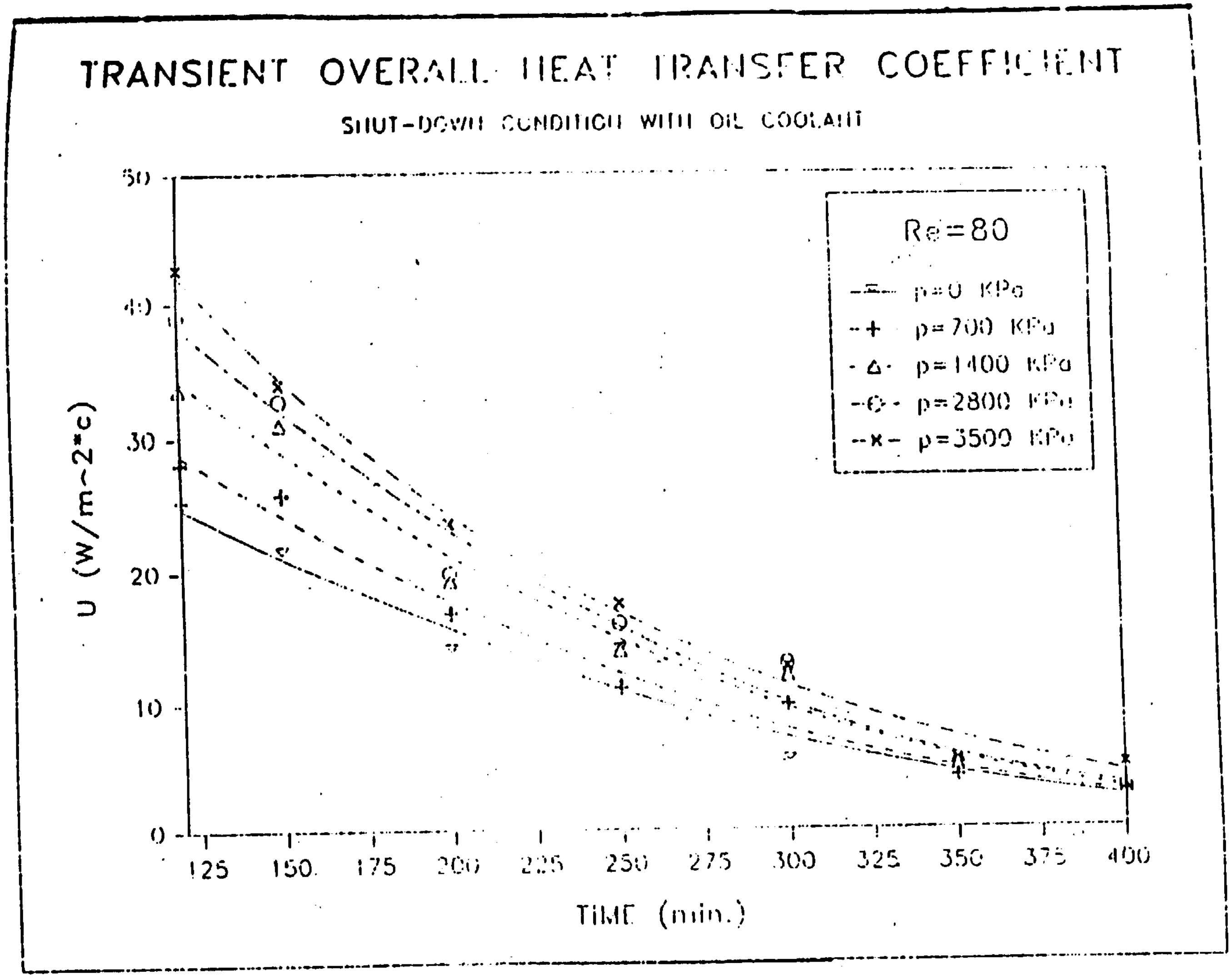

Figure 39. Experimental Transient Overall Heat Transfer Coefficient (Shut-Down Condition with Oil Coolant, Re = 80).

4.3 Developed Experimental Correlations

In order to describe the transient performance of fuel-cell, a mathematical expression that interrelates the cell convection heat transfer coefficient, overall heat transfer coefficient and Nusselt number should be developed. Mathematical correlations with an exponential function of time was found to be the most suitable method to achieve this important research objective. This technique allows the establishment of the relationships between the effective parameters and also will exhibit the sensitivity of the transient function to the variation of every independent variable such as pressure and Re number.

A computer program to calculate the convective heat transfer coefficient, the overall heat transfer coefficient, Nusselt number, thermal contact resistance and the effective temperature drop was developed to simulate the change of those parameters during the transient process. The Matlab and the Picquick softwares at the VAX center of Cleveland State University were utilized to employee the curve fitting needed, linear, polynomial, exponential, flexible, and the other algorithms. Also those two softwares were used to plot the generated results.

The transient mathematical correlations that represent the convection heat transfer coefficient and the Nusselt number were found to be a function of the following:

(1) Reynolds Number (flow condition)

(2) Prandlt Number (working fluid property)

(3) Time intervals and the designed operation conditions that reflects the effect of operation conditions on the cell plate surface temperature.

4.3.1 Start-Up Process

In this section, mathematical correlations will be developed to describe the variation of the convection heat transfer coefficient, overall heat transfer coefficient and the Nusselt number during a start-up process as a function of the flow characteristics. Also the effect of the stack pressure should be demonstrated by the overall heat transfer coefficient.

4.3.1.1 Transient Convection Heat Transfer Coefficient and Transient Nusselt Number

For the start-up operation condition the h(t) and Nu(t) correlations can be written as follows:

$$h(t) = \left[A_1 * F_1(Re,Pr) * e^{\lambda_1 t} - B_1 * G_1(Re,Pr)\right] e^{\alpha_1 0} \quad (14)$$

and

$$Nu(t) = \left[A_2 * F_2(Re,Pr) e^{\lambda_{2,} t} - B_2 * G_2(Re,Pr)\right] e^{\alpha_2 0} \quad (15)$$

where

A_1 = constant,

$F_1(Pr,Re)$ = function of Re and Pr,

$G_1(Pr,Re)$ = function of Re, Pr, and initial operation conditions,

λ_1 = time constant,

o = operations condition parameter,

α_1 = operation condition constant,

B_1 = constant,

A_2 = constant

$F_2(Pr,Re)$ = function of Re, and Pr,

$G_2(Pr,Re)$ = function of Re, Pr, and initial operation condition,

λ_2 = time constant,

α_2 = operation condition constant,

β_2 = constant.

It should be noted that F_1, G_1, F_2, and G_2 are not functions of time but actually are functions of the flow, working fluid properties and design criteria. The developed experimental correlations for both considered working fluids can then be written using equations (14) and is as follows:

(a) <u>Water Coolant (Re = 1250 to Re = 6167)</u>

$$h(t) = 31.088\ (Re^{0.05779})(e^{0.00953t})(Pr^{0.01433})(e^{0.000124o}) - 31.088\ (Re^{0.05779})(Pr^{0.01433})(e^{0.000124o}) \quad (15)$$

$$Nu(t) = 0.3259\ (Re^{0.05632})(e^{0.008219t})(Pr^{0.0385})(e^{0.000123o}) - 0.3259\ (Re^{0.05632})(Pr^{0.00385})(e^{0.000123o}) \quad (16)$$

The variation of Nu(t) with different Re number for the considered start-up process are exhibited by Figure 40. Only five Re number results are shown to summarize. It should be noted that $F_1 = G_2$, $A_1 = B_1$, $A_2 = B_2$ and $F_2 = G_2$ and $\alpha_1 o$, $\alpha_2 o$ are correction factors that will allow the correlation to be sensitive to the effect of P on the cell

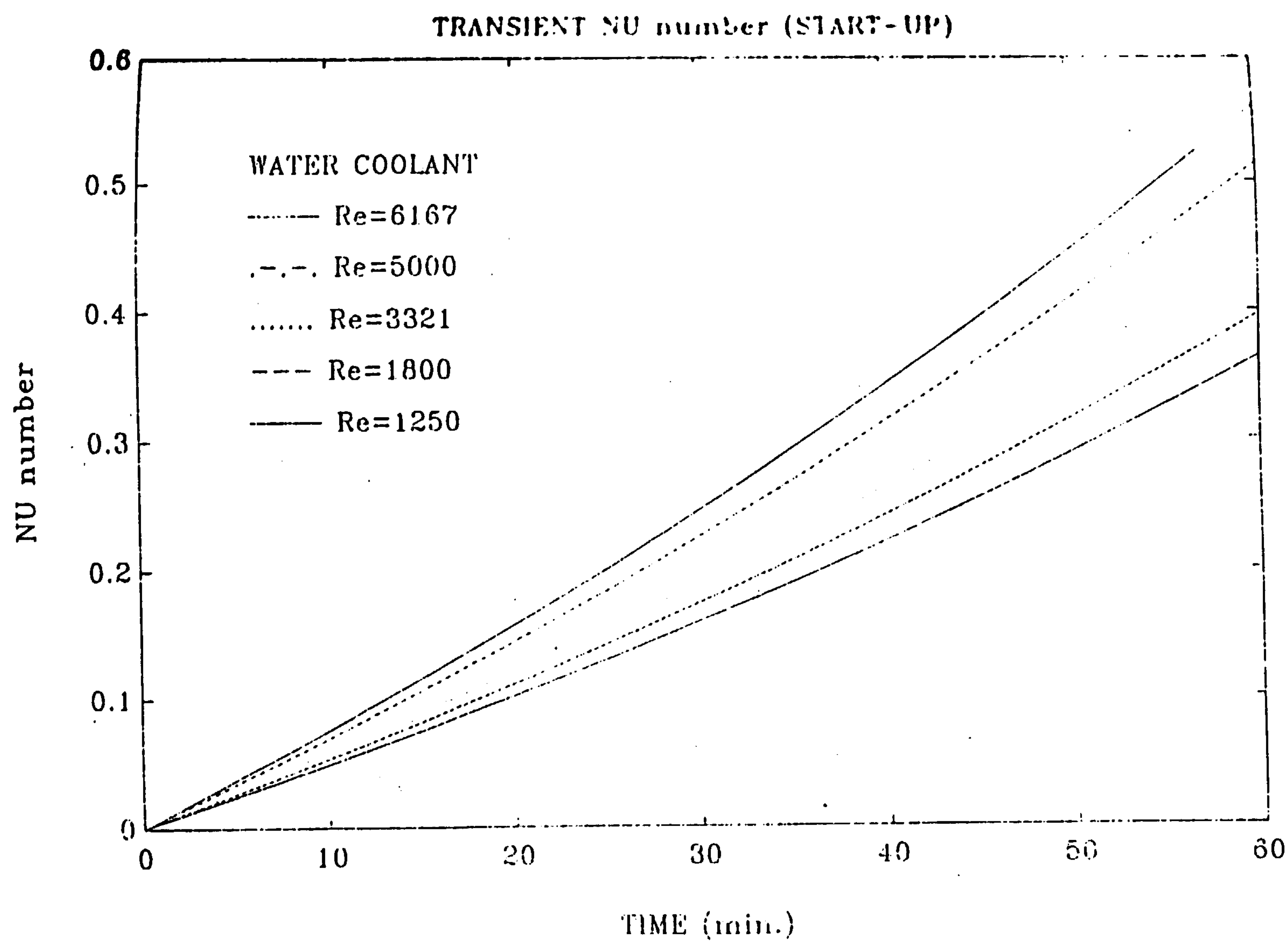

Figure 40. Analytical Transient Nusselt Number (Start-Up Process with Water Coolant).

temperature. The second term of the two equations was used to simulate the initial equation condition of zero heat transfer at t = 0.

(b) Oil Coolant (Re=15 to Re=80)

$$h(t) = 16.088\ (Re^{0.216})\ (e^{0.00961t})\ (Pr^{0.0076})\ (e^{1.356*10-4o})$$
$$-\ 16.088\ (Re^{0.216})\ (Pr^{0.0076})\ (e^{1.356*10-4o}) \quad (17)$$

$$Nu(t) = 0.7326\ (Re^{0.214})\ (Pr^{0.0039})\ (e^{1.356*10-4o}) \quad (18)$$

The variation of Nu(t) with different considered cases start-up processes are shown in Figure 41.

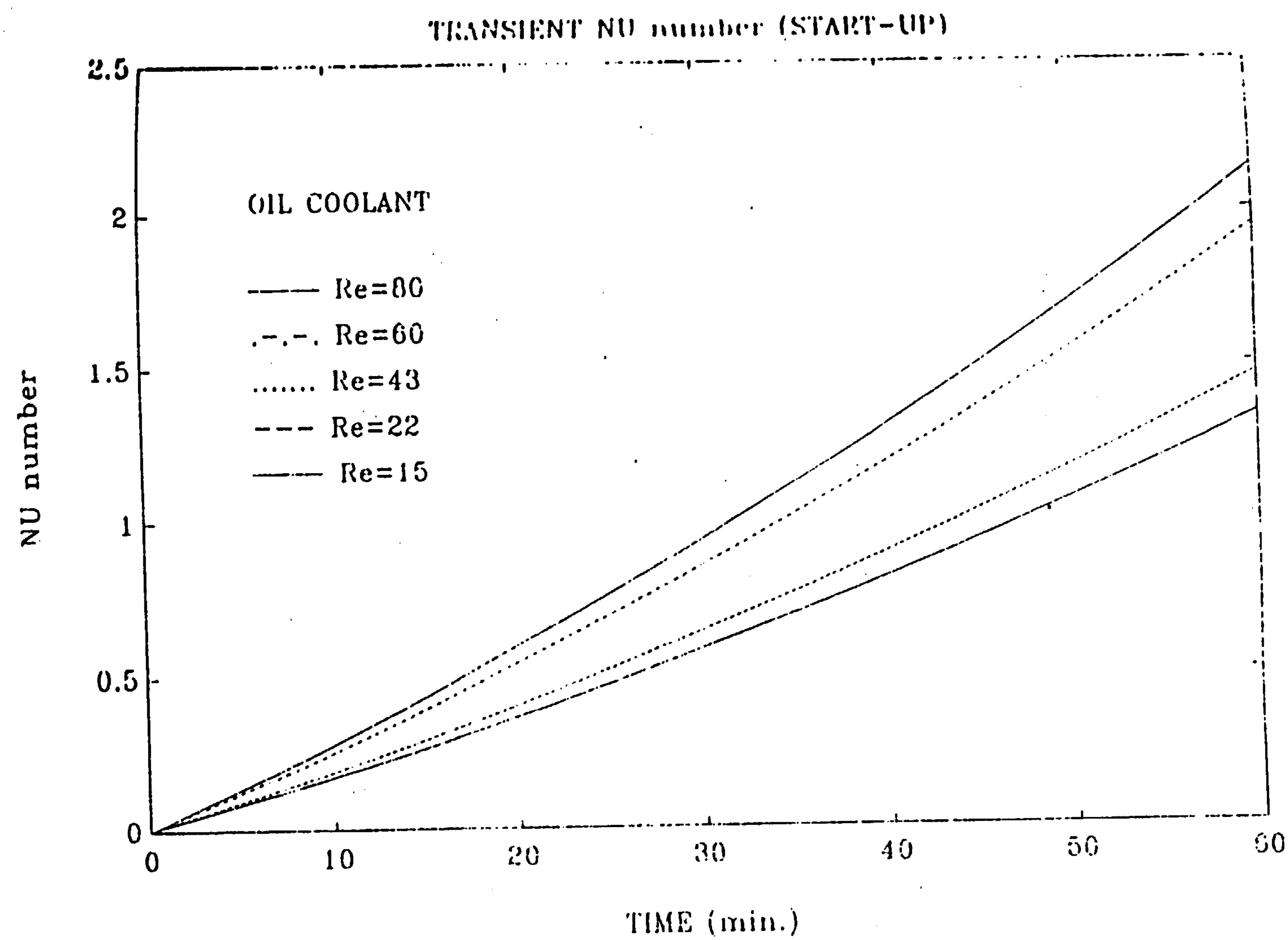

Figure 41. Analytical Transient Nusselt Number (Start-Up Process with Oil Coolant).

4.3.1.2 Transient Thermal Contact Resistance and Effective Temperature Drop

The experimental correlations that were developed to simulate the change of the transient thermal contact resistance and the effective temperature drop must demonstrate the effect of time, stack clamping pressure flow characteristics, and the operation condition as concluded from the experimental results. In general, the developed correlations can be formulated as follows:

$$r_c(t) = A_3\left[W_1(p)*e^{\lambda_3 t} - W_2(p)\right]e^{\gamma_1 O} \qquad (19)$$

$$\Delta T(t) = \left[(A_4 - W_3(p))e^{\lambda_4 t} - (A_5 - W_4(p))\right]e^{\gamma_2 O} \qquad (20)$$

where

A_3, A_4, A_5 = constants,

$W_1(p)$ = function of stack pressure,

λ_3 = time constant,

$W_2(p)$ = function of stack pressure,

p = stack pressure

λ_4 = time constant,

γ_1, γ_2 = operation condition constants,

$W_3(p)$ = function of stack pressure,

$W_4(p)$ = function of stack pressure.

o = operation condition parameter

It is important to notice that W_1, W_2, W_3 and W_4 are not a function of time but a function of the applied stack pressure, therefore, the developed correlation for both considered working fluids can be written as follows:

(a) Water Coolant (Re = 1250 to Re = 6167)

$$r_c(t) = 0.00357[(e^{-0.000236p})*(e^{0.0114t}) - (e^{-0.000236p})]\ e^{-0.0000179o} \quad (21)$$

$$T(t) = [(7.986 - 0.000959p)e^{0.012t} - (7.986 - 0.000959p)]\ e^{-0.0000116o} \quad (22)$$

The results generated by the above two correlations are shown in Figure 42 to Figure 44 and Figures 48 to 50 respectively, for all the stack pressures applied and for the minimum, average, and maximum volumetric flow rate. It should be noticed that $w_1 = w_2$ and $w_3 = w_4$ for this case and o was found to be directly proportional to the flow rate.

(b) Oil Coolant (Re=15 to Re=80)

$$r_c(t) = 3.61*10^{-3}\ (e^{0.0122t})\ *\ (e^{-2.235*10-4p}) - (e^{-2.356*10-4p})]\ e^{-1.796*10-5o} \quad (23)$$

$$T(t) = [(7.985 - 9.597*10^{-4}p)\ e^{0.0122t} - (7.985 - 9.597*10^{-4}p)]\ e^{-0.0000116o} \quad (24)$$

A summary for the results generated by the above two correlations for the oil coolant case are shown in Figure 45 to Figure 47 and Figures 51 to 53 respectively, for all the stack pressures applied and for the minimum, average, and maximum volumetric flow rate.

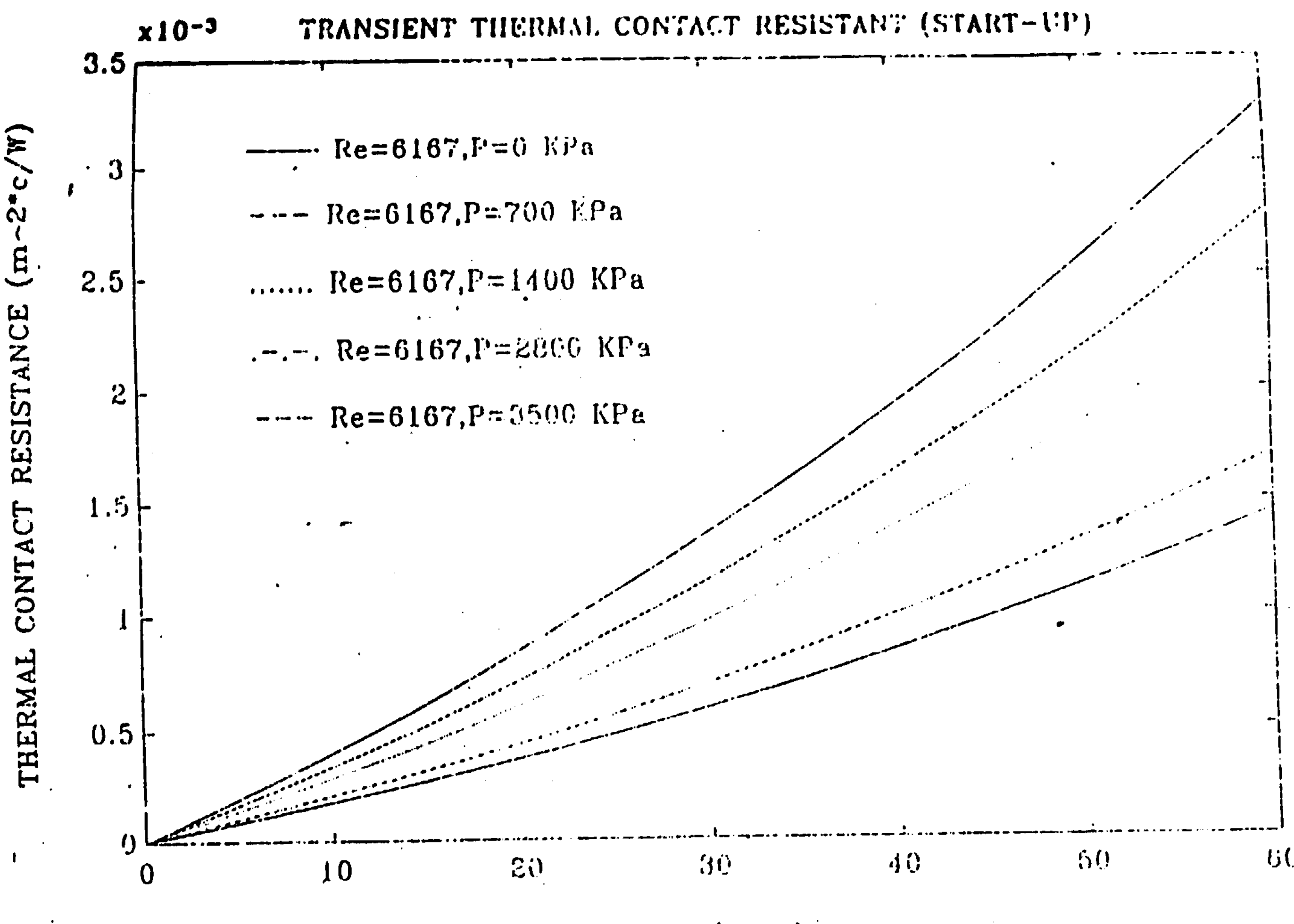

Figure 42. Analytical Transient Thermal Contact Resistance (Start-Up Condition with Water Coolant, Re = 1250).

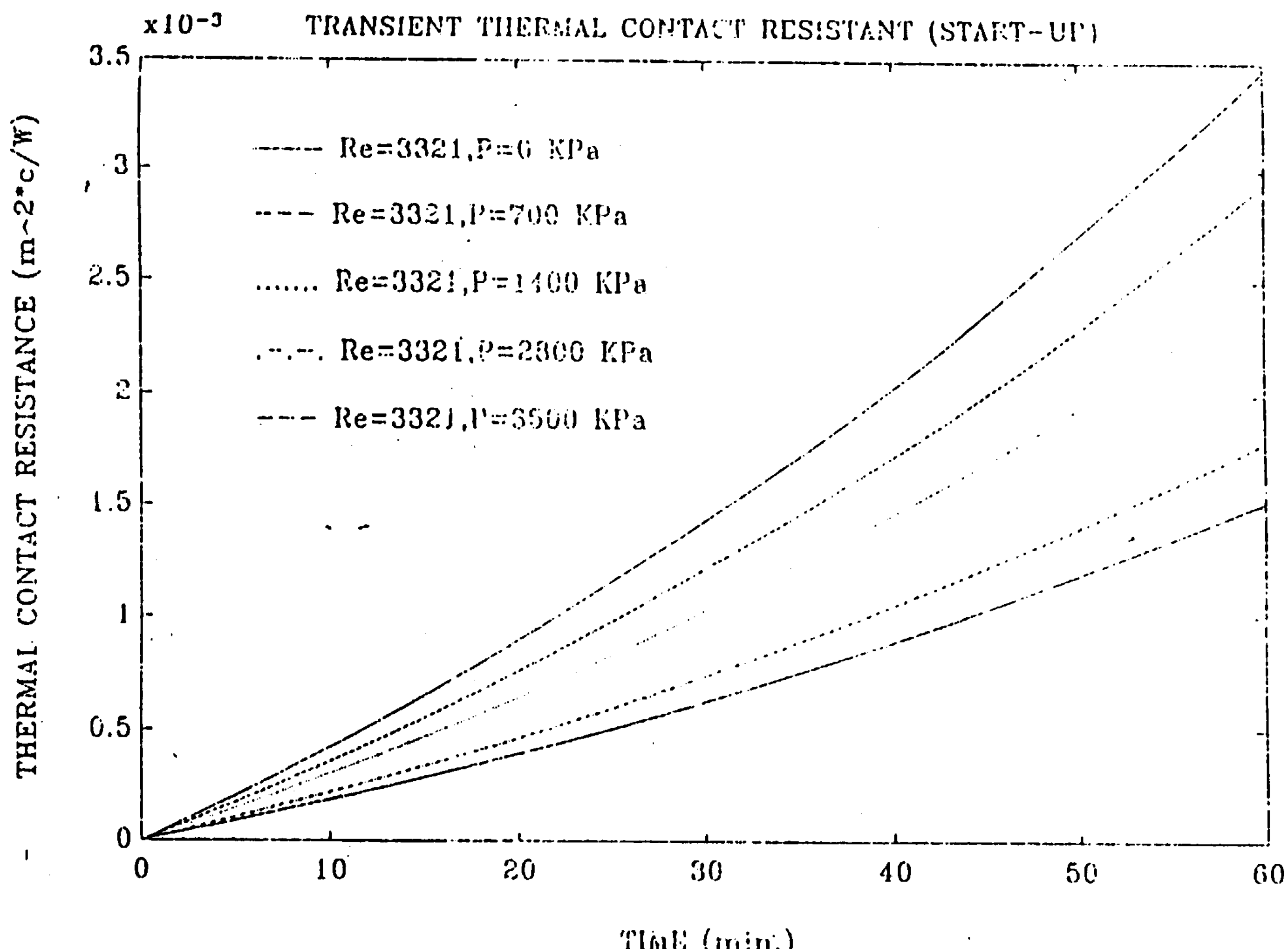

Figure 43. Analytical Transient Thermal Contact Resistance (Start-Up Condition with Water Coolant, Re = 3321).

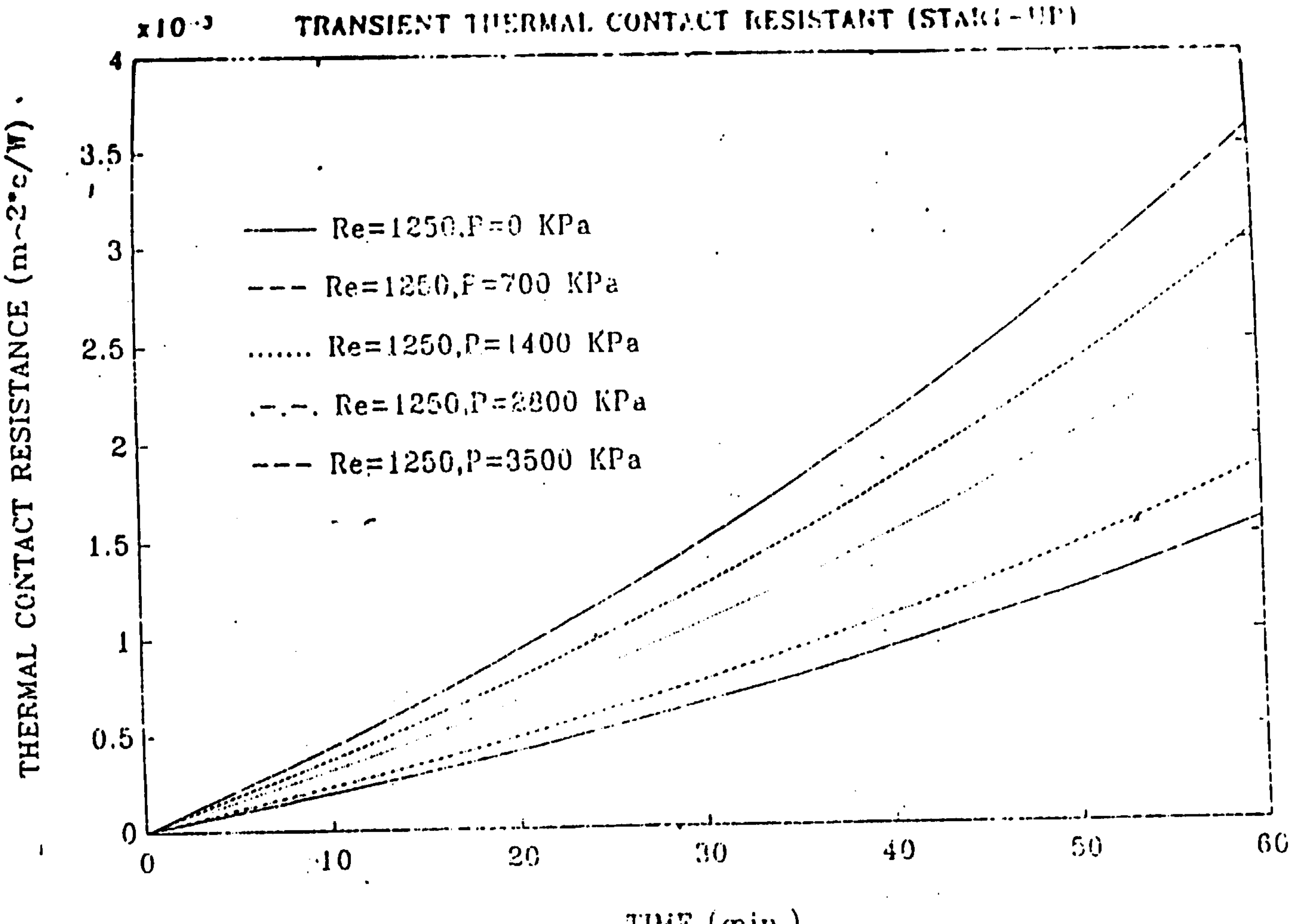

Figure 44. Analytical Transient Thermal Contact Resistance (Start-Up Condition with Water Coolant, Re = 3167).

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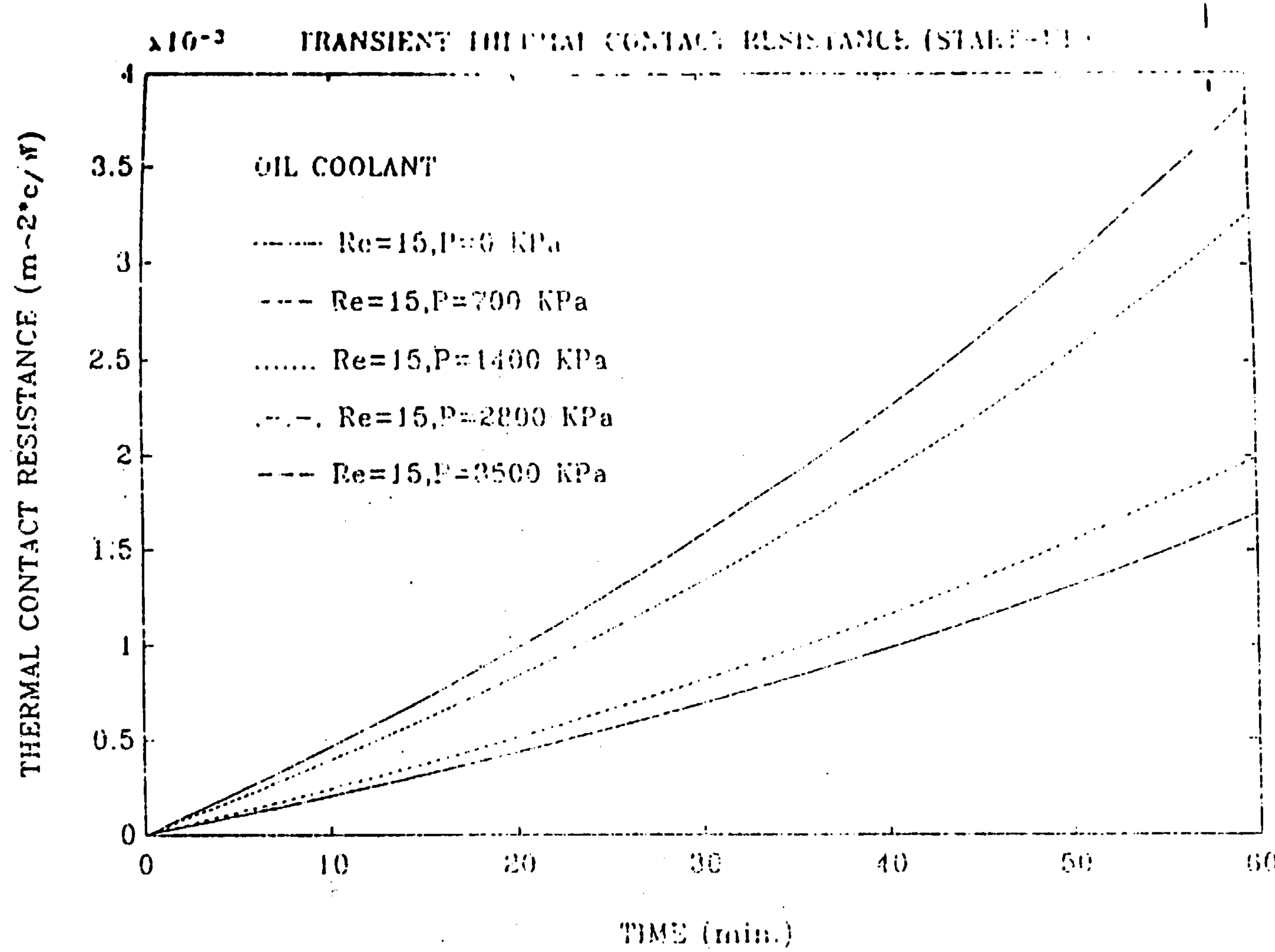

Figure 45. Analytical Transient Thermal Contact Resistance (Start-Up Condition with Oil Coolant, Re = 15).

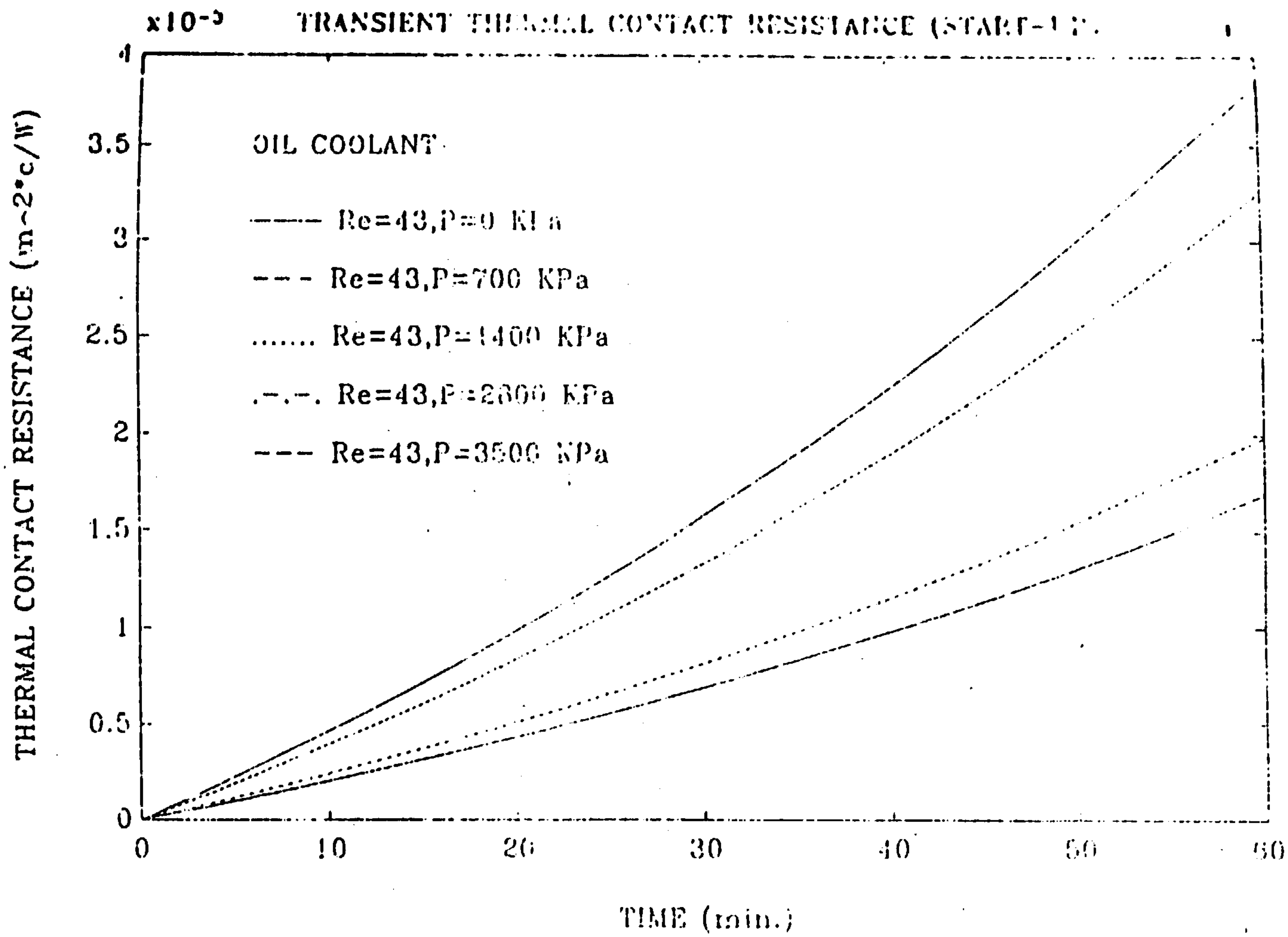

Figure 46. Analytical Transient Thermal Contact Resistance (Start-Up Condition with Oil Coolant, Re = 43).

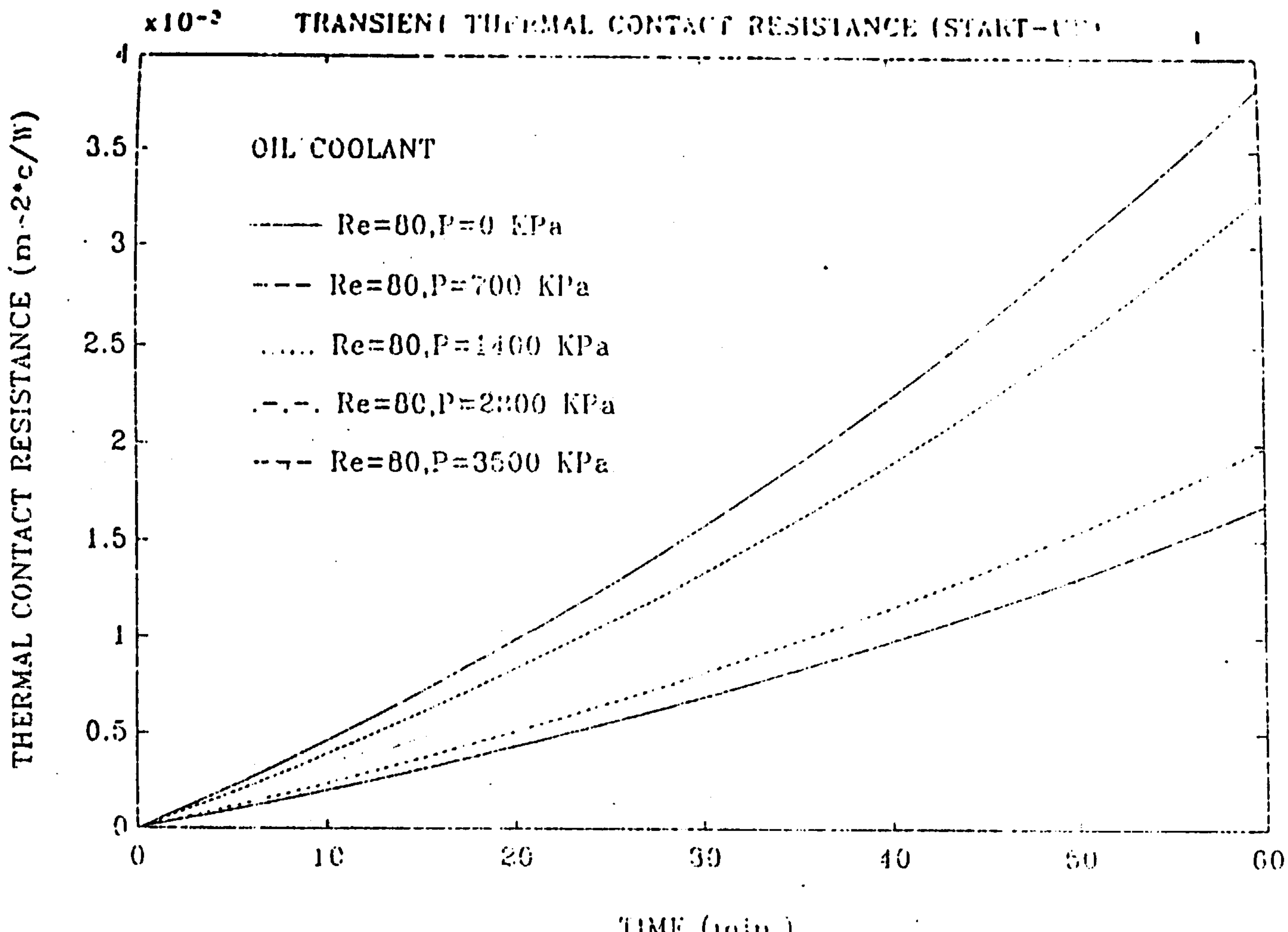

Figure 47. Analytical Transient Thermal Contact Resistance (Start-Up Condition with Oil Coolant, Re = 80).

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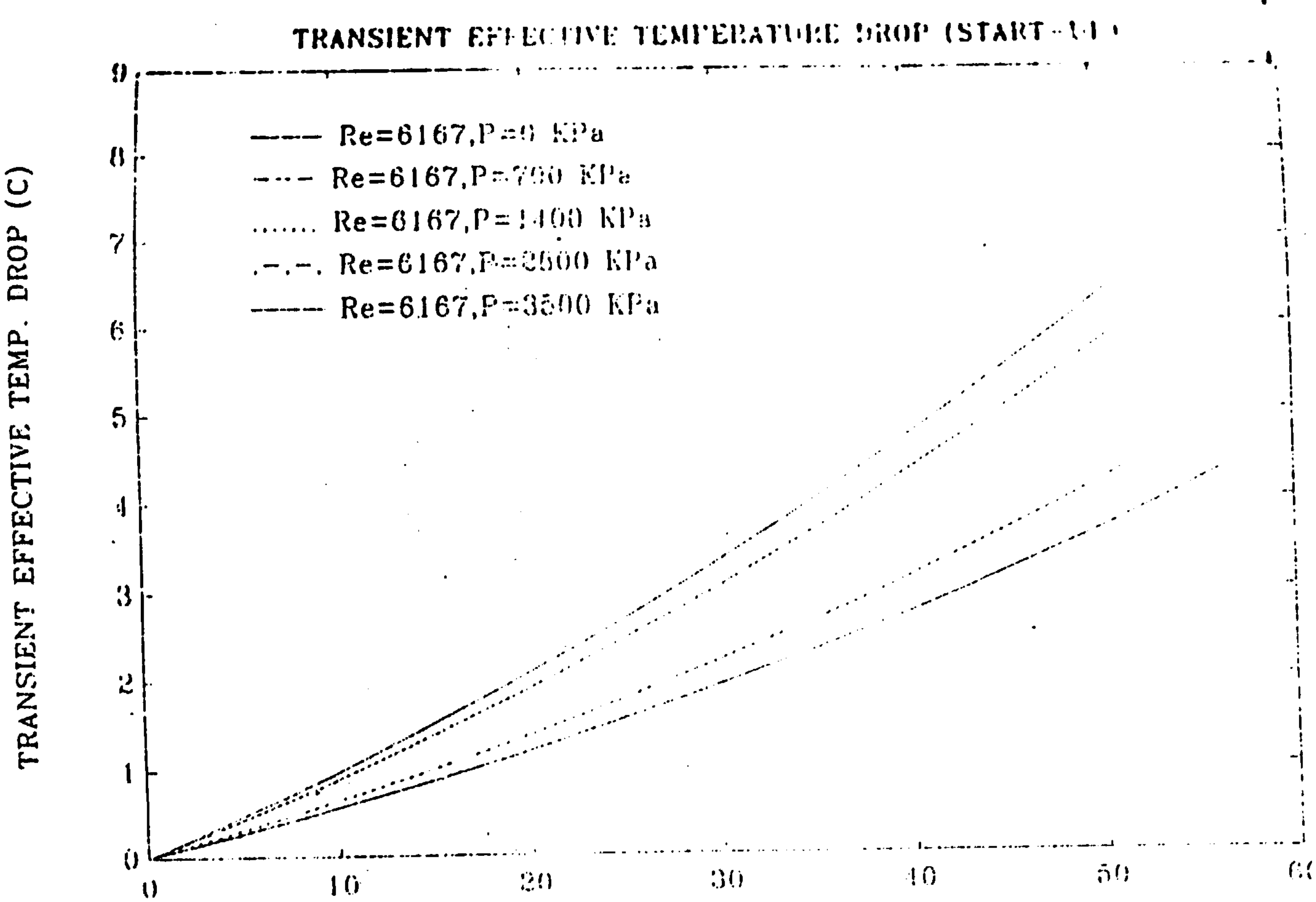

Figure 48. Effective Temperature Drop (Start-Up Condition with Water Coolant, Re = 1250).

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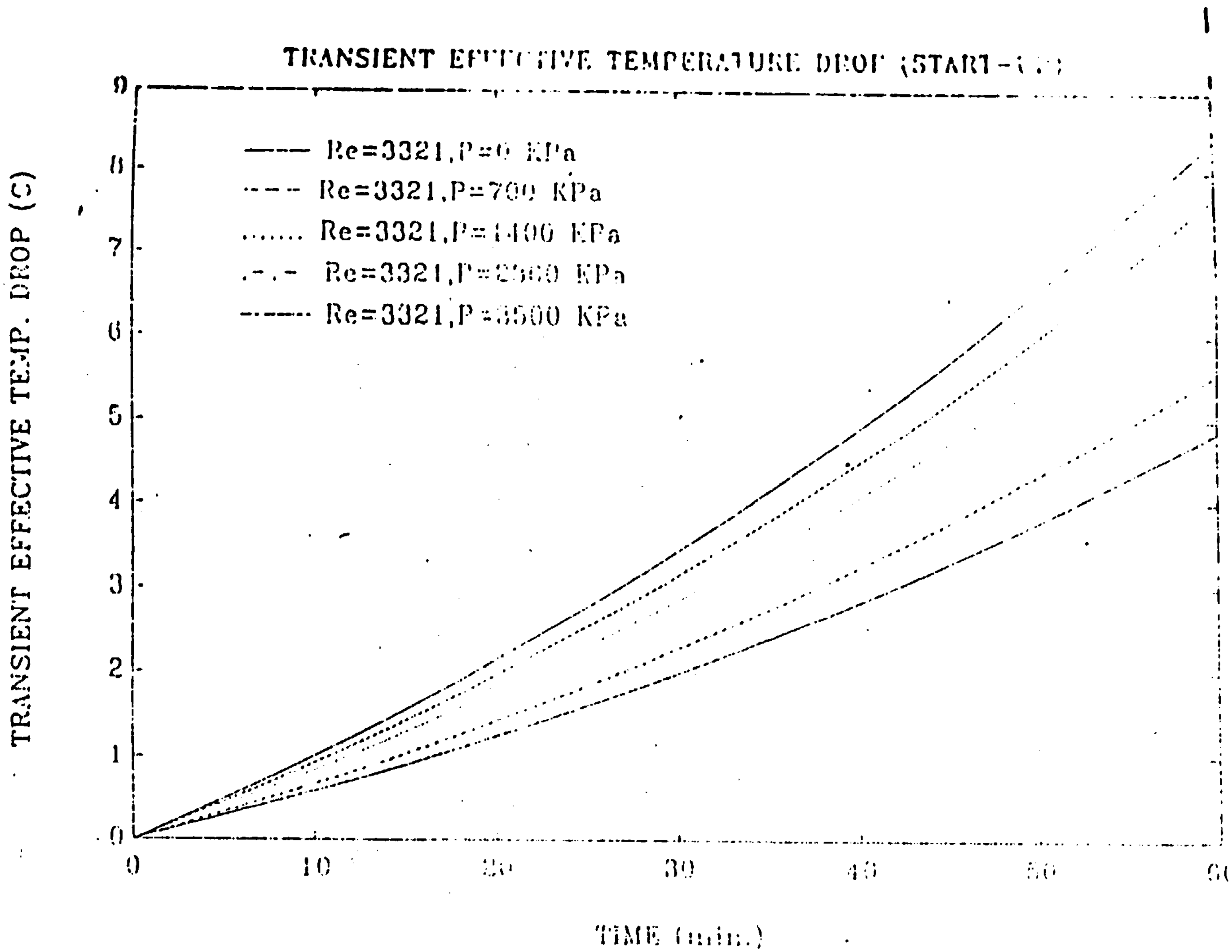

Figure 49. Effective Temperature Drop (Start-Up Condition with Water Coolant, Re = 3321).

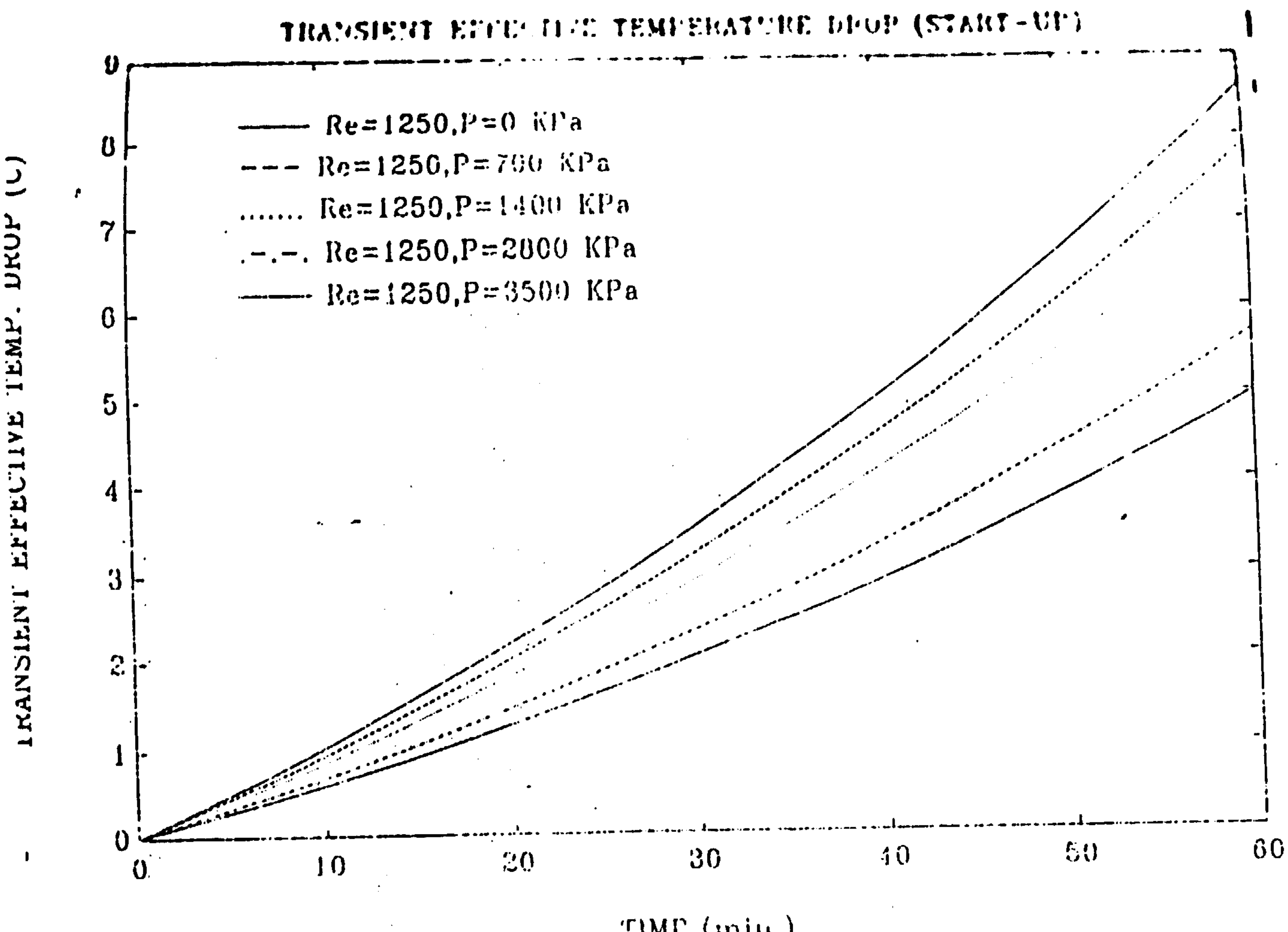

Figure 50. Effective Temperature Drop (Start-Up Condition with Water Coolant, Re = 6167).

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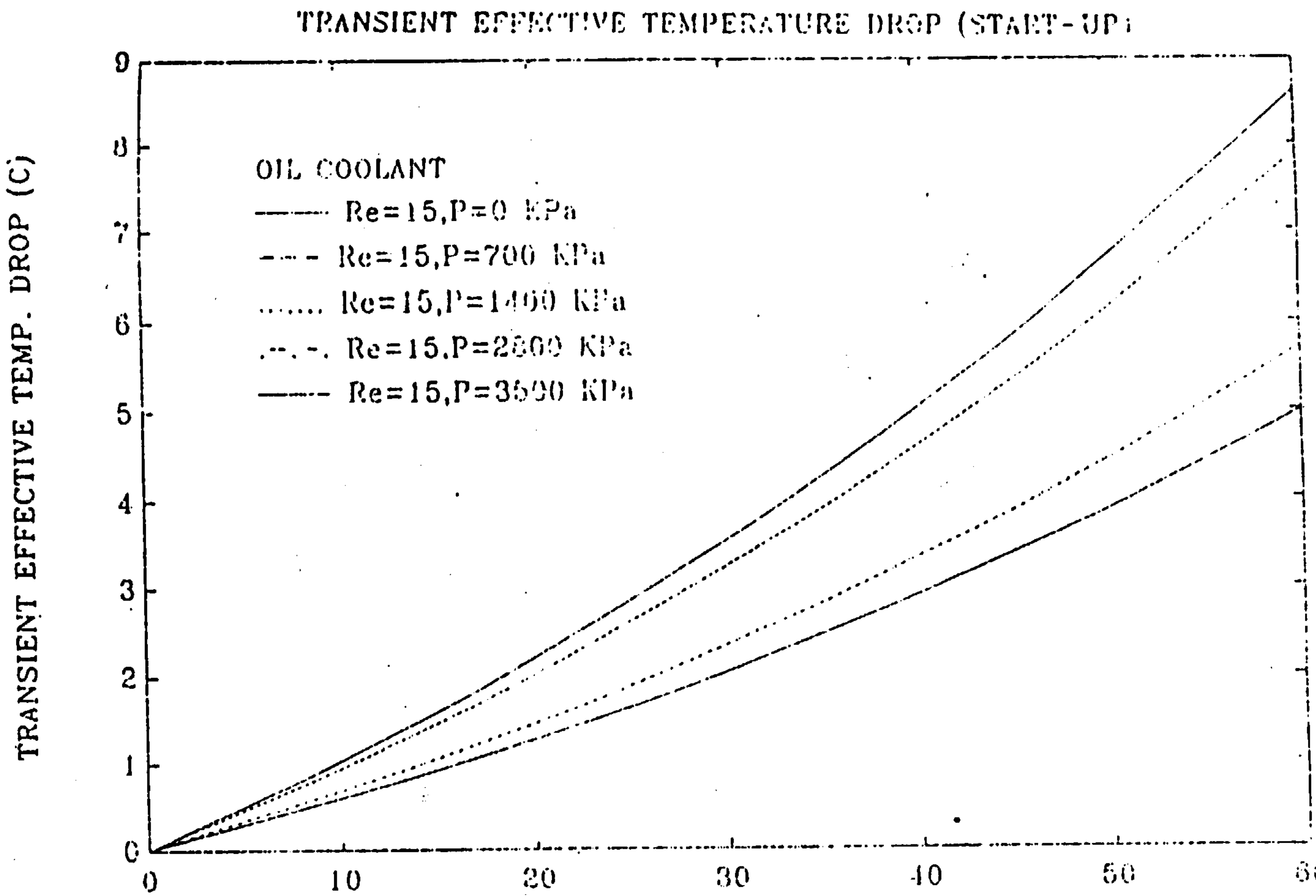

Figure 51. Effective Temperature Drop (Start-Up Condition with Oil Coolant, Re = 15)

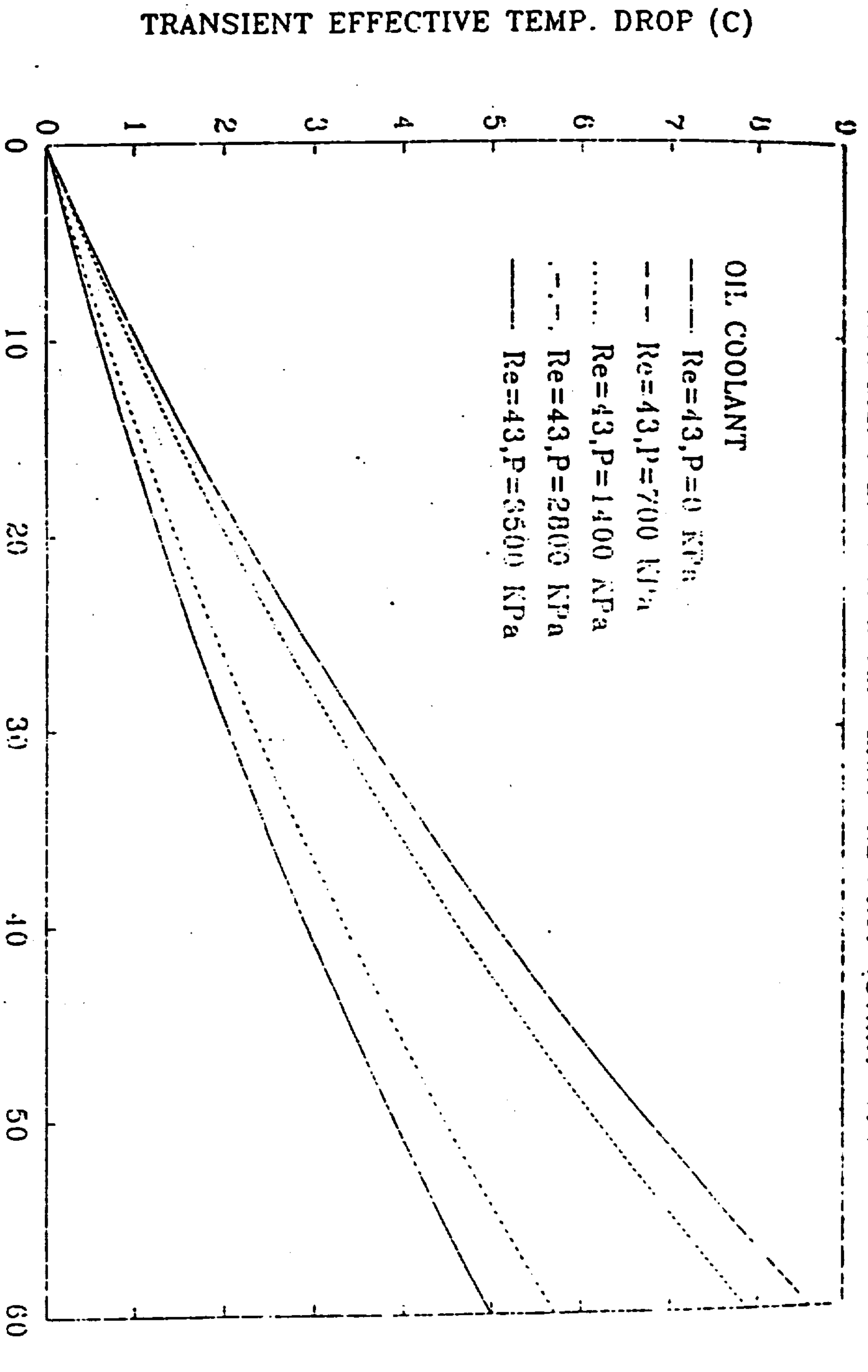

Figure 52. Effective Temperature Drop (Start-Up Condition with Oil Coolant, RE = 43).

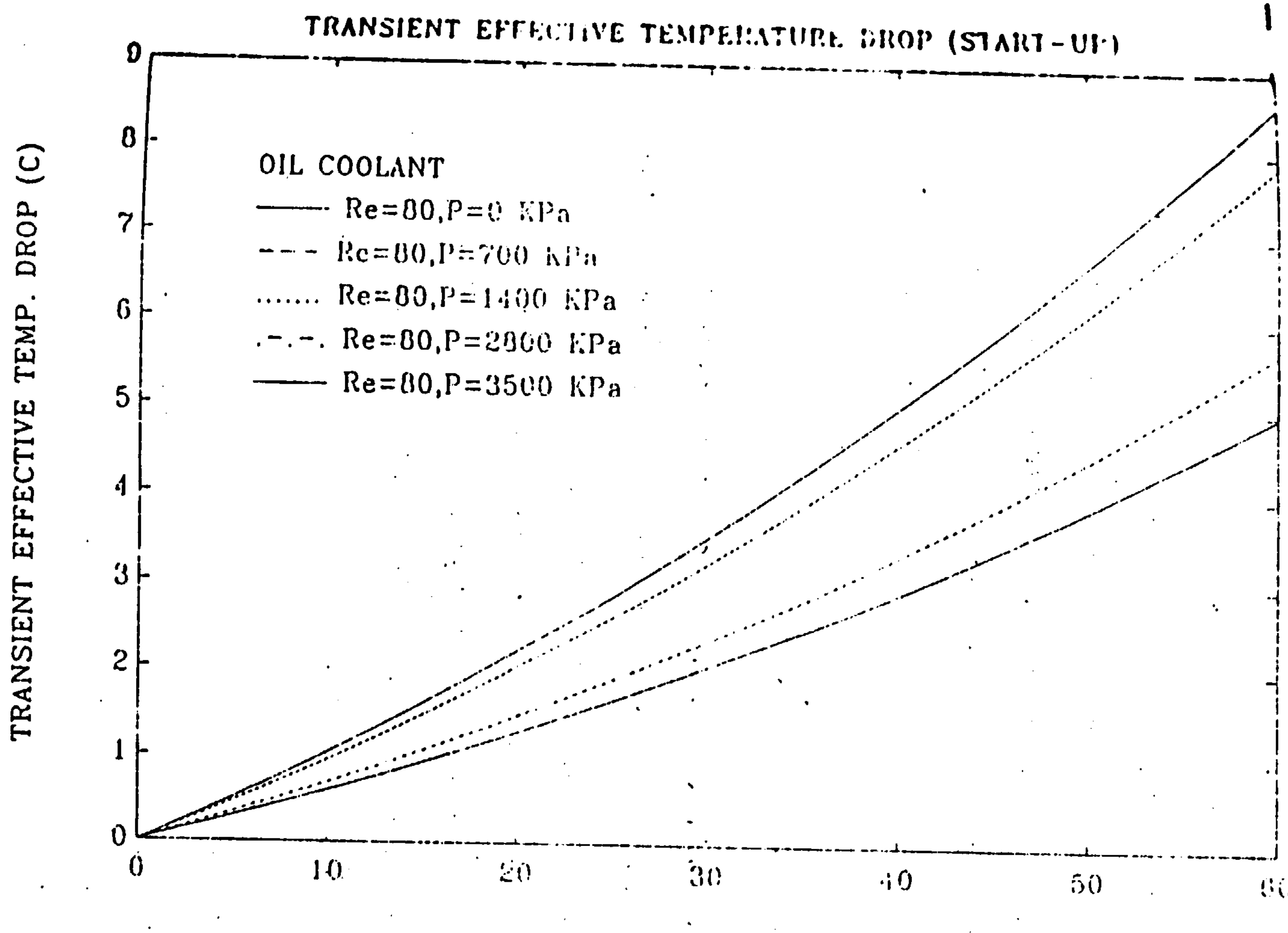

Figure 53. Effective Temperature Drop (Start-Up Condition with Oil Coolant, Re = 80).

4.3.1.3 Calculated Transient Overall Heat Transfer Coefficient

It is important to calculate the transient overall heat transfer coefficient utilizing the correlation results of the transient convective heat transfer coefficient and the transient thermal contact resistance during a start-up process to determine the accuracy of the developed correlations to calculate the value of (U(t)). The following previously developed equation was utilized to calculate (U(t)):

$$U(t) = \frac{1}{\left[\frac{1}{h(t)} + \frac{\Delta x}{K_{total}} + r_c(t) \right]}$$

Results using the developed correlation were utilized to generate results for the two incompressible working fluids:

(a) <u>Water Coolant (Re = 1250 to Re = 6167)</u>

To summarize only the minimum average and maximum Re numbers were used here as exhibited by Figure 54 to Figure 56 in order to demonstrate the effect of the stack-pressure and the flow characteristics on the (U(t)) value.

(b) <u>Oil Coolant (Re=15 to Re=80</u>

Figure 57 to Figure 59 summarizes part of the calculated results for all applied stack pressure and for maximum average and minimum flow rate.

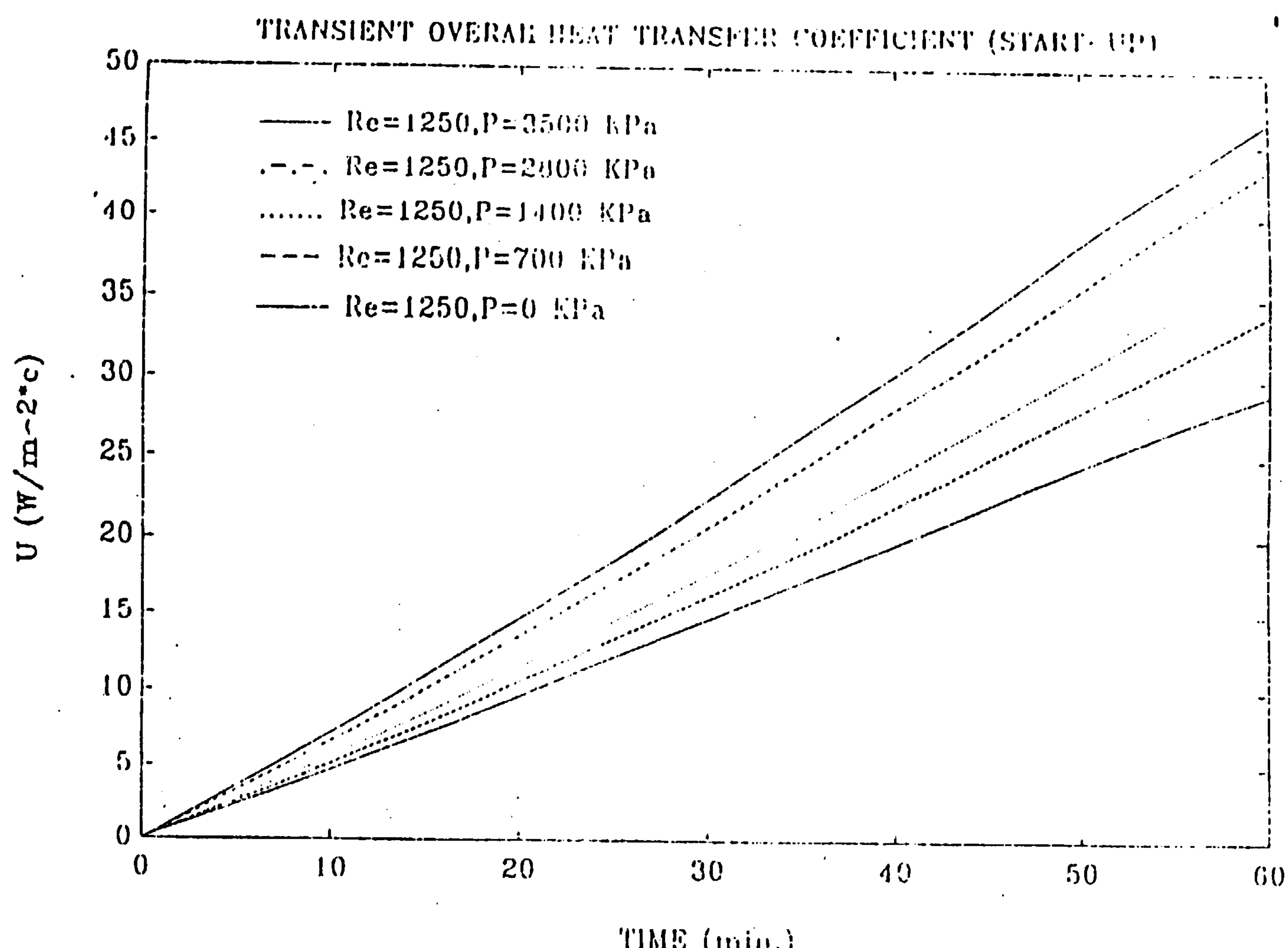

Figure 54. Analytical Transient Overall Heat Transfer Coefficients (Start-Up Condition with Water Coolant, Re = 1250).

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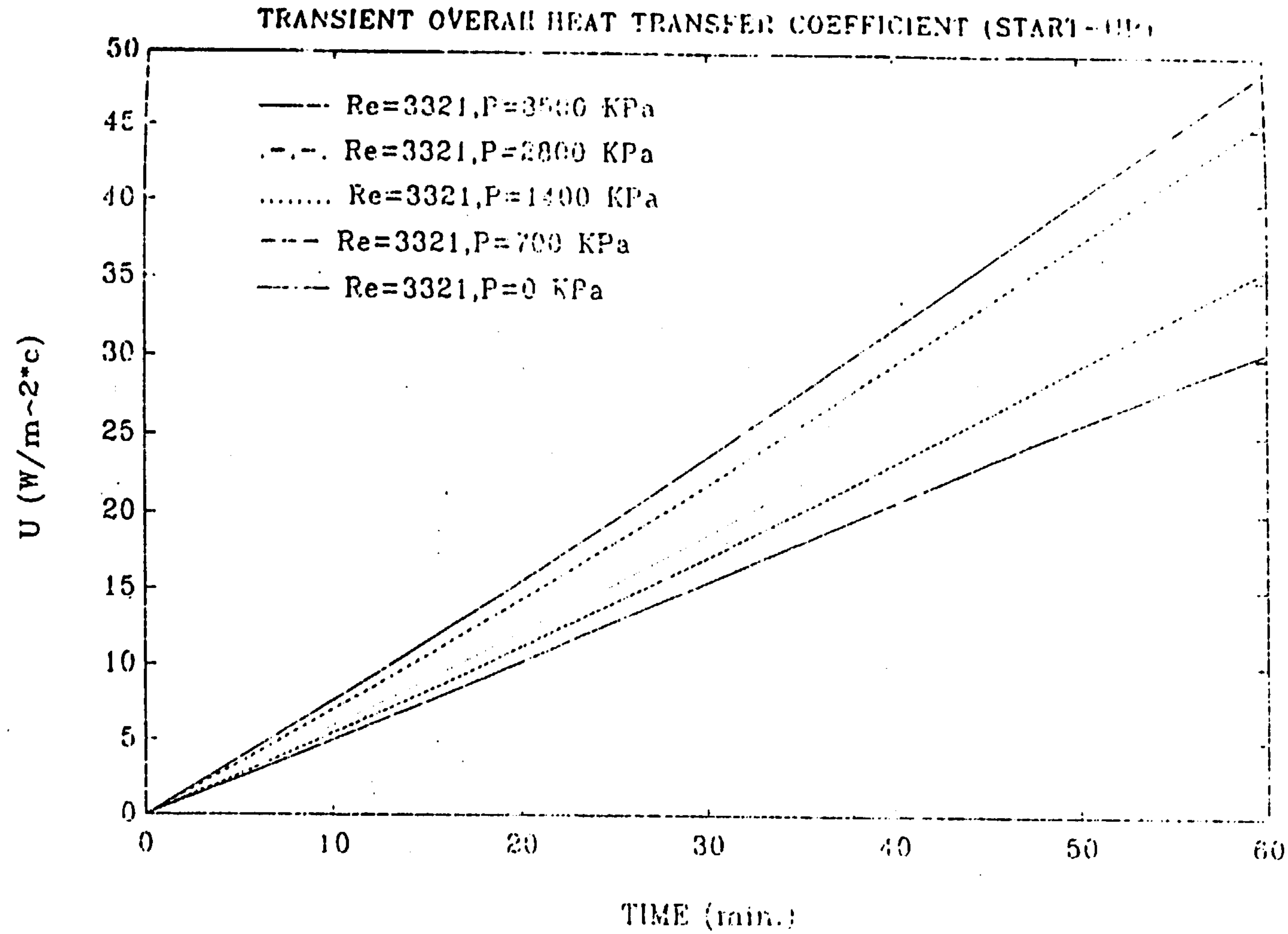

Figure 55. Analytical Transient Overall Heat Transfer Coefficients (Start-Up Condition with Water Coolant, Re = 3321)

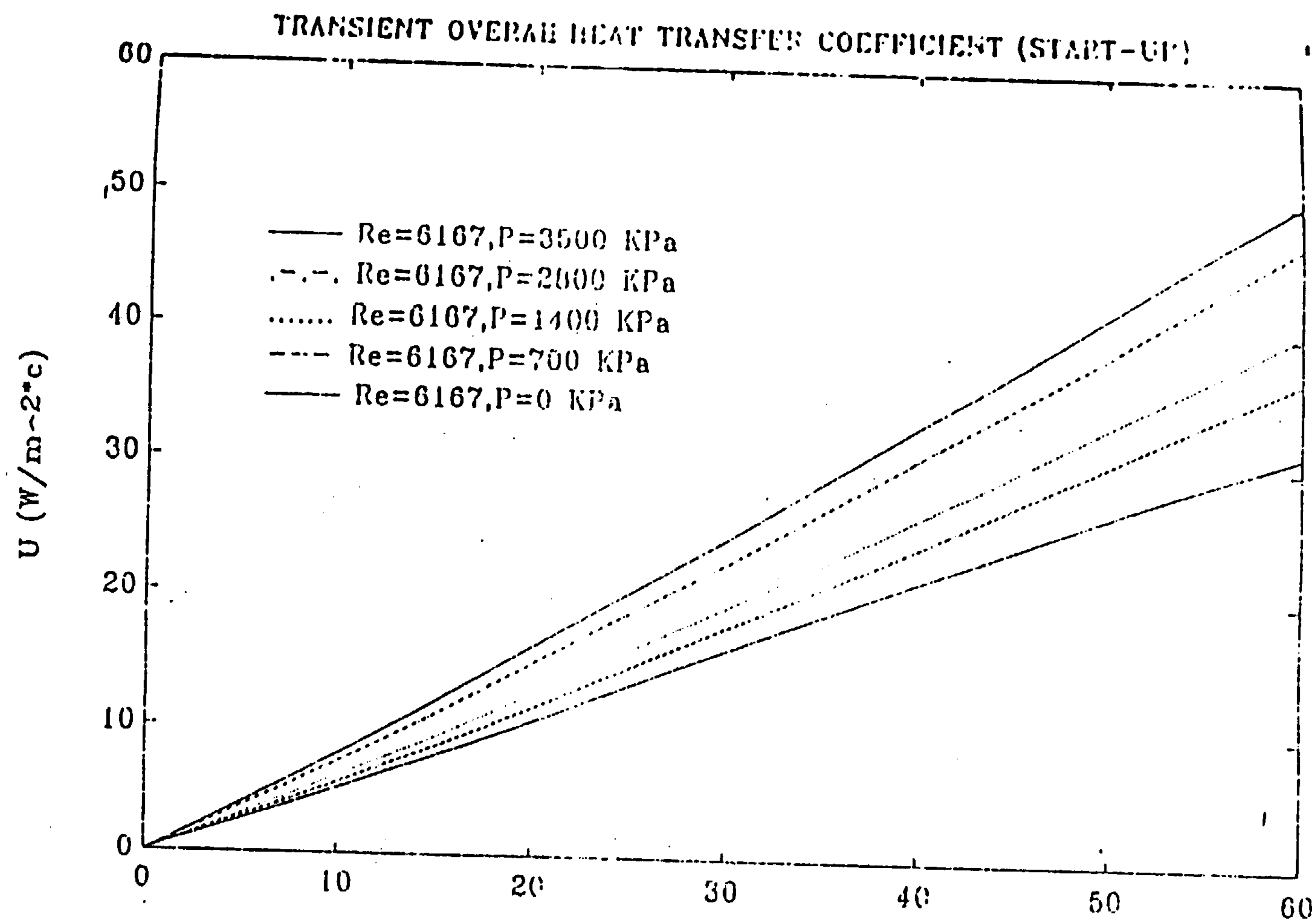

Figure 56. Analytical Transient Overall Heat Transfer Coefficients (Start-Up Condition with Water Coolant, Re = 6167).

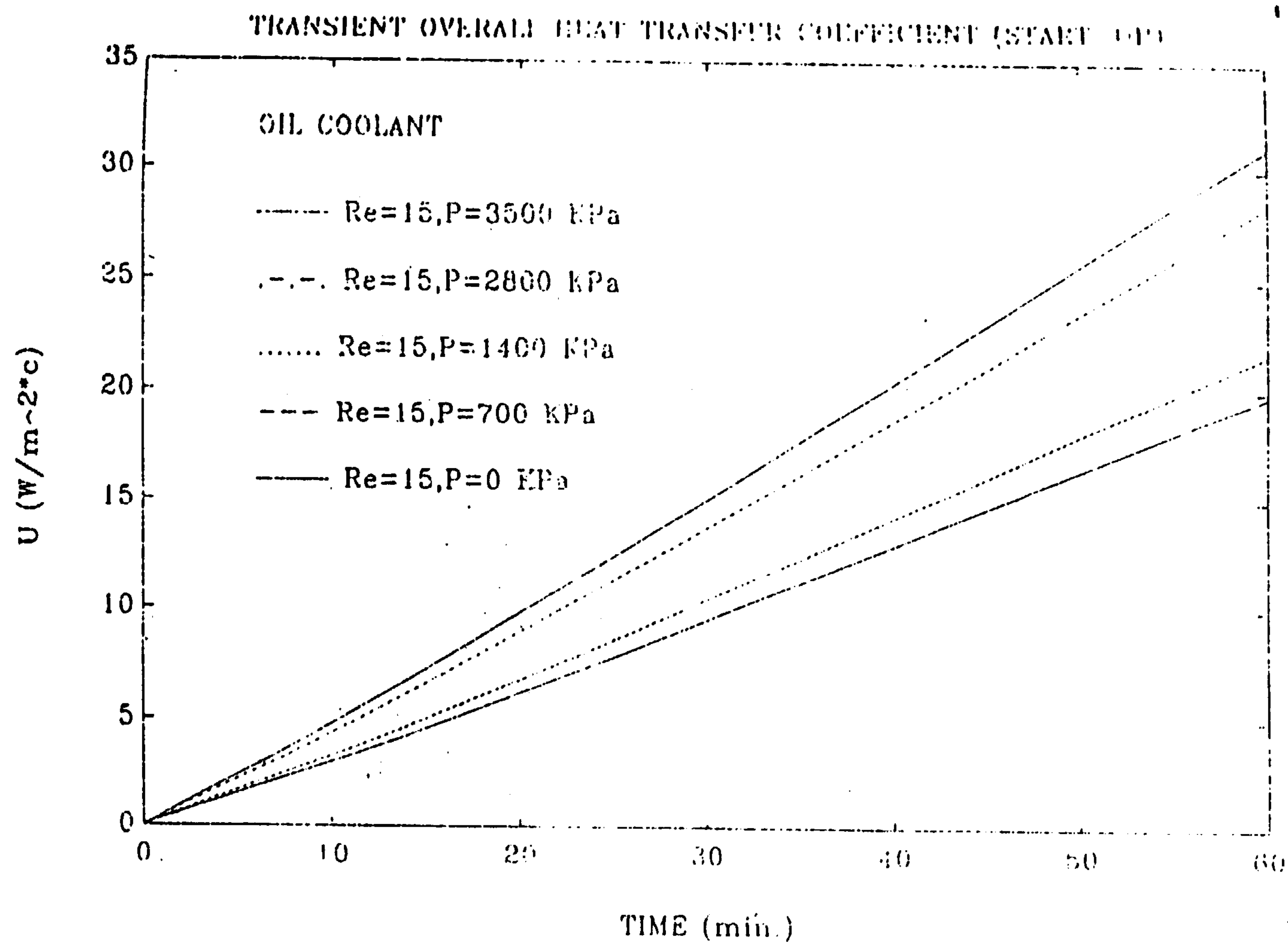

Figure 57. Analytical Transient Overall Heat Transfer Coefficients (Start-Up Condition with Oil Coolant, RE = 15).

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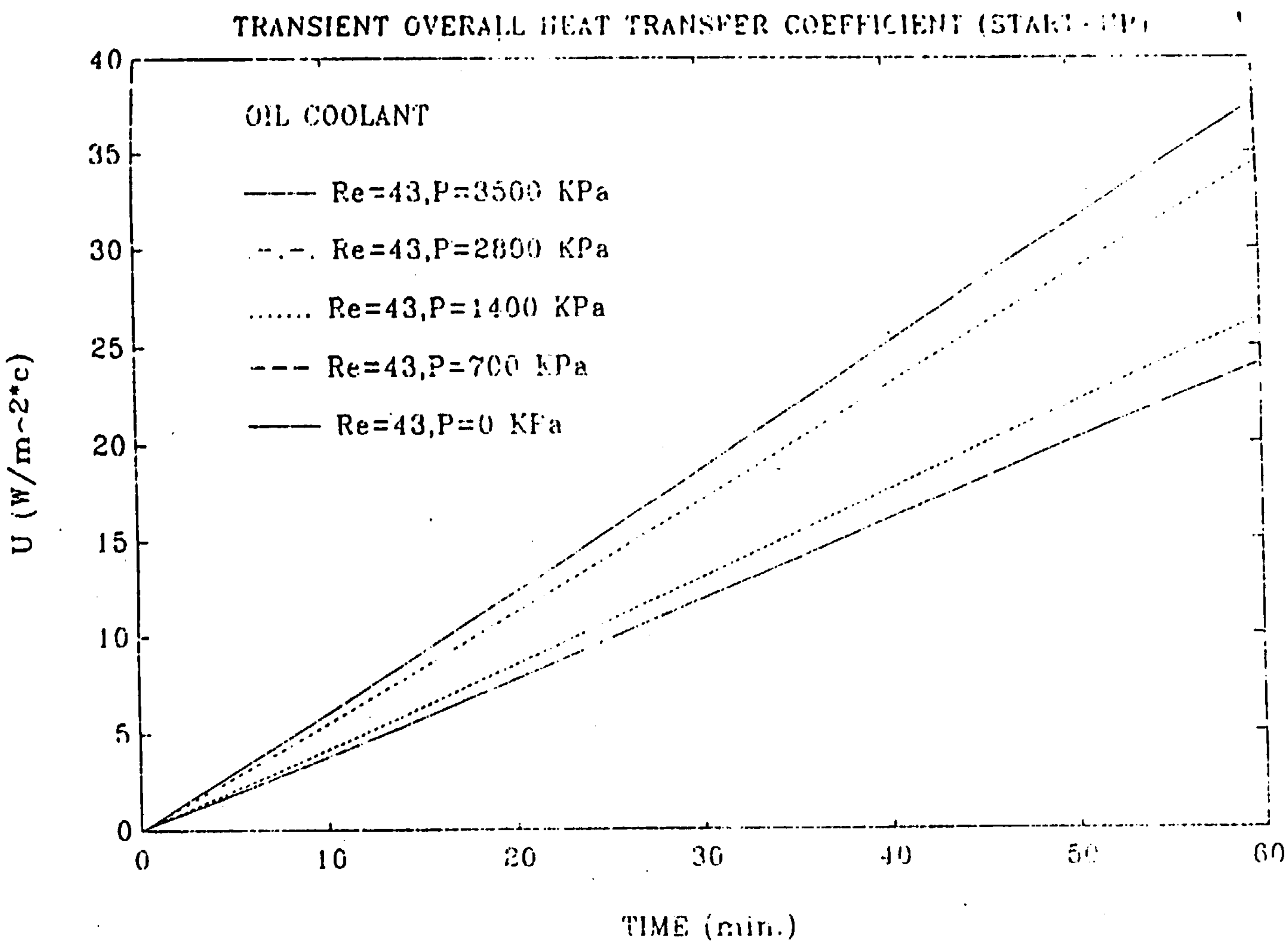

Figure 58. Analytical Transient Overall Heat Transfer Coefficients (Start-Up Condition with Oil Coolant, Re = 43).

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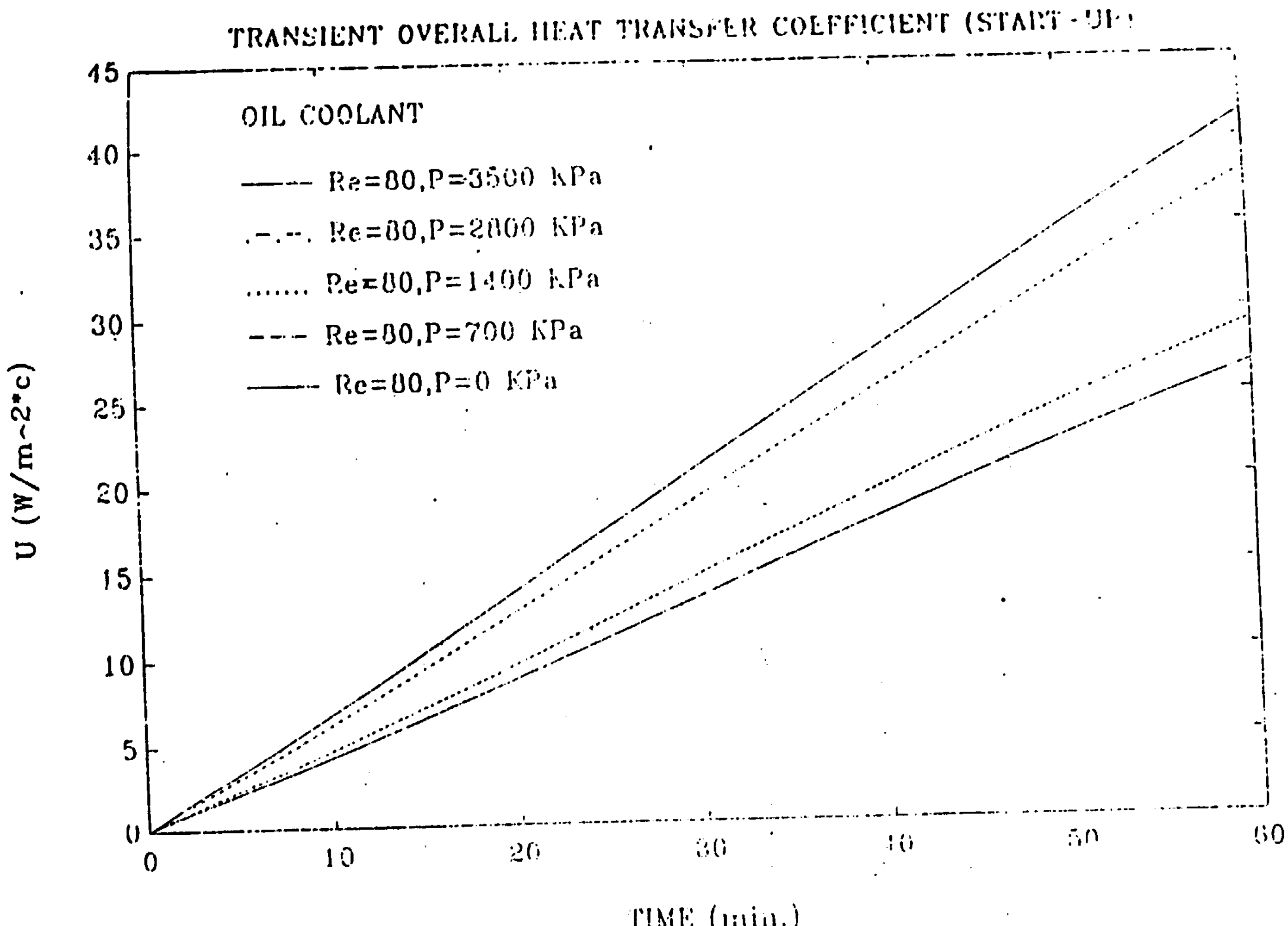

Figure 59. Analytical Transient Overall Heat Transfer Coefficients (Start-Up Condition with Oil Coolant, Re = 80).

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4.3.2 Shut-Down Process

In this section the shut-down mathematical correlation will be developed to demonstrate the variation of heat transfer characteristics of the fuel cell modules for the different considered operation conditions.

4.3.2.1 Transient Convection Heat Transfer Coefficient and the Transient Nusselt Number

The following general correlation can be formulated for the shut-down process:

$$h_s(t) = A_{s1} * H_1(Re,Pr) * [\exp ({}_{s1}t + \alpha_{s1}o)] \quad (25)$$

and

$$Nu_s(t) = A_{s1} * H_2(Re,Pr) * [\exp({}_{s2}t + \alpha_{s2}o)] \quad (26)$$

where

A_{s1}, A_{s2} = shut-down initial condition constants.

$H_1(Re,Pr)$, $H_2(Re,Pr)$ = function of the flow rate and the fluid properties.

λ_{s1}, λ_{s2} = shut-down time constants.

α_{s1}, α_{s2} = operation condition constants.

The developed mathematical correlation utilizing the generated experimental results can be written for both working fluids as follows:

(a) <u>Water Coolant (Re=1250 to Re = 6167</u>

$$h_s(t) = 70.088*(Re^{0.05779})*(Pr^{0.01433})* [\exp (-0.00891t + 0.000123\ o) \quad (27)$$

$$Nu_s(t) = 0.769*(Re^{0.05632})*(Pr^{0.0385})* [\exp(-0.01083t + 0.000124\ o)] \quad (28)$$

Figure 60 demonstrates calculated Nusselt number results when water was used as a coolant.

(b) Oil Coolant (Re=15 to Re=80)

$$h_s(t) = 35.044*(Re^{0.21506})*(Pr^{7.614*10-3})$$
$$[exp\ (-0.00901t + 1.356*10^{-4}\ o) \quad (29)$$
$$Nu_s(t) = 0.771*(Re^{0.2105})*(Pr^{3.86*10-3})*$$
$$[exp(-0.01082t + 1.356*10^{-4}\ o)] \quad (30)$$

The calculated values for the Nu number is stated as a function of time for the Re number during a shut-down process when oil is used as a coolant. Refer to Figure 61.

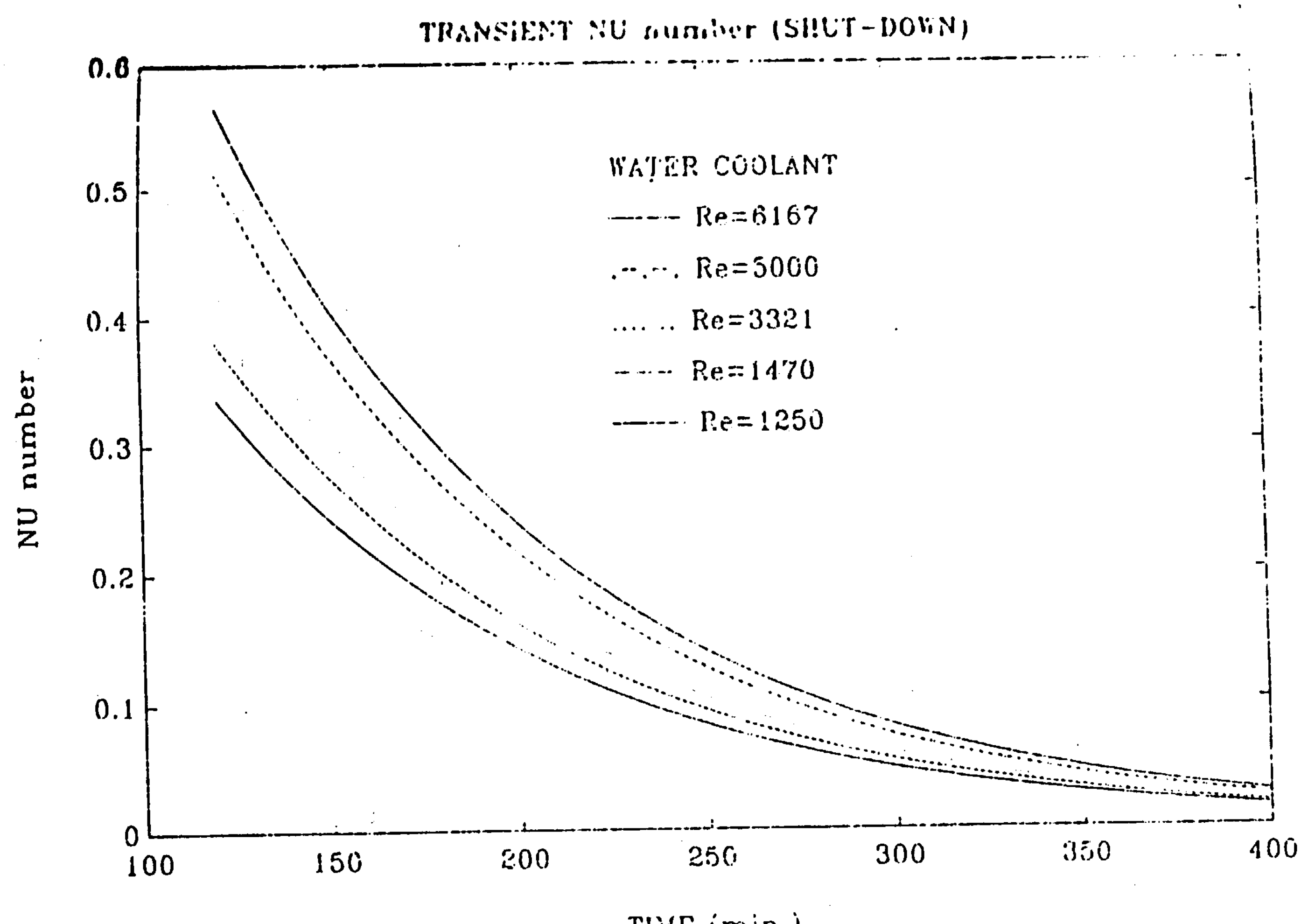

Figure 60. Analytical Transient Nusselt Number (Shut-Down Condition with Water Coolant).

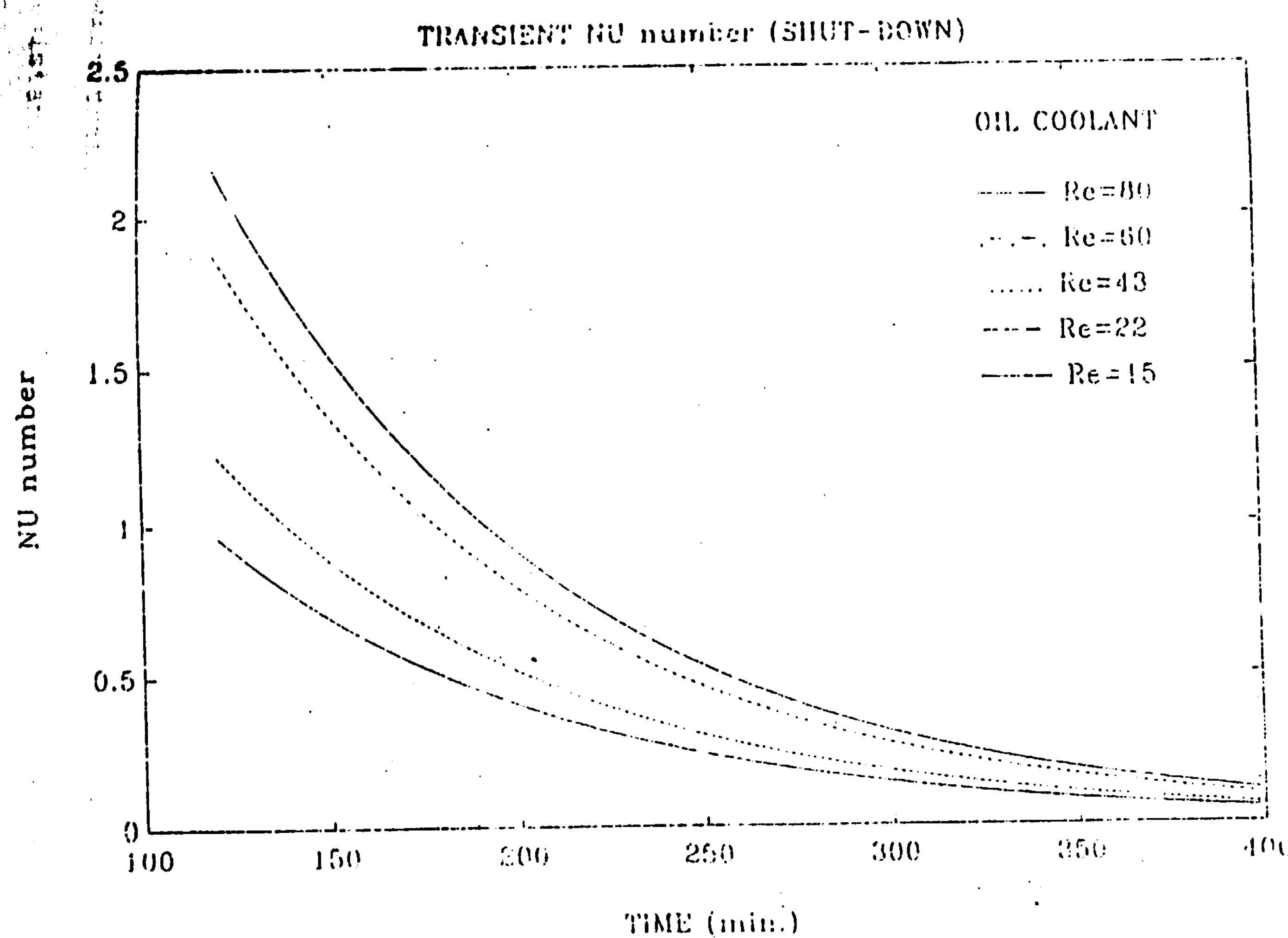

Figure 61. Analytical Transient Nusselt Number (Shut-Down Condition with Water Coolant Re = 1250).

4.3.2.2 Contact Resistance and the Effective Temperature Drop

During a shut-down process the mathematical correlations that simulate the change of contact resistance and the variation of transient thermal contact resistance can be expressed as follows:

$$r_{cs}(t) = A_{s3}W_{s1}(P)*[\exp(\lambda_{s3}t + \gamma_{s1}o)] + A_{s4}*W_{s2}(P) \quad (29)$$

$$\Delta T_s(t) = [A_{s5} - W_{s3}(P)][\exp(\lambda_{s4}t + \gamma_{s2}o)] + [A_{s6} - W_{s4}(P)] \quad (30)$$

where

A_{s3}, A_{s4}, A_{s5} and A_{s6} = constants.

$W_{s1}(P)$ = function of stack pressure.

λ_{s3}, λ_{s4} = shut-down time constant.

o = operation condition parameter.

γ_{s1}, γ_{s2} = operation condition constants.

(a) Water Coolant (Re = 1250 to Re = 6167):

$$r_{cs}(t) = 0.00575*(e^{-0.000236p})*[\exp(-0.00391t - 0.179*10^{-3}\ o)] + 1.802*10^{-3} * (e^{0.000236p}) \quad (31)$$

$$\Delta T_s(t) = [14.986-(0.9597*10^{-2})P][\exp(-0.0046t-0.101*10^{-4}\ o)] + [6.129 - (0.7365*10^{-2})P] \quad (32)$$

Figure 62 to Figure 64 and Figure 68 to Figure 70 demonstrates the variation of the transient thermal contact resistance and the effective temperature drop respectively with different applied stack pressure and Reynolds number

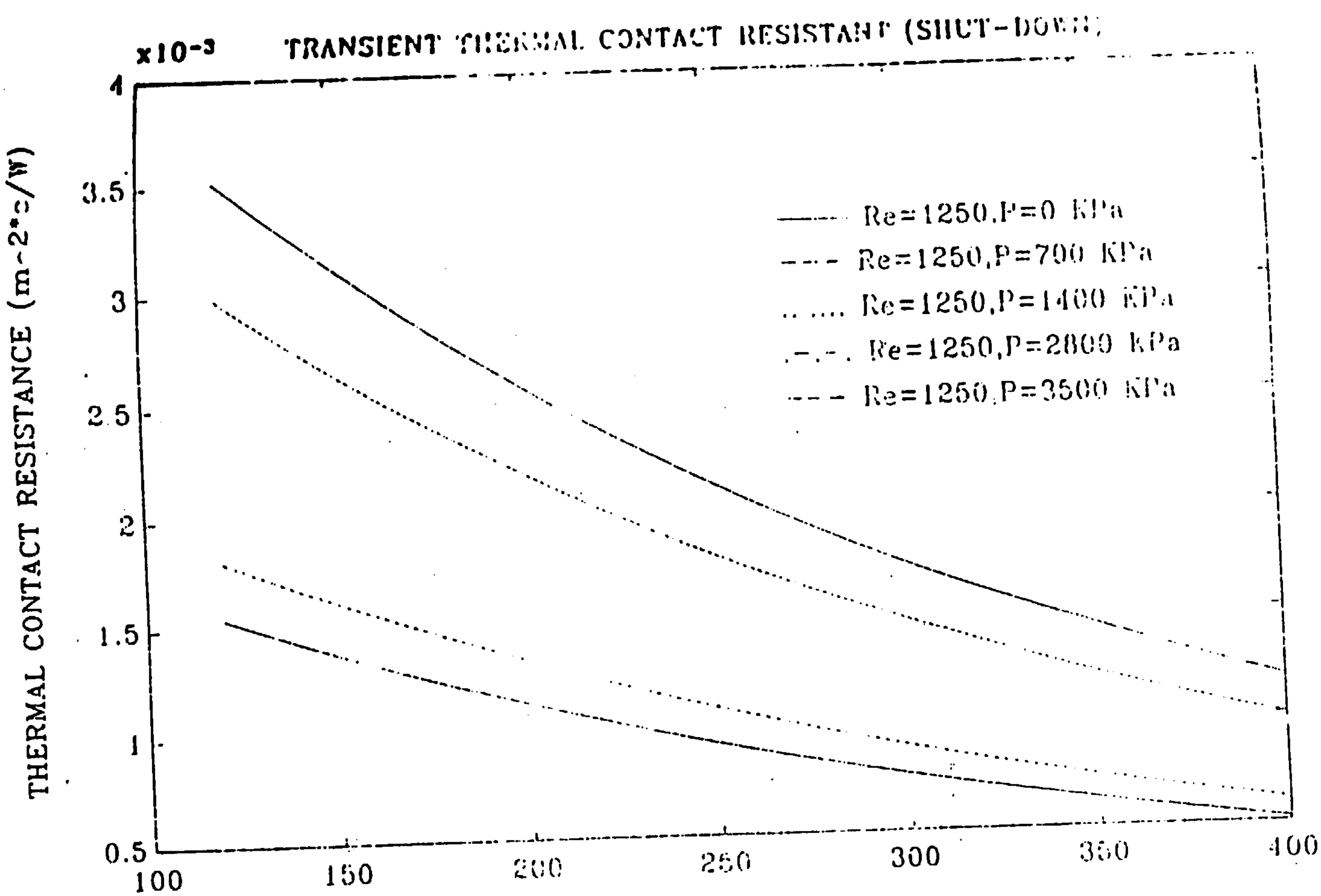

Figure 62. Analytical Transient Thermal Contact Resistance (Shut-Down Condition with Water Coolant Re = 1250).

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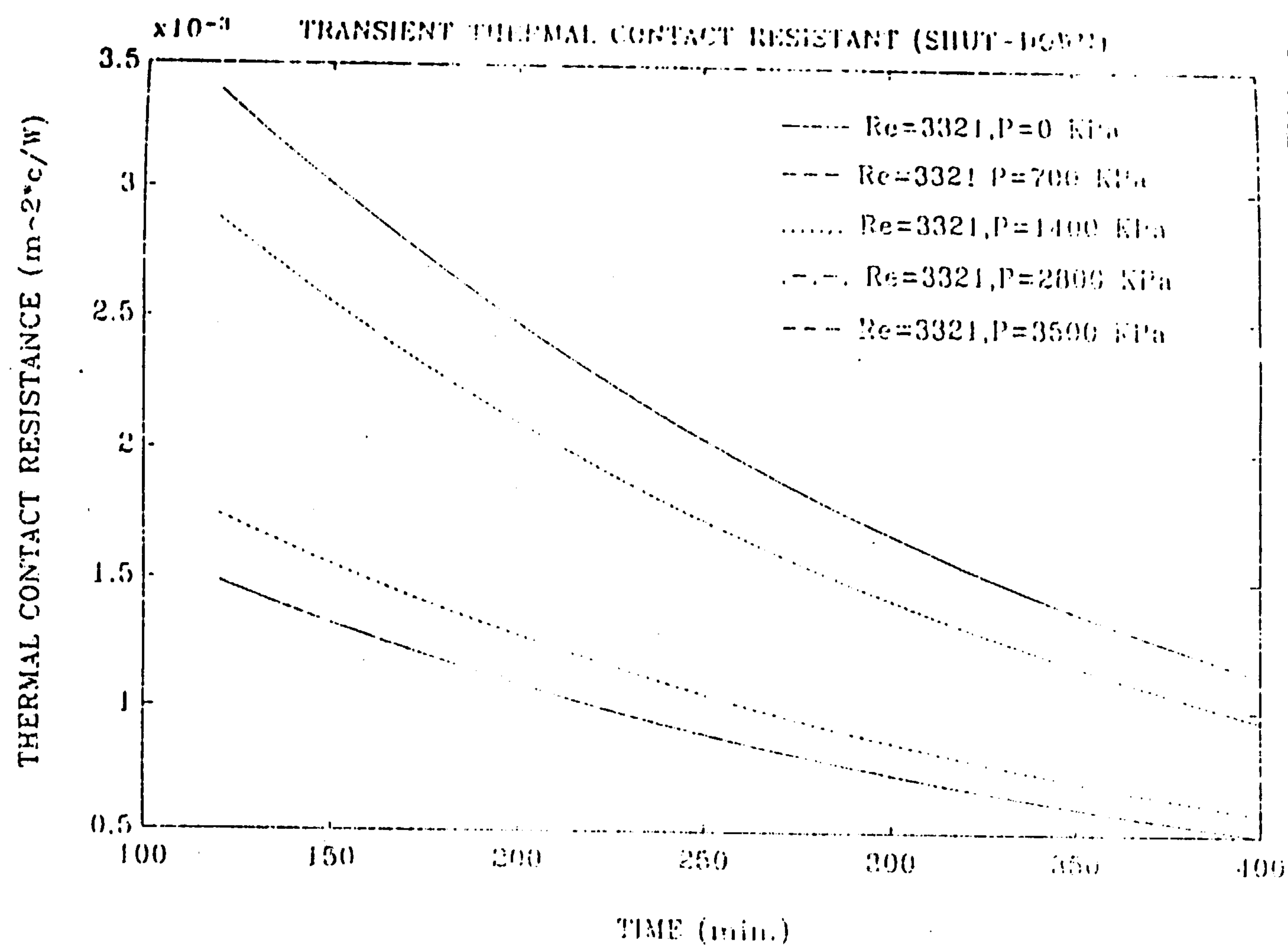

Figure 63. Analytical Transient Thermal Contact Resistance (Shut-Down Condition with Water Coolant, Re = 3321).

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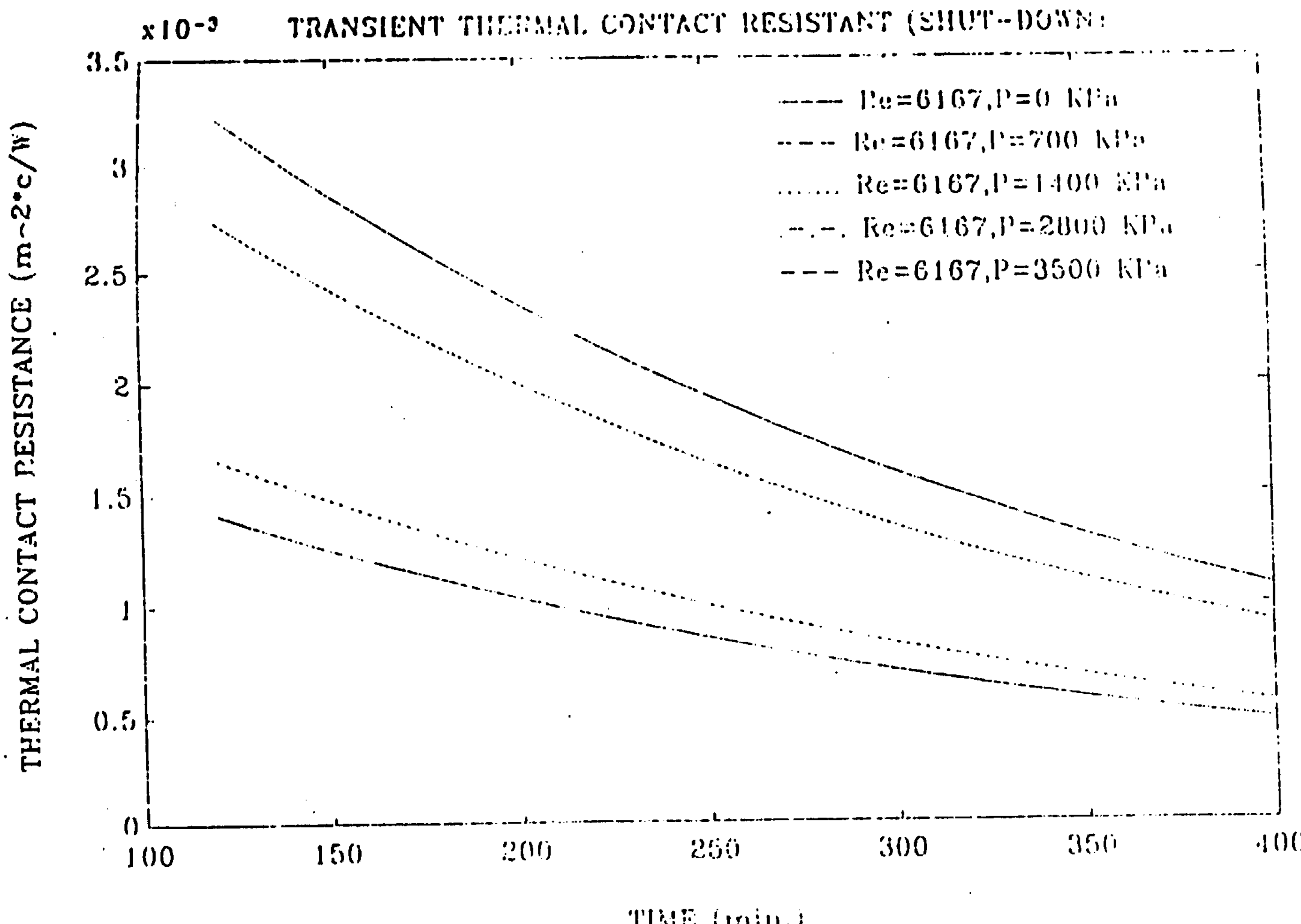

Figure 64. Analytical Transient Thermal Contact Resistance (Shut-Down Condition with Water Coolant, Re = 6167).

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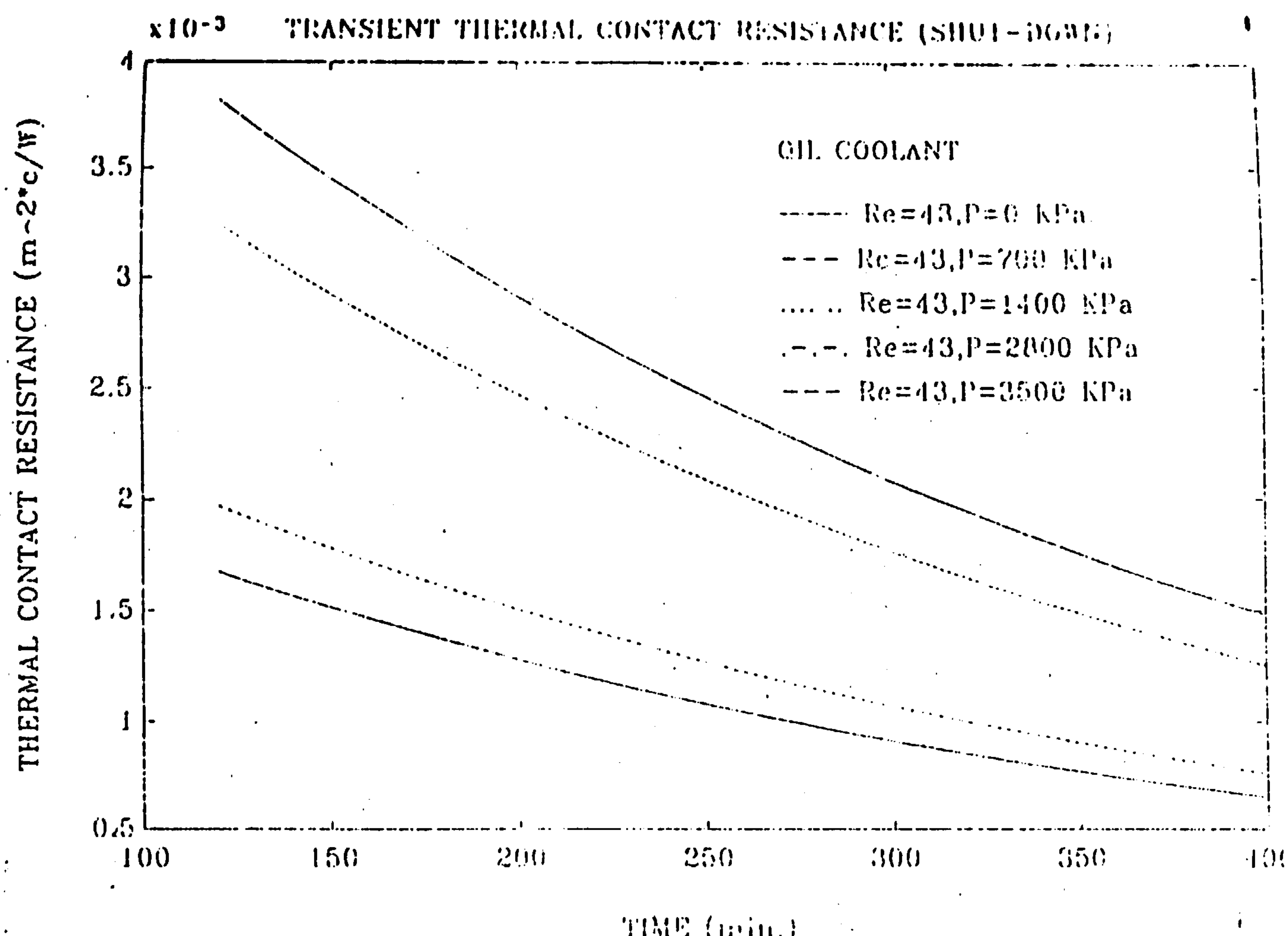

Figure 66. Analytical Transient Thermal Contact Resistance (Shut-Down Condition with Oil Coolant, Re = 43).

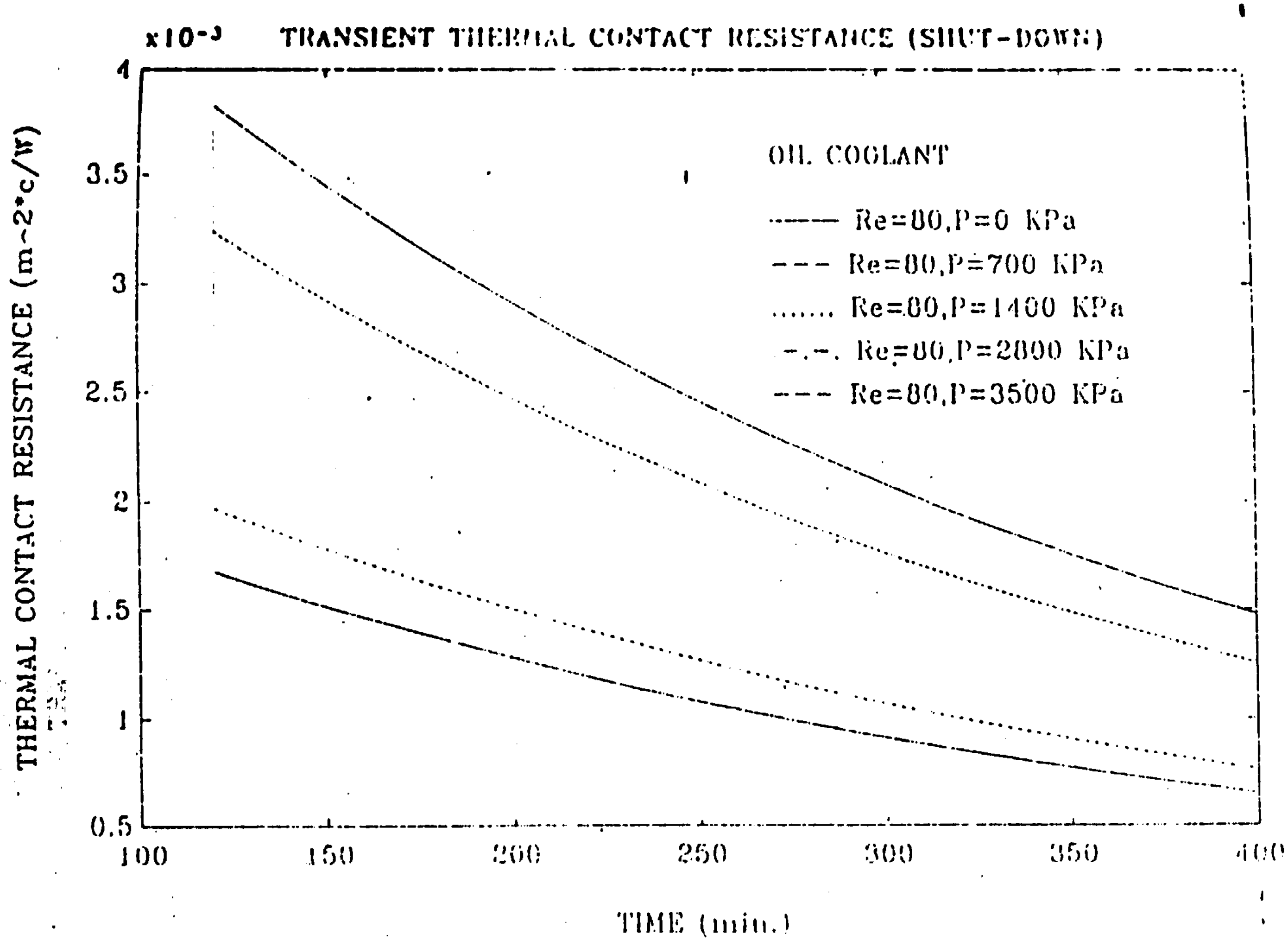

Figure 67. Analytical Transient Thermal Contact Resistance (Shut-Down Condition with Oil Coolant, Re = 80).

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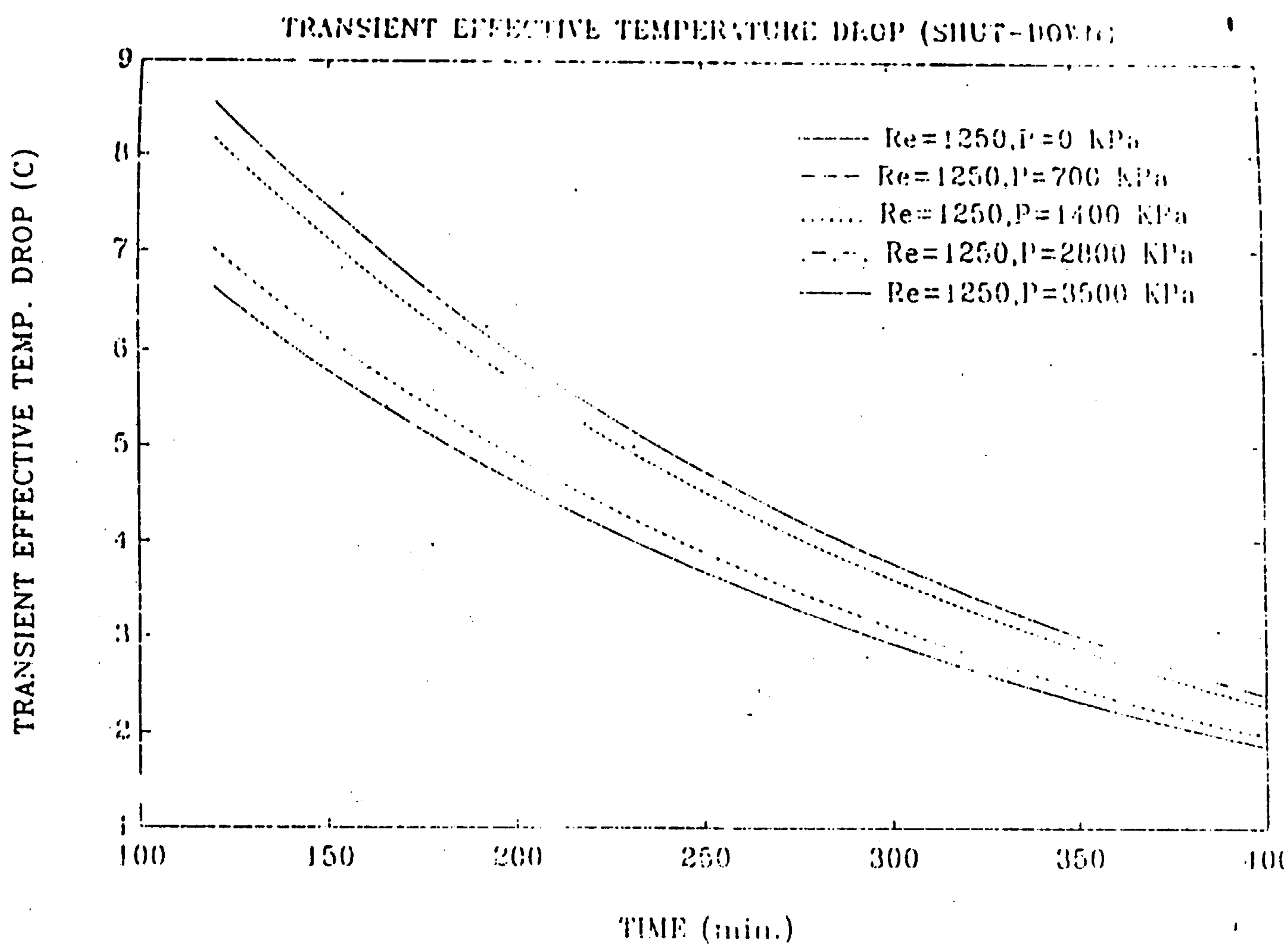

Figure 68. Effective Temperature Drop (Shut-Down Condition with Water Coolant, Re = 1250).

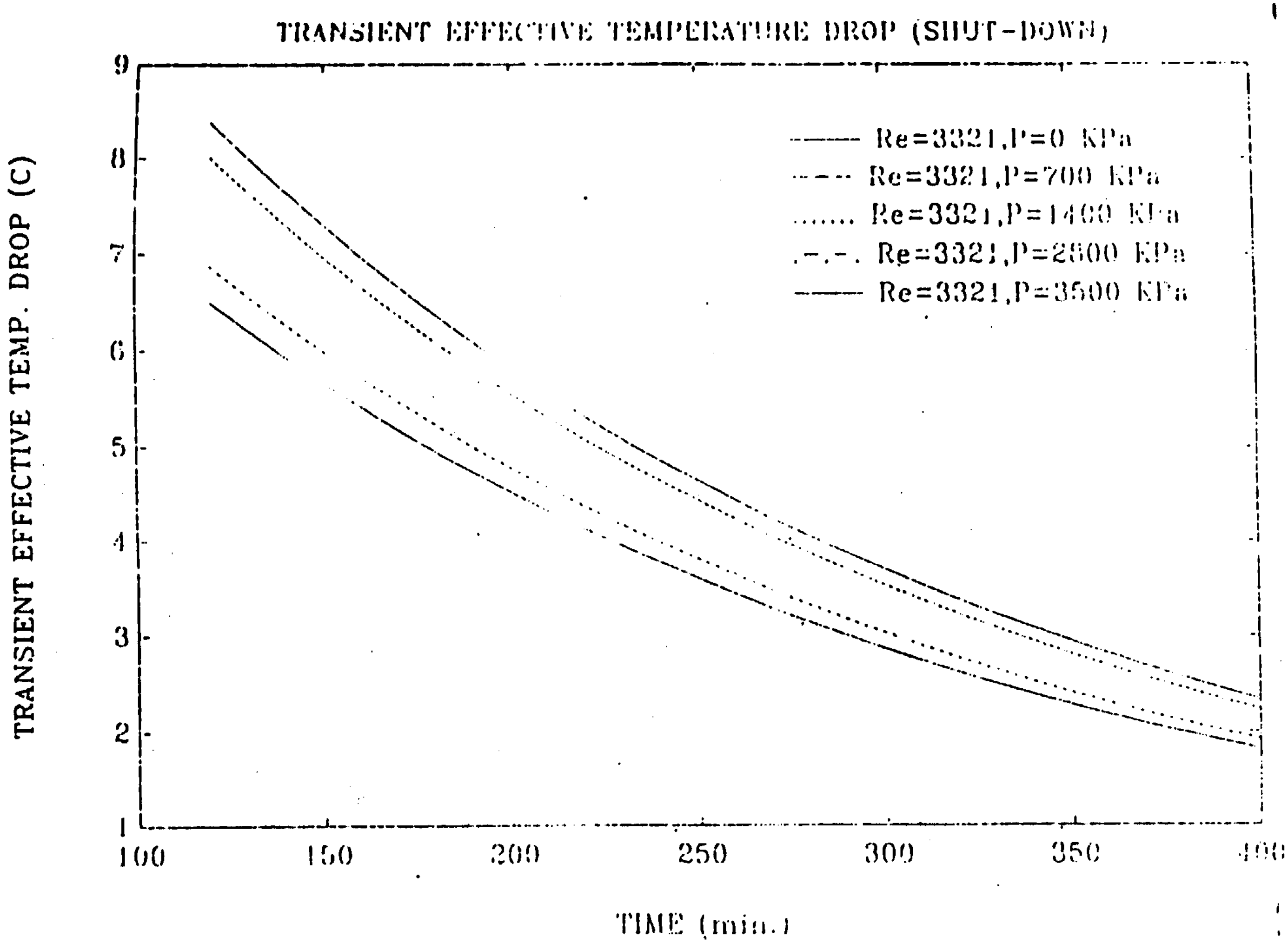

Figure 69. Effective Temperature Drop (Shut-Down Condition with Water Coolant, Re = 3321).

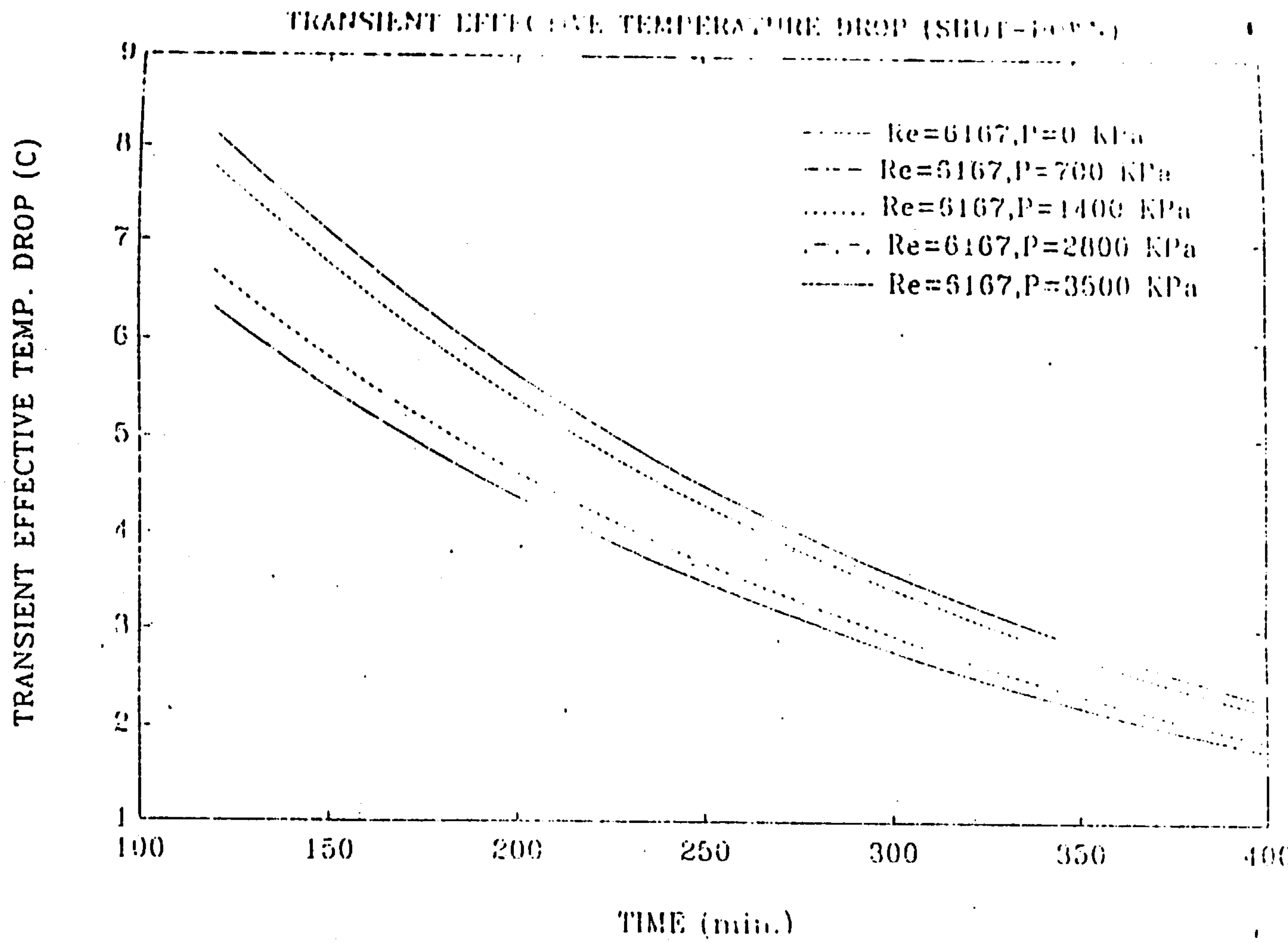

Figure 70. Effective Temperature Drop (Shut-Down Condition with Water Coolant, Re = 6167).

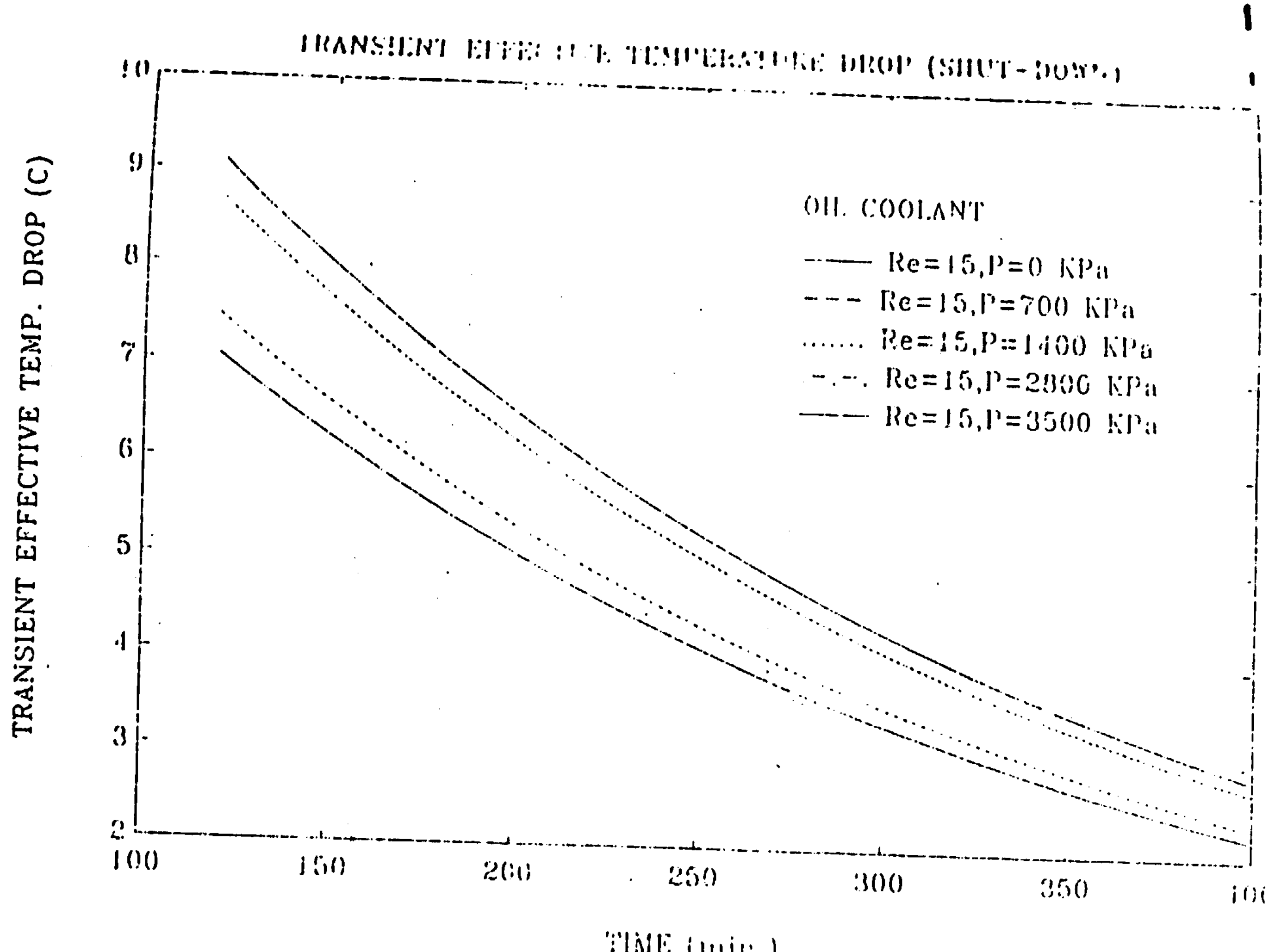

Figure 71. Effective Temperature Drop (Shut-Down Condition with Oil Coolant, Re = 15).

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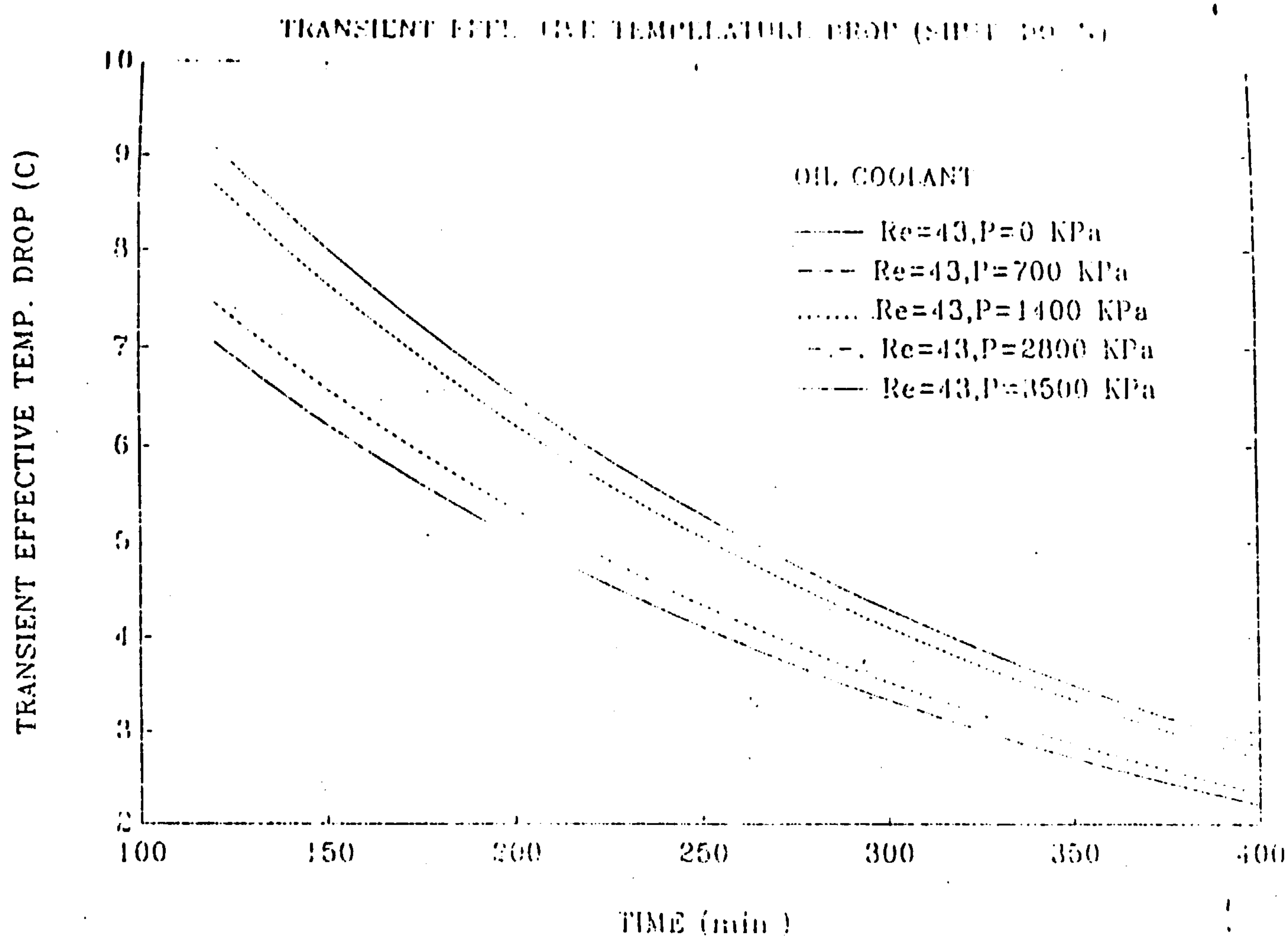

Figure 72. Effective Temperature Drop (Shut-Down Condition with Water Coolant, Re = 43).

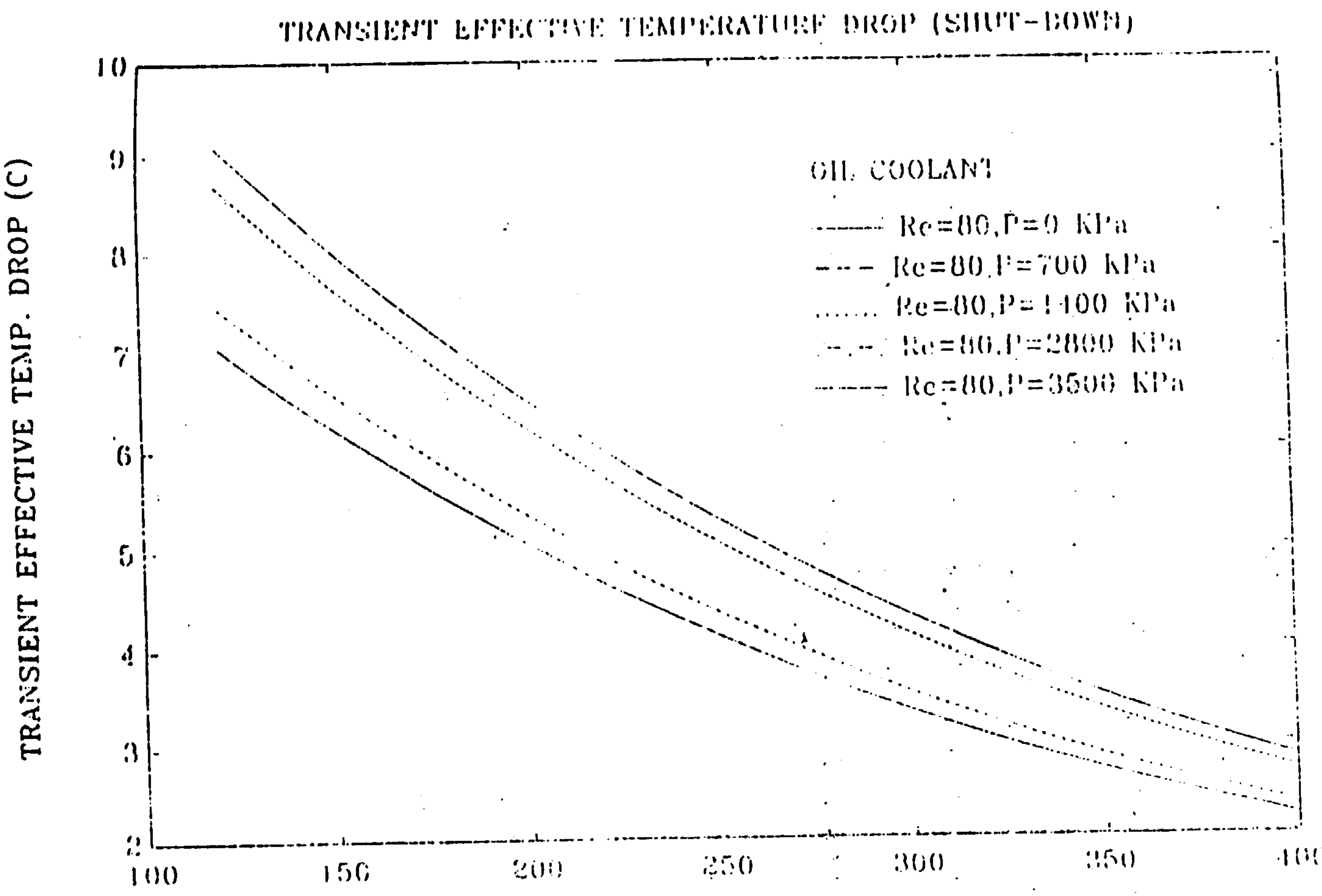

Figure 73. Effective Temperature Drop (Shut-Down Condition with Water Coolant, Re = 80).

using water as a coolant.

(b) <u>Oil Coolant (Re=15 to Re=80):</u>

$$r_{rs}(t) = 0.00575*(e^{-2.36*10^{-4}p})*[\exp(-0.00339t - 1.79*10^{-5}\ o)] + 1.801*10^{-3} * (e^{-2.36*10^{-4}p}) \quad (33)$$

$$\bar{\Delta T_s}(t) = [14.986-(9.597*10^{-4})P][\exp(-4.155*10^{-3}t - 1.012*10^{-5}\ o)] + [6.129 - (7.366*10^{-4})P] \quad (34)$$

Figure 65 to Figure 67 and Figures 71 to 73 represents the generated results for equations [33] and [34] respectively, the maximum, average and the minimum coolant flow rates and the specified stack pressure during a shut-down process.

<u>Note</u>: The difference between the two above correlations set was just the exponential variable factor which will affect the rate slightly.

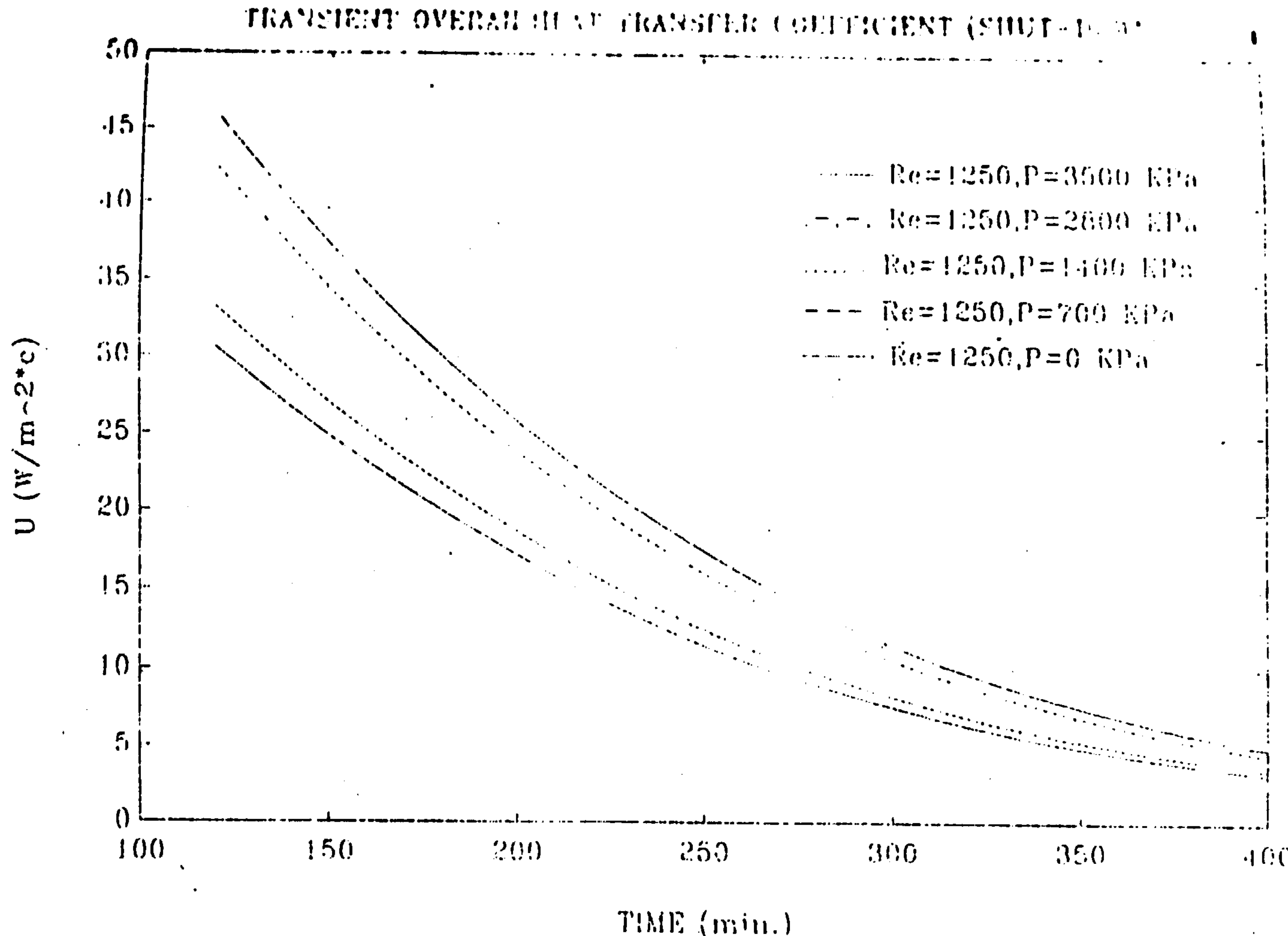

Figure 74. Analytical Transient Overall Heat Transfer Coefficient (Shut-Down Condition with Water Coolant, Re = 1250).

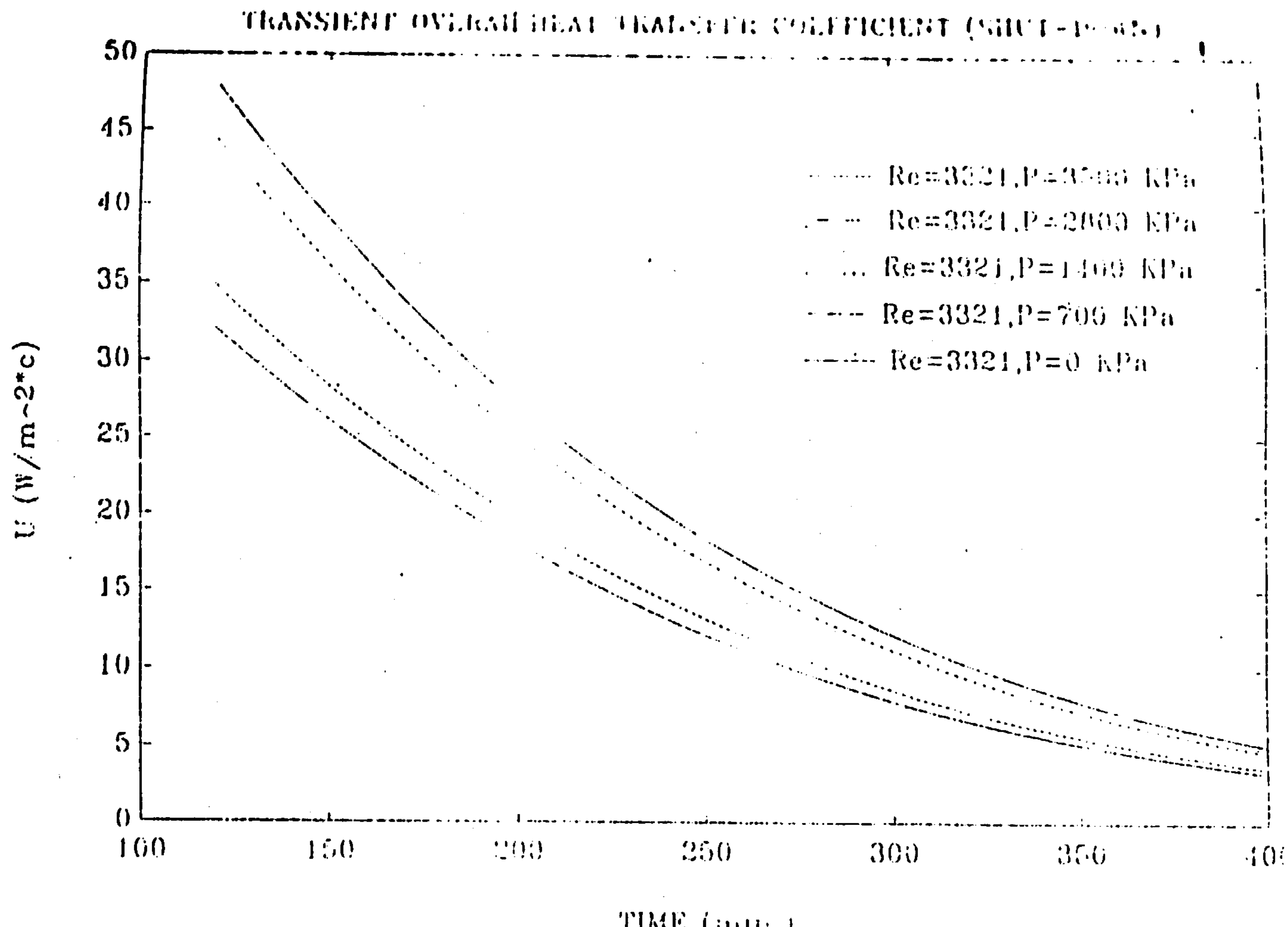

Figure 75. Analytical Transient Overall Heat Transfer Coefficient (Shut-Down Condition with Water Coolant, Re = 3321).

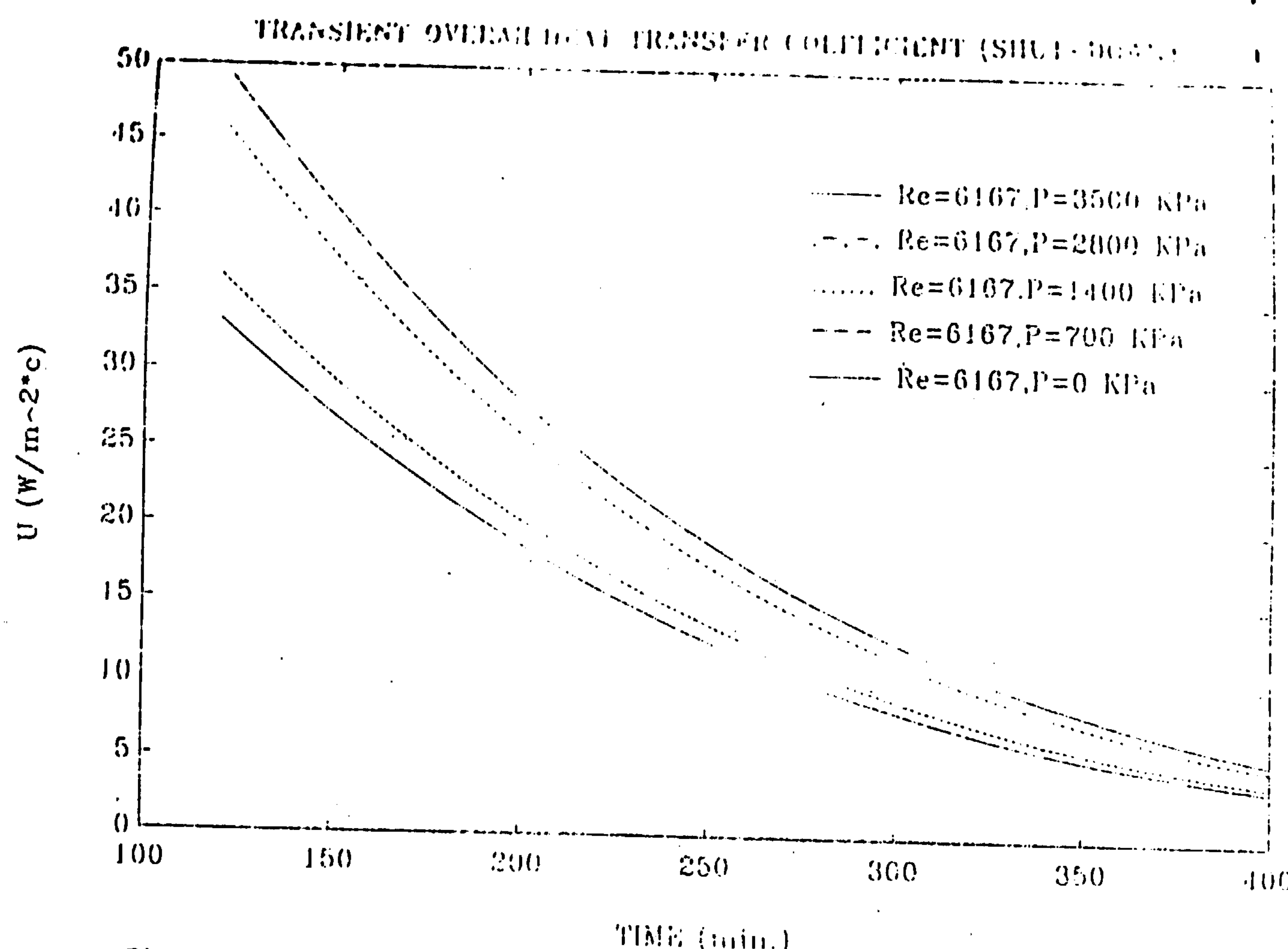

Figure 76. Analytical Transient Overall Heat Transfer Coefficient (Shut-Down Condition with Water Coolant, Re = 6167).

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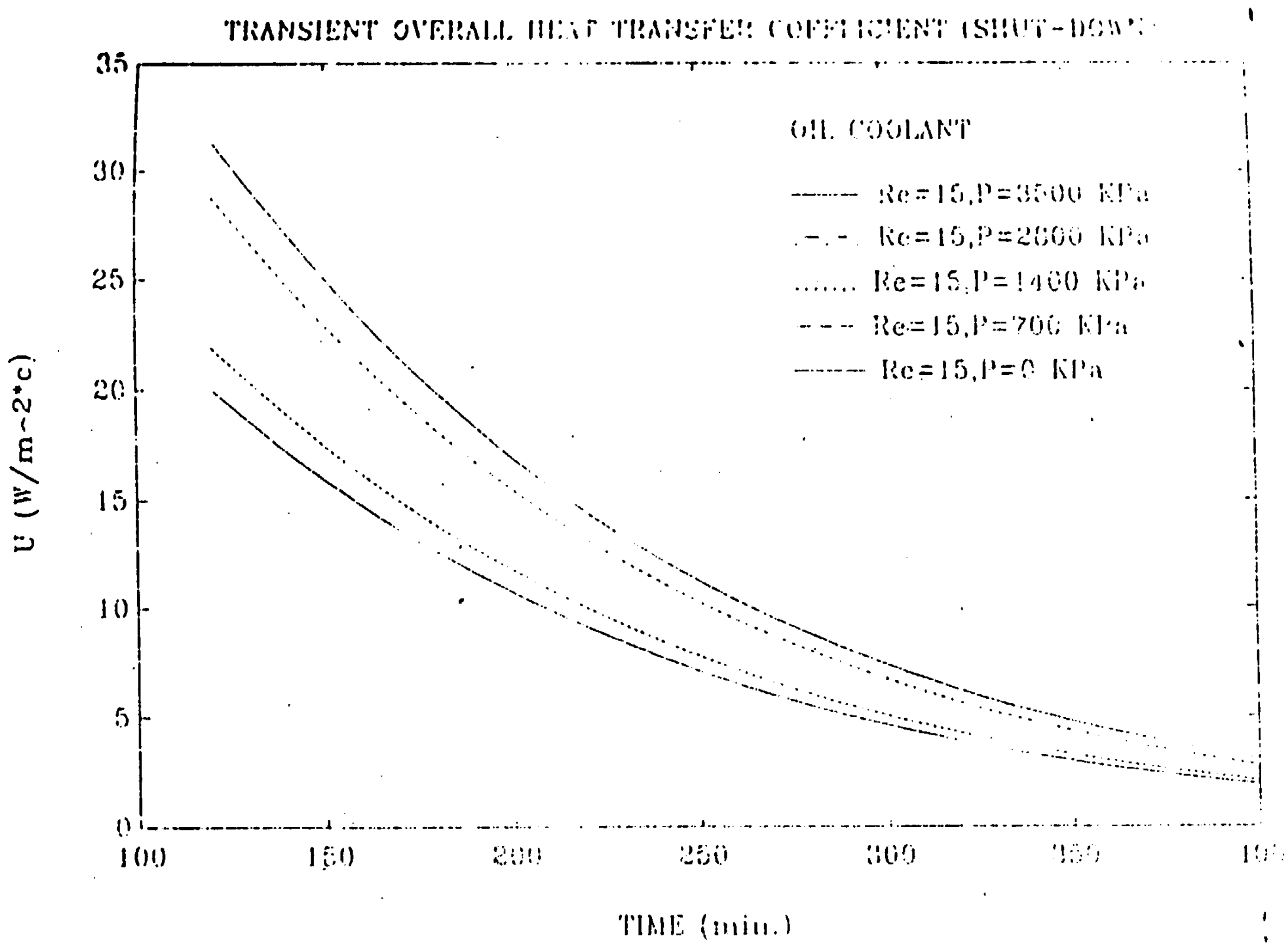


Figure 77. Analytical Transient Overall Heat Transfer Coefficient (Shut-Down Condition with Oil Coolant, Re = 15).

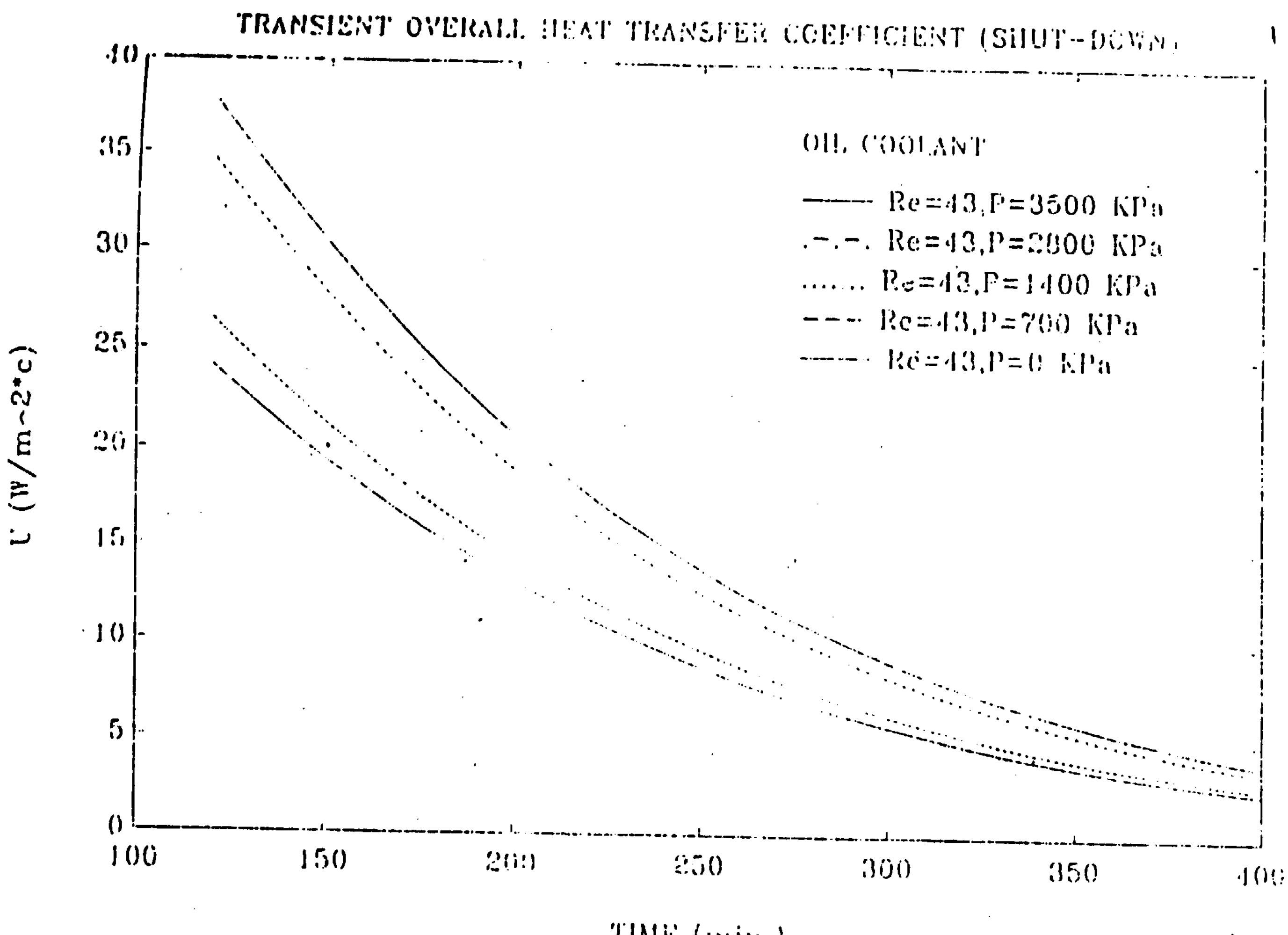


Figure 78. Analytical Transient Overall Heat Transfer Coefficient (Shut-Down Condition with Oil Coolant, Re = 43).

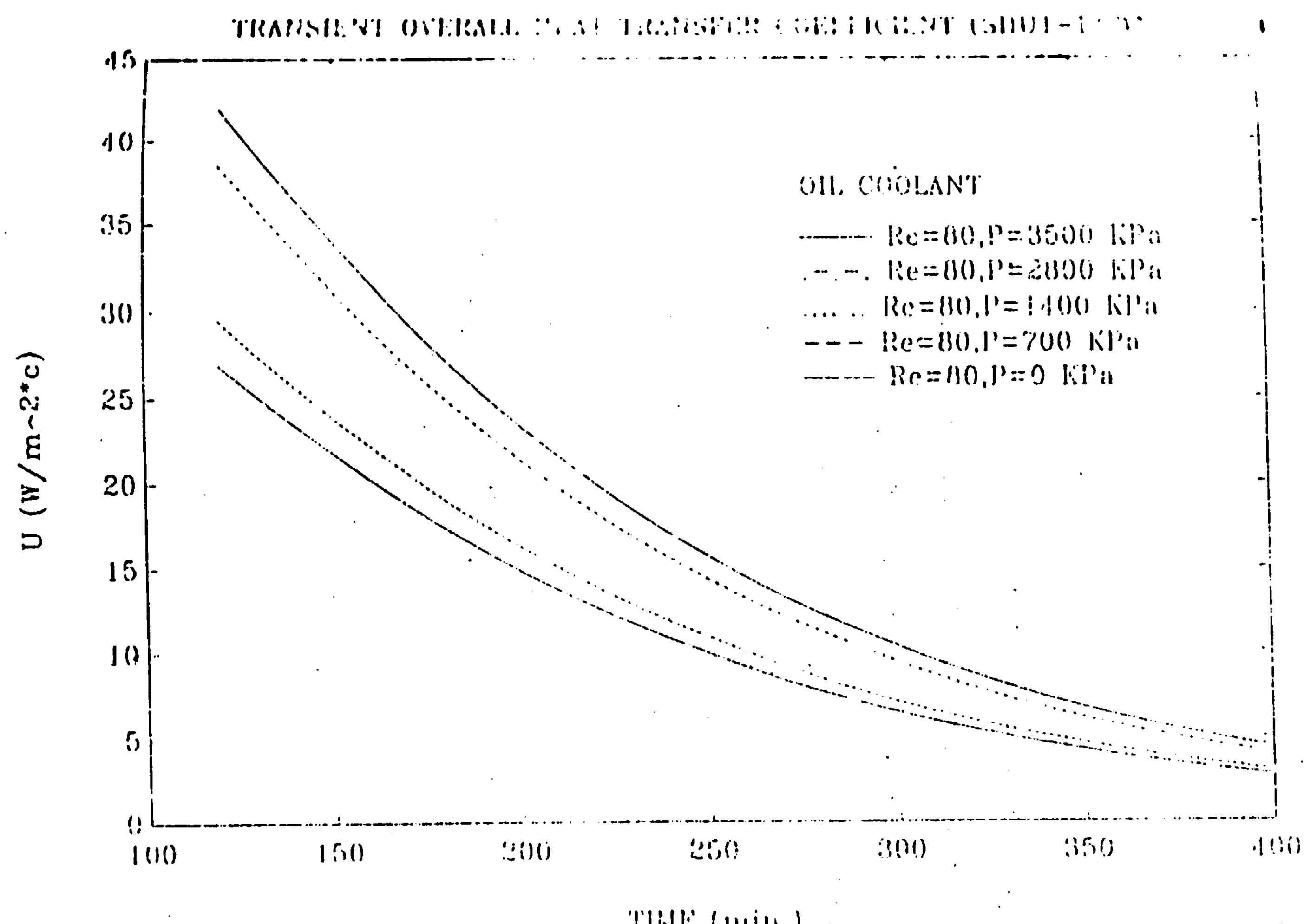


Figure 79. Analytical Transient Overall Heat Transfer Coefficient (Shut-Down Condition with Oil Coolant, Re = 80).

4.3.2.3 Calculated Transient Overall Heat Transfer Coefficient

The transient overall heat transfer coefficient during a shut-down process was calculated using the same method defined in section 4.3.1.3.

(a) Water Coolant (Re = 1250 to Re = 6167)

Part of the calculated results are summarized by Figure 74 through Figure 76 which represents the minimum, average and maximuim water flow rates during a shut-down process.

(b) Oil Coolant (Re=15 to Re=80)

Figure 77 to Figure 79 demonstrates the change in the calculated overall heat transfer coefficient using the experimental calculations for three cases when oil was used as a coolant during a shut-down process.

CHAPTER V

TRANSIENT ELECTRODE TEMPERATURE DISTRIBUTION

The chemical reaction that takes place inside the phosphoric acid fuel cell results in generating thermal energy that approximately equals the electrical energy produced. In order to prevent temperature rise that leads to efficiency drop and high thermal stress, the excessive thermal energy is removed continously by heat transfer to the cooling plate and input gases.

It is extremely important to study the temperature profiles of the electrode to determine the thermal peaks locations and improve the cooling system design. In this chapter the transient temperature profiles developed from the experimental results will be compared with the theoretical results that were generated from the modified Fortran computer code developed originally by Alkasab and Lu [1] in their theoretical study. The internal heat generation produced by the chemical reaction can be simulated accurately by the heat generated by the resistance heating elements. The temperature profiles identify the areas with high thermal energy accumulation which is affected by the operation conditions such as the applied stack pressure, coolant flow rate and coolant fluid properties. The transient isotherm were developed by monitoring the thermocouples readings located at 70 points in the fuel cell plate for the different considered operation conditions. The isotherms were drawn utilizing both the computer generated charts and the printed transient data.

In the following section, the transient experimental temperature profiles during start-up and shut-down processes will be analyzed for different operation conditions to examine the effect of the stack pressure, coolant flow rate and coolant properties on the cell model performance and the cooling system efficiency.

5.1 Experimental Temperature Profiles During Start-Up Process

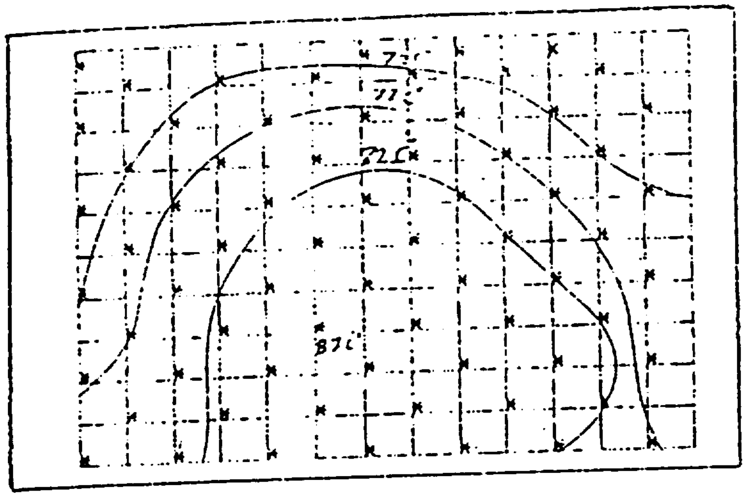
5.1.1 The Effect of the Stack-Pressure on the Transient Temperature Distribution

The effect of the stack pressure on the temperature distribution during a start-up process with a constant volumetric flow rate is demonstrated by Figure 80 through Figure 85 for water coolant and by Figure 87 through Figure 92 for oil coolant. The previous figures represent the generated isotherms that summarizes the thermocouple transient readings. Considering the first set for water, the coolant flow rate was kept constant at Re = 125°, while the stack pressure was changed from 0 Kpa to 3500 Kpa. From these figures, we can observe the increase of the temperature with respect to time until the steady state is reached for any given coolant flow rate and stack pressure. The highest temperature zone location is slightly off the center due to the configuration of the cooling system. With higher stack pressure two effects on the transient electrode temperature distribution were noticed.

(a) Higher transient average electrode temperature with higher applied stack pressure approximately $3.064*10^{3}$ °C/KPa as shown in Figure 86. Considering the most extreme case when water was used as a coolant, with minimum flow rate, the peak electrode temperature as exhibited by Figures 80 to 82 when the applied stack pressure was (0 KPa), increased from 87.1°C to 185.3°C during the considered time intervals. On the other hand, when the applied stack pressure was increased to 3500 KPa the peak electrode temperature increased from 92°C to 189°C before reaching the steady state operation condition. The average transient electrode temperature, when the applied pressure was 3500 KPa, went up from 64.8 °C to 129.3 °C with Re=1250 as shown by Figure 86. The reason for this temperature increase will be explained in Chapter VII.

Similar transient electrode temperature distributions were noticed when oil was used as the cooling fluid for different flow rates, refer to Figures 87 to 93. However, in general the peak and average transient electrode temperatures were higher for oil than those for water as

Instantaneous Electrode Temperature Profile



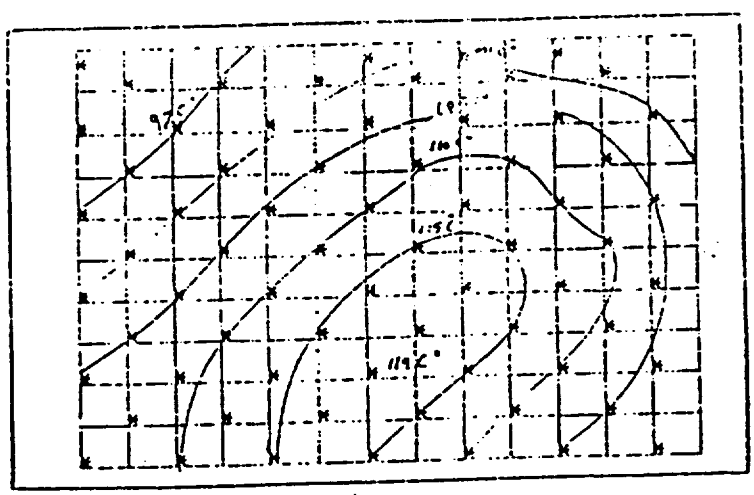
Re - 1250 Coolant Fluid : water

P - 0 (KPa)

E.E. - 1500 (W/m^2)

Figure 80. Instantaneous Temperature Profiles During Start-Ups (Water Coolant, P=0 KPa, Re=1250, E.E.=1500 w/m^2).

Instantaneous Electrode Temperature Profile



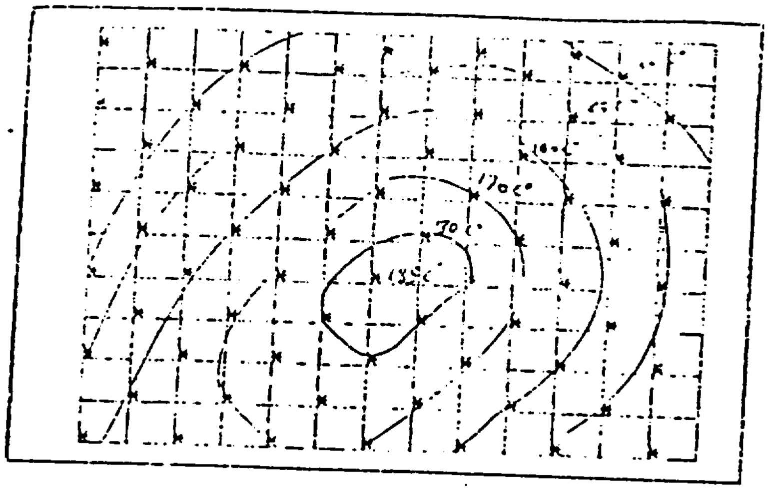
Re - 1250 Coolant Fluid : water

P - 0 (KPa)

E.E. - 2250 (W/m^2)

Figure 81. Instantaneous Temperature Profiles During Start-Ups (Water Coolant, P=0 KPa, Re=1250, E.E.=2250 w/m^2).

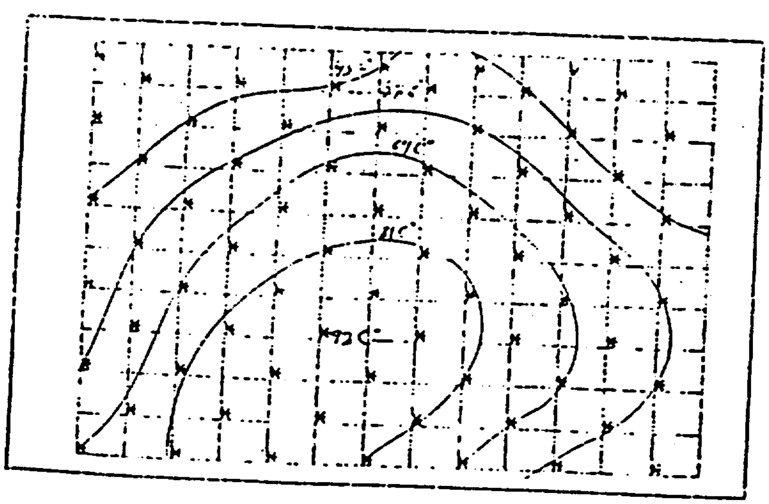
Instantaneous Electrode Temperature Profile



Re = 1250
P = 0 (KPa)
E.E. = 3000 (W/m^2)
Coolant Fluid : water

Figure 82. Instantaneous Temperature Profiles During Start-Ups (Water Coolant, P=0 KPa, Re=1250, E.E.=3000 w/m^2).

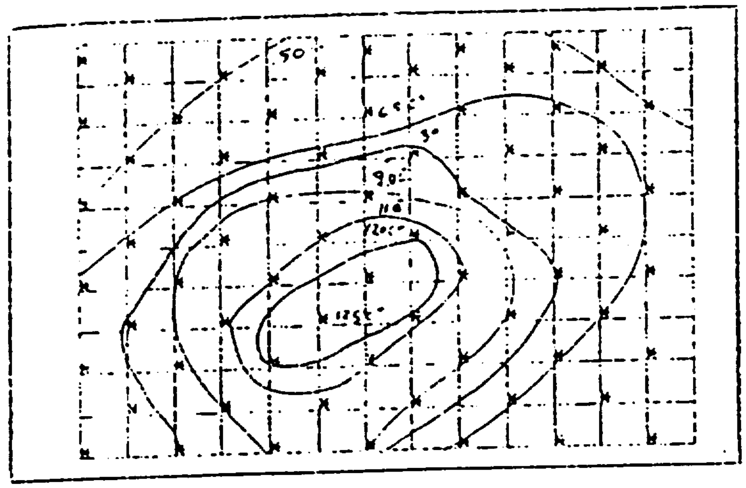
Instantaneous Electrode Temperature Profile



Re = 1250
P = 3500 (KPa)
E.E. = 1500 (W/m^2)
Coolant Fluid : water

Figure 83. Instantaneous Temperature Profiles During Start-Ups (Water Coolant, P=3500 KPa, Re=1250, E.E.= 1500 w/m^2).

Instantaneous Electrode Temperature Profile



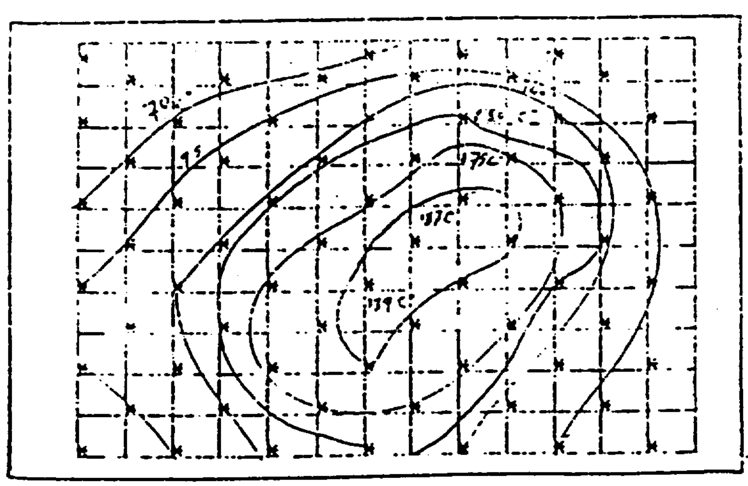
Re - 1250 Coolant Fluid : water

P - 3500 (KPa)

E.E. - 2250 (W/m^2)

Figure 84. Instantaneous Temperature Profiles During Start-Ups (Water Coolant, P=3500 KPa, Re=1250, E.E.=2250 w/m^2).

Instantaneous Electrode Temperature Profile



Re - 1250 Coolant Fluid : water

P - 3500 (KPa)

E.E. - 3000 (W/m^2)

Figure 85. Instantaneous Temperature Profiles During Start-Ups (Water Coolant, P=3500 KPa, Re=1250, E.E.=3000 w/m^2).

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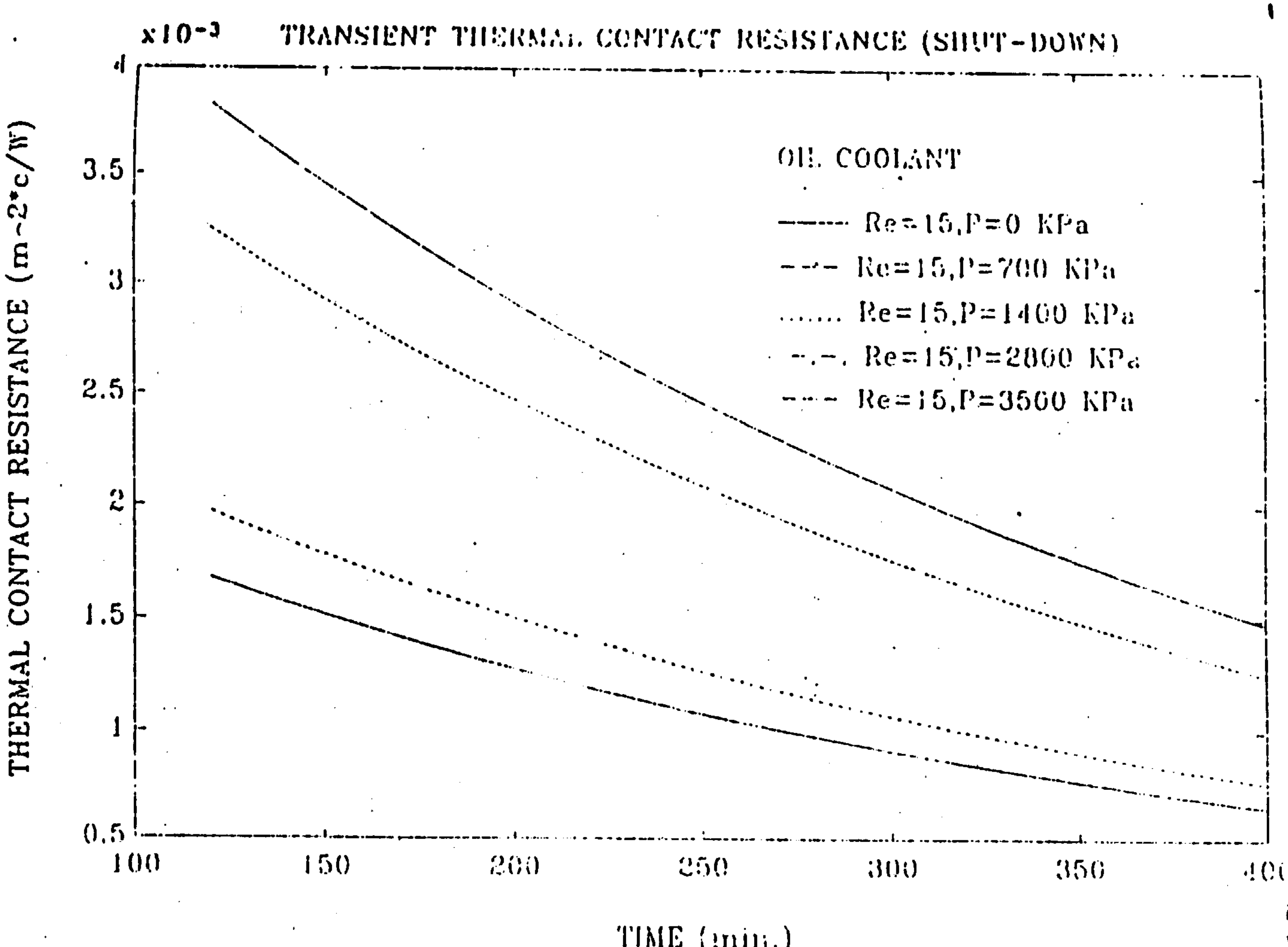

Figure 65. Analytical Transient Thermal Contact Resistance (Shut-Down Condition with Oil Coolant, Re = 15).

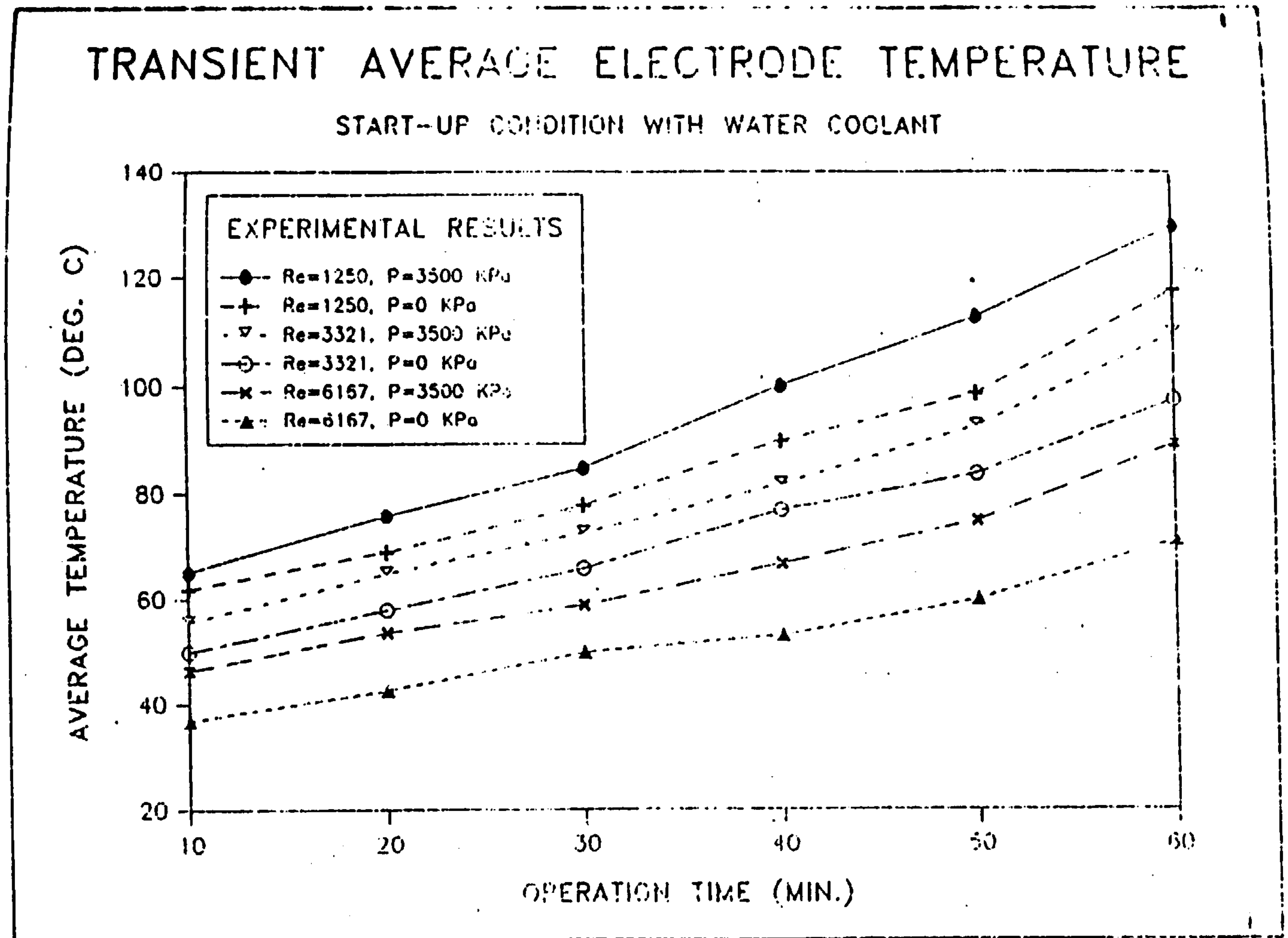

Figure 86. Experimental Transient Average Electrode Temperature During Start-Ups with Water Coolant.

demonstrated by Figure 97 which shows the variation of the experimental transient average temperature. The average transient electrode temperature increase per unit of applied pressure was approximately $2.131 * 10^{-3}$ °C/KPa. These results were unexpected. Higher heat transfer rates to the coolant should decrease the average surface temperature of the cathode plate.

(b) More uniform temperature distribution: the transient isotherms temperature difference decreases and that is basically due to enhancing the surface contacts because of increasing the clamping pressure which causes reducing the thermal contact resistance. This in turn will result in a more even and symmetrical temperature distribution and reduce the existence of high number of thermal peaks. These observations were common for both coolants used.

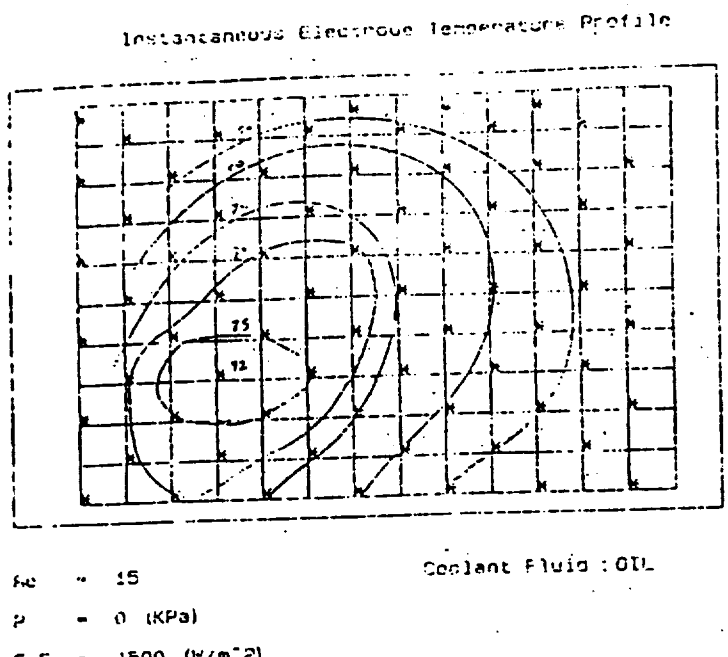

Figure 87. Instantaneous Temperature Profiles During Start-Ups (Oil Coolant, P=0 KPa, Re=15, E.E.=1500 w/m^2).

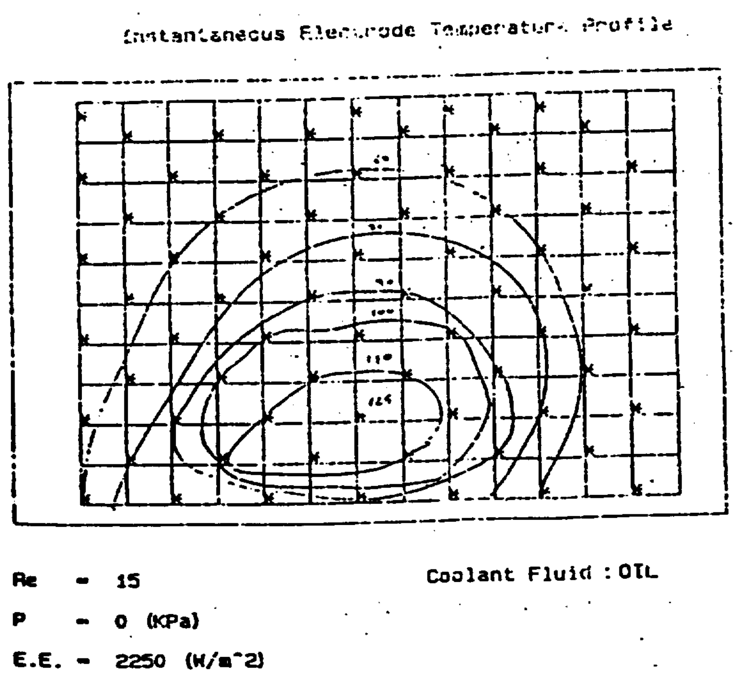

Figure 88. Instantaneous Temperature Profiles During Start-Ups (Oil Coolant, P=0 KPa, Re=15. E.E.=2250 w/m^2).

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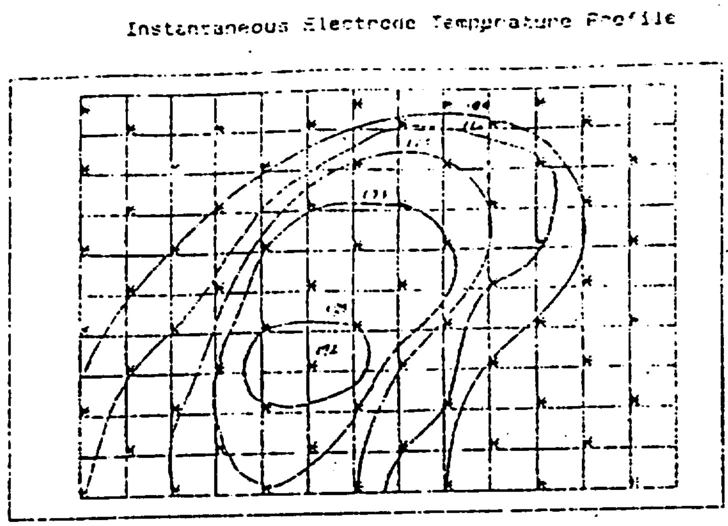

Figure 89. Instantaneous Temperature Profiles During Start-Ups (Oil Coolant, P=0 KPa, Re=15, E.E.=3000 w/m^2).

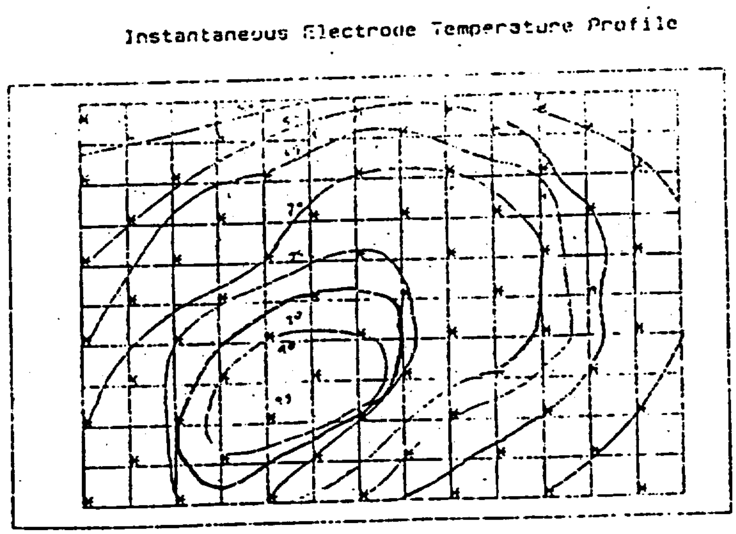

Figure 90. Instantaneous Temperature Profiles During Start-Ups (Oil Coolant, p=3500 KPa, Re=15, E.E.=1500 w/m^2).

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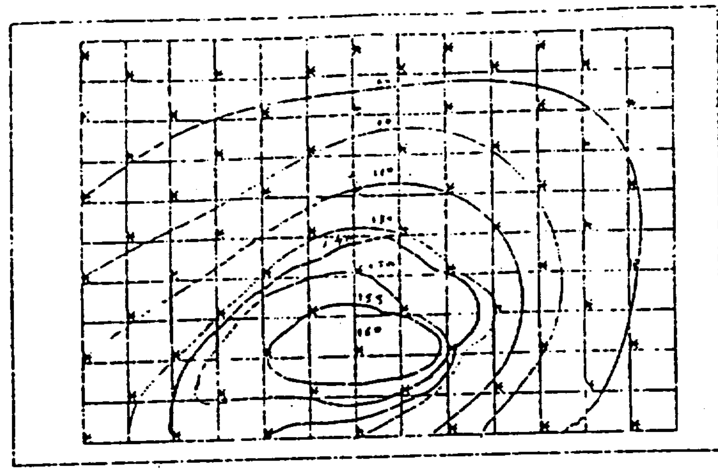
Instantaneous Electrode Temperature Profile



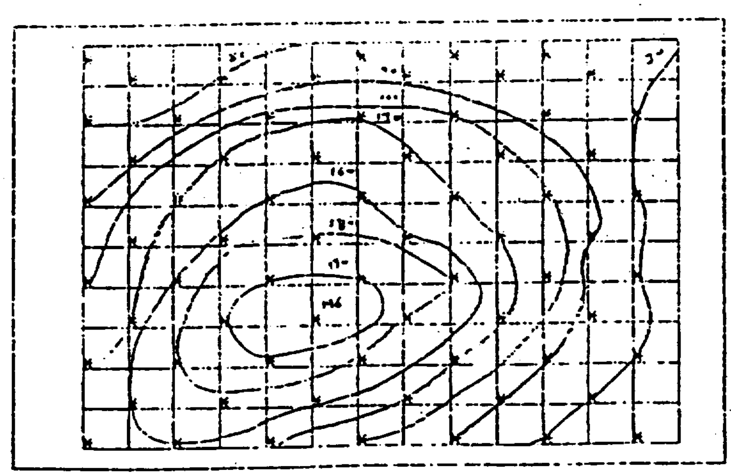
Re = 15 Coolant Fluid . OIL

P = 3500 (KPa)

E.E. = 2250 (W/m^2)

Figure 91. Instantaneous Temperature Profiles During Start-Ups (Oil Coolant, p=3500 KPa, Re=15, E.E.=2250 w/m^2).

Instantaneous Electrode Temperature Profile



Re = 15 Coolant Fluid : OIL

P = 3500 (KPa)

E.E. = 3000 (W/m^2)

Figure 92. Instantaneous Temperature Profiles During Start-Ups (Oil Coolant, p=3500 KPa, Re=15, E.E.=3000 w/m^2).

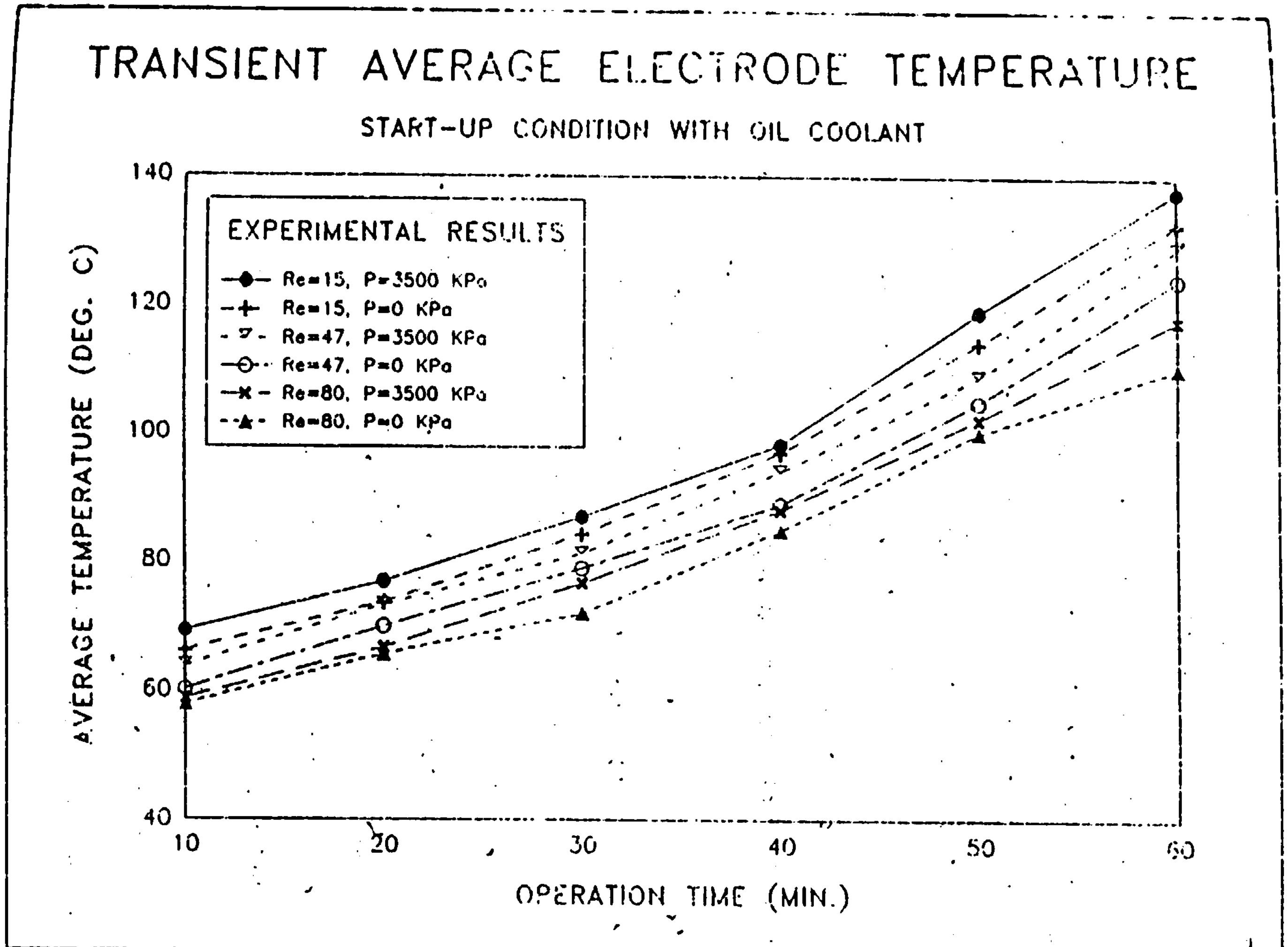


Figure 93. Experimental Transient Average Electrode Temperature During Start-Ups with Oil Coolant.

5.1.2 The Effect of the Coolant Fluid Flow Rate on the Transient Temperature Distribution

The other parameter, beside the stack pressure, that will affect the performance of the fuel cell is the mass flow rate of the cooling system and the thermophysical properties of the fluid. This section was devoted to examine the influence of those two parameters on the transient temperature profiles, transient fuel cell average temperature and peak electrode temperature when the stack pressure is kept constant throughout the considered experimental time intervals.

Referring to Figure 94 through Figure 96, the following can be observed for the water coolant case:

(a) The cell peak electrode temperature increased from 87.1 °C to 185.3 °C when the Re number was 1250 and from 84.3°C to 140°C when Re = 6167 with an applied stack pressure of 0 KPa.

(b) Lower transient average electrode temperature were noticed for both fluids with higher mass flow rate as shown in Figure 101 for Re number. For example comparing between the test done using water coolant with Re=6167 using (0 KPa) applied pressure and that with Re = 1250 using the same applied pressure, the average temperature went up from 37.2 °C to 68.4°C in the first test while the raise in the second case was from 63.3°C to 118.4 °C.

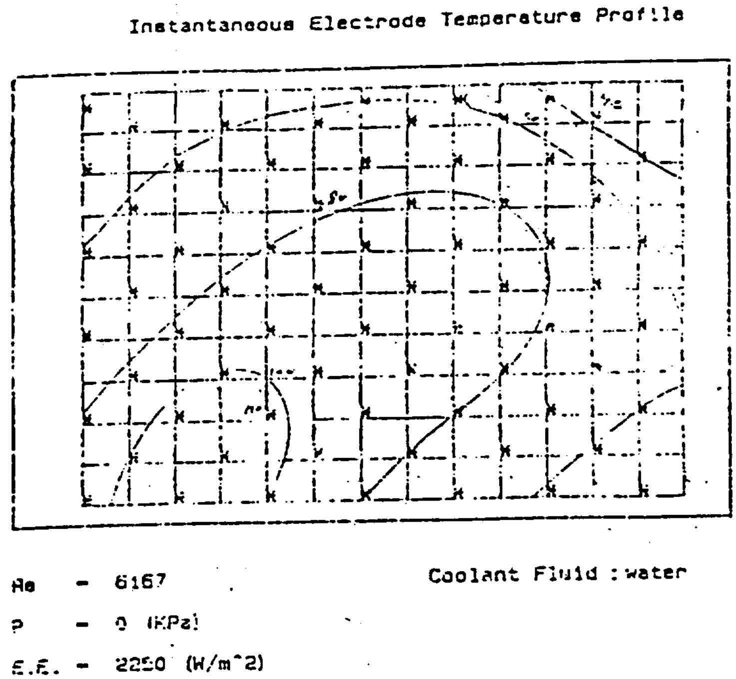


Figure 95. Instantaneous Temperature Profiles During Start-Up (Water Coolant, P=0 KPa, Re=6167 E.E.=2250 w/m^2).

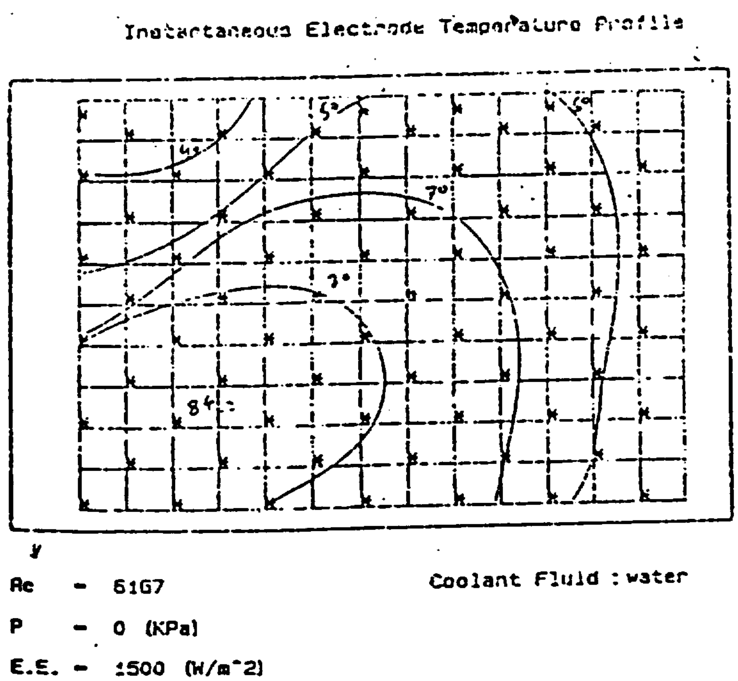
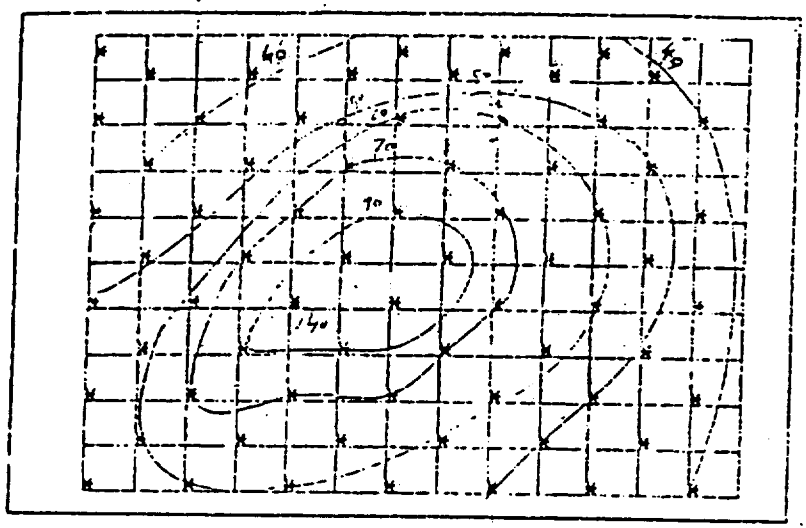


Figure 94. Instantaneous Temperature Profiles During Start-Up (Water Coolant, P=0 KPa, Re=6167, E.E.=1500 w/m^2).

Instantaneous Electrode Temperature Profile



Re = 6157 Coolant Fluid : water

P = 0 (KPa)

E.E. = 3000 (W/m^2)

Figure 96. Instantaneous Temperature Profiles During Start-Up (Water Coolant, P=0 KPa, Re=6167, E.E.=3000 w/m²).

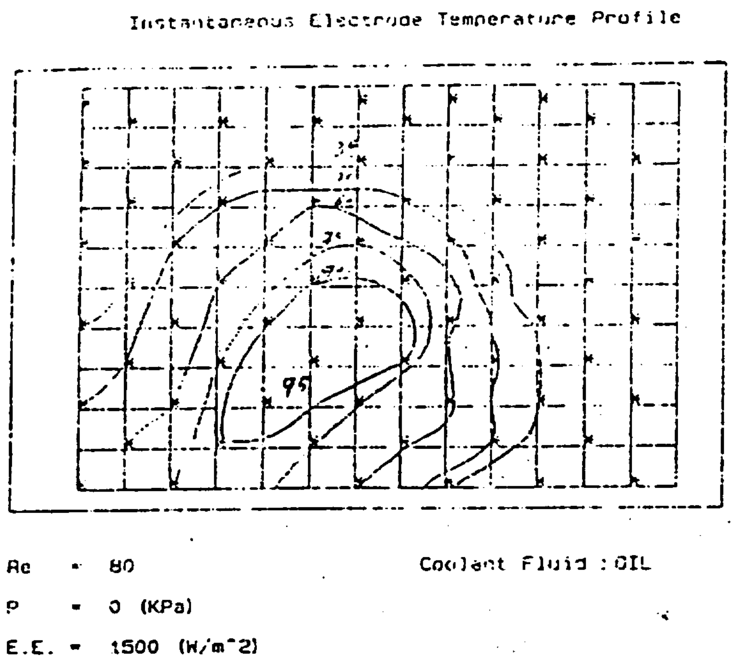


Figure 97. Instantaneous Temperature Profiles During Start-Up (Oil Coolant, P=0 KPa, Re=80, E.E.=1500 w/m^2).

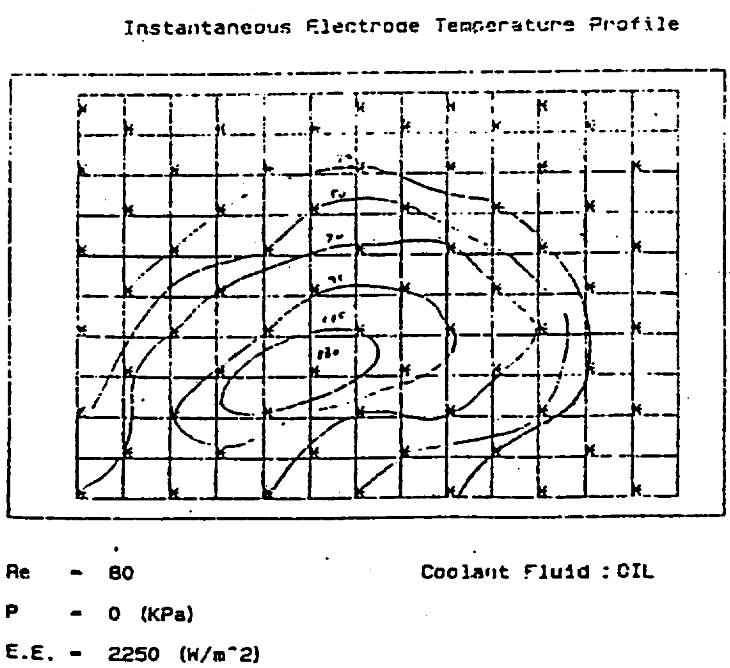


Figure 98. Instantaneous Temperature Profiles During Start-Up (Oil Coolant, P=0 KPa, Re=80, E.E.=2250 w/m^2).

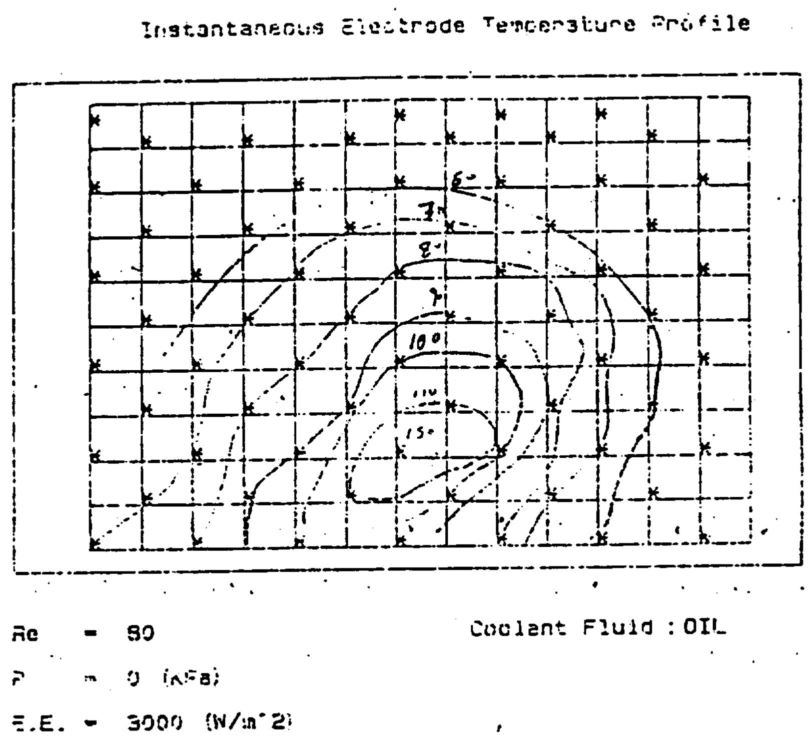


Figure 99. Instantaneous Temperature Profiles During Start-Up (Oil Coolant, P=0 KPa, Re=80, E.E.=3000 w/m^2).

(c) By comparing Figures 80 to 82 and Figures 94 to 96, it can be noticed that the transient temperature profiles propagation rate decreased with increasing the mass flow rate.

On the other hand, when oil was used as a coolant similar observations were noticed with higher volumetric flow rates and constant applied pressure as shown by Figure 97 to Figure 99 which summarizes the effect of the coolant flow rate on the temperature profiles for Re = 15, P = 0KPa and Re =80, P = 0 KPa. Referring to Figure 93, the variation of the average temperature for part of the experimental results are summarized as a function of time. The transient average electrode temperature decreased with high coolant volumetric flow rates remarkably. Also, the decrease in the transient peak electrode temperature was very obvious with higher Re numbers.

5.2 Experimental Temperature Profiles During Shut-Down Process

5.2.1 The Effect of Stack Pressure on the Transient Temperature Distribution

During a shut-down process similar observations were noticed for both working fluids when the effect of the stack pressure is considered while keeping the mass flow rate constant. The variation of the average transient electrode temperature is exhibited by Figure 100 and Figure 101 for both coolant. The electrode of temperature drop rate in the electrode was slower with higher pressure. Also the average increase in the temperature due to increasing the pressure was $2.893 * 10^{-3}$ and $2.011 * 10^{-3}$ °C/KPa for water and oil respectively. On the other hand, the temperature profiles were more uniform than the start-up process as demonstrated by Figure 102 through Figure 107 for water coolant for the whole testing period.

5.2.2 The Effect of the Coolant Fluid Flow Rate on the Transient Temperature Distribution

The higher coolant mass flow rate has increased the electrode temperature drop rate when the pressure is kept constant. Also, the peak electrode temperature was reduced significantly with a higher Re number for both fluids. In addition, the transient isotherms temperature differential decreased dramatically when the mass flow rates were increased.

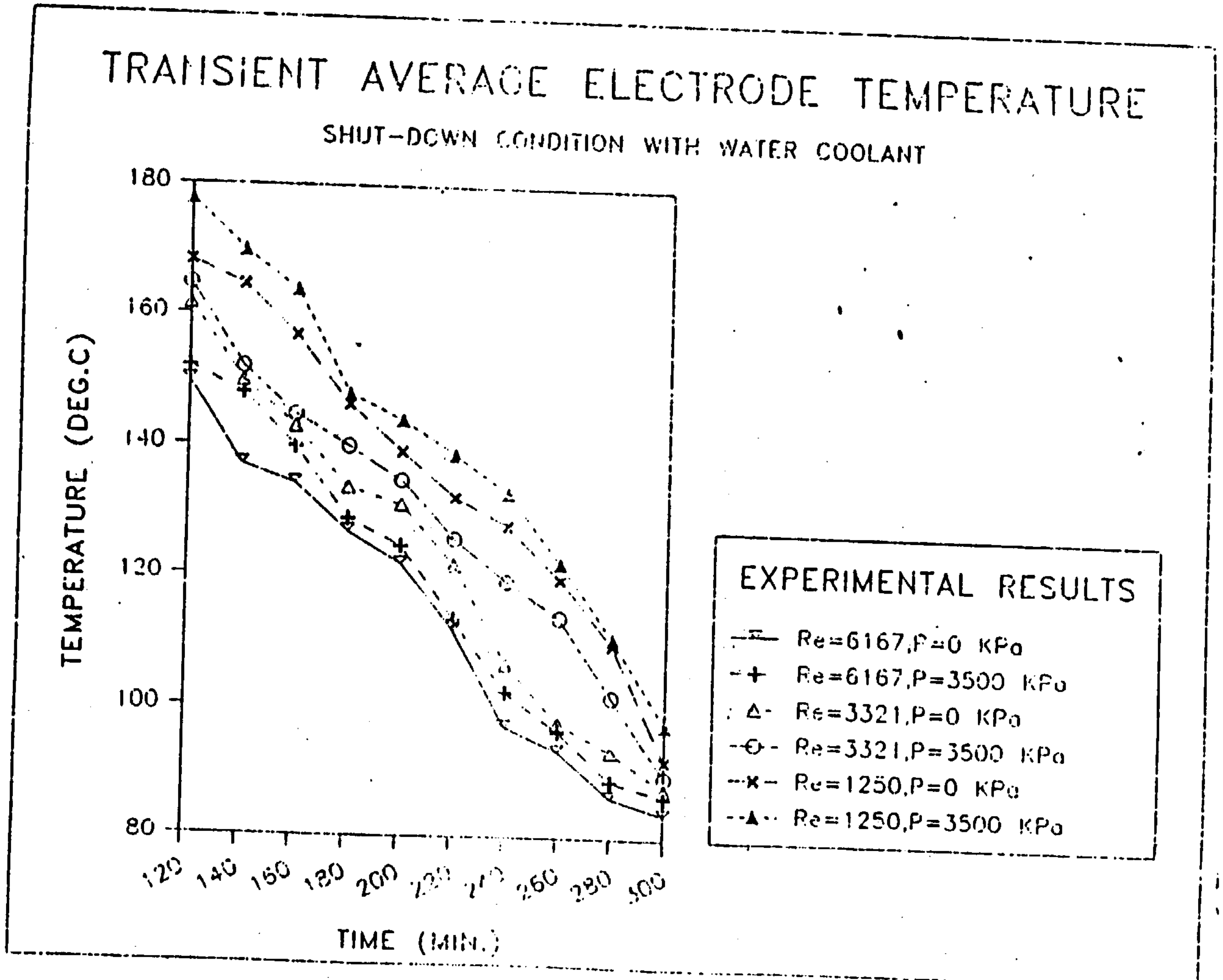


Figure 100. Experimental Average Electrode Temperature During Shut-Down.Using Water Coolant.

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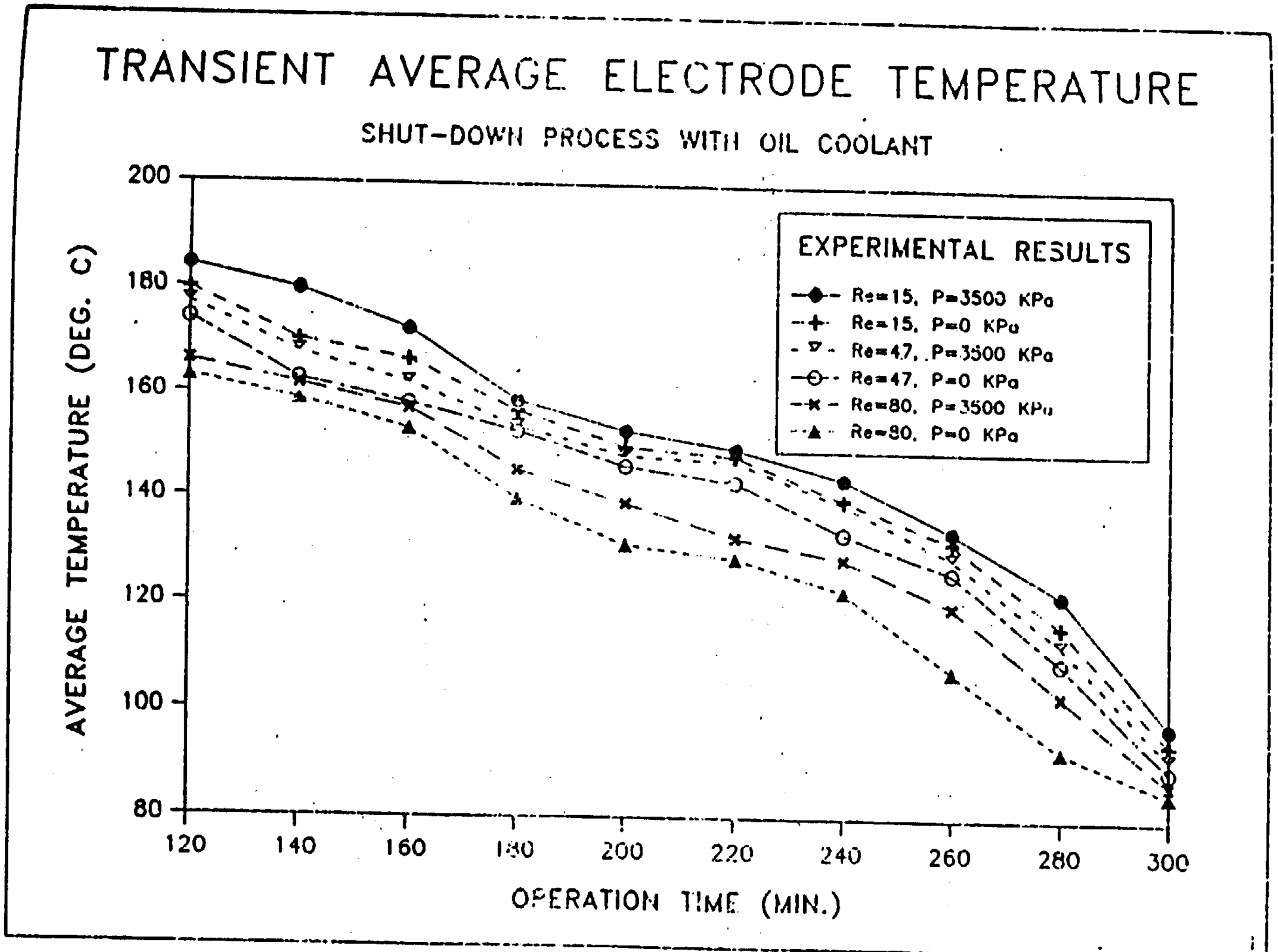

Figure 101. Experimental Average Electrode Temperature During Shut-Down Using Oil Coolant.

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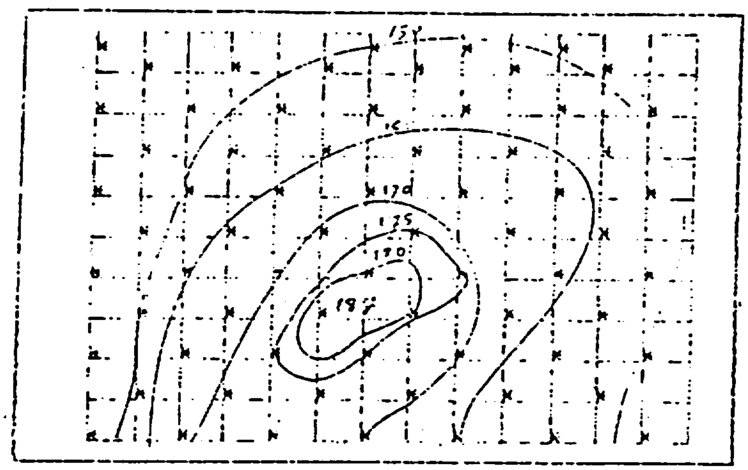


Figure 102. Instantaneous Electrode Temperature Profiles During Shut-Down Process (Water Coolant, P=0 KPa, Re=1250, E.E.=2250 w/m^2).

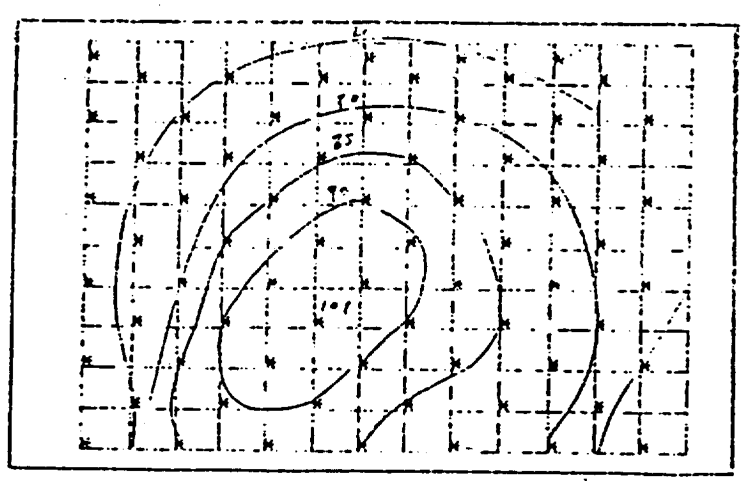
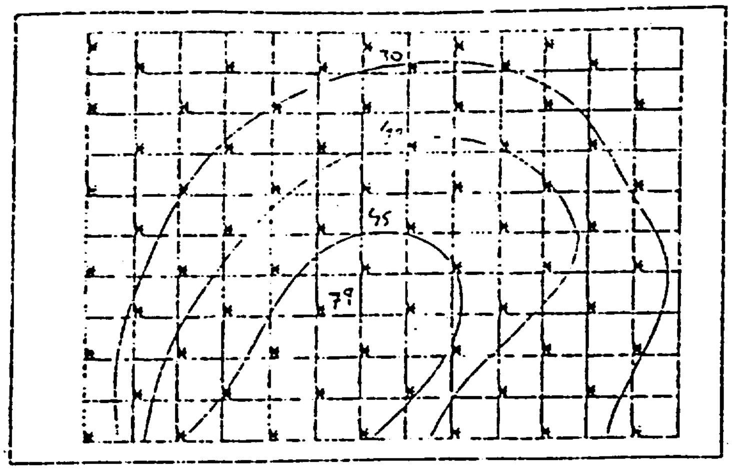


Figure 103. Instantaneous Electrode Temperature Profiles During Shut-Down Process (Water Coolant, P=0 KPa, Re=1250, E.E.=1500 w/m^2).

Instantaneous Electrode Temperature Profile



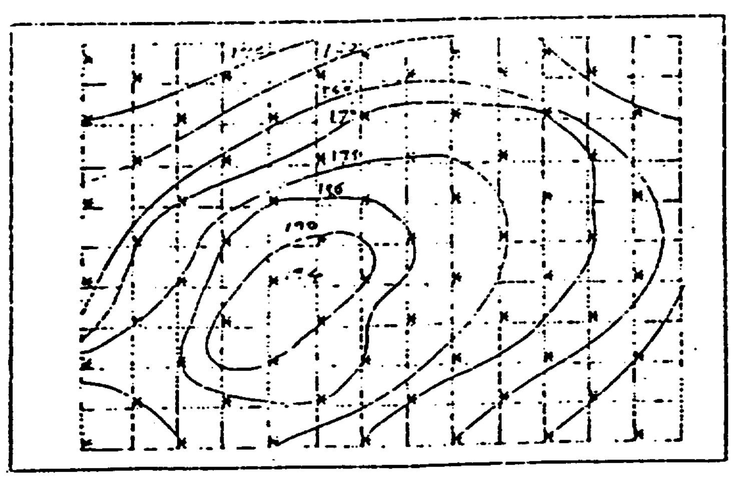
Re - 1250 Coolant Fluid : water

P - 0 (KPa)

E.E. - 0 (W/m^2)

Figure 104. Instantaneous Electrode Temperature Profiles During Shut-Down Process (Water Coolant, P=0 KPa, Re=1250, E.E.=0 w/m^2).

Instantaneous Electrode Temperature Profile



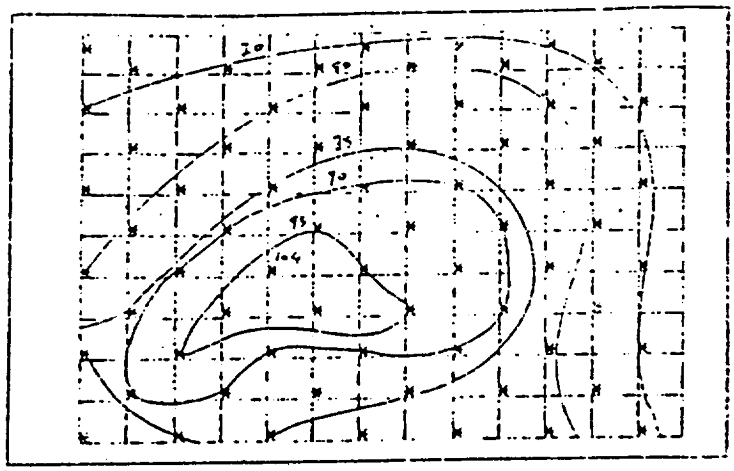
Re - 1250 Coolant Fluid : water

P - 3500 (KPa)

E.E. - 2250 (W/m^2)

Figure 105. Instantaneous Electrode Temperature Profiles During Shut-Down Process (Water Coolant, P=3500 KPa, Re=1250, E.E.= 2250 w/m^2).

Instantaneous Electrode Temperature Profile



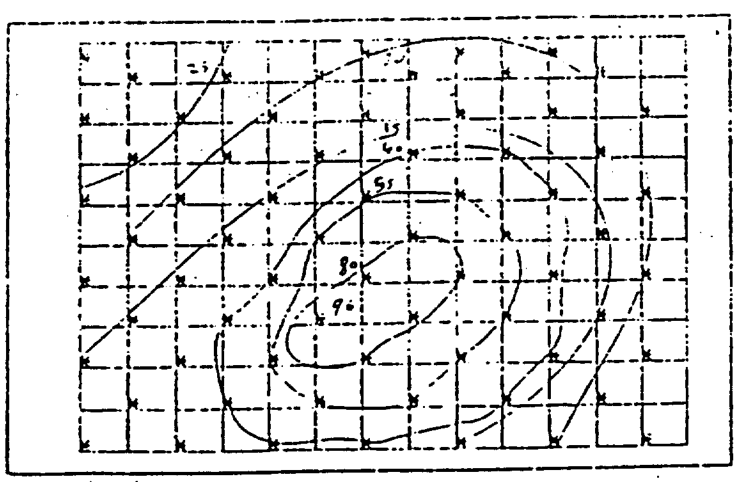
Re - 1250 Coolant Fluid : water

P - 3500 (KPa)

E.E. - 1500 (W/m^2)

Figure 106. Instantaneous Electrode Temperature Profiles During Shut-Down Process (Water Coolant, P=3500 KPa, Re=1250, E.E.=1500 w/m^2).

Instantaneous Electrode Temperature Profile



Re - 1250 Coolant Fluid : water

P - 3500 (KPa)

E.E. - 0 (W/m^2)

Figure 107. Instantaneous Electrode Temperature Profiles During Shut-Down Process (Water Coolant, P=3500 KPa, Re=1250, E.E.=0 w/m^2).

5.3 Theoretical Analysis of the Transient Temperature Distribution

In this section the theoretical analysis developed by Alkasab and Lu [1] was modified for the transient operation condition considered with incompressible cooling fluids. The previous analysis considered the PAFC shown in Figure 108 where the stack consists of a matrix of five cells between each cooling plate sandwich.

The energy balance equation used represents the contribution of fuel cell, cooling plate, process air and coolant in the heat exchange during a transient process. The following assumptions were considered when modifying that model:

(a) The total thermal resistance of the system is dependent on the applied stack pressure, i.e. (K_x) is not constant and will be modified using the experimental correlations for the thermal contact resistance developed in the previous chapter.

(b) A symmetrical behavior of identical halves throughout the fuel cell stack.

(c) One-phase flow.

(d) Incompressible working fluids.

(e) Constant processing and cooling fluid specific heat and densities values during the considered time intervals.

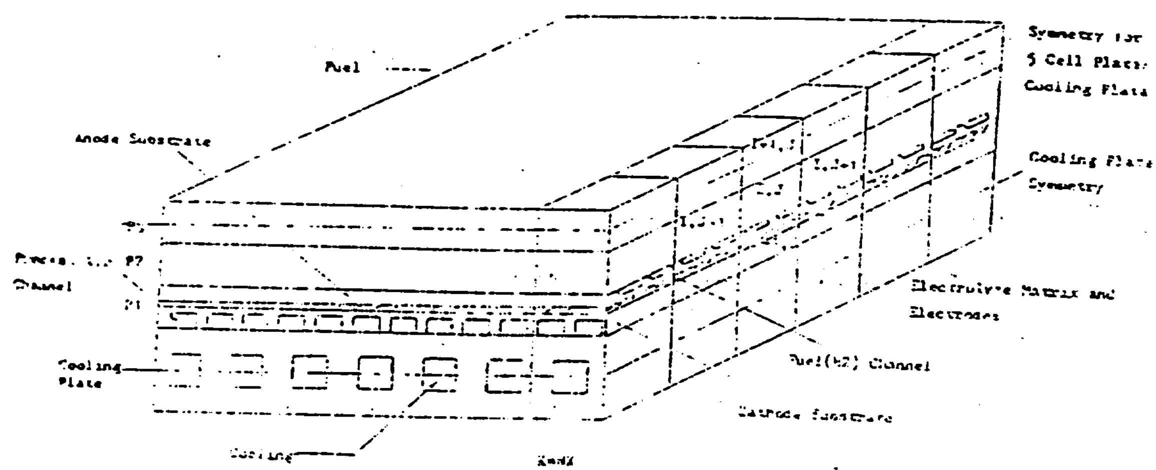


Figure 108. Geometry of the Theoretical Analysis Model.

(f) Temperature gradient in the z-direction is negligibly small.

(g) A adiabatic (isothermal and reversable) behavior is assumed of the fuel cell edges, no correction factor will be used to modify the heat transfer coefficients for the cell and cooling plates.

(h) The transient experimental expression for the cooling fluid convection heat transfer coefficient will be used.

For the chemical reaction inside the fuel cell, the following was assumed:

(a) Fuel to process air operational ratios remains constant throughout the considered testing time intervals.

(b) Phorphoric acid concentration does not change during the considered time intervals.

(c) No significant accumulation in reaction components.

The governing equation can be written as follows for a transient for the considered PAFC components:

Fuel Cell Plate:

The governing equation for the fuel cell plate should include the conduction heat transfer in the x-direction, considering the effect of the thermal contact resistance on the conduction heat transfer in the y-direction, the heat loss to the process air by convection, the internal heat generation and the effect on the internal energy of the fuel cell plate as follows:

$$K_x \frac{\partial T}{\partial x}\Big|_{x+L_1} - K_x \frac{\partial T}{\partial x}\Big|_x + L_1 K_y \frac{\partial^2 T}{\partial y^2}\Big|_y$$

$$- \frac{c_1 \dot{m}_1}{M_1} \frac{\partial T_1}{\partial y}\Big|_y + I\ (\frac{\Delta H}{F} - V) = \rho_1 c_1 L_1 (\frac{\partial T}{\partial t}) \quad (35)$$

Cooling Plate:

The governing equation for the fuel cell plate should include the heat conduction in the x-direction, the heat conduction in the y-direction, heat loss to the cooling fluid by convection and the effect of the internal energy of the cooling plate; as follows

$$\left[2K_x \frac{\partial T}{\partial x}\Big|_{x+\frac{L_2}{2}} \right] + L_2\ K_y \frac{\partial^2 T}{\partial y^2}\Big|_y - \frac{c_2 \dot{m}_2}{M_2} =$$

$$\rho_2\ c_2\ L_2\ (\frac{\partial T}{\partial t}) \quad (36)$$

Process Air:

The governing equation for the process air is composed of the heat gain by the process air by convection, the change of the air enthalpy, and the effect of the air enternal energy as follows:

$$h_1 P_1 (T - T_{\infty 1}) - \dot{m}_1\ c_{p1} \frac{\partial T_1}{\partial t} = \rho_a\ A_1\ C_1 \frac{\partial T_1}{\partial t} \qquad (37)$$

Cooling Fluid:

The governing equation for the cooling fluid should include the heat transfer to the cooling fluid by convection, the change in the enthalpy of the cooling fluid, and the effect on the internal energy of the cooling fluid, as follows:

$$h_2 P_2 (T - T_2) - \dot{m}_2\ C_{p2} \frac{\partial T_2}{\partial y} = \rho_f\ A_2 \frac{\partial T_2}{\partial t} \qquad (38)$$

The initial and boundary condition can be minimized as follows:

(A) START-UP PROCESS

Start-Up Initial Conditions:

Room temperature at (t=0) = T(x,y,t) = T(x,y,0)

Transient Boundary Conditions:

Geometrical Symmetry (1) $\frac{\partial T}{\partial x} = 0$ at x=0, t>0

Adiabatic Process (2) $\frac{\partial T}{\partial y} = 0$ at y=0, t>0

Geometrical Symmetry (3) $\frac{\partial T}{\partial x} = 0$ at $x = L_x$, t>0

Adiabatic Process (4) $\frac{\partial T}{\partial y} = 0$ at $y = L_y$, t>0

Negligible Temperature Changes in the Z-Direction $\frac{\partial T}{\partial z} = 0$ at $0<z\leq L_z$, t>0

Process air inlet temperature (6) $T_1(x,0,t) = \overset{*}{C}_1$ t>0

Coolant fluid inlet temperature (7) $T_2(x,0,t) = \overset{*}{C}_2$ t>0

except in the case of oil coolant): $T_2(x,0,t) = \overset{*}{C}_3$ t>0

where $\overset{*}{C}_3 = \overset{*}{C}_2 + \eta$

Note: For water coolant $h_2(t) = 31.088\ (Re^{0.05779})(e^{0.00953t})$
$(Pr^{0.01433})(e^{0.0001240}) - 31.088$
$(Re^{0.05779})(Pr^{0.01433})(e^{0.0001240})$

For oil coolant $h_2(t) = 16.088\ (Re^{0.216})(e^{0.00961t})$
$(Pr^{0.0076})(e^{1.356*10-4o}) - 16.088$
$(Re^{0.216})(Pr^{0.0076})(e^{1.356*10-4o})$

(B) SHUT-DOWN PROCESS

The initial and boundary conditions can be summarized as follows for the shut-down process that will start from a steady state operation condition when t=120 minutes:

Shut-Down Initial Conditions:

Average cell temperature at (t=120 minutes) = t(x,y,t) = T(x,y,120)

Transient Boundary Condition:

Geometrical symmetry (1) $\frac{\partial T}{\partial x} = 0$ at x=0, t>120

Adiabatic process (2) $\frac{\partial T}{\partial y} = 0$ at y=0, t>120

Geometrical symmetry (3) $\frac{\partial T}{\partial y} = 0$ at $y=L_x$, t>120

Adiabatic process (4) $\frac{\partial T}{\partial y} = 0$ at $y=L_y$, t>120

Negligible temperature $\frac{\partial T}{\partial z} = 0$ at $z \leq L_z$, $t>120$

change in the z-direction (5)

Process air inlet temperature (6) $T_1(x,0,t) = \overset{*}{C}_1$ $t>120$ min

Coolant fluid inlet temperature (7) $T_2(x,0,t) = \overset{*}{C}_2$ $t>120$ min

(except in oil case): $T_2(x,0,t) = \overset{*}{C}_3$ $t>120$ min

Note: For water coolant: $h_s(t) = 70.088*(Re^{0.05779})*(Pr^{0.01433})*$
[exp (-0.00891t + 0.000123 o)

For oil coolant: $h_s(t) = 35.044*(Re^{0.21506})*$
$(Pr^{7.614*10^{-3}})$ [exp (-0.00901t +
$1.356*10^{-4}$ o)

where

$T = T(x,y,t)$ = Temperature converted to (C°)

T_1 = fuel cell plate temperature (C°)

T_2 = cooling plate temperature (C°)

K_x = effective thermal conductivity in stacking direction in $(\frac{W}{m-C})$

K_y = effective thermal conductivity in the process air direction in $(\frac{W}{m\ C^o})$

$\dot{m}_1$ = process air mass flow rate (Kg/hr)

$\dot{m}_2$ = cooling fluid mass flow rate (Kg/hr)

L_1 = fuel cell plate thickness (m)

L_2 = cooling plate thickness (m)

L_x = high of the considered slice (m)

L_y = length of the considered slice (m)

ΔH = molar heat of reaction of hydrogen

F = Faraday's constant, (constant/meter)

V = voltage (volts)

I = Current density $(\frac{Amps}{m^2})$

c_{p1} = fuel cell plate specific heat $(\frac{J}{K_g - C^o})$

c_{p2} = cooling plate specific heat $\frac{J}{KgC^o})$

M_1 = fuel cell plate pitch (m)

M_2 = cooling plate pitch (m)

ρ_1 = fuel cell plate density (Kg/m^3)

ρ_2 = cooling plate density (Kg/m^3)

ρ_a = molar density of air $(gm\text{-}mk/m^3)$

P_1 = process air channel perimeter (m)

P_2 = cooling tube perimeter (m)

A_1 = process air channel cross-section area (m^2)

A_2 = cooling air channel cross-section area (m^2)

h_1 = convection heat transfer inside process air channel $\frac{W}{m^2\ C^o})$

h_2 = convection heat transfer coefficient inside cooling tubes $(\frac{W}{m^2\ C^o})$

<u>Note</u>: The purpose for using $(^*C_3)$ in the case of oil, is to account for the higher temperature of the cooling fluid due to the effectiveness of the cooling heat exchange of the secondary cooling system.

The partial differential equations were solved by the finite difference method utilizing the available initial and boundary conditions. The developed Fortran computer code was then used to generate the theoretical temperature profiles, the average temperature, the current density profiles and the average current density for the start-up and shut-down process under different operations conditions and for the two incompressible fluids.

The importance and the accuracy of the data generated by the electrode depends on the consideration of the design and operation parameters, the cooling system configuration, cooling fluid properties and current density effects on the electrode temperature distribution.

In addition, two of the parameters that affect the performance of the cooling system predicted by the computer code are the plates dimensions and the fuel cell stack material construction and design. The consideration of those two parameters will make the code sensitive to the material properties of the cooling and cell plates, such as the thermal conductivity, the cooling system and the sandwiched cell plates configurations, and the properties of the working fluid.

In the theoretical analysis considered above, the computer code was modified in order to predict the performance of a fuel cell that was simulated by the experimental model by considering the following design parameters:

(a) Cooling and fuel cell plates dimensions.

(b) Cooling and fuel cell plate thermal conductivities.

(c) Mass flow rate of cooling incompressible fluids utilized.

(d) Serpentine cooling system dimensions and configurations.

(e) Thermophysical properties of the utilized cooling fluids.

(f) Inlet temperature of the cooling fluid (oil coolant only.

(g) Total applied stack pressure.

(h) The sequence of the monitoring time intervals.

The output data file modified to demonstrate the transient electrode temperature distribution. The initial conditions will determine whether the performed test is a start-up or a shut-down process.

5.4 Analytical Results

In this section the results generated by the theoretical analysis will be presented and appropriate analysis will be made to provide the needed information for a comparison betweeen the experimental and theoretical results.

5.4.1 Start-Up Process

The transient temperature profiles for a start-up process are demonstrated by Table I to Table IV, only for maximum and minimum applied stack pressure, with minimum, average, and maximum mass flow rates, when water is employed as a coolant. Figure 109 summarizes the variation in the average electrode temperature during the different considered start-up processes. As noticed in the experimental results, there is a tendency toward a higher average electrode temperature with higher applied stack pressure on the average of nearly $2.075 * 10^{-3}$ °C per additional KPa. On the other hand, the average electrode temperature will drop with higher coolant mass flow rate or Re numbers. In addition, the transient temperature differential seems to decrease remarkably between the isotherms with higher stack pressure, but the opposite is noticed with the same stack pressure but lower mass flow rates.

Similar results were observed when oil was used as the cooling fluid as exhibited by sample Table C-I and Table-II in the appendix, which show maximum and minimum applied stack pressure for the minimum, maximum, and average Re numbers, the change of the electrode temperature distribution during a start-up. The temperature distribution gradually becomes more uniform with higher applied stack pressure. Figure 110 shows the variation of the average temperature for the considered as a function of time and also a dependent of the applied stack pressure approximately $1.109 * 10^{-3}$ °C/KPa.

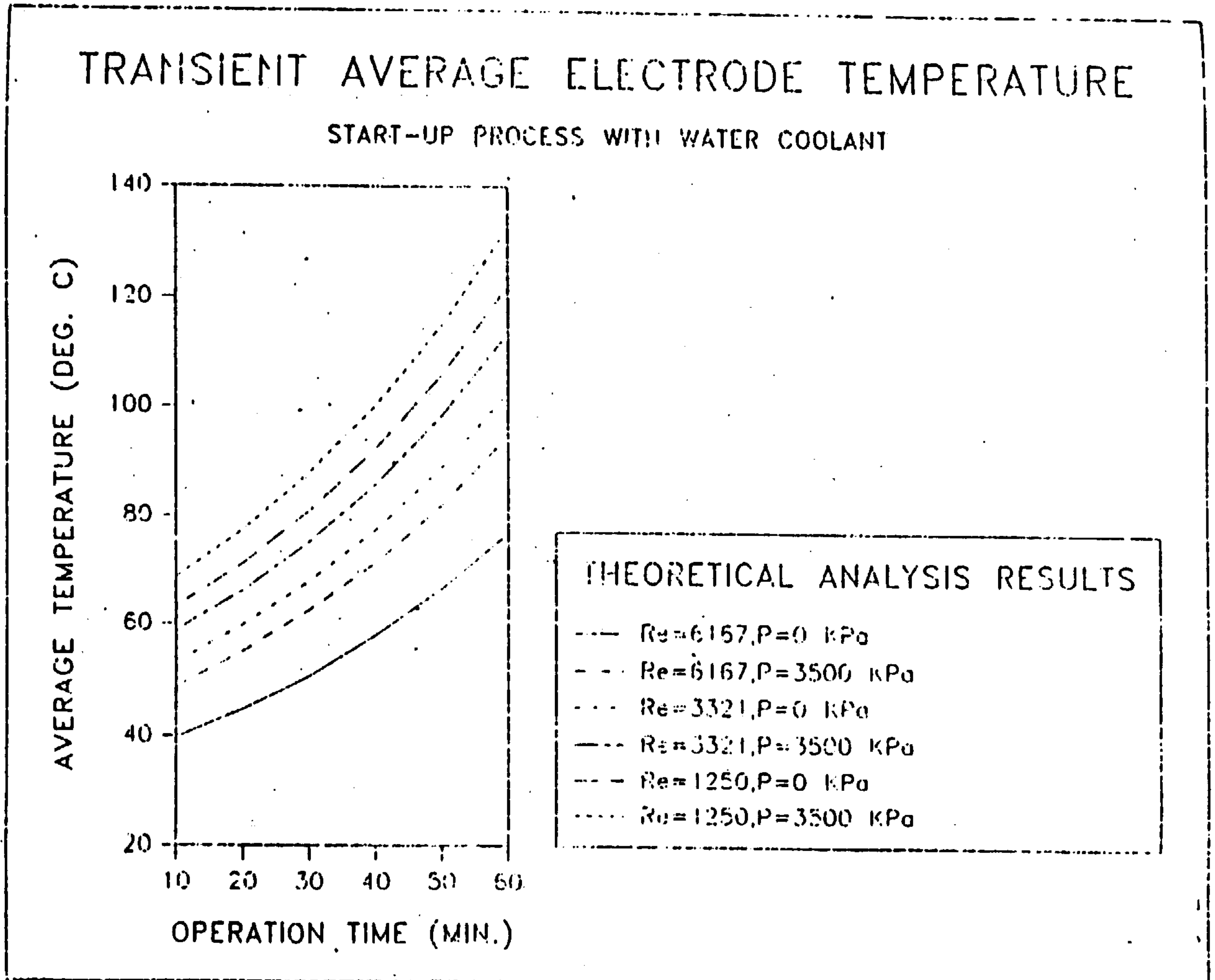


Figure 109. Theoretical Transient Average Electrode Temperature During Start-Ups with Water Coolant.

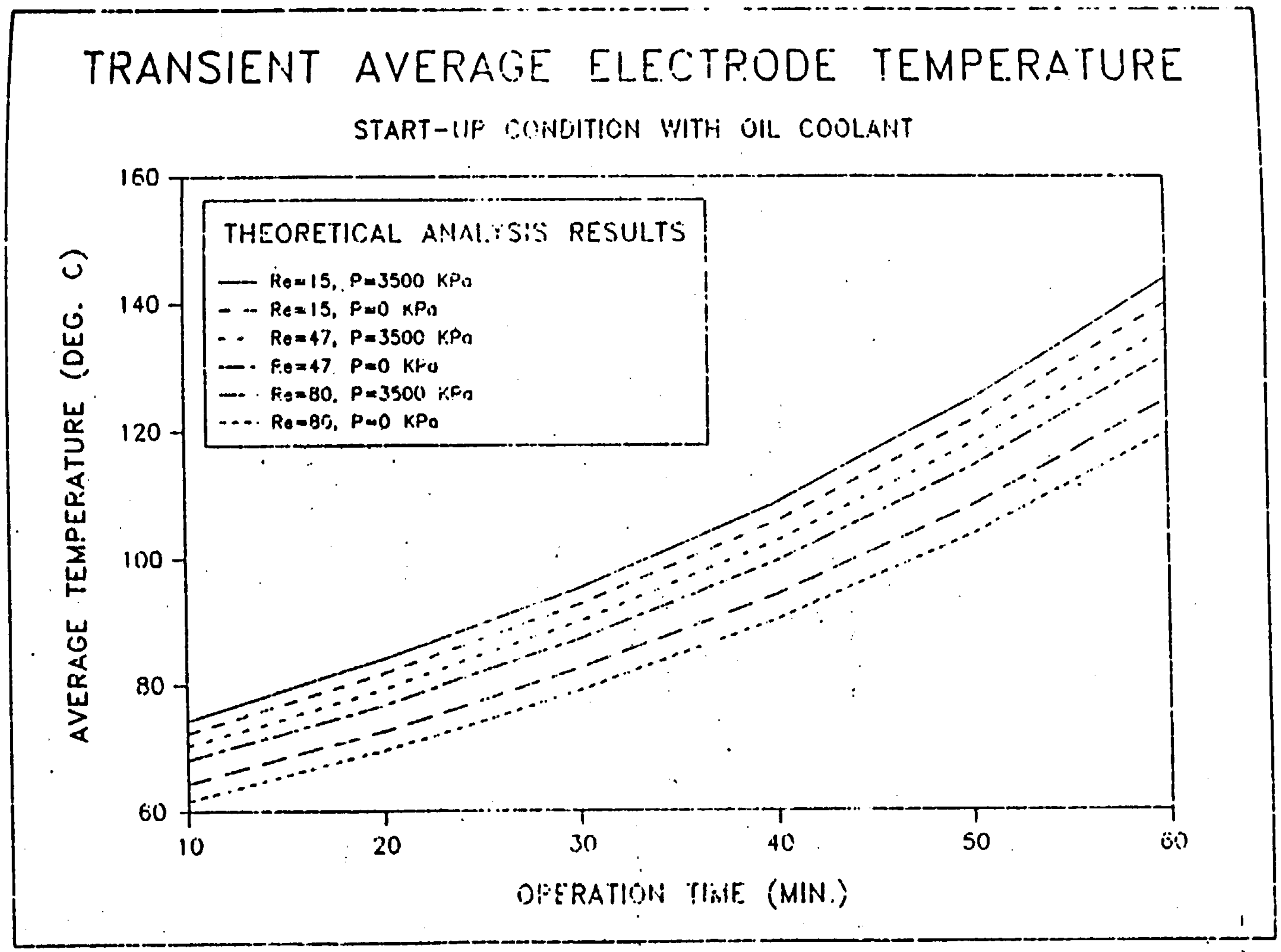


Figure 110. Theoretical Transient Average Electrode Temperature During Start-Ups with Oil Coolant.

Table I. Start-Up Process with Water Coolant (P=3500 KPa, Re=1250)

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 10.00
ENDING TIME = 20.00
AVERAGE TEMPERATURE = 68.631
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.12500E+04
COOLANT:WATER

83.162	82.404	81.645	80.886	80.128	79.369	78.611	77.852	77.094
81.509	80.748	79.988	79.228	78.467	77.707	76.946	76.186	75.426
79.719	78.958	78.197	77.436	76.675	75.914	75.153	74.392	73.631
78.009	77.246	76.484	75.722	74.959	74.197	73.434	72.672	71.910
76.252	75.489	74.725	73.962	73.199	72.435	71.672	70.908	70.145
74.509	73.824	73.058	72.293	71.527	70.762	69.996	69.231	68.466
72.734	71.969	71.203	70.438	69.672	68.907	68.141	67.376	66.610
70.140	69.382	68.625	67.867	67.109	66.352	65.594	64.836	64.079
68.257	67.499	66.742	65.985	65.228	64.470	63.713	62.956	62.199
66.346	65.569	64.833	64.076	63.320	62.563	61.807	61.050	60.294
63.467	62.722	61.978	61.233	60.489	59.745	59.000	58.256	57.512
59.268	58.552	57.837	57.121	56.405	55.690	54.974	54.259	53.543

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 20.00
ENDING TIME = 30.00
AVERAGE TEMPERATURE = 77.372
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.12500E+04
COOLANT:WATER

94.006	93.148	92.291	91.433	90.576	89.718	88.861	88.003	87.146
92.341	91.480	90.618	89.757	88.895	88.034	87.172	86.311	85.450
90.384	89.521	88.658	87.795	86.932	86.070	85.207	84.344	83.481
88.601	87.735	86.869	86.003	85.137	84.271	83.406	82.540	81.674
86.713	85.844	84.976	84.108	83.240	82.372	81.504	80.636	79.768
85.038	84.165	83.292	82.420	81.547	80.675	79.802	78.929	78.057
82.969	82.096	81.222	80.349	79.476	78.603	77.729	76.856	75.983
79.187	78.331	77.476	76.620	75.765	74.910	74.054	73.199	72.343

Table I (Continued).

[illegible]	76.165	75.310	74.456	73.601	72.747	71.892	71.038	70.183
[illegible]	73.936	73.083	72.231	71.378	70.525	69.672	68.819	67.967
[illegible]	69.563	68.738	67.912	67.087	66.261	65.436	64.610	63.784
[illegible]	62.432	61.669	60.906	60.143	59.380	58.617	57.854	57.091

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 30.00
ENDING TIME = 40.00
AVERAGE TEMPERATURE = 87.744
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.12500E+04
COOLANT:WATER

106.888	105.913	104.938	103.963	102.989	102.014	101.039	100.064	99.089
105.209	104.227	103.246	102.264	101.283	100.301	99.320	98.338	97.357
103.057	102.074	101.090	100.106	99.122	98.139	97.155	96.171	95.187
101.194	100.205	99.216	98.227	97.238	96.249	95.260	94.271	93.282
99.150	98.157	97.164	96.172	95.179	94.186	93.194	92.201	91.208
97.474	96.473	95.473	94.473	93.473	92.472	91.472	90.472	89.471
95.192	94.190	93.189	92.187	91.185	90.183	89.181	88.179	87.177
[illegible]	88.947	87.976	87.005	86.033	85.062	84.091	83.119	82.148
87.410	86.440	85.471	84.501	83.531	82.562	81.592	80.622	79.652
84.795	83.829	82.862	81.895	80.928	79.961	78.994	78.027	77.060
79.513	77.592	76.671	75.750	74.829	73.908	72.988	72.067	71.146
67.773	66.954	66.136	65.318	64.499	63.681	62.863	62.045	61.226

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 40.00
ENDING TIME = 50.00
AVERAGE TEMPERATURE =100.100
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.12500E+04
COOLANT:WATER

[illegible]2.251	121.136	120.021	118.906	117.791	116.676	115.561	114.446	113.331
[illegible]0.552	119.428	118.303	117.179	116.054	114.929	113.805	112.680	111.556
[illegible]8.177	117.049	115.920	114.792	113.664	112.536	111.408	110.280	109.152
[illegible]5.224	115.088	113.952	112.817	111.681	110.545	109.409	108.273	107.137

Table I (Continued).

[illegible]	112.852	111.711	110.569	109.428	108.287	107.146	106.004	104.863
[illegible]	111.178	110.025	108.873	107.720	106.567	105.415	104.262	103.109
109.850	108.694	107.538	106.381	105.225	104.069	102.913	101.757	100.600
102.597	101.586	100 478	99.369	98.260	97.150	96.041	94.931	93.822
99.779	98.672	97.565	96.458	95.351	94.244	93.137	92.030	90.923
96.690	95.596	94.493	93.391	92.288	91.185	90.083	88.980	87.878
88.074	87.041	86.008	84.976	83.943	82.910	81.877	80.844	79.811
73.103	72.221	71.338	70.456	69.573	68.690	67.808	66.925	66.043

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 50.00
ENDING TIME = 60.00
AVERAGE TEMPERATURE =114.872
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.12500E+04
COOLANT:WATER

140.645	139.362	138.079	136.796	135.514	134.231	132.948	131.665	130.382
138.921	137.625	136.329	135 033	133.737	132.441	131.145	129.849	128.553
136.284	134.983	133.682	132.381	131.080	129 779	128.478	127.177	125.877
134.233	132.921	131.609	130.297	128.986	127.674	126.362	125.050	123.738
131.779	130.460	129.140	127.821	126.502	125.182	123.863	122.544	121.224
130.151	128.816	127.480	126.145	124.809	123.473	122.138	120.802	119.467
127.500	126.158	124.816	123.474	122.132	120.790	119.448	118.106	116.764
117.972	116.697	115.423	114.148	112.874	111.600	110.325	109.051	107.777
114.557	113.206	112.016	110.745	109.474	108.203	106.932	105.661	104.390
110.912	109.647	108.382	107.118	105.853	104.588	103.323	102.059	100.794
99.366	98.200	97.035	95.869	94.704	93.539	92.373	91.208	90.042
79.311	78.353	77.396	76.438	75.481	74.523	73.566	72.608	71.650

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 60.00
ENDING TIME = 70.00
AVERAGE TEMPERATURE =132.605
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.12500E+04
COOLANT:WATER

Table I. (Continued).

2.758	161.273	159.789	158.304	156.820	155.335	153.850	152.366	150.861
0.999	159.497	157.995	156.494	154.992	153.490	151.988	150.486	148.984
8.059	156.551	155.042	153.533	152.024	150.515	149.007	147.498	145.989
5.900	154.376	152.852	151.329	149.805	148.281	146.758	145.234	143.711
.53.177	151.643	150.110	148.576	147.042	145.509	143.975	142.442	140.908
.51.613	150.057	148.501	146.945	145.390	143.834	142.278	140.722	139.166
48.843	147.277	145.710	144.143	142.577	141.010	139.444	137.877	136.310
36.304	134.831	133.359	131.887	130.414	128.942	127.469	125.997	124.525
32.288	130.820	129.353	127.885	126.417	124.950	123.482	122.014	120.547
27.952	126.493	125.034	123.575	122.116	120.657	119.198	117.739	116.280
12.745	111.423	110.100	108.778	107.456	106.133	104.811	103.489	102.166
86.544	85.500	84.455	83.410	82.365	81.320	80.275	79.230	78.185

Table II. Start-Up Process with Water Coolant (P=0 KPa, Re=1250).

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 10.00
ENDING TIME = 20.00
AVERAGE TEMPERATURE = 63.163
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.12500E+04
COOLANT:WATER

77.543	76.818	76.094	75.369	74.644	73.919	73.194	72.469	71.744
75.866	75.140	74.413	73.686	72.960	72.233	71.507	70.780	70.054
74.062	73.334	72.607	71.880	71.153	70.426	69.699	68.971	68.244
72.321	71.602	70.874	70.145	69.417	68.688	67.960	67.231	66.503
70.557	69.827	69.098	68.368	67.639	66.909	66.180	65.450	64.721
69.868	69.137	67.405	66.674	65.942	65.211	64.480	63.748	63.017
67.302	66.271	65.539	64.808	64.076	63.345	62.613	61.882	61.150
64.457	63.733	63.009	62.285	61.561	60.837	60.113	59.389	58.665
62.567	61.843	61.119	60.396	59.672	58.949	58.225	57.501	56.778
60.651	59.928	59.205	58.482	57.760	57.037	56.314	55.591	54.868
57.853	57.142	56.431	55.720	55.008	54.297	53.586	52.874	52.163
53.862	53.178	52.495	51.811	51.127	50.443	49.760	49.076	48.392

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 20.00
ENDING TIME = 30.00
AVERAGE TEMPERATURE = 71.214
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.12500E+04
COOLANT:WATER

87.654	86.835	86.015	85.196	84.377	83.557	82.738	81.919	81.099
85.949	85.125	84.302	83.479	82.656	81.833	81.010	80.187	79.363
83.970	83.145	82.321	81.496	80.672	79.847	79.023	78.199	77.374
82.152	81.325	80.497	79.670	78.843	78.015	77.188	76.360	75.533
80.236	79.406	78.577	77.747	76.917	76.088	75.258	74.429	73.599
78.516	77.682	76.848	76.014	75.180	74.346	73.512	72.678	71.845
76.430	75.596	74.761	73.927	73.093	72.258	71.424	70.589	69.755
72.770	71.953	71.136	70.318	69.501	68.684	67.866	67.049	66.231

Table II. Continued.

[illegible]	69.782	68.965	68.149	67.332	66.516	65.699	64.883	64.066
68.370	67.555	66.740	65.925	65.110	64.295	63.480	62.665	61.851
64.164	63.375	62.586	61.797	61.008	60.219	59.430	58.642	57.853
57.431	56.702	55.973	55.244	54.515	53.786	53.056	52.327	51.598

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 30.00
ENDING TIME = 40.00
AVERAGE TEMPERATURE = 80.768
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.12500E+04
COOLANT:WATER

99.666	98.735	97.803	96.872	95.940	95.008	94.077	93.145	92.213
97.926	96.988	96.050	95.112	94.174	93.236	92.298	91.361	90.423
95.744	94.804	93.864	92.924	91.984	91.044	90.104	89.164	88.224
93.829	92.884	91.939	90.994	90.049	89.104	88.159	87.211	86.265
91.744	90.795	89.847	88.898	87.950	87.001	86.053	85.104	84.156
89.998	89.042	88.086	87.130	86.174	85.218	84.263	83.307	82.351
[illegible]	86.733	85.776	84.818	83.861	82.904	81.946	80.989	80.032
82.633	81.705	80.777	79.849	78.920	77.992	77.064	76.136	75.206
80.123	79.197	78.270	77.343	76.417	75.490	74.563	73.637	72.710
77.517	76.593	75.669	74.746	73.822	72.898	71.974	71.050	70.126
71.569	70.689	69.809	68.929	68.049	67.169	66.289	65.409	64.530
61.591	60.809	60.028	59.246	58.464	57.682	56.900	56.118	55.336

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 40.00
ENDING TIME = 50.00
AVERAGE TEMPERATURE = 92.149
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.12500E+04
COOLANT:WATER

113.991	112.926	111.860	110.795	109.729	108.664	107.598	106.533	105.467
112.207	111.132	110.058	108.983	107.909	106.834	105.759	104.685	103.610
109.790	108.712	107.634	106.556	105.479	104.401	103.323	102.245	101.167
107.765	106.680	105.594	104.509	103.423	102.338	101.253	100.167	99.082

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Table II. Continued.

105.479	104.388	103.296	102.207	101.115	100.026	98.935	97.845	96.754
103.715	102.614	101.512	100.411	99.309	98.208	97.106	96.005	94.903
101.193	100.088	98.983	97.879	96.774	95.669	94.564	93.459	92.355
94.376	93.316	92.256	91.196	90.136	89.076	88.016	86.956	85.895
91.461	90.403	89.345	88.287	87.229	86.172	85.114	84.056	82.998
88.399	87.345	86.291	85.238	84.184	83.131	82.077	81.023	79.970
80.285	79.298	78.311	77.324	76.337	75.350	74.363	73.375	72.388
66.436	65.593	64.749	63.906	63.062	62.219	61.376	60.532	59.689

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 50.00
ENDING TIME = 60.00
AVERAGE TEMPERATURE =105.756
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.12500E+04
COOLANT:WATER

131.142	129.916	128.691	127.465	126.239	125.013	123.787	122.561	121.335
129.304	128.065	125.827	125.589	124.350	123.112	121.873	120.635	119.397
126.613	125.370	124.127	122.883	121.640	120.397	119.154	117.911	116.668
124.463	123.209	121.956	120.702	119.449	118.195	116.942	115.688	114.434
121.936	120.675	119.415	118.154	116.893	115.633	114.372	113.111	111.850
120.169	118.893	117.617	116.340	115.064	113.788	112.512	111.235	109.959
117.452	116.170	114.887	113.605	112.323	111.040	109.758	108.476	107.193
108.413	107.195	105.977	104.760	103.542	102.324	101.107	99.889	98.671
105.007	103.793	102.579	101.364	100.150	98.935	97.721	96.506	95.292
101.392	100.183	98.975	97.766	96.558	95.349	94.141	92.932	91.724
90.578	89.464	88.350	87.237	86.123	85.009	83.896	82.782	81.669
72.077	71.162	70.247	69.332	68.417	67.502	66.587	65.672	64.757

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 60.00
ENDING TIME = 70.00
AVERAGE TEMPERATURE =122.091
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.12500E+04
COOLANT:WATER

Table II. Continued.

[illegible]	150.342	148.924	147.505	146.087	144.668	143.250	141.831	140.412
149.854	148.419	146.984	145.548	144.113	142.678	141.243	139.808	138.373
146.843	145.401	143.959	142.518	141.076	139.634	138.192	136.751	135.309
144.553	143.097	141.641	140.185	138.729	137.273	135.817	134.361	132.905
141.735	140.270	138.804	137.339	135.874	134.408	132.943	131.478	130.012
139.984	138.498	137.011	135.524	134.038	132.551	131.064	129.578	128.091
137.113	135.616	134.119	132.622	131.126	129.629	128.132	126.635	125.138
125.260	123.853	122.446	121.039	119.632	118.225	116.818	115.411	114.004
121.260	119.857	118.455	117.053	115.650	114.248	112.845	111.443	110.041
116.969	115.575	114.181	112.787	111.393	109.998	108.604	107.210	105.816
102.774	101.510	100.247	98.983	97.719	96.456	95.192	93.929	92.665
78.651	77.653	76.654	75.656	74.657	73.659	72.660	71.662	70.663

Table III. Start-Up Process with Water Coolant
(P=3500 KPa, Re=3321).

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 10.00
ENDING TIME = 20.00
AVERAGE TEMPERATURE = 58.739
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.33210E+04
COOLANT:WATER

71.924	71.166	70.407	69.649	68.890	68.132	67.373	66.614	65.856
70.484	69.724	68.963	68.203	67.442	66.682	65.922	65.161	64.401
68.925	66.164	67.403	66.642	65.881	65.120	64.359	63.598	62.837
67.436	66.673	65.911	65.149	64.386	63.624	62.861	62.099	61.337
65.906	65.143	64.379	63.616	62.852	62.089	61.326	60.562	59.799
64.457	63.692	62.926	62.161	61.395	60.630	59.864	59.099	58.334
62.842	62.077	61.311	60.546	59.780	59.015	58.249	57.484	56.718
60.589	59.831	59.073	58.316	57.558	56.800	56.043	55.285	54.5[illegible]
58.950	58.192	57.435	56.678	55.921	55.163	54.406	53.649	52.892
57.287	56.530	55.774	55.017	54.261	53.504	52.748	51.991	51.235
54.788	54.043	53.299	52.555	51.810	51.066	50.322	49.577	48.833
51.150	50.435	49.719	49.004	48.288	47.573	46.857	46.142	45.42[illegible]

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 20.00
ENDING TIME = 30.00
AVERAGE TEMPERATURE = 66.220
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.33210E+04
COOLANT:WATER

81.303	80.445	79.588	78.730	77.873	77.015	76.158	75.300	74.443
79.851	78.990	78.128	77.267	76.405	75.544	74.682	73.821	72.960
78.146	77.283	76.421	75.558	74.695	73.832	72.969	72.107	71.244
76.592	75.727	74.861	73.995	73.129	72.263	71.397	70.531	69.665
74.947	74.079	73.211	72.343	71.475	70.607	69.738	68.870	68.00[illegible]
73.486	72.614	71.741	70.868	69.996	69.123	68.251	67.378	66.505
71.685	70.812	69.939	69.065	68.192	67.319	66.445	65.572	64.699
58.404	67.548	66.693	65.837	64.982	64.127	63.271	62.416	61.56[illegible]

Table III. Continued.

[illegible]	65.663	64.809	63.954	63.099	62.245	61.390	60.536	59.68[illegible]
[illegible]	63.724	62.871	62.019	61.166	60.313	59.460	58.607	57.755
60.764	59.938	59.112	58.287	57.461	56.636	55.810	54.985	54.159
54.540	53.777	53.014	52.251	51.488	50.725	49.962	49.199	48.436

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 30.00
ENDING TIME = 40.00
AVERAGE TEMPERATURE = 75.039
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.33210E+04
COOLANT:WATER

92.444	91.469	90.494	89.520	88.545	87.570	86.595	85.620	84.645
90.978	89.997	89.015	88.034	87.052	86.071	85.089	84.108	83.126
89.104	88.120	87.137	86.153	85.169	84.185	83.202	82.218	81.234
87.479	86.490	85.501	84.512	83.523	82.534	81.545	80.556	79.567
85.697	84.704	83.711	82.719	81.726	80.733	79.741	78.748	77.756
84.233	83.233	82.232	81.232	80.232	79.232	78.231	77.231	76.231
92.246	81.244	80.242	79.240	78.238	77.237	76.235	75.233	74.231
77.674	76.703	75.731	74.760	73.789	72.817	71.846	70.875	69.903
75.491	74.522	73.552	72.582	71.612	70.643	69.673	68.703	67.733
73.217	72.250	71.283	70.316	69.350	68.383	67.416	66.449	65.482
67.776	66.855	65.935	65.014	64.093	63.172	62.251	61.330	60.410
58.490	57.672	56.854	56.036	55.217	54.399	53.581	52.763	51.944

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 40.00
ENDING TIME = 50.00
AVERAGE TEMPERATURE = 85.675
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.33210E+04
COOLANT:WATER

105.731	104.616	103.501	102.386	101.271	100.156	99.041	97.926	96.811
104.246	103.122	101.997	100.873	99.748	98.623	97.499	96.374	95.250
102.176	101.048	99.920	98.792	97.664	96.536	95.408	94.280	93.151
100.472	99.336	98.200	97.064	95.928	94.792	93.657	92.521	91.385

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Table III. Continued.

98.526	97.385	96.244	95.103	93.961	92.820	91.679	90.538	89.396
97.072	95.919	94.767	93.614	92.461	91.308	90.156	89.003	87.850
94.910	93.754	92.598	91.442	90.286	89.129	87.973	86.817	85.661
88.712	87.603	86.494	85.384	84.275	83.166	82.056	80.947	79.838
86.173	85.066	83.959	82.852	81.745	80.639	79.532	78.425	77.318
83.495	82.392	81.290	80.187	79.084	77.982	76.879	75.777	74.674
76.031	74.998	73.965	72.932	71.899	70.866	69.833	68.800	67.767
63.091	62.209	61.326	60.443	59.561	58.678	57.795	56.913	56.030

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 50.00
ENDING TIME = 60.00
AVERAGE TEMPERATURE = 93.320
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.33210E+04
COOLANT:WATER

121.639	120.357	119.074	117.791	116.508	115.225	113.942	112.659	111.376
120.130	118.834	117.538	116.242	114.946	113.650	112.354	111.058	109.763
117.832	116.531	115.230	113.929	112.628	111.327	110.026	108.725	107.425
116.040	114.728	113.416	112.104	110.792	109.480	108.169	106.857	105.545
113.899	112.580	111.260	109.941	108.622	107.302	105.983	104.664	103.344
112.472	111.136	109.801	108.465	107.130	105.794	104.458	103.123	101.787
110.160	108.918	107.476	106.134	104.792	103.450	102.108	100.766	99.424
101.907	100.633	99.358	98.084	96.810	95.535	94.261	92.987	91.712
98.937	97.666	96.395	95.124	93.853	92.582	91.311	90.041	88.770
95.767	94.503	93.238	91.973	90.709	89.444	88.179	86.914	85.650
85.778	84.612	83.447	82.282	81.116	79.951	78.785	77.620	76.454
68.449	67.491	66.533	65.576	64.618	63.661	62.703	61.746	60.798

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 60.00
ENDING TIME = 70.00
AVERAGE TEMPERATURE =113.499
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.33210E+04
COOLANT:WATER

Table III. Continued.

[illegible]	139.286	137.795	136.310	134.826	133.341	131.857	130.372	128.888
9.223	137.721	136.219	134.717	133.215	131.713	130.211	128.709	127.207
36.659	135.150	133.641	132.133	130.624	129.115	127.606	126.097	124.589
34.770	133.246	131.722	130.199	128.675	127.152	125.628	124.104	122.581
32.393	130.860	129.326	127.793	126.259	124.726	123.192	121.658	120.125
31.018	129.462	127.906	126.351	124.795	123.239	121.683	120.127	118.571
28.600	127.034	125.467	123.901	122.334	120.767	119.201	117.634	116.068
17.743	116.271	114.798	113.326	111.853	110.381	108.909	107.436	105.964
14.250	112.782	111.315	109.847	108.379	106.912	105.444	103.977	102.509
10.430	109.022	107.563	106.104	104.645	103.186	101.727	100.268	98.809
97.328	96.005	94.683	93.361	92.038	90.716	89.394	88.071	86.749
74.691	73.646	72.602	71.557	70.512	69.467	68.422	67.377	66.332

Table IV. Start-Up Process with Water Coolant (P=0 KPa, Re=3321).

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 10.00
ENDING TIME = 20.00
AVERAGE TEMPERATURE = 53.056
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.33210E+04
COOLANT:WATER

66.305	65.406	64.507	52.608	62.709	51.510	60.911	60.012	59.113
64.978	64.076	63.175	62.274	61.373	60.472	59.571	58.669	57.768
63.541	62.639	61.737	60.835	59.933	59.031	58.130	57.228	56.326
62.160	61.264	60.361	59.457	58.554	57.650	56.747	55.843	54.939
60.758	59.853	58.949	58.044	57.139	56.234	55.329	54.424	53.520
59.422	58.515	57.608	56.701	55.793	54.886	53.979	53.072	52.165
57.934	57.027	56.119	55.212	54.305	53.397	52.490	51.583	50.675
55.856	54.958	54.060	53.162	52.265	51.367	50.469	49.571	48.673
54.346	53.448	52.551	51.653	50.756	49.858	48.961	48.063	47.166
52.813	51.916	51.019	50.123	49.226	48.329	47.433	46.536	45.640
50.509	49.627	48.745	47.862	46.980	46.098	45.216	44.333	43.451
47.156	46.308	45.460	44.612	43.764	42.915	42.067	41.219	40.371

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 20.00
ENDING TIME = 30.00
AVERAGE TEMPERATURE = 59.815
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.33210E+04
COOLANT:WATER

74.951	73.935	72.919	71.902	70.886	69.870	68.854	67.837	56.821
73.613	72.592	71.571	70.550	69.529	68.508	67.487	66.466	65.445
72.041	71.019	69.996	68.974	67.951	66.929	65.506	64.994	63.861
70.609	69.583	68.557	67.531	66.504	65.478	64.452	63.426	62.399
69.093	68.064	67.035	66.006	64.977	63.948	62.919	61.890	60.862
67.746	66.712	65.678	64.644	63.609	62.575	61.541	60.507	59.472
66.086	65.051	64.016	62.981	61.945	60.911	59.876	58.841	57.806
63.061	62.047	61.033	60.019	59.006	57.992	56.978	55.964	54.950

Table IV. Continued.

61.322	60.309	59.297	58.284	57.271	56.258	55.246	54.233	53.220
59.533	58.523	57.512	56.501	55.491	54.480	53.469	52.458	51.448
56.018	55.040	54.061	53.083	52.104	51.126	50.147	49.169	48.191
50.280	49.376	48.472	47.568	46.663	45.759	44.855	43.950	43.046

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 30.00
ENDING TIME = 40.00
AVERAGE TEMPERATURE = 57.837
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.33210E+04
COOLANT:WATER

85.222	84.067	82.911	81.756	80.600	79.445	78.289	77.134	75.978
83.871	82.708	81.545	80.381	79.218	78.055	76.892	75.728	74.565
82.143	80.977	79.812	78.646	77.480	76.314	75.148	73.982	72.816
80.645	79.473	78.301	77.129	75.957	74.785	73.613	72.441	71.268
79.003	77.826	76.650	75.473	74.297	73.120	71.944	70.767	69.591
77.653	76.466	75.292	74.097	72.911	71.726	70.540	69.355	68.169
75.822	74.635	73.447	72.260	71.072	69.885	68.697	67.510	66.322
71.607	70.456	69.305	68.154	67.002	65.851	64.700	63.549	62.398
69.595	66.443	67.297	66.147	64.998	63.849	62.699	61.550	60.401
67.499	66.353	65.207	64.061	62.915	61.769	60.623	59.477	58.331
62.483	61.392	60.300	59.209	58.118	57.026	55.935	54.844	53.752
53.923	52.953	51.983	51.013	50.044	49.074	48.104	47.134	46.164

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 40.00
ENDING TIME = 50.00
AVERAGE TEMPERATURE = 77.391
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.33210E+04
COOLANT:WATER

97.471	96.150	94.828	93.507	92.185	90.863	89.542	88.220	86.899
96.103	94.770	93.437	92.104	90.771	89.438	88.106	86.773	85.440
94.194	92.857	91.520	90.183	88.846	87.509	86.172	84.835	83.498
92.623	91.277	89.931	88.585	87.238	85.892	84.546	83.200	81.854

Table IV. Continued.

[illegible]	89.477	88.125	86.772	85.420	84.067	82.714	81.362	80.009
87.490	86.124	86.757	85.391	84.025	82.659	81.293	79.926	78.560
[illegible]	86.127	84.756	83.386	82.016	80.649	79.275	77.905	76.535
[illegible]	80.469	79.154	77.839	76.524	75.210	73.895	72.580	71.265
[illegible]	78.131	76.819	75.507	74.195	72.883	71.571	70.259	68.947
76.974	75.667	74.360	73.053	71.747	70.440	69.133	67.826	66.519
70.093	68.869	67.644	66.420	65.196	63.972	62.747	61.523	60.299
58.164	57.118	56.072	55.026	53.980	52.934	51.888	50.842	49.796

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME - 50.00
ENDING TIME - 60.00
AVERAGE TEMPERATURE - 88.815
PRESURE- 0.0 KPa
REYNOLD'S NUMBER- 0.33210E+04
COOLANT:WATER

112.137	110.616	109.096	107.575	106.055	104.534	103.014	101.494	99.973
110.745	109.210	107.674	106.138	104.602	103.066	101.530	99.994	98.458
108.627	107.085	105.543	104.002	102.460	100.918	93.376	97.834	96.292
106.975	105.420	103.866	102.311	100.756	99.203	97.646	96.092	94.537
105.002	103.438	101.875	100.311	98.747	97.184	95.620	94.056	92.493
103.687	102.104	100.521	98.938	97.355	95.772	94.189	92.606	91.023
101.555	99.965	98.374	56.784	95.193	93.603	92.012	90.422	88.831
93.948	92.437	90.927	89.416	87.906	86.396	84.885	83.375	81.865
91.210	69.704	88.197	86.691	85.185	83.678	82.172	80.666	79.159
88.288	86.789	85.290	83.791	82.292	80.793	79.295	77.796	76.297
79.079	77.698	76.316	74.935	73.554	72.173	70.791	69.410	68.029
63.103	61.968	60.833	59.698	58.564	57.429	56.294	55.159	54.024

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME - 60.00
ENDING TIME - 70.00
AVERAGE TEMPERATURE -102.529
PRESURE- 0.0 KPa
REYNOLD'S NUMBER- 0.33210E+04
COOLANT:WATER

Table IV. Continued.

129.767	128.008	126.248	124.489	122.729	120.970	119.210	117.451	115.691
128.346	126.566	124.786	123.006	121.226	119.446	117.666	115.886	114.105
125.983	124.195	122.407	120.619	118.831	117.042	115.754	113.466	111.678
124.242	122.436	120.630	118.825	117.019	115.213	113.407	111.602	109.796
122.051	120.234	118.416	116.599	114.781	112.964	111.146	109.329	107.511
120.784	118.940	117.096	115.252	113.408	111.564	109.720	107.876	106.032
118.556	116.699	114.842	112.985	111.129	109.272	107.415	105.559	103.702
108.547	106.801	105.056	103.311	101.565	99.821	98.076	96.331	94.586
105.327	103.587	101.848	100.108	98.369	96.630	94.890	93.151	91.411
101.852	100.123	98.394	96.664	94.935	93.206	91.477	89.748	88.019
89.727	88.159	86.592	85.025	83.456	81.891	80.323	78.756	77.189
69.258	67.620	66.382	65.143	63.905	62.666	61.428	60.190	58.951

Table V. Start-Up Process with Water Coolant (P=3500 KPa, Re=6167).

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 10.00
ENDING TIME = 20.00
AVERAGE TEMPERATURE = 48.874
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.61670E+04
COOLANT.WATER

64.058	63.195	62.332	61.469	60.606	59.742	58.879	58.016	57.153
62.330	61.455	60.600	59.735	58.870	58.005	57.140	56.274	55.409
60.497	59.631	58.765	57.900	57.034	56.168	55.302	54.436	53.570
58.723	57.856	56.988	56.121	55.253	54.386	53.519	52.651	51.784
56.913	56.044	55.175	54.307	53.438	52.570	51.701	50.833	49.964
55.170	54.299	53.428	52.557	51.686	50.815	49.944	49.074	48.203
53.284	52.413	51.542	50.671	49.800	48.929	48.058	47.187	46.316
50.861	49.999	49.137	48.275	47.413	46.551	45.689	44.827	43.965
48.961	48.099	47.237	46.376	45.514	44.653	43.791	42.929	42.068
47.041	46.180	45.319	44.458	43.598	42.737	41.876	41.015	40.155
44.444	43.597	42.750	41.903	41.056	40.209	39.362	38.515	37.668
40.954	40.140	39.326	38.512	37.698	36.883	36.069	35.255	34.441

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 20.00
ENDING TIME = 30.00
AVERAGE TEMPERATURE = 55.121
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.61670E+04
COOLANT:WATER

72.410	71.435	70.459	69.484	68.508	67.532	66.557	65.581	64.606
70.614	69.634	68.654	67.674	66.693	65.713	64.733	63.753	62.773
68.590	67.609	66.627	65.645	64.664	63.682	62.700	61.719	60.737
66.697	65.712	64.726	63.741	62.756	61.771	60.785	59.800	58.815
64.720	63.732	62.744	61.757	60.769	59.781	56.794	57.806	56.818
62.898	61.905	60.912	59.920	58.927	57.934	56.941	55.948	54.955
60.782	59.788	58.794	57.801	56.807	55.814	54.820	53.827	52.833
57.422	56.448	55.475	54.502	53.529	52.555	51.582	50.609	49.636

Table V. Continued.

55.246	54.273	53.301	52.329	51.357	50.385	49.413	48.440	47.466
[illegible].027	52.057	51.086	50.115	49.146	48.176	47.205	46.235	45.265
49.291	48.352	47.413	46.473	45.534	44.595	43.656	42.716	41.777
[illegible].668	42.800	41.932	41.063	40.195	39.327	38.459	37.591	36.723

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 30.00
ENDING TIME = 40.00
AVERAGE TEMPERATURE = 62.536
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.61670E+04
COOLANT:WATER

82.334	81.224	80.115	79.006	77.896	76.787	75.678	74.569	73.459
80.454	79.337	78.221	77.104	75.987	74.871	73.754	72.637	71.520
78.208	77.089	75.970	74.850	73.731	72.612	71.493	70.373	69.254
76.177	75.051	73.926	72.801	71.676	70.550	69.425	68.300	67.175
74.003	72.873	71.744	70.614	59.485	68.356	67.226	66.097	64.967
72.095	70.958	69.820	68.682	67.544	66.406	65.268	64.130	62.992
69.736	58.536	67.456	66.316	65.176	64.036	62.897	61.757	60.617
65.204	64.099	62.993	61.888	60.783	59.678	58.573	57.468	56.363
62.699	61.596	60.493	59.389	58.286	57.183	56.079	54.975	53.872
60.122	59.022	57.922	56.822	55.721	54.621	53.521	52.421	51.321
54.980	53.932	52.885	51.837	50.789	49.742	48.694	47.646	46.598
46.831	45.900	44.969	44.038	43.107	42.176	41.245	40.314	39.383

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 40.00
ENDING TIME = 50.00
AVERAGE TEMPERATURE = 71.369
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.61670E+04
COOLANT:WATER

94.167	92.899	91.630	90.361	89.092	87.824	86.555	85.286	84.017
92.187	90.908	89.628	88.349	87.069	85.790	84.510	83.231	81.951
89.682	88.398	87.115	85.831	84.548	83.264	81.981	80.697	79.414
87.491	86.198	84.906	83.614	82.321	81.029	79.737	78.444	77.152

Table V. Continued.

[illegible]	83.753	82.405	81.186	79.884	78.569	77.291	75.997	74.69[illegible]
83.086	81.774	80.463	79.151	77.839	76.528	75.216	73.905	72.593
80.474	79.159	77.843	76.528	75.212	73.897	72.581	71.266	69.950
74.470	73.208	71.946	70.683	69.421	68.159	66.897	65.635	64.372
71.571	70.312	69.052	67.793	66.533	65.274	64.014	62.755	61.495
68.561	67.307	66.052	64.798	63.543	62.289	61.034	59.780	58.525
61.676	60.501	59.325	58.150	56.975	55.799	54.624	53.449	52.274
50.515	49.511	48.506	47.502	46.498	45.494	44.489	43.485	42.481

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 50.00
ENDING TIME = 60.00
AVERAGE TEMPERATURE = 81.937
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.61670E+04
COOLANT:WATER

108.336	106.876	105.416	103.957	102.497	101.037	99.578	98.118	96.659
106.234	104.759	103.285	101.810	100.336	98.861	97.387	95.912	94.438
102.423	101.943	100.463	98.983	97.503	96.023	94.542	93.062	91.583
101.047	99.555	98.062	96.570	95.077	93.584	92.092	90.599	89.106
96.356	96.855	95.354	93.853	92.352	90.851	89.350	87.849	86.348
96.267	94.747	93.227	91.708	90.188	88.668	87.149	85.629	84.110
93.404	91.877	90.350	88.823	87.297	85.770	84.243	82.716	81.189
85.546	84.096	82.646	81.196	79.746	78.297	76.847	75.397	73.947
82.172	80.726	79.280	77.834	76.388	74.942	73.496	72.050	70.604
78.639	77.200	75.761	74.322	72.883	71.444	70.005	68.566	67.127
69.583	68.257	66.931	65.605	64.279	62.953	61.627	60.301	58.975
54.804	53.715	52.625	51.536	50.446	49.357	48.267	47.178	46.088

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 60.00
ENDING TIME = 70.00
AVERAGE TEMPFRATURE = 94.613
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.61670E+04
COOLANT:WATER

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Table V. Continued.

125.369	123.679	121.990	120.301	118.612	116.923	115.234	113.545	111.856
123.119	121.409	119.700	117.991	116.282	114.573	112.864	111.156	109.447
119.946	118.232	116.515	114.798	113.082	111.365	109.648	107.931	106.215
117.357	115.624	113.890	112.157	110.423	108.690	106.956	105.223	103.489
114.327	112.582	110.837	109.092	107.348	105.603	103.858	102.113	100.368
112.041	110.270	108.500	106.830	105.060	103.290	101.519	99.749	97.979
109.040	107.257	105.475	103.693	101.910	100.128	98.345	96.563	94.780
98.840	97.164	95.489	93.814	92.139	90.463	88.788	87.113	85.438
94.890	93.220	91.550	89.881	88.211	86.541	84.871	83.201	81.531
90.721	89.061	87.401	85.741	84.081	82.421	80.761	79.101	77.441
78.952	77.448	75.943	74.439	72.934	71.430	69.925	68.420	66.915
59.803	58.614	57.425	56.236	55.047	53.858	52.669	51.481	50.292

Table VI. Start-Up Process with Water Coolant .
(P=0 KPa, Re=6167).

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 10.00
ENDING TIME = 20.00
AVERAGE TEMPERATURE = 39.696
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.61670E+04
COOLANT:WATER

52.820	52.095	51.370	50.645	49.921	49.196	48.471	47.746	47.021
51.297	50.570	49.843	49.117	48.390	47.664	46.937	46.210	45.484
49.685	48.958	48.231	47.504	46.777	46.050	45.323	44.595	43.868
48.123	47.395	46.666	45.938	45.209	44.481	43.752	43.024	42.295
46.530	45.801	45.071	44.342	43.612	42.883	42.153	41.424	40.695
44.992	44.261	43.530	42.798	42 057	41.335	40.604	39.873	39.141
43.338	42.609	41.875	41.143	40.411	39.680	38.948	38.217	37.485
41.247	40.523	39.799	39.075	38.351	37.627	36.903	36.179	35.455
39.561	38.858	38.135	37.411	36.687	35.964	35.240	34.516	33.793
37.901	37.178	36.455	35.732	35.009	34.286	33.563	32.841	32.118
35.677	34.965	34.254	33.543	32.832	32.120	31.409	30.698	29.986
[illegible]	32.060	31.376	30.692	30.009	29.325	28.641	27.957	27.273

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 20.00
ENDING TIME = 30.00
AVERAGE TEMPERATURE = 44.768
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.61670E+04
COOLANT:WATER

59.707	58.888	58.069	57.249	56.430	55.611	54.791	53.972	53.152
58.114	57.291	56.467	55.644	54.821	53.998	53.175	52.352	51.529
56.332	55.508	54.684	53.859	53.035	52.210	51.386	50.561	49.737
54.557	53.830	53.003	52.175	51.348	50.520	49.693	48.865	48.038
52.913	52.084	51.254	50.425	49.595	48.766	47.936	47.107	46.277
51.295	50.461	49.627	48.794	47.960	47.126	46.292	45.458	44.624
49.436	48.601	47.767	46.932	46.098	45.263	44.429	43.594	42.760
46.568	45.750	44.933	44.115	43.298	42.481	41.663	40.846	40.029

Table VI. Continued.

[illegible]	43.846	43.030	42.213	41.397	40.580	39.764	38.947	38.131
42.724	41.909	41.094	40.279	39.465	38.650	37.835	37.020	36.205
39.569	38.779	37.990	37.201	36.413	35.624	34.835	34.046	33.257
34.913	34.184	33.455	32.726	31.997	31.268	30.539	29.810	29.081

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 30.00
ENDING TIME = 40.00
AVERAGE TEMPERATURE = 50.796
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.61670E+04
COOLANT:WATER

67.890	66.958	66.026	65.095	64.163	63.231	62.300	61.368	60.437
66.212	65.274	64.336	63.398	62.460	61.523	50.585	59.647	58.709
64.232	63.292	62.352	61.412	60.472	59.531	58.591	57.651	56.711
62.426	61.481	60.536	59.591	58.646	57.701	56.756	55.811	54.866
60.503	59.554	58.606	57.657	56.709	55.760	54.812	53.863	52.914
[illegible]	57.841	56.685	55.929	54.973	54.017	53.062	52.106	51.150
[illegible]	55.761	54.804	53.847	52.889	51.932	50.974	50.017	49.060
52.879	51.951	51.022	50.094	49.166	48.238	47.310	46.382	45.454
50.689	49.762	48.835	47.909	46.982	46.055	45.129	44.202	43.275
48.440	47.517	46.593	45.669	44.745	43.821	42.897	41.973	41.049
44.135	43.255	42.375	41.495	40.615	39.735	38.855	37.975	37.095
37.442	36.660	35.879	35.097	34.315	33.533	32.751	31.969	31.187

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 40.00
ENDING TIME = 50.00
AVERAGE TEMPERATURE = 57.977
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.61570E+04
COOLANT:WATER

77.647	76.582	75.516	74.451	73.385	72.320	71.254	70.189	69.123
75.868	74.794	73.719	72.644	71.570	70.495	69.420	68.346	67.271
73.655	72.577	71.499	70.421	69.343	68.265	67.187	66.109	65.031
71.698	70.613	69.527	68.442	67.356	66.271	65.186	64.100	63.015

Table VI. Continued.

[illegible]	68.470	67.379	66.289	65.198	64.108	63.017	61.927	[illegible]
[illegible]	66.657	65.556	64.454	63.353	62.251	61.150	60.048	58.947
65.452	64.347	63.243	62.138	61.033	59.928	58.823	57.719	56.614
60.393	59.333	58.273	57.213	56.153	55.093	54.033	52.973	51.913
[illegible]	56.803	55.746	54.686	53.630	52.572	51.514	50.457	49.399
55.240	54.186	53.133	52.079	51.026	49.972	48.918	47.865	46.811
49.510	48.523	47.536	46.549	45.561	44.574	43.587	42.600	41.613
40.383	39.544	38.701	37.857	37.014	36.171	35.327	34.484	33.640

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 50.00
ENDING TIME = 60.00
AVERAGE TEMPERATURE = 66.564
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.61570E+04
COOLANT:WATER

89.330	88.104	86.878	85.652	84.427	83.201	81.975	80.749	79.523
87.428	86.190	84.951	83.713	82.475	81.236	79.998	78.759	77.521
84.940	83.697	82.454	81.211	79.968	78.725	77.482	76.239	74.996
82.806	81.554	80.300	79.047	77.793	76.540	75.286	74.033	72.779
80.414	79.153	77.892	76.632	75.371	74.110	72.850	71.589	70.328
78.508	77.232	75.955	74.679	73.403	72.127	70.850	69.574	68.298
75.969	74.686	73.404	72.122	70.839	69.557	68.275	66.992	65.710
69.376	68.158	66.941	65.723	64.505	63.287	62.070	60.852	59.634
56.431	65.217	64.002	62.783	61.573	60.359	59.145	57.930	56.716
63.350	62.151	60.943	59.734	58.526	57.317	56.109	54.900	53.692
55.857	54.743	53.630	52.516	51.402	50.289	49.175	48.062	46.948
43.817	42.902	41.987	41.072	40.157	39.242	38.327	37.412	36.497

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 60.00
ENDING TIME = 70.00
AVERAGE TEMPERATURE = 75.874
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.61670E+04
COOLANT:WATER

Table VI. Continued.

[illegible]3.375	101.956	100.538	99.119	97.700	96.282	94.863	93.445	92.026
[illegible].323	99.898	98.453	97.017	95.582	94.147	92.712	91.277	89.842
98.512	97.070	95.629	94.187	92.745	91.303	89.862	88.420	86.978
96.173	94.718	93.262	91.806	90.350	88.894	87.438	85.982	84.526
93.471	92.005	90.540	89.075	87.609	86.144	84.679	83.213	81.748
91.454	89.967	88.480	86.994	85.507	84.020	82.533	81.047	79.560
[illegible].535	87.109	85.692	84.195	82.698	81.201	79.704	78.207	76.710
80.157	78.750	77.343	75.936	74.529	73.122	71.715	70.308	68.901
76.713	75.311	73.908	72.506	71.103	69.701	68.299	66.896	65.494
73.094	71.700	70.306	68.911	67.517	66.123	64.729	63.335	61.941
63.376	62.114	60.851	59.587	58.324	57.060	55.797	54.532	53.269
47.813	46.815	45.816	44.818	43.819	42.821	41.823	40.824	39.826

5.4.2 Shut-Down Process

The transient temperature distribution is exhibited by Table I to Table XII for the same cases considered in the previous section. Also, Figure 111 demonstrates the change of the average electrode temperature as a function of time during the considered shut down process. The average transient decrease in the average transient electrode temperature was 4.665 * 10^{-4} °C per KPa. In addition, the increase in the coolant mass flow rate was somewhat less effective in rapidly reducing the transient electrode temperature. Both of these negative behaviors of the cooling system is due to the accumulation of heat and also because the heat loss to the surrounding was eliminated absolutely by the assumptions.

Considering the test results for the oil coolant, the temperature distribution for the considered examples are demonstrated by sample Table III and Table IV in the Appendix. Figure 112 shows the average electrode temperature decrease during a shut-down process. The curves that represent the different cases are closer to each other and with higher incremental slope. The average temperature differential during a shut-down process was 2.146 * 10^{-4} °C/KPa.

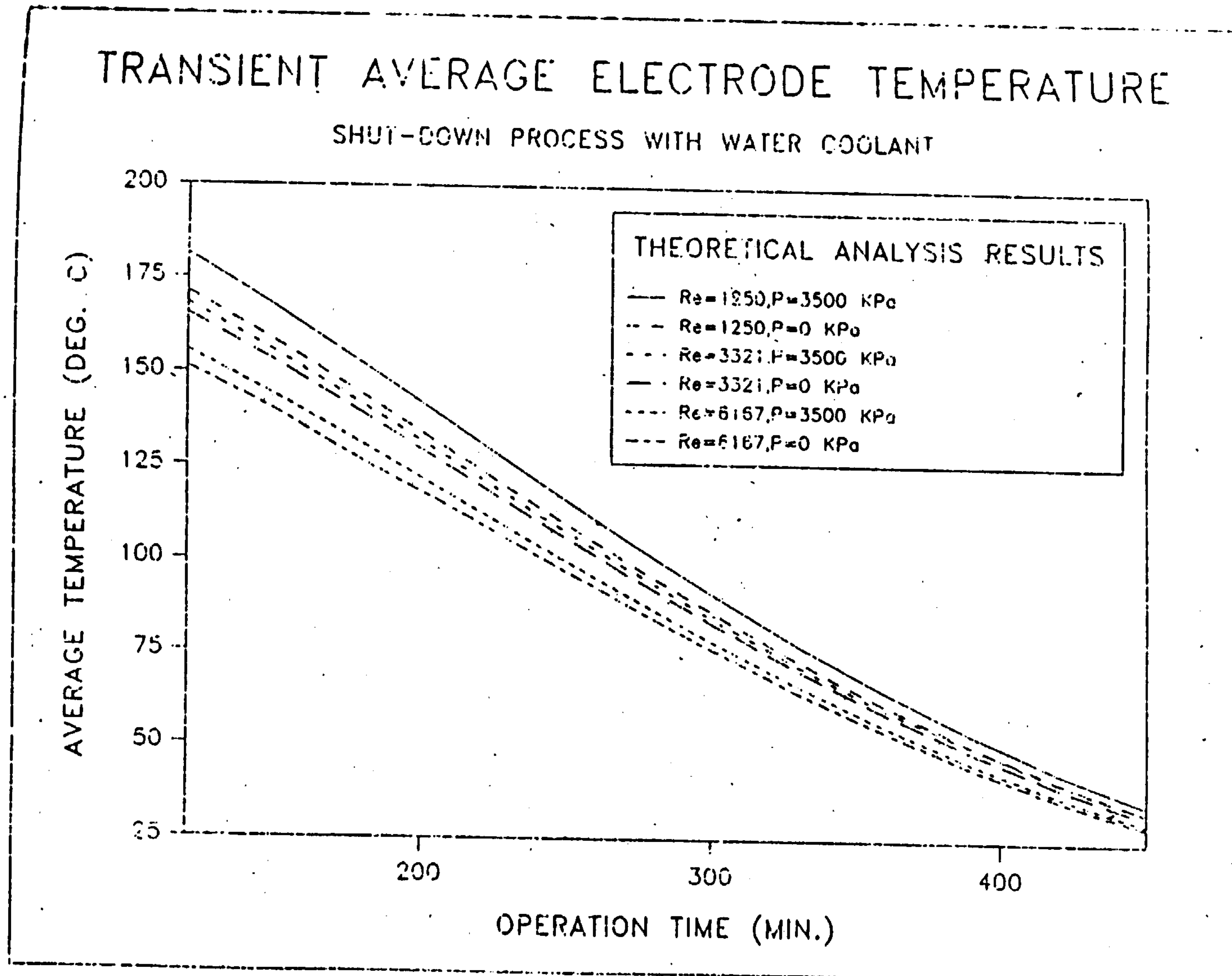

Figure 111. Theoretical Transient Average Electrode Temperature During Shut-Downs with Water Coolant.

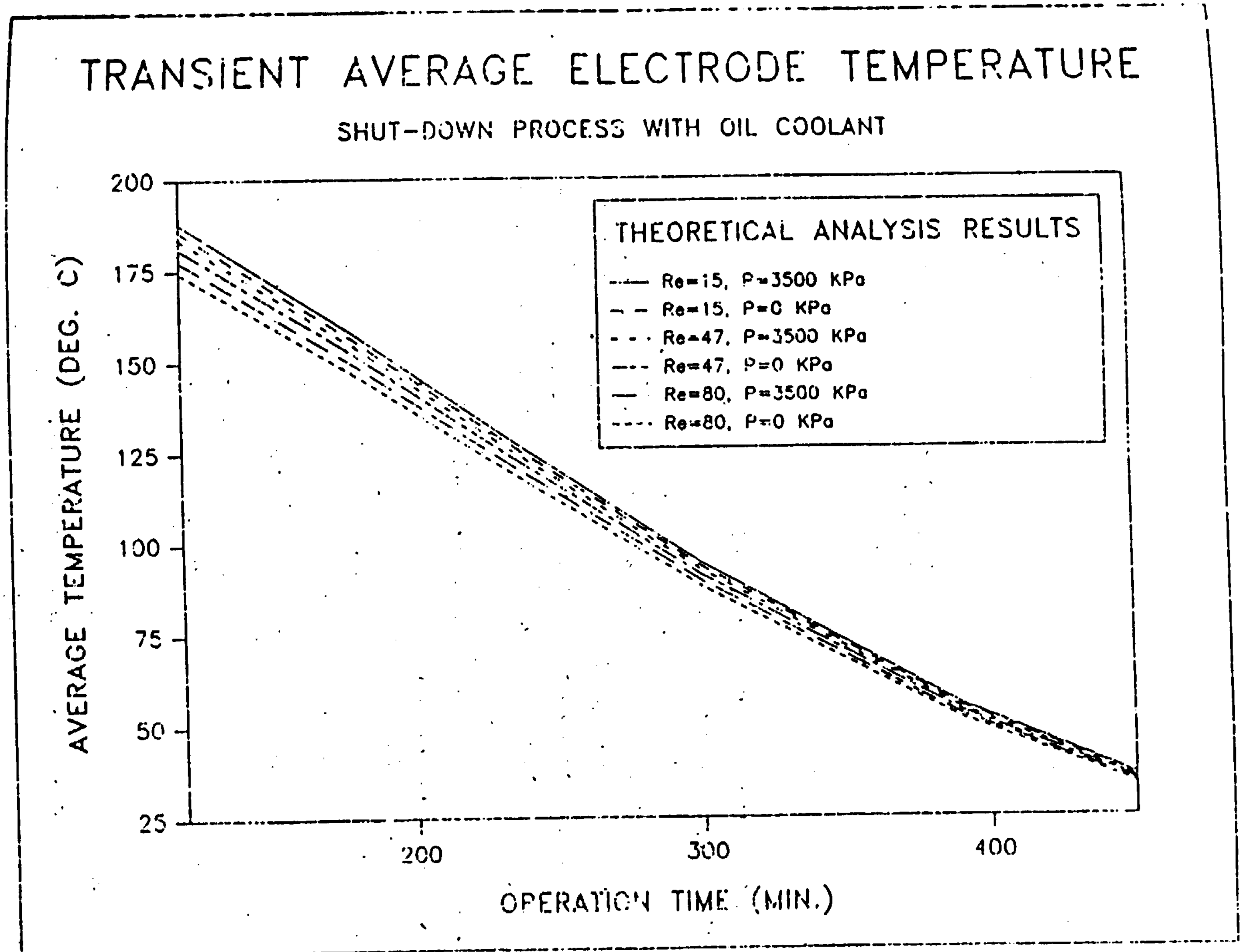

Figure 112. Theoretical Transient Average Electrode Temperature During Shut-Downs with Oil Coolant.

Table VII. Shut-Down Process with Water Coolant (P=3500 KPa, Re=1250).

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =120.00
ENDING TIME =150.00
AVERAGE TEMPERATURE =181.319
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.12500E+04
COOLANT:WATER

198.416	197.164	195.912	194.660	193.409	192.157	190.905	189.653	188.401
196.844	195.592	194.340	193.088	191.836	190.584	189.332	188.080	186.829
194.436	193.190	191.943	190.697	189.450	188.204	186.957	185.711	184.464
192.450	191.206	189.962	188.719	187.475	186.231	184.987	183.744	182.500
190.561	189.419	188.176	186.934	185.692	184.450	183.208	181.966	180.723
188.874	187.533	186.393	185.152	183.911	182.671	181.430	180.189	178.949
187.093	185.854	184.615	183.376	182.137	180.898	179.658	178.419	177.180
185.277	184.039	182.802	181.565	180.327	179.090	177.852	176.615	175.378
.83.515	182.277	181.041	179.806	178.570	177.334	176.098	174.862	173.626
.81.747	180.512	179.278	178.044	176.810	175.575	174.341	173.106	171.872
.80.093	178.860	177.626	176.392	175.159	173.925	172.691	171.458	170.224
.78.315	177.083	175.851	174.619	173.387	172.155	170.923	169.691	168.459

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =150.00
ENDING TIME =180.00
AVERAGE TEMPERATURE =167.440
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.12500E+04
COOLANT:WATER

85.249	184.080	182.911	181.743	180.574	179.405	178.236	177.067	175.898
83.772	182.604	181.435	180.266	179.098	177.929	176.760	175.591	174.423
80.506	179.349	178.192	177.035	175.878	174.721	173.563	172.406	171.249
78.208	177.056	175.904	174.753	173.601	172.449	171.298	170.146	168.994
76.281	175.133	173.984	172.836	171.687	170.539	169.390	168.242	167.093
74.359	173.214	172.069	170.923	169.778	168.633	167.488	166.342	165.197
72.451	171.309	170.167	169.025	167.883	166.741	165.599	164.456	163.314
70.470	169.331	168.193	167.055	165.916	164.778	163.639	162.501	161.362

Table VII. Continued.

[illegible]599	167.464	166.329	165.193	164.058	162.922	161.787	160.651	159.516
166.724	165.592	164.460	163.327	162.195	161.062	159.930	158.798	157.665
165.084	163.950	162.819	161.688	160.557	159.427	158.296	157.165	156.031
163.181	162.054	160.926	159.799	158.671	157.544	156.416	155.289	154.187

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =180.00
ENDING TIME =210.00
AVERAGE TEMPERATURE =152.461
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.12500E+04
COOLANT:WATER

170.903	169.827	168.749	167.670	166.592	165.514	164.435	163.357	162.279
169.534	168.456	167.378	166.299	165.221	164.143	163.065	161.987	160.909
165.370	164.310	163.250	162.190	161.130	160.070	159.010	157.949	156.889
162.795	161.743	160.691	159.639	158.587	157.535	156.483	155.431	154.379
160.740	159.693	158.646	157.598	156.551	155.504	154.457	153.410	152.362
158.693	157.651	156.609	155.566	154.524	153.481	152.439	151.397	150.354
156.569	155.631	154.594	153.556	152.518	151.481	150.443	149.405	148.368
154.535	153.503	152.471	151.438	150.406	149.374	148.342	147.310	146.278
152.570	151.542	150.515	149.487	148.460	147.432	146.405	145.377	144.350
150.599	149.576	148.553	147.530	146.507	145.484	144.462	143.439	142.416
148.977	147.957	146.936	145.916	144.895	143.875	142.854	141.834	140.813
146.972	145.956	144.941	143.925	142.910	141.894	140.879	139.864	138.848

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =210.00
ENDING TIME =240.00
AVERAGE TEMPERATURE =136.886
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.12500E+04
COOLANT:WATER

155.803	154.820	153.837	152.854	151.871	150.888	149.905	148.922	147.939
154.543	153.561	152.578	151.595	150.612	149.629	148.646	147.663	146.681
149.511	148.552	147.594	146.635	145.677	144.718	143.760	142.801	141.843
146.712	145.764	144.816	143.867	142.919	141.971	141.023	140.075	139.127

Table VII. Continued.

144.550	143.608	142.666	141.724	140.782	139.841	138.899	137.957	137.015
142.401	141.465	140.530	139.595	138.659	137.724	136.788	135.853	134.918
140.283	139.354	138.425	137.496	136.567	135.638	134.709	133.780	132.851
138.024	137.102	136.180	135.259	134.337	133.415	132.493	131.572	130.650
135.989	135.073	134.157	133.241	132.325	131.410	130.494	129.578	128.662
133.948	133.038	132.128	131.218	130.309	129.399	128.489	127.579	126.670
132.364	131.457	130.550	129.644	128.737	127.830	126.923	126.017	125.110
130.280	129.380	128.480	127.580	126.680	125.780	124.880	123.980	123.079

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =240.00
ENDING TIME =270.00
AVERAGE TEMPERATURE =121.191
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.12500E+04
COOLANT:WATER

140.352	139.466	138.581	137.695	136.810	135.924	135.039	134.153	133.268
139.207	138.322	137.436	136.551	135.666	134.780	133.895	133.010	132.124
133.394	132.539	131.684	130.829	129.973	129.118	128.263	127.408	126.553
130.435	129.592	128.749	127.907	127.064	126.221	125.378	124.535	123.692
128.199	127.364	126.528	125.693	124.858	124.023	123.186	122.352	121.517
125.981	125.154	124.326	123.499	122.671	121.843	121.016	120.188	119.361
123.804	122.985	122.165	121.345	120.525	119.705	118.885	118.065	117.245
121.460	120.649	119.838	119.027	118.216	117.404	116.593	115.782	114.971
119.388	118.584	117.780	116.976	116.172	115.368	114.564	113.760	112.956
117.311	116.515	115.718	114.921	114.124	113.328	112.531	111.734	110.937
115.782	114.989	114.196	113.403	112.610	111.817	111.024	110.231	109.437
113.560	112.874	112.089	111.304	110.519	109.733	108.948	108.163	107.377

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =270.00
ENDING TIME =300.00
AVERAGE TEMPERATURE =105.807
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.12500E+04
COOLANT:WATER

Table VII. Continued.

124.934	124.146	123.358	122.569	121.781	120.993	120.205	119.416	118.628
123.905	123.117	122.329	121.541	120.753	119.965	119.177	118.389	117.601
117.449	116.696	115.943	115.190	114 437	113.685	112.932	112.179	111.426
114.402	113.662	112.923	112.184	111.444	110.705	109.966	109.226	108.487
112.131	111.400	110.670	109.939	109.209	108.478	107.748	107.017	106.287
109.885	109.163	108.442	107.720	106.998	106.276	105.554	104.833	104.111
107.690	106.976	106.263	105.550	104.837	104.123	103.410	102.697	101.984
105.309	104.605	103.902	103.199	102.496	101.792	101.089	100.386	99.682
103.239	102.543	101.848	101.153	100.458	99.762	99.067	98.372	97.676
101.157	100 479	99.792	99.105	98.418	97.731	97.044	96.357	95.670
99.711	99.028	98.345	97.661	96.978	96.295	95.612	94.929	94.246
97.592	96.918	96.244	95.569	94.895	94.221	93.547	92.872	92.198

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =300.00
ENDING TIME =330.00
AVERAGE TEMPERATURE = 91.099
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.12500E+04
COOLANT:WATER

109.892	109.159	108.505	107.812	107.118	106.425	105.732	105.038	104.345
108.977	108.284	107.591	106.898	106.205	105.511	104.818	104.125	103.432
102.050	101.396	100.742	100.087	99.433	98.779	98.125	97.471	96.816
98.987	98.347	97.707	97.068	96.428	95.788	95.148	94.509	93.869
96.725	96.095	95.465	94.835	94.205	93.575	92.944	92.314	91.684
94.456	93.875	93.254	92.634	92.013	91.392	90.771	90.151	89.530
92.325	91.713	91.102	90.490	89.879	89.267	88.656	88.044	87.433
89.959	89.358	88.758	88.157	87.556	86.955	86.354	85.754	85.153
87.932	87.340	86.747	86.155	85.563	84.971	84.379	83.787	83.194
85.906	85.323	84.739	84.156	83.572	82.989	82.406	81.822	81.239
84.540	83.961	83.382	82.803	82.224	81.645	81.066	80.487	79.908
82 472	81.902	81.332	80.762	80.193	79.523	79.053	78.483	77.913

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =330.00

Table VII. Continued.

ENDING TIME =360.00
AVERAGE TEMPERATURE = 77.354
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.12500E+04
COOLANT:WATER

5.515	94.912	94.310	93.707	93.104	92.502	91.899	91.296	90.694
4.710	94.108	93.505	92.903	92.301	91.698	91.096	90.494	89.891
7.504	86.943	86.382	85.821	85.260	84.699	84.138	83.577	83.016
4.494	83.948	83.402	82.856	82.310	81.764	81.218	80.672	80.126
2.287	81.751	81.215	80.678	80.142	79.606	79.070	78.534	77.998
0.117	79.591	79.065	78.538	78.012	77.486	76.960	76.433	75.907
8.013	77.497	76.980	76.463	75.947	75.430	74.913	74.397	73.880
5.714	75.208	74.703	74.197	73.692	73.186	72.680	72.175	71.669
3.769	73.272	72.775	72.279	71.782	71.285	70.788	70.291	69.794
1.830	71.342	70.854	70.366	69.878	69.391	68.903	68.415	67.927
0.569	70.086	69.602	69.119	68.635	68.152	67.669	67.185	66.702
8.593	68.119	67.645	67.171	66.697	66.223	65.749	65.275	64.801

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =360.00
ENDING TIME =390.00
AVERAGE TEMPERATURE = 64.732
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.12500E+04
COOLANT:WATER

2.035	81.517	80.999	80.482	79.964	79.447	78.929	78.411	77.894
1.335	80.817	80.300	79.783	79.266	78.748	78.231	77.714	77.196
4.044	73.569	73.094	72.620	72.145	71.670	71.196	70.721	70.246
1.152	70.692	70.232	69.772	69.313	68.853	68.393	67.933	67.473
9.039	68.589	68.139	67.690	67.240	66.790	66.340	65.890	65.441
5.970	66.530	66.090	65.650	65.210	64.770	64.330	63.890	63.451
4.972	64.542	64.112	63.681	63.251	62.821	62.390	61.960	61.530
2.785	62.366	61.947	61.528	61.108	60.689	60.270	59.850	59.431
0.957	60.546	60.136	59.725	59.315	58.904	58.494	58.083	57.673
9.139	58.738	58.336	57.934	57.533	57.131	56.729	56.328	55.926

Table VII. Continued.

57.995	57.597	57.200	56.803	56.405	56.008	55.611	55.214	54.816
56.149	55.760	55.372	54.984	54.595	54.200	53.820	53.432	53.044

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =390.00
ENDING TIME =420.00
AVERAGE TEMPERATURE = 53.512
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.12500E+04
COOLANT:WATER

69.622	69.182	68.743	68.304	67.865	67.425	66.986	66.547	66.107
69.019	68.581	68.142	67.703	67.264	66.825	66.386	65.947	65.508
61.830	61.434	61.037	60.641	60.245	59.848	59.452	59.055	58.659
59.109	58.727	58.345	57.963	57.581	57.199	56.817	56.435	56.053
57.126	56.754	56.381	56.009	55.637	55.265	54.893	54.520	54.148
55.191	54.829	54.466	54.104	53.741	53.379	53.016	52.654	52.291
53.333	52.979	52.626	52.273	51.920	51.567	51.213	50.860	50.507
51.297	50.954	50.612	50.269	49.927	49.584	49.242	48.899	48.556
49.613	49.279	48.945	48.611	48.277	47.943	47.608	47.274	46.940
47.944	47.619	47.293	46.968	46.642	46.316	45.991	45.665	45.339
46.923	46.602	46.280	45.959	45.637	45.316	44.994	44.673	44.352
45.234	44.922	44.609	44.297	43.984	43.672	43.359	43.047	42.734

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =420.00
ENDING TIME =450.00
AVERAGE TEMPERATURE = 43.602
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.12500E+04
COOLANT:WATER

58.386	58.018	57.650	57.281	56.913	56.545	56.176	55.808	55.439
57.874	57.506	57.138	56.770	56.402	56.034	55.666	55.298	54.930
50.952	50.625	50.299	49.972	49.645	49.319	48.992	48.666	48.339
48.442	48.129	47.816	47.503	47.190	46.877	46.564	46.251	45.938
46.617	46.313	46.009	45.706	45.402	45.098	44.795	44.491	44.187
44.844	44.550	44.255	43.960	43.666	43.371	43.077	42.782	42.488

Table VII. Continued.

43.149	42.863	42.577	42.291	42.005	41.720	41.434	41.148	40.862
41.293	41.017	40.741	40.466	40.190	39.914	39.638	39.363	39.087
39.773	39.506	39.238	38.970	38.702	38.434	38.166	37.898	37.631
38.273	38.013	37.753	37.493	37.233	36.973	36.713	36.453	36.193
37.377	37.121	36.865	36.609	36.353	36.097	35.841	35.585	35.329
35.866	35.618	35.371	35.123	34.875	34.627	34.379	34.132	33.884

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =450.00
ENDING TIME =480.00
AVERAGE TEMPERATURE = 35.047
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.12500E+04
COOLANT:WATER

48.384	48.079	47.773	47.468	47.163	46.858	46.552	46.247	45.942
47.952	47.648	47.343	47.038	46.733	46.428	46.123	45.818	45.513
41.435	41.170	40.904	40.639	40.373	40.107	39.842	39.576	39.310
39.166	38.912	38.659	38.406	38.153	37.900	37.647	37.394	37.141
37.517	37.273	37.028	36.784	36.539	36.295	36.051	35.806	35.562
35.923	35.688	35.452	35.216	34.980	34.744	34.508	34.272	34.036
34.407	34.179	33.951	33.723	33.495	33.268	33.040	32.812	32.584
32.750	32.531	32.313	32.094	31.875	31.656	31.438	31.219	31.000
31.406	31.194	30.983	30.771	30.560	30.348	30.137	29.925	29.714
30.084	29.880	29.675	29.471	29.267	29.063	28.858	28.654	28.450
29.313	29.112	28.911	28.710	28.510	28.309	28.108	27.907	27.707
27.989	27.795	27.602	27.409	27.215	27.022	26.828	26.635	26.442

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OF POOR QUALITY

Table VIII. Shut-Down Process with Water Coolant (P=0 KPa, Re=1250).

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =120.00
ENDING TIME =150.00
AVERAGE TEMPERATURE =171.316
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.12500E+04
COOLANT:WATER

188.968	187.910	186.851	185.793	184.735	183.677	182.618	181.560	180.502
187.084	186.025	184.967	183.909	182.851	181.793	180.735	179.676	178.618
184.408	183.354	182.301	181.247	180.194	179.140	178.086	177.033	175.979
182.134	181.083	180.031	178.980	177.929	176.878	175.826	174.775	173.724
180.049	178.998	177.948	176.898	175.843	174.798	173.748	172.698	171.648
177.955	176.917	175.868	174.819	173.771	172.722	171.673	170.625	169.576
175.890	174.842	173.795	172.747	171.700	170.652	169.605	168.558	167.510
173.781	172.735	171.689	170.643	169.597	168.551	167.505	166.460	165.414
171.723	170.679	169.634	168.589	167.545	166.500	165.455	164.411	163.366
169.664	168.621	167.577	166.534	165.490	164.447	163.404	162.360	161.317
167.710	166.668	165.625	164.582	163.539	162.496	161.454	160.411	159.368
165.542	164.500	163.559	162.517	161.476	160.435	159.393	158.352	157.310

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =150.00
ENDING TIME =180.00
AVERAGE TEMPERATURE =158.211
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.12500E+04
COOLANT:WATER

.76.428	175.440	174.452	173.464	172.476	171.488	170.500	169.512	168.524
.74.661	173.673	172.685	171.697	170.709	169.721	168.733	167.745	166.757
171.197	170.219	169.240	168.262	167.284	166.306	165.328	164.350	163.372
.68.655	167.682	166.708	165.735	164.761	163.788	162.814	161.841	160.867
.66.469	165.498	164.527	163.557	162.585	161.615	160.644	159.673	158.703
.64.289	163.321	162.353	161.385	160.417	159.449	158.481	157.513	156.544
.62.125	161.159	160.194	159.228	158.263	157.297	156.332	155.367	154.401
59.893	158.931	157.968	157.006	156.044	155.081	154.119	153.157	152.194

Table VIII. Continued.

157.768	156.808	155.848	154.888	153.929	152.969	152.009	151.049	150.089
155.640	154.683	153.726	152.768	151.811	150.854	149.897	148.940	147.983
153.730	152.774	151.818	150.862	149.907	148.951	147.995	147.039	146.083
151.583	150.630	149.677	148.724	147.771	146.818	145.865	144.912	143.959

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =180.00
ENDING TIME =210.00
AVERAGE TEMPERATURE =144.065
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.12500E+04
COOLANT:WATER

162.767	161.856	160.944	160.033	159.121	158.210	157.298	156.387	155.475
161.129	160.217	159.305	158.394	157.483	156.571	155.660	154.749	153.837
156.841	155.945	155.049	154.153	153.257	152.361	151.465	150.568	149.672
154.069	153.180	152.291	151.401	150.512	149.623	148.733	147.844	146.955
151.793	150.908	150.023	149.138	148.252	147.367	146.482	145.597	144.711
149.528	148.647	147.766	146.885	146.004	145.122	144.241	143.360	142.479
147.267	146.410	145.533	144.656	143.779	142.902	142.025	141.148	140.271
144.946	144.074	143.202	142.329	141.457	140.585	139.712	138.840	137.967
142.768	141.899	141.031	140.162	139.294	138.425	137.557	136.688	135.819
140.586	139.722	138.857	137.993	137.128	136.263	135.399	134.534	133.670
138.734	137.871	137.009	136.146	135.283	134.421	133.558	132.696	131.833
136.526	135.668	134.809	133.951	133.093	132.234	131.376	130.517	129.659

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =210.00
ENDING TIME =240.00
AVERAGE TEMPERATURE =129.358
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.12500E+04
COOLANT:WATER

148.384	147.553	146.722	145.891	145.060	144.229	143.398	142.567	141.737
146.881	146.050	145.219	144.389	143.558	142.727	141.896	141.065	140.235
141.800	140.989	140.179	139.369	138.559	137.749	[illegible]	[illegible]	[illegible]

Table VIII. Continued.

135.504	135.708	134.912	134.116	133.320	132.524	131.728	130.932	130.135
134.176	133.386	132.595	131.804	131.014	130.223	129.432	128.642	127.851
131.883	131.097	130.312	129.527	128.741	127.956	127.171	126.385	125.600
129.460	128.681	127.902	127.123	126.343	125.564	124.785	124.006	123.227
127.252	126.478	125.704	124.930	124.156	123.381	122.607	121.833	121.059
125.042	124.273	123.504	122.735	121.966	121.197	120.428	119.659	118.890
123.262	122.496	121.730	120.963	120.197	119.430	118.664	117.898	117.131
121.021	120.260	119.499	118.738	117.977	117.217	116.456	115.695	114.934

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =240.00
ENDING TIME =270.00
AVERAGE TEMPERATURE =114.536
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.12500E+04
COOLANT.WATER

133.669	132.920	132.172	131.423	130.674	129.926	129.177	128.429	127.680
132.205	131.557	130.808	130.060	129.312	128.562	127.815	127.067	126.318
126.514	125.791	125.068	124.346	123.623	122.900	122.177	121.454	120.731
123.444	122.731	122.019	121.305	120.594	119.881	119.169	116.456	117.744
121.063	120.357	119.651	118.945	118.239	117.533	116.827	116.121	115.415
118.705	118.005	117.306	116.607	115.907	115.208	114.508	113.809	113.109
116.391	115.698	115.005	114.311	113.618	112.925	112.232	111.539	110.846
113.924	113.238	112.553	111.867	111.181	110.496	109.810	109.124	108.439
111.718	111.038	110.359	109.679	108.999	108.320	107.640	106.960	106.281
109.512	108.839	108.165	107.492	106.818	106.145	105.471	104.798	104.124
107.821	107.151	106.480	105.810	105.140	104.469	103.799	103.128	102.458
105.581	104.918	104.254	103 590	102.926	102.262	101.599	100.935	100.271

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =270.00
ENDING TIME =300.00
AVERAGE TEMPERATURE =100.006
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.12500E+04
COOLANT:WATER

Table VIII. Continued.

118.985	118.319	117.652	116.986	116.320	115.653	114.987	114.321	113.655
117.762	117.096	116.429	115.763	115.097	114.431	113.765	113.099	112.433
111.392	110.755	110.119	109.482	108.846	108.209	107.573	106.937	106.300
108.270	107.645	107.020	106.395	105.770	105.145	104.520	103.895	103.270
105.890	105.272	104.655	104.037	103.419	102.802	102.184	101.567	100.949
103.539	102.929	102.318	101.708	101.098	100.488	99.878	99.268	98.658
101.241	100.638	100.035	99.432	98.829	98.226	97.624	97.021	96.418
98.775	98.180	97.586	96.991	96.397	95.802	95.208	94.613	94.019
96.606	96.019	95.431	94.843	94.255	93.667	93.080	92.492	91.904
94.441	93.860	93.279	92.698	92.117	91.537	90.956	90.375	89.794
92.855	92.277	91.700	91.123	90.545	89.968	89.391	88.813	88.236
90.656	90.086	89.516	88.946	88.376	87.806	87.236	86.666	86.096

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =300.00
ENDING TIME =330.00
AVERAGE TEMPERATURE = 86.112
PRESURE= 0 0 KPa
REYNOLD'S NUMBER= 0.12500E+04
COOLANT:WATER

104.659	104.073	103.487	102.901	102.315	101.729	101.142	100.556	99.970
103.573	102.988	102.402	101.816	101.230	100.644	100.059	99.473	98.887
96.787	96.234	95.681	95.128	94.575	94.022	93.469	92.916	92.363
93.681	93.140	92.599	92.059	91.518	90.977	90.436	89.896	89.355
91.342	90.809	90.276	89.744	89.211	88.678	88.146	87.613	87.080
89.038	88.513	87.989	87.464	86.939	86.415	85.890	85.365	84.841
86.796	86.279	85.762	85.245	84.729	84.212	83.695	83.178	82.661
84.377	83.870	83.362	82.854	82.346	81.838	81.331	80.823	80.315
82.283	81.782	81.281	80.781	80.280	79.780	79.279	78.779	78.278
80.195	79.702	79.209	78.715	78.222	77.729	77.236	76.743	76.249
78.728	78.238	77.749	77.259	76.770	76.280	75.791	75.301	74.812
76.610	76.129	75.647	75.165	74.684	74.202	73.720	73.239	72.757

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =330.00

Table VIII. Continued.

ENDING TIME =300.00
AVERAGE TEMPERATURE = 73.125
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.12500E+04
COOLANT:WATER

90.966	90.457	89.948	89.438	88.929	88.419	87.910	87.401	86.891
90.014	89.505	88.996	88.487	87.978	87.468	86.959	86.450	85.941
82.991	82.516	82.042	81.568	81.094	60.620	80.145	79.671	79.197
79.965	79.504	79.042	78.581	78.119	77.658	77.196	76.734	76.273
77.707	77.253	76.800	76.347	75.894	75.441	74.988	74.534	74.081
73.490	75.045	74.600	74.155	73.711	73.266	72.821	72.376	71.931
73.342	72.905	72.468	72.032	71.595	71.158	70.721	70.285	69.848
71.016	70.569	70.161	69.734	69.307	68.879	68.452	68.024	67.597
69.030	68.610	68.190	67.770	67.350	66.930	66.510	66.090	65.670
67.054	66.642	66.230	65.817	65.405	64.992	64.580	64.168	63.755
65.717	65.308	64.899	64.491	64.082	63.674	63.265	62.856	62.448
63.716	63.317	62.916	62.515	62.115	61.715	61.314	60.913	60.513

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =360.00
ENDING TIME =390.00
AVERAGE TEMPERATURE = 61.251
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.12500E+04
COOLANT:WATER

78.128	77.691	77.253	76.816	76.378	75.941	75.503	75.066	74.528
77.302	76.865	76.427	75.990	75.553	75.116	74.678	74.241	73.804
70.225	69.824	69.422	69.021	68.620	68.219	67.817	67.416	67.015
67.338	66.949	66.561	66.172	65.783	65.395	65.006	64.617	64.229
65.196	64.816	64.436	64.055	63.675	63.295	62.915	62.535	62.154
63.102	62.730	62.358	61.986	61.615	61.243	60.871	60.499	60.127
61.082	60.718	60.354	59.990	59.627	59.263	58.899	58.535	58.172
58.890	58.535	58.181	57.827	57.472	57.118	56.763	56.409	56.054
57.041	56.694	56.347	56.000	55.653	55.306	54.959	54.612	54.265
55.207	54.868	54.528	54.189	53.849	53.510	53.170	52.831	52.491

Table VIII. Continued.

[illegible]	53.671	53.335	53.000	52.664	52.328	51.992	51.656	51.321
[illegible]	51.829	51.501	51.173	50.845	50.517	50.190	49.862	49.534

ELECTRODE TEMPERATURE DISTRISUTION
STARTING TIME =390.00
ENDING TIME =420.00
AVERAGE TEMPERATURE = 50.602
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.12500E+04
COOLANT:WATER

66.306	65.935	65.564	65.192	64.821	64.450	64.078	63.707	63.336
65.597	65.226	64.855	64.484	64.113	63.742	63.371	63.000	62.629
58.641	58.306	57.971	57.636	57.301	56.966	56.631	56.296	55.961
55.940	55.617	55.295	54.972	54.649	54.326	54.003	53.680	53.357
53.946	53.631	53.317	53.002	52.688	52.373	52.058	51.744	51.429
52.004	51.697	51.391	51.085	50.778	50.472	50.165	49.859	49.552
50.139	49.840	49.542	49.243	48.945	48.646	48.348	48.049	47.750
48.114	47.825	47.535	47.246	46.956	46.666	46.377	46.087	45.798
46.426	46.142	45.861	45.578	45.296	45.014	44.731	44.449	44.166
44.757	44.482	44.206	43.931	43.656	43.381	43.105	42.830	42.555
43.697	43.425	43.153	42.862	42.610	42.338	42.056	41.795	41.523
42.019	41.755	41.491	41.227	40.963	40.698	40.434	40.170	39.906

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =120.00
ENDING TIME =450.00
AVERAGE TEMPERATURE = 41.236
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.12500E+04
COOLANT:WATER

55.606	55.295	54.983	54.672	54.361	54.049	53.738	53.426	53.115
55.005	54.694	54.382	54.071	53.760	53.449	53.138	52.827	52.516
48.324	48.048	47.772	47.496	47.220	46.944	46.668	46.391	46.115
45.846	45.581	45.316	45.052	44.787	44.523	44.258	43.993	43.729
44.022	43.765	43.509	43.252	42.995	42.739	42.482	42.225	41.968
42.254	42.005	41.756	41.507	41.258	41.009	40.760	40.511	40.262

Table VIII. Continued.

40.565	40.323	40.082	39.840	39.598	39 357	39.115	38.874	38.632
38.731	39 498	38.265	38.032	37.798	37.565	37.332	37.099	36.866
37.218	36.992	36.765	36.539	36.312	36.086	35.860	35.633	35.407
35.728	35.509	35.289	35.069	34.850	34.630	34.410	34.190	33.971
34.307	34.591	34.375	34.158	33.942	33.725	33.509	33.292	33.076
33.317	33.108	32.898	32.689	32.479	32.270	32.060	31.851	31.641

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =450.00
ENDING TIME =480.00
AVERAGE TEMPERATURE = 33.151
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.12500E+04
COOLANT:WATER

46.080	45.822	45 564	45.306	45.048	44.790	44.532	44.274	44.016
45.575	45.318	45.060	44.802	44.544	44.286	44.029	43.771	43.513
39.298	39.074	38 849	38.625	38.400	38.176	37.951	37.727	37.502
37.066	36.852	36.638	36.424	36.210	35.996	35.782	35.569	35.355
35.429	35.222	35.016	34.809	34.532	34.396	34.189	33.982	33.776
33.849	33.649	33.450	33.250	33.051	32.851	32.652	32.452	32.253
32.347	32.154	31.961	31.769	31.576	31.383	31.191	30.998	30.806
30 718	30.533	30.348	30.163	29.979	29.794	29.609	29.424	29.239
29.389	29.209	29.031	28.852	28.673	28.494	28.316	28.137	27.958
28.084	27.911	27.739	27.566	27.393	27.220	27.048	26.875	26.702
27.297	27.128	26.958	26.788	26.618	26.449	26.279	26.109	25.940
26.000	25.836	25.673	25.509	25.346	25.182	25.019	24.855	24.692

Table IX. Shut-Down Process with Water Coolant (P=3500 KPa, Re=3321).

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =120.00
ENDING TIME =150.00
AVERAGE TEMPERATURE =168.220
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.33210E+04
COOLANT.WATER

189.913	188.127	196.341	184.555	182.770	180.984	179.193	177.412	175.627
183.016	186.231	184.445	182.659	180.873	179.088	177.302	175.516	173.731
185.324	183.546	181.768	179.990	178.212	176.434	174.656	172.878	171.100
183.036	181.262	179.488	177.714	175.940	174.166	172.392	170.616	168.844
180.937	179.165	177.393	175.621	173.850	172.078	170.306	168.534	166.762
178.841	177.071	175.302	173.532	171.762	169.993	168.223	166.453	164.683
176.752	174.984	173.217	171.449	169.682	167.914	166.147	164.379	162.612
174.630	172.865	171.100	169.335	167.570	165.805	164.040	162.275	160.510
172.559	170.796	169.033	167.270	165.507	163.744	161.982	160.219	158.456
170.487	168.726	166.965	165.204	163.444	161.683	159.922	158.161	156.401
165.520	166.761	165.001	163.241	161.482	159.722	157.962	156.202	154.443
166.433	164.651	162.924	161.166	159.409	157.652	155.894	154.137	152.379

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =150.00
ENDING TIME =180.00
AVERAGE TEMPERATURE =155.352
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.33210E+04
COOLANT:WATER

177.310	175.643	173.975	172.308	170.641	168.974	167.306	165.639	163.972
175.531	173.864	172.197	170.530	168.863	167.196	165.529	163.862	162.194
172.047	170.397	168.746	167.095	165.445	163.794	162.144	160.493	158.842
169.491	167.848	166.205	164.562	162.920	161.277	159.634	157.991	156.349
167.291	165.653	164.014	162.376	160.738	159.100	157.461	155.823	154.185
165.097	163.464	161.830	160.196	158.563	156.929	155.295	153.662	152.028
162.919	161.290	159.661	158.032	156.403	154.773	153.144	151.515	149.886
160.674	159.050	157.426	155.802	154.178	152.554	150.930	149.306	147.683

Table IX. Continued.

[illegible]	156.916	155.295	153.677	152.057	150.437	148.818	147.198	145.578
[illegible]	154.779	153.164	151.549	149.934	148.318	146.703	145.088	143.473
[illegible]	152.859	151.246	149.633	148.020	146.407	144.794	143.181	141.568
152.312	150.704	149.096	147.488	145.880	144.271	142.663	141.055	139.447

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =180.00
ENDING TIME =210.00
AVERAGE TEMPERATURE =141.464
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.33210E+04
COOLANT:WATER

163.581	162.043	160.505	158.966	157.428	155.890	154.352	152.814	151.276
161.931	160.393	158.855	157.318	155.780	154.242	152.704	151.166	149.628
157.621	156.108	154.596	153.084	151.572	150.060	148.547	147.035	145.523
154.832	153.332	151.831	150.339	148.830	147.329	145.828	144.327	142.827
152.542	151.049	149.555	148.061	146.567	145.073	143.580	142.086	140.592
150.264	148.777	147.290	145.803	144.316	142.829	141.342	139.855	138.368
148.009	146.529	145.049	143.569	142.089	140.609	139.129	137.649	136.169
[illegible]	144.183	142.710	141.238	139.766	138.294	136.822	135.350	133.877
[illegible]	141.997	140.531	139.066	137.600	136.134	134.669	133.203	131.737
141.268	139.809	138.350	136.891	135.432	133.973	132.514	131.055	129.596
139.404	137.948	136.493	135.037	133.581	132.126	130.670	129.214	127.759
137.183	135.734	134.286	132.837	131.389	129.940	128.492	127.043	125.595

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =210.00
ENDING TIME =240.00
AVERAGE TEMPERATURE =127.023
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.33210E+04
COOLANT:WATER

149.126	147.724	146.322	144.919	143.517	142.115	140.713	139.310	137.908
147.613	146.211	144.809	143.407	142.005	140.603	139.201	137.799	136.397
142.504	141.137	139.770	138.403	137.035	135.668	134.301	132.934	131.567
139.535	138.183	136.831	135.478	134.126	132.773	131.421	130.068	128.716

Table IX. Continued.

[illegible]	135.834	134.491	133.148	131.804	130.461	129.118	127.774	126.431
134.835	133.502	132.168	130.834	129.499	128.165	126.831	125.497	124.162
132.529	131.204	129.879	128.553	127.228	125.903	124.578	123.252	121.927
130.092	128.778	127.463	126.148	124.833	123.518	122.203	120.889	119.574
127.871	126.565	125.259	123.952	122.646	121.340	120.033	118.727	117.420
125.649	124.351	123.053	121.756	120.458	119.160	117.863	116.565	115.267
123.850	122.564	121.271	119.978	118.684	117.391	116.098	114.805	113.511
121.602	120.319	119.035	117.751	116.467	115.183	113.899	112.615	111.331

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =240.00
ENDING TIME =270.00
AVERAGE TEMPERATURE =112.469
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.33210E+04
COOLANT:WATER

134.337	133.074	131.811	130.547	129.284	128.021	126.758	125.495	124.232
132.964	131.702	130.439	129.176	127.913	126.650	125.387	124.125	122.862
127.143	125.923	124.703	123.483	122.264	121.044	119.824	118.604	117.384
124.055	122.853	121.650	120.448	119.246	118.043	116.841	115.639	114.436
121.561	120.469	119.278	118.087	116.895	115.704	114.512	113.321	112.130
119.289	118.109	116.928	115.748	114.567	113.387	112.207	111.026	109.846
116.961	115.792	114.622	113.452	112.283	111.113	109.944	108.774	107.604
114.481	113.324	112.166	111.009	109.852	108.695	107.538	106.381	105.224
112.252	111.115	109.966	108.821	107.674	106.527	105.380	104.233	103.087
110.043	108.907	107.770	106.634	105.497	104.361	103.224	102.088	100.951
108.342	107.211	106.079	104.948	103.817	102.686	101.554	100.423	99.292
106.089	104.969	103.849	102.729	101.609	100.489	99.368	98.248	97.128

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =270.00
ENDING TIME =300.00
AVERAGE TEMPERATURE = 98.202
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.33210E+04
COOLANT:WATER

Table IX. Continued.

[illegible]	1[illegible]5.455	117.331	116 207	115.082	113 958	112.834	111.709	110.583
[illegible]	117.725	116 101	114.977	113 853	112.729	111.604	110.480	109.356
[illegible].945	110.671	109.797	108.723	107.645	106.575	105.501	104.427	103.353
[illegible].805	107.751	106.697	105.642	104.587	103.533	102.478	101.424	100.369
[illegible].412	105.370	104.328	103.286	102.244	101.202	100.150	99.118	98.076
104.048	103.018	101.989	100.959	99.930	98.900	97.871	96.841	95.811
101.737	100.720	99.702	98.685	97.668	96.650	95.633	94.616	93.598
99.257	98.254	97.251	96.248	95.244	94.241	93.238	92.235	91.232
[illegible].076	96.084	95.093	94.101	93.109	92.117	91.126	90.134	89.142
94.899	93.918	92.938	91.958	90.978	89.998	89.018	88.038	87.058
93 303	92.329	91.354	90.380	89.406	88.432	87.457	86.483	85.509
91.092	90.130	89.168	88.207	87.245	86.283	85.321	84.359	83.398

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =300.00
ENDING TIME =330.00
AVERAGE TEMPERATURE = 84.561
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.33210E+04
COOLANT:WATER

105.182	104.193	103.204	102.215	101.226	100.237	99.248	98.259	97.270
104.090	103.101	102.113	101.124	100.135	99.147	98.158	97.170	96.181
97.268	96.334	95.401	94.468	93.535	92.602	91.669	90.735	89.802
94.145	93.232	92.320	91.407	90.495	89.582	88.670	87.757	86.845
91.792	90.894	89.995	89.096	88.197	87.298	86.399	85.500	84.601
89.476	88.591	87.705	86.820	85.935	85.049	84.164	83.278	82.393
87.222	86.349	85.477	84.605	83.733	82.860	81.988	81.116	80.244
84.790	83.933	83.076	82.219	81.362	80.505	79.648	78.791	77.934
82.683	81.838	80.994	80.149	79.304	78.460	77.615	76.770	75.925
80.584	79.752	78.919	78.087	77.255	76.423	75.590	74.758	73.926
79.108	78.282	77.456	76.630	75.804	74.978	74.152	73.326	72.499
76.979	76.166	75.353	74.540	73.728	72.915	72.102	71.289	70.476

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =330.00

Table IX. Continued.

[illegible]	53.701	53.134	52.568	52.001	51.434	50.868	50.301	49.734
[illegible]	51.855	51.301	50.748	50.195	49.641	49.088	48.534	47.981

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =390.00
ENDING TIME =420.00
AVERAGE TEMPERATURE = 49.692
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.33210E+04
COOLANT:WATER

66.638	66.011	65.385	64.758	64.131	63.505	62.878	62.252	61.625
65.924	65.298	64.672	64.046	63.420	62.794	62.168	61.542	60.915
58.933	58.367	57.802	57.236	56.671	56.106	55.540	54.975	54.409
56.217	55.673	55.128	54.583	54.038	53.493	52.948	52.403	51.858
54.212	53.681	53.151	52.620	52.089	51.558	51.027	50.496	49.965
52.260	51.743	51.225	50.708	50.191	49.674	49.157	48.640	48.123
50.385	49.881	49.377	48.873	48.369	47.866	47.362	46.858	46.354
48.349	47.861	47.372	46.883	46.395	45.906	45.417	44.929	44.440
46.652	46.175	45.698	45.222	44.745	44.269	43.792	43.315	42.839
44.974	44.509	44.045	43.580	43.116	42.652	42.187	41.723	41.258
43.908	43.449	42.991	42.532	42.074	41.615	41.157	40.698	40.240
42.221	41.776	41.330	40.884	40.438	39.992	39.547	39.101	38.655

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =420.00
ENDING TIME =450.00
AVERAGE TEMPERATURE = 40.496
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.33210E+04
COOLANT:WATER

55.884	55.359	54.833	54.308	53.782	53.257	52.731	52.206	51.680
55.279	54.754	54.229	53.704	53.179	52.654	52.129	51.604	51.079
48.564	48.098	47.632	47.166	46.701	46.235	45.769	45.303	44.837
46.073	45.626	45.180	44.733	44.286	43.840	43.393	42.947	42.500
44.239	43.806	43.373	42.940	42.507	42.073	41.640	41.207	40.774
42.462	42.042	41.622	41.201	40.781	40.361	39.941	39.521	39.101

Table IX. Continued.

40.764	40.354	39.943	39.542	39.133	38.725	38.318	37.910	37.502
39.920	38.527	38.133	37.740	37.347	36.953	36.560	36.167	35.773
37.399	37.017	36.635	36.253	35.871	35.489	35.107	34.725	34.343
35.902	35.531	35.160	34.789	34.419	34.048	33.677	33.306	32.935
34.976	34.610	34.245	33.880	33.515	33.149	32.784	32.419	32.054
33.477	33.124	32.770	32.417	32.063	31.710	31.356	31.003	30.649

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =450.00
ENDING TIME =480.00
AVERAGE TEMPERATURE = 32.536
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.33210E+04
COOLANT:WATER

46.210	45.875	45.439	45.004	44.569	44.133	43.698	43.262	42.827
45.803	45.368	44.933	44.498	44.063	43.628	43.193	42.757	42.322
39.494	39.115	38.736	38.357	37.978	37.599	37.220	35.641	36.462
37.250	36.889	36.528	36.167	35.806	35.445	35.084	34.722	34.361
35.604	35.255	34.906	34.556	34.209	33.860	33.512	33.163	32.814
34.015	33.679	33.342	33.005	32.669	32.332	31.996	31.659	31.323
32.505	32.180	31.855	31.530	31.205	30.880	30.555	30.230	29.905
30.868	30.556	30.244	29.932	29.620	29.308	28.996	28.684	28.372
29.531	29.230	28.928	28.626	28.325	28.023	27.721	27.419	27.118
28.220	27.929	27.637	27.346	27.054	26.763	26.471	26.180	25.889
27.429	27.143	26.856	26.570	26.284	25.997	25.711	25.424	25.138
26.125	25.849	25.573	25.297	25.021	24.745	24.470	24.194	23.918

Table X. Shut-Down Process with Water Coolant (P=0 KPa, Re=3321).

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =120.00
ENDING TIME =150.00
AVERAGE TEMPERATURE =165.467
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.33210E-04
COOLANT:WATER

178.575	178.019	177.464	176.909	176.354	175.799	175.243	174.688	174.133
177.005	176.450	175.895	175.340	174.785	174.230	173.674	173.119	172.564
174.685	174.134	173.581	173.028	172.475	171.923	171.370	170.817	170.264
172.747	172.195	171.643	171.092	170.540	169.989	169.437	168.886	168.334
170.985	170.434	169.883	169.332	168.781	168.230	167.679	167.128	166.578
169.225	168.674	168.124	167.574	167.024	166.474	165.924	165.373	164.823
167.471	166.921	166.372	165.822	165.273	164.723	164.174	163.624	163.075
165.685	165.137	164.588	164.039	163.490	162.942	162.393	161.844	161.295
163.948	163.400	162.852	162.304	161.755	161.207	160.659	160.111	159.563
162.208	161.661	161.113	160.566	160.019	159.471	158.924	158.376	157.829
160.569	160.022	159.475	158.928	158 381	157.834	157.287	156.739	156.192
[illegible]	158.273	157 727	157.180	156.634	156.087	155.541	154.995	154.449

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =150.00
ENDING TIME =180.00
AVERAGE TEMPERATURE =152.804
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.33210E+04
COOLANT:WATER

166.724	166.206	165.687	165.169	164.651	164.132	163.614	163.096	162.577
165.252	164.733	164.215	163.697	163.178	162.660	162.142	161.624	161.105
162.172	161.658	161.145	160.632	160.119	159.606	159.093	158.579	158.066
159.963	159.452	158.941	158.430	157.920	157.409	156.898	156.387	155.877
158.089	157.580	157.070	156.561	156.052	155.542	155.033	154.524	154.014
156.220	155.712	155.204	154.696	154.189	153.681	153.173	152.665	152.157
154.365	153.859	153.352	152.845	152.339	151.832	151.326	150.819	150.313
152.444	151.939	151.435	150.930	150.425	149.920	149.415	148.910	148.405

Table X: Continued.

150.624	150.121	149.617	149.113	148.610	148.106	147.603	147.099	146.596
148.800	148.298	147.796	147.294	146.792	146.289	145.787	145.285	144.783
147.164	146.682	146.181	145.680	145.178	144.677	144.175	143.674	143.172
145.340	144.840	144.340	143.840	143.340	142.840	142.340	141.840	141.340

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =180.00
ENDING TIME =210.00
AVERAGE TEMPERATURE =139.137
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.33210E+04
COOLANT:WATER

153.815	153.337	152.858	152.380	151.902	151.424	150.946	150.467	149.989
152.448	151.970	151.492	151.014	150.536	150.057	149.579	149.101	148.623
148.573	148.103	147.633	147.163	146.692	146.222	145.752	145.282	144.812
146.128	145.662	145.195	144.729	144.262	143.795	143.329	142.862	142.396
144.152	143.687	143.223	142.759	142.294	141.830	141.365	140.901	140.436
142.184	141.722	141.259	140.797	140.335	139.873	139.410	138.948	138.485
140.238	139.777	139.317	138.857	138.397	137.937	137.477	137.016	136.556
138.194	137.736	137.279	136.821	136.363	135.906	135.448	134.990	134.533
136.302	135.848	135.392	134.936	134.481	134.025	133.569	133.114	132.658
134.408	133.955	133.501	133.048	132.594	132.140	131.687	131.233	130.780
132.826	132.374	131.921	131.469	131.016	130.564	130.111	129.658	129.206
130.903	130.453	130.002	129.552	129.102	128.651	128.201	127.751	127.300

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =210.00
ENDING TIME =240.00
AVERAGE TEMPERATURE =124.926
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.33210E+04
COOLANT:WATER

140.223	139.787	139.351	138.915	138.479	138.043	137.607	137.171	136.735
138.968	138.532	138.097	137.661	137.225	136.789	136.353	135.917	135.481
134.324	133.899	133.474	133.049	132.624	132.199	131.774	131.349	130.924
131.691	131.271	130.850	130.430	130.010	129.589	129.169	128.748	128.328

Table X. Continued.

32	129.215	129.797	128.379	127.962	127.544	127.125	126.706	126.291
186	127.171	126.757	126.342	125.927	125.512	125.097	124.683	124.268
170	125.159	124.746	124 334	123.922	123.510	123.098	122.686	122.274
29	123.020	122.612	122.203	121.794	121.385	120.977	120.568	120.159
490	121.094	120.678	120.272	119.866	119.459	119.053	118.647	118.241
547	119.144	118.740	118.337	117.934	117.530	117.127	116.723	116.320
014	117.612	117.210	116.808	116.405	116.003	115.601	115.199	114.797
.037	115.637	115.238	114.839	114.440	114.041	113.641	113.242	112.843

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =240.00
ENDING TIME =270.00
AVERAGE TEMPERATURE =110.606
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.33210E+04
COOLANT:WATER

5.317	125.924	125.531	125.139	124.746	124.353	123.961	123.568	123.175
5.178	124.785	124.392	124.000	123.607	123.215	122.822	122.429	122.037
9.845	119.465	119.086	118.707	118.328	117.948	117.569	117.190	116.811
7.081	116.707	116.334	115.960	115.586	115.212	114.838	114.465	114.091
.4.969	114.599	114.228	113.858	113.487	113.117	112.746	112.376	112.006
.2.875	112.508	112.141	111.774	111.407	111.040	110.672	110.306	109.939
10.820	110.456	110.093	109.729	109.365	109.002	108.638	108.274	107.911
08.617	108.257	107.897	107.538	107.178	106.818	106.459	106.099	105.739
06.659	106.303	105.946	105.590	105.233	104.877	104.520	104.163	103.807
04.700	104.346	103.993	103.640	103.286	102.933	102.580	102.226	101.873
.03.230	102.878	102.527	102.175	101.823	101.472	101.120	100.769	100.416
101.233	100.885	100.536	100.188	99.840	99.492	99.143	98.795	98.447

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =270.00
ENDING TIME =300.00
AVERAGE TEMPERATURE = 96.569
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.33210E+04
COOLANT:WATER

Table X. Continued.

ENDING TIME =360.00
AVERAGE TEMPERATURE = 70.606
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.33210E+04
COOLANT:WATER

85.963	85.696	85.429	85.162	84.894	84.627	84.360	84.093	83.825
85.165	84.898	84.631	84.364	84.097	83.829	83.562	83.295	83.028
78.615	78.367	78.118	77.869	77.620	77.372	77.123	76.874	76.625
75.844	75.602	75.359	75.117	74.875	74.632	74.391	74.149	73.907
73.795	73.557	73.319	73.082	72.844	72.606	72.368	72.131	71.893
71.782	71.549	71.316	71.082	70.849	70.615	70.382	70.149	69.915
69.831	69.602	69.373	69.144	68.915	68.686	68.457	68.227	67.998
67.708	67.484	67.260	67.035	66.812	66.587	66.363	66.138	65.914
65.904	65.684	65.463	65.243	65.023	64.802	64.582	64.362	64.141
64.108	63.891	63.675	63.459	63.242	63.026	62.810	62.593	62.377
62.918	62.704	62.490	62.275	62.061	61.847	61.632	61.418	61.203
61.093	60.883	60.673	60.463	60.253	60.042	59.832	59.622	59.412

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =360.00
ENDING TIME =390.00
AVERAGE TEMPERATURE = 59.133
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.33210E+04
COOLANT:WATER

73.831	73.602	73.372	73.142	72.913	72.683	72.454	72.224	71.995
73.138	72.908	72.679	72.449	72.220	71.991	71.761	71.532	71.302
66.523	66.312	66.102	65.891	65.681	65.470	65.260	65.049	64.839
63.867	63.663	63.459	63.256	63.052	62.848	62.644	62.440	62.236
61.914	61.715	61.515	61.316	61.116	60.917	60.717	60.518	60.318
60.003	59.806	59.613	59.417	59.222	59.027	58.832	58.637	58.442
58.158	57.967	57.776	57.585	57.395	57.204	57.013	56.822	56.631
56.146	55.961	55.775	55.589	55.403	55.217	55.031	54.845	54.659
54.458	54.276	54.094	53.912	53.730	53.548	53.366	53.184	53.002
52.781	52.603	52.425	52.247	52.069	51.891	51.713	51.535	51.356

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Table X. Continued.

[illegible]1.707	51.531	51.355	51.179	51.003	50.826	50.650	50.474	50.298
[illegible].009	49.837	49.665	49.493	49.321	49.149	48.977	48.805	48.633

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =390.00
ENDING TIME =420.00
AVERAGE TEMPERATURE = 48.849
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.33210E+04
COOLANT:WATER

62.659	62.465	62.270	62.075	61.880	61.685	61.491	61.296	61.101
62.064	61.869	61.674	61.480	61.285	61.090	60.896	60.701	60.506
55.550	55.374	55.198	55.022	54.847	54.671	54.495	54.319	54.143
53.057	52.868	52.718	52.549	52.380	52.210	52.041	51.871	51.702
51.230	51.065	50.900	50.735	50.570	50.405	50.240	50.075	49.910
49.450	49.289	49.128	48.967	48.807	48.646	48.485	48.324	48.164
47.739	47.583	47.426	47.269	47.113	46.956	46.799	46.643	46.486
45.873	45.721	45.569	45.417	45.265	45.113	44.961	44.809	44.657
44.324	44.175	44.027	43.879	43.731	43.583	43.435	43.286	43.138
42.790	42.646	42.501	42.357	42.212	42.068	41.924	41.779	41.635
41.836	41.693	41.551	41.408	41.266	41.123	40.981	40.838	40.695
40.289	40.150	40.011	39.873	39.734	39.596	39.457	39.318	39.180

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =420.00
ENDING TIME =450.00
AVERAGE TEMPERATURE = 39.804
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.33210E+04
COOLANT:WATER

52.548	52.384	52.221	52.058	51.894	51.731	51.568	51.404	51.241
52.042	51.879	51.715	51.552	51.389	51.225	51.062	50.899	50.736
45.777	45.632	45.487	45.342	45.197	45.052	44.907	44.763	44.618
43.483	43.344	43.205	43.066	42.927	42.789	42.650	42.511	42.372
41.806	41.671	41.537	41.402	41.267	41.133	40.998	40.863	40.729
40.179	40.048	39.918	39.787	39.656	39.526	39.395	39.264	39.134

Table X. Continued.

[illegible]	38.496	38.379	38.243	38.126	37.989	37.863	37.736	37.609
36.927	26.804	36.682	36.560	36.437	36.315	36.193	36.071	35.948
35.533	35.414	35.295	35.177	35.058	34.939	34.820	34.701	34.582
34.159	34.043	33.928	33.813	33.697	33.582	33.467	33.351	33.236
33.325	33.212	33.098	32.985	32.871	32.758	32.644	32.530	32.417
31.945	31.835	31.725	31.615	31.505	31.395	31.285	31.176	31.066

ELECTROOE TEMPERATURE DISTRIBUTION
STARTING TIME =450.00
ENDING TIME =480.00
AVERAGE TEMPERATURE = 31.995
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.33210E+04
COOLANT:WATER

43.546	43.410	43.275	43.139	43.004	42.869	42.733	42.598	42.463
43.120	42.985	42.850	42.714	42.579	42.444	42.309	42.174	42.038
37.227	37.109	36.991	36.873	36.755	36.638	36.520	36.402	36.284
35.156	35.043	34.931	34.819	34.707	34.594	34.482	34.370	34.258
33.645	33.537	33.429	33.320	33.212	33.103	32.995	32.887	32.779
32.186	32.082	31.977	31.872	31.768	31.663	31.558	31.454	31.349
30.798	30.697	30.596	30.495	30.394	30.293	30.192	30.091	29.990
29.287	29.190	29.093	28.996	28.899	28.802	28.705	28.608	28.511
28.058	27.964	27.870	27.776	27.682	27.589	27.495	27.401	27.307
26.850	26.759	26.669	26.578	26.487	26.397	26.306	26.216	26.125
26.135	25.046	25.957	25.868	25.779	25.690	25.601	25.512	25.423
24.929	24.843	24.757	24.671	24.586	24.500	24.414	24.328	24.243

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Table XI. Shut-Down Process with Water Coolant (P=3500 KPa, Re=6167).

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =120.00
ENDING TIME =150.00
AVERAGE TEMPERATURE =155.638
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.61670E+04
COOLANT:WATER

169.126	168.505	167.885	167.264	166.643	166.022	165.402	164.781	164.160
167.538	166.917	166.296	165.675	165.055	164.434	163.813	163.192	162.572
165.240	164.622	164.003	163.385	162.767	162.149	161.531	160.913	160.295
163.301	162.684	162.068	161.451	160.834	160.218	159.601	158.984	158.367
161.531	160.915	160.299	159.683	159.067	158.451	157.835	157.219	156.603
159.763	159.148	158.533	157.917	157.302	156.687	156.072	155.457	154.842
158.001	157.387	156.772	156.158	155.543	154.929	154.315	153.700	153.086
156.210	155.596	154.982	154.369	153.755	153.142	152.528	151.915	151.302
154.464	153.851	153.238	152.625	152.012	151.400	150.787	150.174	149.561
152.716	152.104	151.492	150.880	150.268	149.656	149.044	148.432	147.819
151.063	150.451	149.840	149.228	148.616	148.005	147.393	146.781	146.169
149.306	148.695	148.085	147.474	146.863	146.252	145.641	145.030	144.419

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =150.00
ENDING TIME =180.00
AVERAGE TEMPERATURE =143.729
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.61670E+04
COOLANT:WATER

157.903	157.323	156.744	156.164	155.584	155.005	154.425	153.846	153.266
156.413	155.833	155.253	154.674	154.094	153.515	152.935	152.356	151.776
153.402	152.828	152.254	151.680	151.106	150.533	149.959	149.385	148.811
151.216	150.645	150.074	149.503	148.932	148.361	147.790	147.219	146.648
149.349	148.779	148.209	147.640	147.070	146.501	145.931	145.362	144.792
147.486	146.918	146.350	145.782	145.214	144.646	144.078	143.510	142.942
145.636	145.070	144.503	143.937	143.371	142.804	142.238	141.672	141.105
143.726	143.161	142.597	142.032	141.468	140.903	140.339	139.774	139.210

Table XI. Continued.

[illegible]	141.348	140.785	140.222	139.659	139.096	138.533	137.970	[illegible]
0.095	139.531	138.970	138.408	137.847	137.285	136.724	136.162	135.601
8.470	137.910	137.349	136.788	136.228	135.667	135.106	134.545	133.985
36.634	136.075	135.516	134.957	134.398	133.839	133.280	132.721	132.162

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =160.00
ENDING TIME =210.00
AVERAGE TEMPERATURE =130.877
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.61670E+04
COOLANT:WATER

45.677	145.142	144.607	144.072	143.538	143.003	142.468	141.934	141.399
44.294	143.759	143.225	142.690	142.155	141.621	141.086	140.552	140.017
40.538	140.013	139.487	138.961	138.436	137.910	137.384	136.859	136.333
38.139	137.616	137.095	136.573	136.052	135.530	135.008	134.486	133.965
36.182	135.662	135.143	134.624	134.105	133.585	133.066	132.547	132.027
34.234	133.717	133.200	132.684	132.167	131.650	131.133	130.616	130.099
32.308	131.793	131.279	130.764	130.250	129.735	129.221	128.706	128.192
30.291	129.779	129.267	128.755	128.244	127.732	127.220	126.708	126.197
28.418	127.909	127.399	126.890	126.380	125.871	125.361	124.852	124.342
26.543	126.036	125.529	125.021	124.514	124.007	123.500	122.993	122.486
24.963	124.457	123.951	123.445	122.939	122.433	121.927	121.421	120.915
23.062	122.559	122.055	121.552	121.048	120.544	120.041	119.537	119.034

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =210.00
ENDING TIME =240.00
AVERAGE TEMPERATURE =117.512
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.61670E+04
COOLANT:WATER

32.804	132.316	131.829	131.341	130.854	130.367	129.879	129.392	128.904
31.535	131.048	130.560	130.073	129.586	129.098	128.611	128.124	127.636
27.060	126.585	126.110	125.634	125.159	124.684	124.209	123.733	123.258
24.491	124.021	123.550	123.080	122.610	122.140	121.670	121.200	120.730

Table XI. Continued.

122.465	121.998	121.531	121.064	120.597	120.130	119.663	119.196	118.729
120.453	119.989	119.525	119.061	118.597	118.134	117.670	117.206	116.742
118.470	118.009	117.549	117.088	116.627	116.167	115.706	115.245	114.784
116.370	115.913	115.456	114.999	114.542	114.085	113.628	113.171	112.714
114.462	114.008	113.554	113.100	112.646	112.192	111.737	111.283	110.829
112.552	112.100	111.649	111.198	110.747	110.296	109.845	109.394	108.943
111.027	110.578	110.128	109.678	109.229	108.779	108.330	107.880	107.431
109.086	108.640	108.193	107.747	107.301	106.854	106.408	105.962	105.516

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =240.00
ENDING TIME =270.00
AVERAGE TEMPERATURE =104.044
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.61670E+04
COOLANT:WATER

119.633	119.194	118.755	118.316	117.877	117.438	116.999	116.560	116.121
118.482	118.043	117.604	117.165	116.726	116.287	115.848	115.409	114.970
113.364	112.940	112.516	112.091	111.667	111.243	110.819	110.395	109.971
110.679	110.261	109.843	109.426	109.008	108.590	108.172	107.754	107.336
108.612	108.198	107.784	107.370	106.955	106.541	106.127	105.713	105.299
106.564	106.154	105.743	105.333	104.923	104.512	104.102	103.692	103.282
104.554	104.147	103.740	103.334	102.927	102.521	102.114	101.707	101.301
102.405	102.003	101.601	101.198	100.796	100.394	99.992	99.590	99.187
100.489	100.091	99.692	99.293	98.895	98.496	98.097	97.699	97.300
98.573	98.178	97.783	97.388	96.992	96.597	96.202	95.807	95.412
97.119	96.725	96.332	95.939	95.546	95.152	94.759	94.366	93.973
95.169	94.780	94.390	94.001	93.612	93.222	92.833	92.444	92.054

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =270.00
ENDING TIME =300.00
AVERAGE TEMPERATURE = 90.842
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.61670E+04
COOLANT:WATER

Table XI. Continued.

106.492	106.101	105.710	105.319	104.928	104.537	104.146	103.756	103.365
105.458	105.067	104.677	104.286	103.895	103.504	103.114	102.723	102.332
99.813	99.440	99.066	98.693	98.320	97.946	97.573	97.200	96.826
97.074	96.708	96.341	95.974	95.608	95.241	94.875	94.508	94.142
94.999	94.637	94.275	93.912	93.550	93.188	92.826	92.463	92.101
92.949	92.591	92.233	91.875	91.517	91.159	90.801	90.443	90.085
90.944	90.591	90.237	89.883	89.530	89.176	88.822	88.469	88.115
88.787	88.439	88.090	87.741	87.392	87.044	96.695	86.346	85.998
86.896	86.551	86.207	85.862	85.517	85.172	84.828	84.483	84.138
85.007	84.666	84.325	83.985	83.644	83.303	82.963	82.622	82.281
83.638	83.299	82.960	82.622	82.283	81.944	81.606	81.267	80.928
81.716	81.381	81.047	80.713	80.378	80.044	79.710	79.375	79.041

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =300.00
ENDING TIME =330.00
AVERAGE TEMPERATURE = 78.239
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.61670E+04
COOLANT:WATER

93.670	93.326	92.982	92.638	92.295	91.951	91.607	91.263	90.919
92.752	92.409	92.065	91.721	91.378	91.034	90.690	90.347	90.003
86.726	86.402	86.077	85.753	85.429	85.104	84.780	84.455	84.131
83.994	83.677	83.360	83.042	82.725	82.408	82.091	81.774	81.456
81.947	81.635	81.322	81.010	80.697	80.385	80.073	79.760	79.448
79.931	79.623	79.316	79.008	78.700	78.392	78.085	77.777	77.469
77.969	77.666	77.362	77.059	76.756	76.453	76.150	75.846	75.543
75.846	75.548	75.250	74.952	74.654	74.356	74.059	73.761	73.463
74.012	73.719	73.425	73.132	72.838	72.544	72.251	71.957	71.663
72.184	71.895	71.606	71.316	71.027	70.738	70.448	70.159	69.870
70.913	70.626	70.339	70.052	69.764	69.477	69.190	68.903	68.616
69.055	68.773	68.490	68.208	67.925	67.642	67.360	67.077	66.795

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =330.00

Table XI. Continued.

ENDING TIME =360.00
AVERAGE TEMPERATURE = 66.4[illegible]
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.61670E+04
COOLANT:WATER

81.415	81.116	80.817	80.519	80.220	79.921	79.622	79.323	79.024
80.610	80.311	80.012	79.714	79.415	79.116	78.818	78.519	78.220
74.364	74.086	73.808	73.530	73.251	72.973	72.695	72.417	72.139
71.697	71.426	71.155	70.884	70.614	70.343	70.072	69.801	69.531
69.715	69.449	69.183	68.917	68.651	68.386	68.120	67.854	67.588
67.769	67.508	67.247	65.986	66.725	66.464	66.203	65.942	65.681
65.883	65.627	65.370	65.114	64.858	64.602	64.346	64.089	63.833
63.836	63.585	63.334	63.084	62.832	62.582	62.331	62.081	61.830
62.092	61.845	61.599	61.352	61.106	60.860	60.613	60.367	60.121
60.356	60.114	59.872	59.630	59.389	59.147	58.905	58.663	58.421
59.194	58.954	58.714	58.474	58.235	57.995	57.755	57.516	57.276
57.434	57.199	56.964	56.729	56.494	56.259	56.024	55.789	55.554

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =360.00
ENDING TIME =390.00
AVERAGE TEMPERATURE = 55.632
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.61670E+04
COOLANT:WATER

69.925	69.668	69.411	69.155	68.898	68.641	68.385	68.128	67.872
69.226	68.969	68.713	68.456	68.200	67.943	67.687	67.430	67.174
62.925	62.690	62.455	62.219	61.984	61.748	61.513	61.278	61.042
60.375	60.147	59.919	59.691	59.463	59.235	59.007	58.779	58.551
58.491	58.268	58.045	57.822	57.599	57.376	57.153	56.930	56.707
56.648	56.430	56.212	55.993	55.775	55.557	55.339	55.121	54.903
54.869	54.656	54.443	54.229	54.015	53.803	53.569	53.376	53.162
52.935	52.727	52.520	52.312	52.104	51.896	51.608	51.480	51.272
51.308	51.104	50.901	50.697	50.493	50.290	50.086	49.883	49.679
49.693	49.494	49.294	49.095	48.896	48.697	48.498	48.299	48.099

Table XI. Continued.

48.646	48.449	48.252	48.055	47.858	47.661	47.464	47.267	47.070
47.013	46.821	46.629	46.436	46.244	46.052	45.859	45.667	45.475

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =390.00
ENDING TIME =420.00
AVERAGE TEMPERATURE = 45.958
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.61670E+04
COOLANT:WATER

59.344	59.126	58.909	58.691	58.473	58.255	58.037	57.819	57.602
58.744	58.526	58.309	58.091	57.873	57.656	57.438	57.220	57.003
52.546	52.349	52.153	51.956	51.760	51.563	51.366	51.170	50.973
50.156	49.967	49.777	49.586	49.398	49.209	49.020	48.830	48.642
48.398	48.213	48.029	47.844	47.660	47.475	47.291	47.106	46.921
46.685	46.505	46.325	46.146	45.966	45.786	45.606	45.427	45.247
45.040	44.865	44.689	44.514	44.339	44.164	43.989	43.814	43.639
43.249	43.079	42.910	42.740	42.570	42.400	42.230	42.060	41.890
41.760	41.594	41.428	41.262	41.097	40.931	40.765	40.600	40.434
40.286	40.125	39.963	39.802	39.640	39.479	39.317	39.156	38.994
39.359	39.200	39.040	38.881	38.722	38.562	38.403	38.244	38.084
37.875	37.720	37.566	37.411	37.256	37.101	36.946	36.791	36.636

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =420.00
ENDING TIME =450.00
AVERAGE TEMPERATURE = 37.450
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.61670E+04
COOLANT:WATER

49.768	49.585	49.402	49.220	49.037	48.854	49.672	48.489	48.306
49.258	49.075	48.893	48.710	48.528	48.345	48.163	47.980	47.798
43.301	43.139	42.977	42.615	42.653	42.491	42.329	42.167	42.005
41.105	40.950	40.795	40.639	40.484	40.329	40.174	40.018	39.863
39.495	39.344	39.193	39.043	38.892	38.742	38.591	38.440	38.290
37.932	37.786	37.640	37.494	37.348	37.202	37.056	36.910	36.764

Table XI. Continued.

36.439	36.297	36.156	36.014	35.872	35.731	35.589	35.447	35.306
34.815	34.678	34.541	34.405	34.268	34.131	33.994	33.858	33.721
33.477	33.345	33.212	33.079	32.946	32.813	32.681	32.548	32.415
32.159	32.031	31.902	31.773	31.644	31.515	31.386	31.257	31.128
31.352	31.225	31.098	30.972	30.845	30.718	30.591	30.464	30.337
30.031	29.908	29.786	29.663	29.540	29.417	29.294	29.171	29.049

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =450.00
ENDING TIME =480.00
AVERAGE TEMPERATURE = 30.105
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.61670E+04
CCOLANT:WATER

41.242	41.090	40.939	40.787	40.636	40.485	40.333	40.182	40.031
40.814	40.662	40.511	40.360	40.209	40.058	39.906	39.755	39.604
35.213	35.082	34.950	34.818	34.687	34.555	34.423	34.292	34.160
33.233	33.108	32.982	32.857	32.731	32.606	32.480	32.355	32.229
31.785	31.664	31.543	31.422	31.300	31.179	31.058	30.937	30.816
30.387	30.270	30.153	30.036	29.919	29.802	29.685	29.568	29.451
29.057	28.944	28.831	28.718	28.605	28.492	28.379	28.266	28.153
27.612	27.504	27.395	27.287	27.178	27.070	26.961	26.853	26.744
26.434	26.330	26.225	26.120	26.015	25.910	25.805	25.700	25.595
25.279	25.177	25.076	24.975	24.873	24.772	24.671	24.569	24.468
24.588	24.488	24.389	24.289	24.190	24.090	23.990	23.891	23.791
23.435	23.340	23.244	23.148	23.052	22.956	22.860	22.764	22.668

Table XII. Shut-Down Process with Water Coolant (P=0 KPa, Re=6167).

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =120.00
ENDING TIME =150.00
AVERAGE TEMPERATURE =151.337
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.61670E+04
COOLANT:WATER

165.347	164.709	164.071	163.434	162.796	162.150	161.520	160.882	160.245
163.673	163.036	162.398	161.760	161.122	160.485	159.847	159.209	158.571
161.307	160.672	160.037	159.402	158.767	158.132	157.497	156.862	156.227
159.293	158.659	158.026	157.392	156.759	156.125	155.491	154.858	154.224
157.443	156.811	156.178	155.545	154.912	154.279	153.647	153.014	152.381
155.596	154.964	154.332	153.700	153.068	152.436	151.804	151.172	150.540
153.755	153.124	152.493	151.862	151.230	150.599	149.968	149.337	148.705
151.886	151.255	150.625	149.995	149.364	148.734	148.104	147.473	146.843
150.061	149.431	148.802	148.172	147.543	146.913	146.283	145.654	145.024
148.235	147.606	146.977	146.348	145.720	145.091	144.462	143.833	143.204
146.501	145.872	145.244	144.616	143.987	143.359	142.730	142.102	141.473
144.667	144.039	143.411	142.784	142.156	141.528	140.901	140.273	139.645

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =150.00
ENDING TIME =180.00
AVERAGE TEMPERATURE =139.760
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.61670E+04
COOLANT:WATER

154.374	153.779	153.183	152.588	151.992	151.397	150.802	150.206	149.611
152.805	152.209	151.614	151.019	150.423	149.828	149.232	148.637	148.042
149.751	149.161	148.572	147.982	147.393	146.803	146.214	145.624	145.035
147.505	146.918	146.331	145.744	145.158	144.571	143.984	143.398	142.811
145.569	144.984	144.399	143.814	143.229	142.644	142.058	141.473	140.888
143.639	143.056	142.472	141.889	141.305	140.722	140.138	139.555	138.971
141.723	141.141	140.559	139.977	139.395	138.813	138.231	137.650	137.068
139.748	139.168	138.588	138.008	137.428	136.848	136.268	135.688	135.109

Table XII. Continued.

[illegible]	119.686	118.406	117.927	117.447	116.967	116.487	116.008	115.529
117.311	116.835	116.359	115.882	115.405	114.929	114.452	113.976	113.499
115.286	114.813	114.340	113.867	113.393	112.920	112.447	111.973	111.500
113.149	112.680	112.210	111.740	111.271	110.801	110.332	109.862	109.392
111.200	110.733	110.267	109.800	109.333	108.867	108.400	107.934	107.467
109.249	108.786	108.322	107.859	107.395	106.932	106.468	106.005	105.541
107.674	107.212	106.750	106.298	105.827	105.365	104.903	104.441	103.979
105.696	105.238	104.779	104.321	103.862	103.405	102.945	102.486	102.026

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =240.00
ENDING TIME =270.00
AVERAGE TEMPERATURE =101.179
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.61670E+04
COOLANT:WATER

116.960	116.509	116.058	115.607	115.155	114.704	114.253	113.802	113.351
115.749	115.298	114.847	114.396	113.945	113.494	113.043	112.592	112.141
110.666	110.230	109.795	109.359	108.923	108.488	108.052	107.616	107.181
107.963	107.534	107.104	106.675	106.245	105.816	105.386	104.957	104.528
105.864	105.438	105.013	104.587	104.162	103.736	103.311	102.885	102.460
103.785	103.363	102.941	102.520	102.098	101.677	101.255	100.834	100.412
101.744	101.326	100.909	100.491	100.073	99.655	99.238	98.820	98.402
99.571	99.157	98.744	98.331	97.918	97.504	97.091	96.678	96.265
97.625	97.216	96.806	96.396	95.987	95.577	95.168	94.758	94.348
95.680	95.274	94.869	94.463	94.057	93.651	93.245	92.839	92.433
94.186	93.782	93.378	92.974	92.570	92.166	91.762	91.357	90.953
92.212	91.812	91.412	91.012	90.612	90.212	89.811	89.411	89.011

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =270.00
ENDING TIME =300.00
AVERAGE TEMPERATURE = 88.344
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.61670E+04
COOLANT:WATER

Table XII. Continued.

[illegible]	103.710	103.309	102.907	102.506	102.104	101.702	101.301	100.899
[illegible]	102.624	102.223	101.821	101.420	101.019	100.617	100.216	99.81[illegible]
97.438	97.054	96.671	96.287	95.903	95.520	95.136	94.753	94.369
94.692	94.315	93.938	93.562	93.185	92.809	92.432	92.055	91.679
92.595	92.223	91.851	91.479	91.107	90.734	90.362	89.990	89.618
90.525	90.157	89.789	89.421	89.054	88.686	88.318	87.951	87.583
88.501	88.137	87.774	87.411	87.047	86.684	86.320	85.957	85.594
86.330	85.972	85.613	85.255	84.897	84.538	84.180	83.822	83.464
84.419	84.065	83.711	83.357	83.003	82.648	82.294	81.940	81.586
82.512	82.162	81.812	81.462	81.112	80.762	80.412	80.062	79.712
81.112	80.764	90.416	80.068	79.720	79.372	79.024	78.676	78.328
79.176	78.833	78.489	78.146	77.802	77.459	77.115	76.772	76.428

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =330.00
ENDING TIME =330.00
AVERAGE TEMPERATURE = 7[illegible].071
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.61670E+04
COOLANT:WATER

91.577	91.223	90.870	90.517	90.164	89.810	89.457	89.104	88.751
90.513	90.260	89.907	89.554	89.201	88.848	88.495	88.142	87.789
84.662	81.329	83.996	83.663	83.329	82.996	82.663	82.329	81.996
81.932	81.607	81.281	80.955	80.629	80.303	79.977	79.651	79.325
79.874	79.553	79.232	78.911	78.590	78.268	77.947	77.626	77.305
77.847	77.530	77.214	76.898	76.582	76.266	75.949	75.633	75.31[illegible]
75.874	75.562	75.251	74.939	74.628	74.316	74.004	73.693	73.38[illegible]
73.747	73.441	73.134	72.828	72.522	72.216	71.910	71.604	71.298
71.903	71.601	71.300	70.998	70.696	70.395	70.093	69.791	69.490
70.066	69.769	69.472	69.174	68.877	62.580	68.283	67.985	67.688
68.771	58.476	68.181	67.886	67.591	67.296	67.001	66.706	66.41[illegible]
66.909	56.619	66.329	66.038	65.748	65.458	65.168	64.877	64.58[illegible]

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =330.00

Table XII. Continued.

ENDING TIME =360.00
AVERAGE TEMPERATURE = 64.601
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.61670E+04
COOLANT:WATER

79.596	79.289	78.982	78.575	78.368	78.061	77.754	77.447	77.140
76.750	78.444	78.137	77.830	77.523	77.216	76.909	76.602	76.296
72.594	72.309	72.023	71.737	71.451	71.166	70.880	70 594	70.308
69.937	69.659	69.381	69.103	69.824	68 546	68.268	67.990	67.712
67.951	67.677	67.404	67.131	66.858	66.585	66.312	66.039	65.766
56.001	65.733	65.465	65.197	64.929	64.651	64.393	64.125	63.857
64.112	63.849	63.586	63.323	63.059	62.796	62.533	62.270	62.007
62.069	61.811	61.554	61.296	61.038	60.781	60.523	60.256	60.008
60.322	60.069	59.816	59.562	59.309	59.056	58.803	58.550	58.297
58.555	58.337	58.088	57.840	57.591	57.342	57.094	56.845	56.597
57.406	57.160	56.913	56.667	56.421	56.175	55.928	55.652	55.436
55.649	55.408	55.166	54.925	54.683	54.442	54.201	53.959	53.718

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =360.00
ENDING TIME =390.00
AVERAGE TEMPERATURE = 54.108
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.61670E+04
COOLANT:WATER

68.362	68.098	67.835	67.571	67.307	67.044	66.780	66.516	66.253
67.629	67.365	67.102	66.838	66.575	66.311	66.048	65.784	65.521
61.428	61.186	60.944	60.702	60.461	60.219	59.977	59.735	59.493
58.893	58.659	58.425	58.191	57.956	57.722	57.488	57.254	57.019
57.011	56.782	56.552	56.323	56.094	55.865	55.636	55.407	55.178
55.170	54.946	54.722	54.498	54.274	54.050	53.826	53.602	53.378
53.395	53.176	52.957	52.737	52.518	52.299	52.080	51.860	51.641
51.470	51.257	51.043	50.829	50.616	50.402	50.189	49.975	49.761
49.845	49.636	49.427	49.218	49.009	48.800	48.590	48.381	48.172
48.235	48.030	47.825	47.621	47.416	47.211	47.007	46.802	46.598

Table XII. Continued.

[illegible]	46.975	46.772	46.570	46.367	46.165	45.963	45.760	45.558
[illegible]	45.355	45.157	44.960	44.762	44.564	44.367	44.169	43.971

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =390.00
ENDING TIME =420.00
AVERAGE TEMPERATURE = 44.701
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.61670E+04
COOLANT:WATER

58.018	57.794	57.570	57 347	57.123	56.899	56.675	56.452	56.228
57.389	57.165	56.942	56.718	55.494	56.271	56.047	55.824	55.600
51.295	51.093	50.891	50.689	50.488	50.286	50.084	49.882	49.680
48.925	48.730	49.536	48.341	48.147	47.952	47.757	47.563	47.368
47.173	46.984	46.794	46.604	46.415	46.225	46.036	45.846	45.656
45.467	45.283	45.098	44.913	44.729	44.544	44.359	44.175	43.990
43.829	43.649	43.470	43.290	43 110	42.930	42.750	42.570	42.390
42.052	41.878	41.703	41.529	41.354	41.180	41.005	40.831	40.656
40.569	40.399	40.229	40.059	39.888	39.718	39.548	39.378	39.208
39.134	38.938	38.772	38.606	38.440	38.275	38.109	37.943	37.777
38.171	38.007	37.843	37.679	37.516	37.352	37.188	37.024	36.861
36.698	36.539	36.380	36.221	36.062	35.902	35.743	35.584	35.425

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =420.00
ENDING TIME =450.00
AVERAGE TEMPERATURE = 36.428
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.61670E+04
COOLANT:WATER

48.655	48.468	48.280	48.092	47.905	47.717	47.529	47.342	47.154
48.122	47.934	47.747	47.559	47.372	47.184	46.997	46.809	46.621
42.271	42.104	41.938	41.771	41.605	41.439	41.272	41.106	40.939
40.096	39.937	39.777	39.618	39.458	39.299	39.139	38.980	38.820
38.495	38.340	38.186	38.031	37.876	37.722	37.567	37.412	37.257
36.943	36.793	36.643	36.493	36.343	36.193	36.043	35.893	[illegible]

Table XII. Continued.

35.459	35.314	35.163	35.023	34.878	34.732	34.586	34.441	34.295
33.851	33.711	33.570	33.430	33.289	33.149	33.008	32.868	32.727
32.523	32.367	32.250	32.114	31.977	31.841	31.704	31.568	31.432
31.216	31.083	30.951	30.819	30.686	30.554	30.421	30.289	30.156
30.406	30.275	30.145	30.014	29.884	29.753	29.623	29.492	29.362
29.098	28.972	28.846	28.719	28.593	28.467	28.341	28.214	28.088

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =450.00
ENDING TIME =480.00
AVERAGE TEMPERATURE = 29.285
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.61670E+04
COOLANT:WATER

40.320	40.164	40.009	39.853	39.698	39.542	39.387	39.231	39.076
39.872	39.717	39.562	39.406	39.251	39.096	38.940	38.785	38.630
34.375	34.240	34.105	33.970	33.834	33.699	33.564	33.428	33.293
32.418	32.289	32.160	32.031	31.902	31.773	31.644	31.515	31.386
30.981	30.856	30.732	30.607	30.483	30.358	30.234	30.109	29.985
29.594	29.474	29.354	29.234	29.113	28.993	28.873	28.753	28.632
28.276	28.160	28.044	27.928	27.812	27.696	27.579	27.463	27.347
26.848	26.736	26.625	26.513	26.402	26.291	26.179	26.068	25.956
25.681	25.573	25.466	25.358	25.250	25.142	25.035	24.927	24.819
24.537	24.433	24.329	24.225	24.121	24.016	23.912	23.808	23.704
23.845	23.743	23.641	23.538	23.436	23.334	23.231	23.129	23.027
22.707	22.609	22.510	22.412	22.313	22.215	22.116	22.018	21.919

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Chapter VI

CURRENT DENSITY DISTRIBUTION

In this chapter, the modified computer code was employed to simulate the current density distribution during the considered transient processes. The procedure used divides the considered cell plate into symmetrical finite difference grids with small reactant concentration difference. Initial conditions and boundary conditions are then utilized within an iterative process to obtain a solution for each grid that is subjected to the prespecified restrictions of the average boundary operation conditions and the input data, refer to Chapter V and Appendix, which can be listed as follows:

(a) Fuel flow rate and temperature

(b) Process air flow rate and temperature

(c) Coolant flow rate

(d) Oxygen utilization rate

(e) Hydrogen utilization rate

(f) Average cell plate temperature

The electrode current density variation is affected mainly by the concentration of oxygen and hydrogen inside the fuel cell during any transient process. However, the current density distribution is a function of the transient temperature distribution of the electrode. As concluded in Chapter V the electrode temperature distribution is a function of the stack pressure, coolant volumetric flow rates and thermophysical properties.

This chapter is devoted to study the variation of the transient electrode current density distribution during start-up and shut-down process. For the sake of comparison the same cooling fluids flow rates and applied stack pressure used in the previous chapters results were utilized. The affects of these two important parameters on the electrode current density distribution were then presented by utilizing two-dimensions and three-dimensions contours figures.

6.1 Transient Electrode Current Density Distribution During a Start-Up Process

Figure 115 to Figure 120 exhibits the variation of the current density distribution with time in (Ampere/cm**2) for water Re=1250 and P=3500 Kpa which is the most critical case due to high thermal energy accumulation inside the fuel cell which causes the highest temperature increase rate in the electrode average temperature. Comparing Figure 121 to Figure 126, which represents the current density when water is used for the equal time intervals during a starting process the following is observed.

1. The highest local current densities are located close to fuel entrance upper edge during the start-up process but will shift slightly toward

the center of the electrode. During the start-up process the increase in the temperatures, before reaching the steady-state, will increase the generation rate of free electrons.

2. During a start-up process the increase in the coolant mass flow reduced the peak current density value and area and caused the peak area to shift further toward the upper edge close to fuel entrance side, as shown in Figure 127 to Figure 132 which represents the case where water was used with Re=6167 and P=0 Kpa.
3. The transient average current density for the electrode was affected negatively by the higher Re number and particularly with higher stack pressure after the first 20 minutes during the start-up process, before reaching the steady state, as shown by Figure 113. That also was related to the effect of the local temperature distribution.
4. When oil was used as a coolant similar observations were recorded. However, higher current density peak values and larger areas were noticed since oil as a cooling fluid with the law velocity restrictions was less efficient in removing thermal energy from the electrode plate and that caused the higher average current densities.

**Note: Each time interval represents 10 minutes.

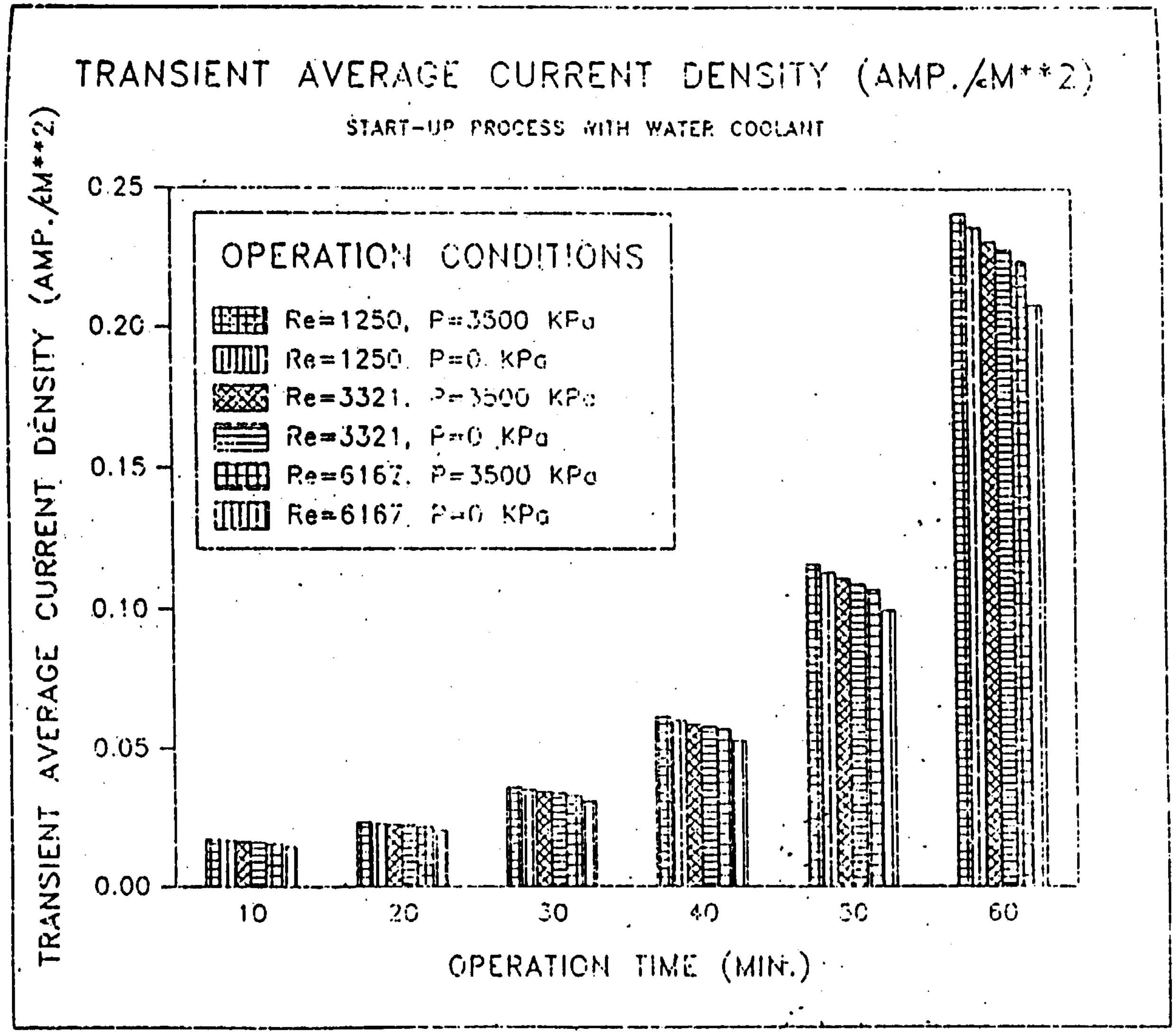

Figure 113. Transient Average Current Density During a Start-Up Process (Water Coolant).

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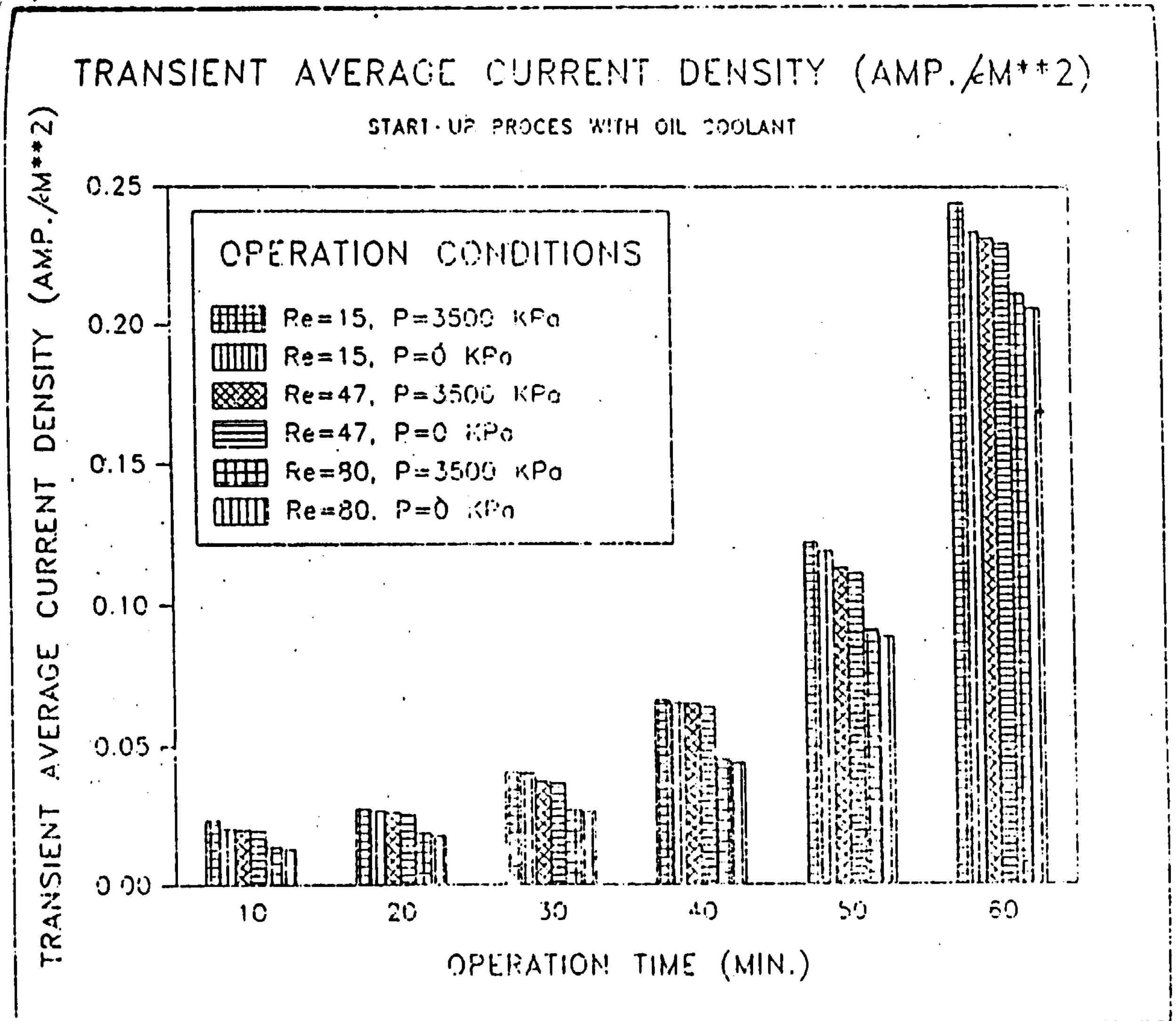


Figure 114. Transient Average Current Density During a Start-Up Process (Oil Coolant).

TRANSIENT CURRENT DENSITY DISTRIBUTION

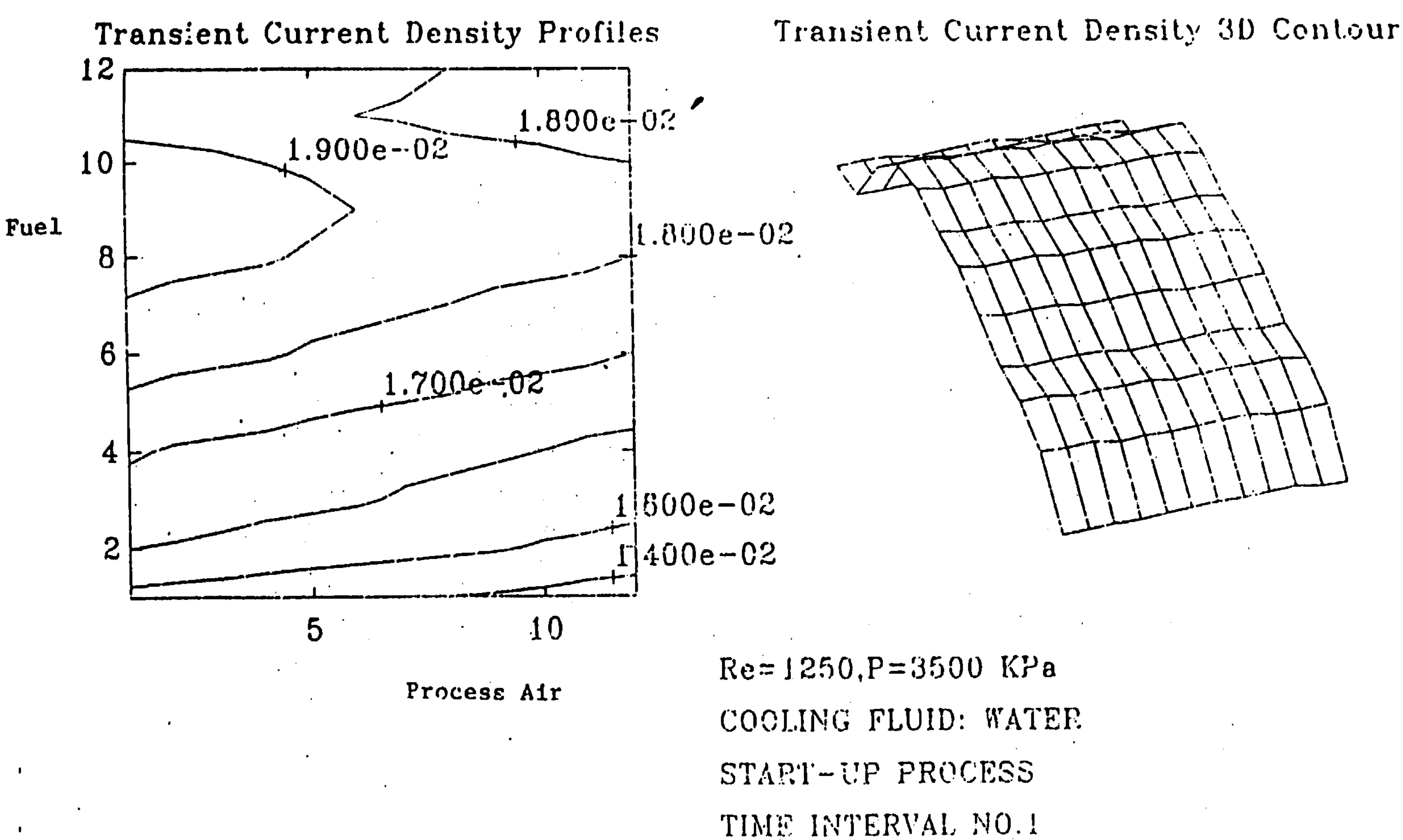
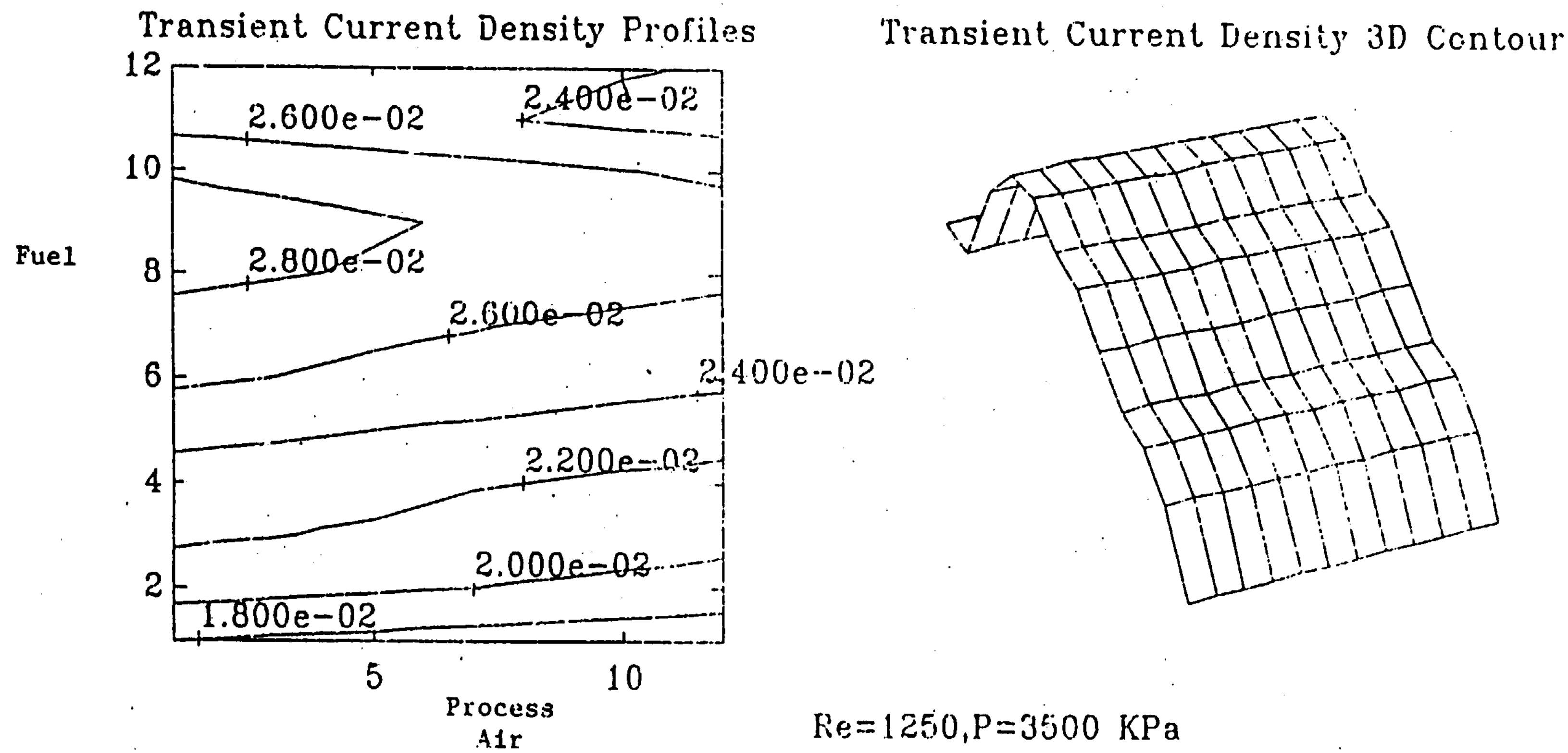


Figure 115. Transient Current Density Distribution During a Start-Up Process (Water Coolant, P=3500 KPa, Re=1250, T.I.=1).

TRANSIENT CURRENT DENSITY DISTRIBUTION



Re=1250,P=3500 KPa

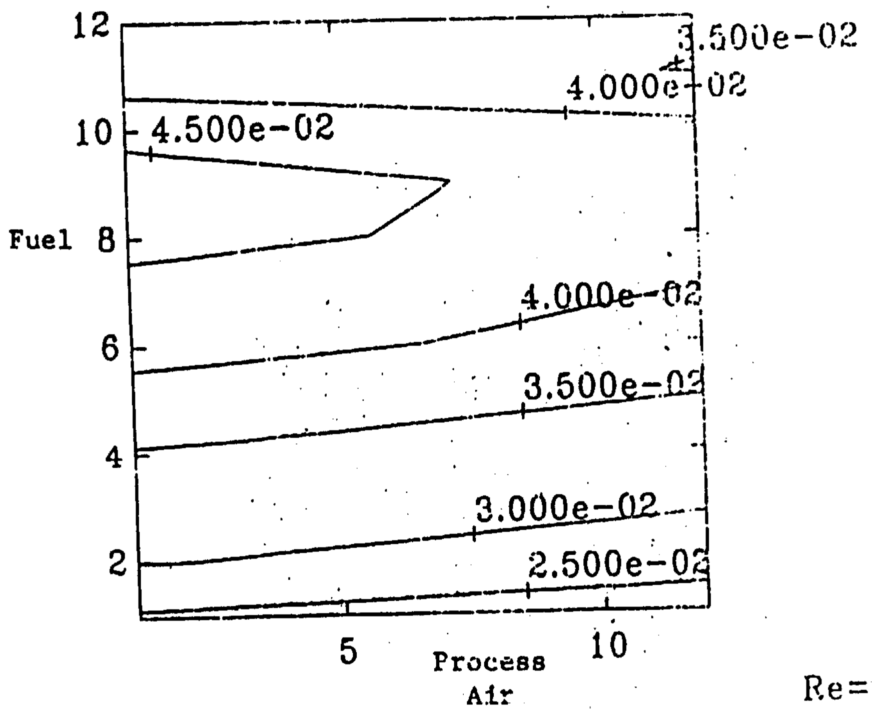
COOLING FLUID: WATER

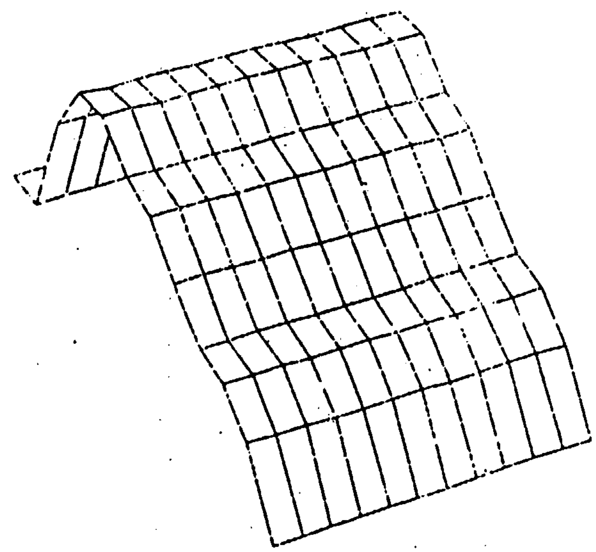
START-UP PROCESS

TIME INTERVAL NO.2

Figure 116. Transient Current Density Distribution During a Start-Up Process (Water Coolant, P=3500 KPa, Re=1250, T.I.=2).

TRANSIENT CURRENT DENSITY DISTRIBUTION





Re=1250,P=3500 KPa

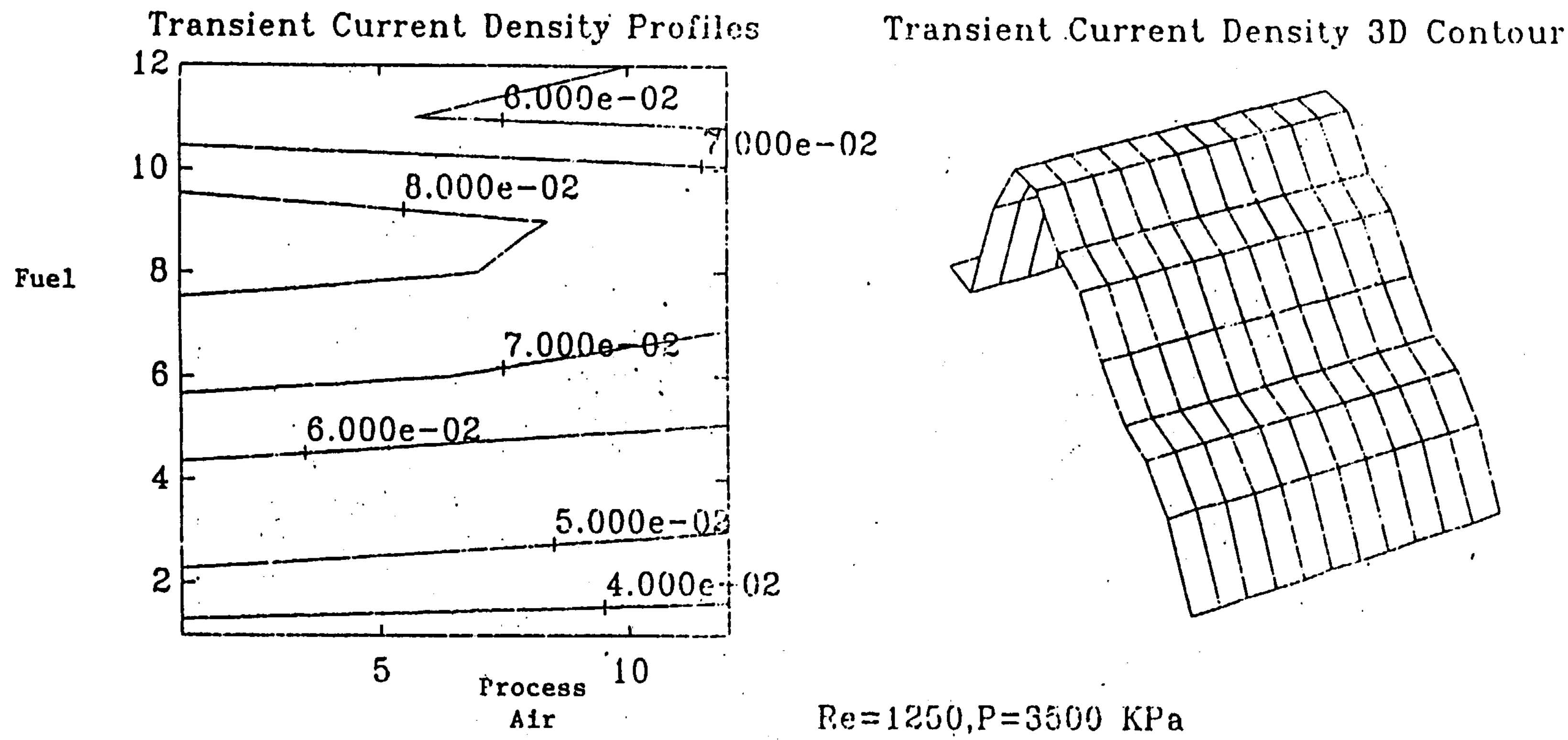
COOLING FLUID: WATER

START-UP PROCESS

TIME INTERVAL NO.3

Figure 117. Transient Current Density Distribution During a Start-Up Process (Water Coolant, P=3500 KPa, Re=1250, T.I.=3).

TRANSIENT CURRENT DENSITY DISTRIBUTION



Re=1250,P=3500 KPa

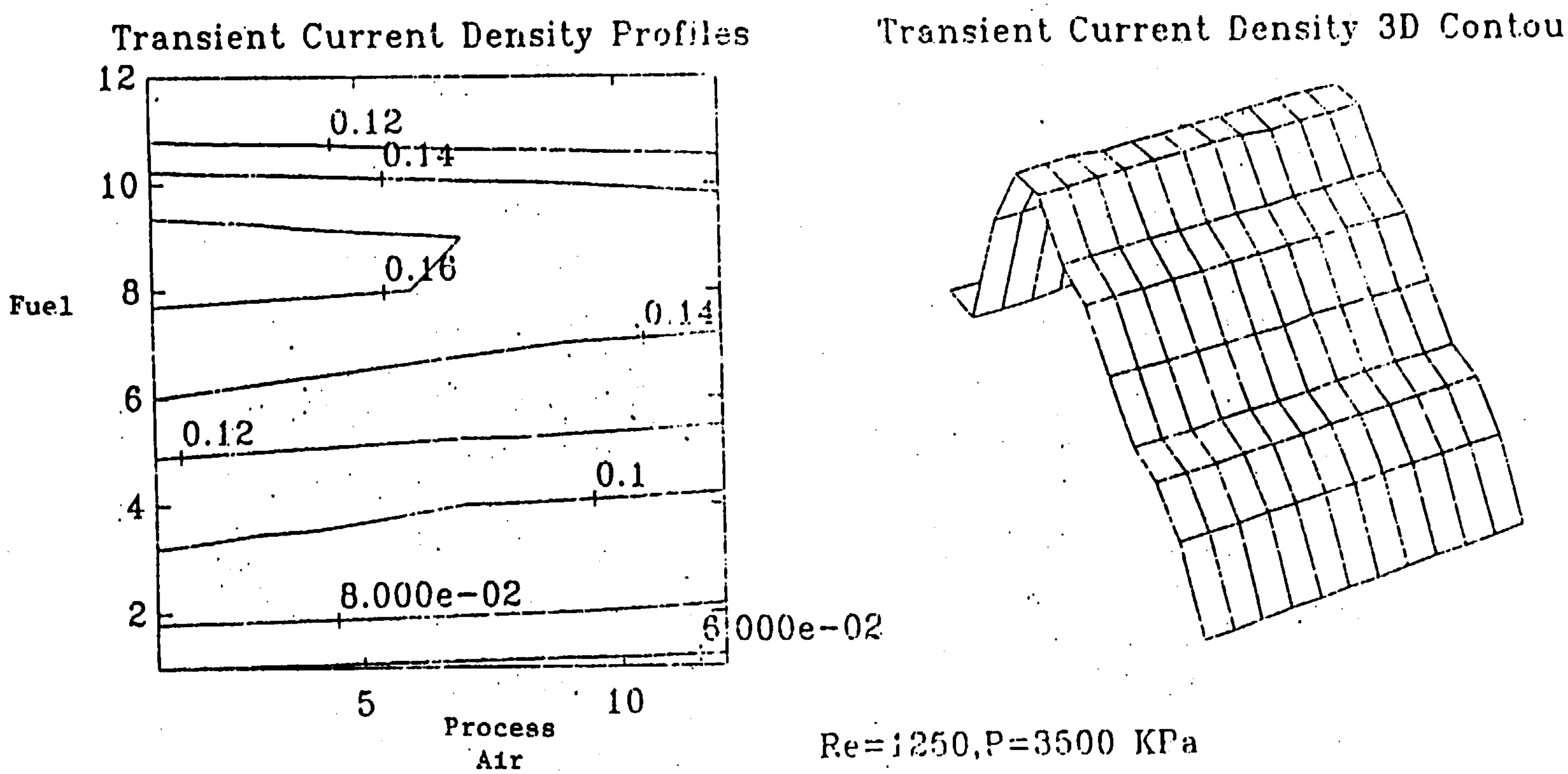
COOLING FLUID: WATER

START-UP PROCESS

TIME INTERVAL NO.4

Figure 118. Transient Current Density Distribution During a Start-Up Process (Water Coolant, P=3500 KPa, Re=1250, T.I.=3).

TRANSIENT CURRENT DENSITY DISTRIBUTION



Re=1250,P=3500 KPa

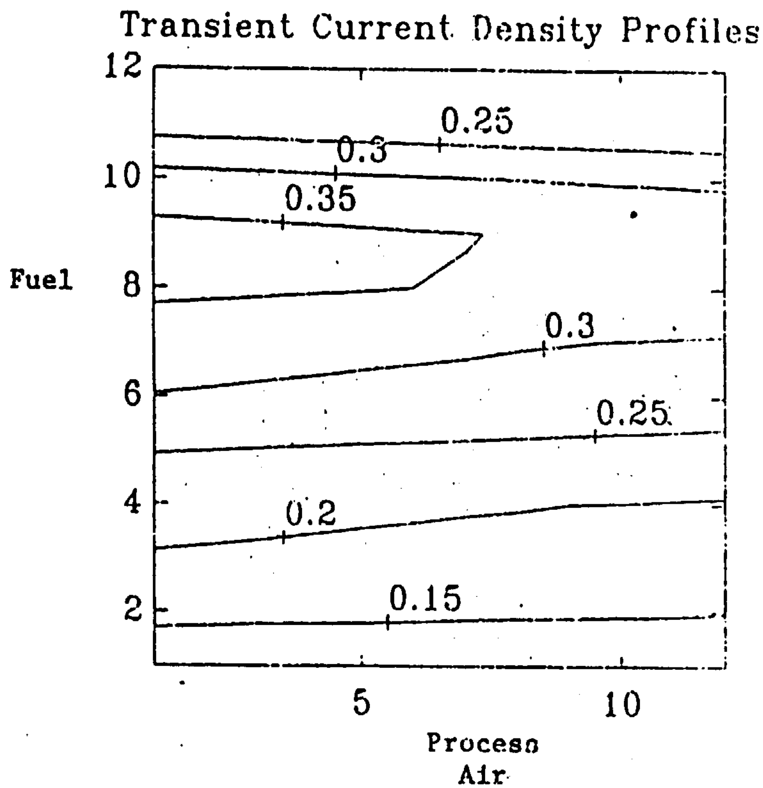
COOLING FLUID: WATER

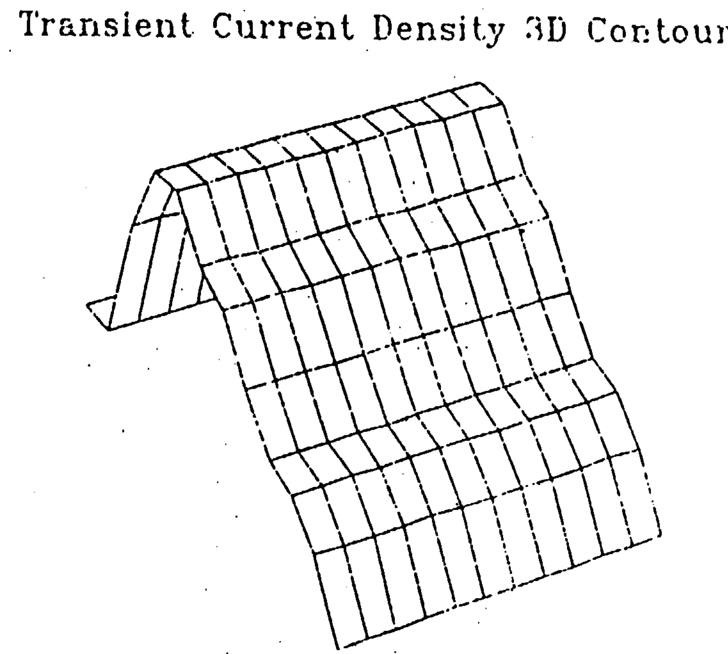
START-UP PROCESS

TIME INTERVAL NO.5

Figure 119. Transient Current Density Distribution During a Start-Up Process (Water Coolant, P=3500 KPa, Re=1250, T.I.=5).

TRANSIENT CURRENT DENSITY DISTRIBUTION





Re=1250,P=3500 KPa

COOLING FLUID: WATER

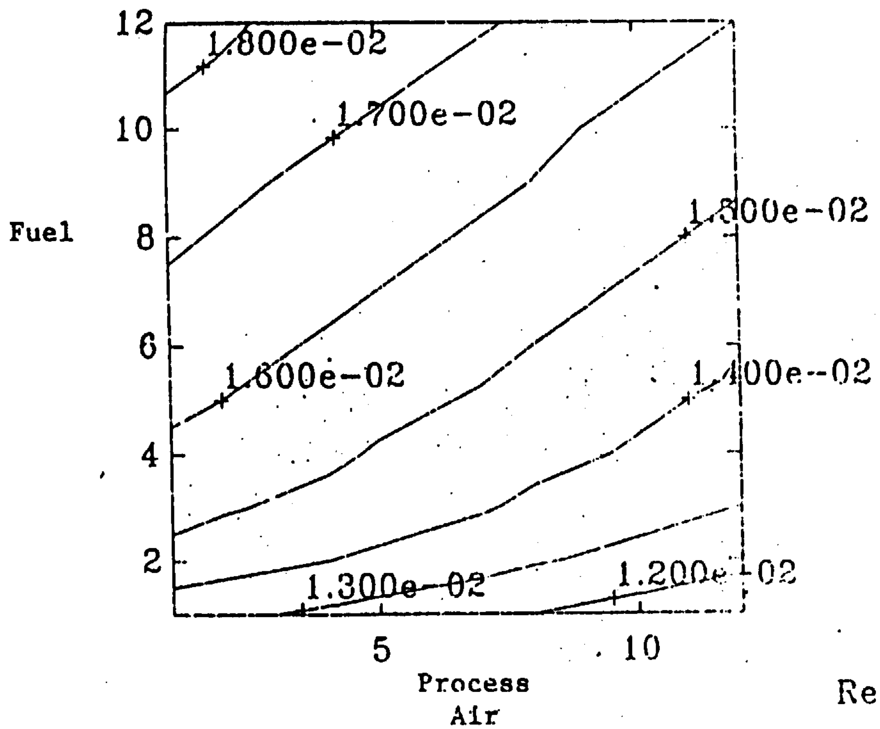
START-UP PROCESS

TIME INTERVAL NO.6

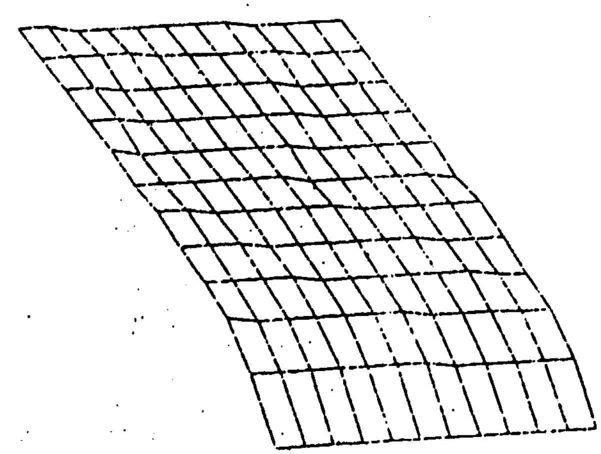
Figure 120. Transient Current Density Distribution During a Start-Up Process (Water Coolant, P=3500 KPa, Re=1250, T.I.=6).

TRANSIENT CURRENT DENSITY DISTRIBUTION

Transient Current Density Profiles



Transient Current Density 3D Contour



Re=1250,P=0 KPa

COOLING FLUID: WATER

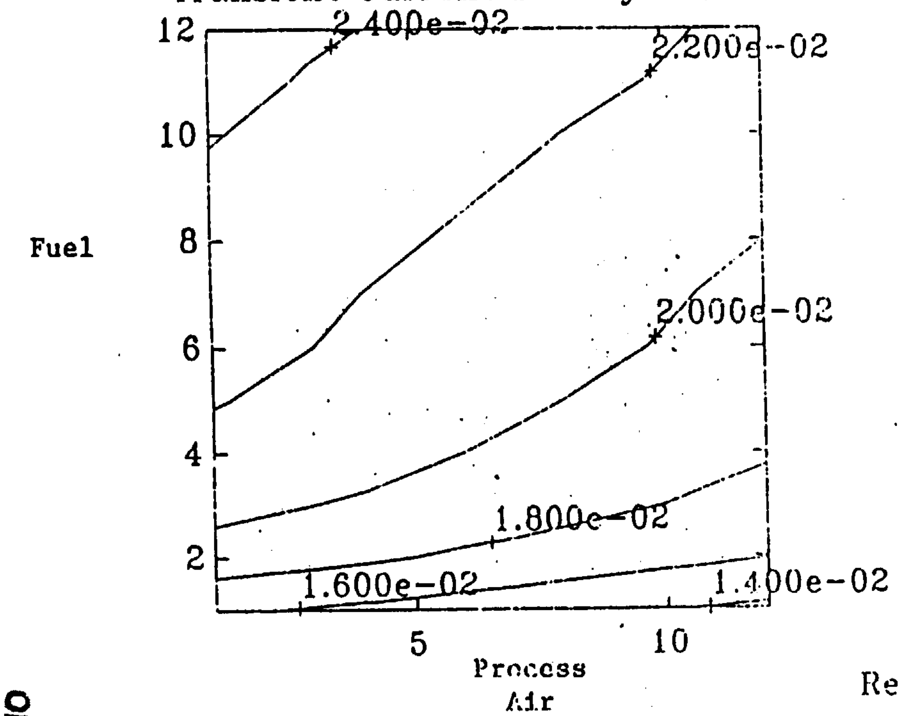
START-UP PROCESS

TIME INTERVAL NO.1

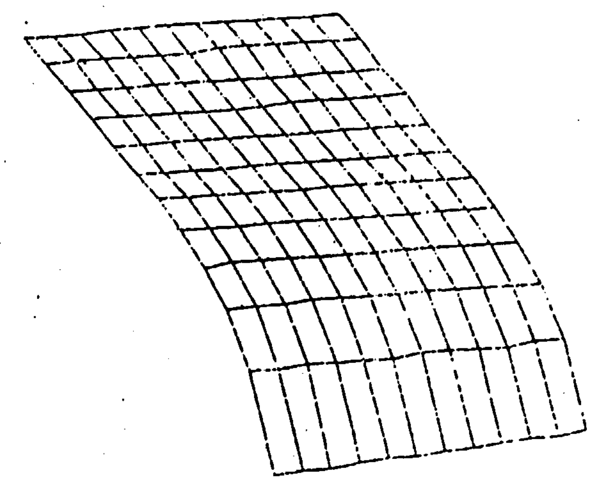
Figure 121. Transient Current Density Distribution During a Start-Up Process (Water Coolant, P=0 KPa, Re=1250, T.I.=1).

TRANSIENT CURRENT DENSITY DISTRIBUTION

Transient Current Density Profiles



Transient Current Density 3D Contour



Re=1250,P=0 KPa

COOLING FLUID: WATER,

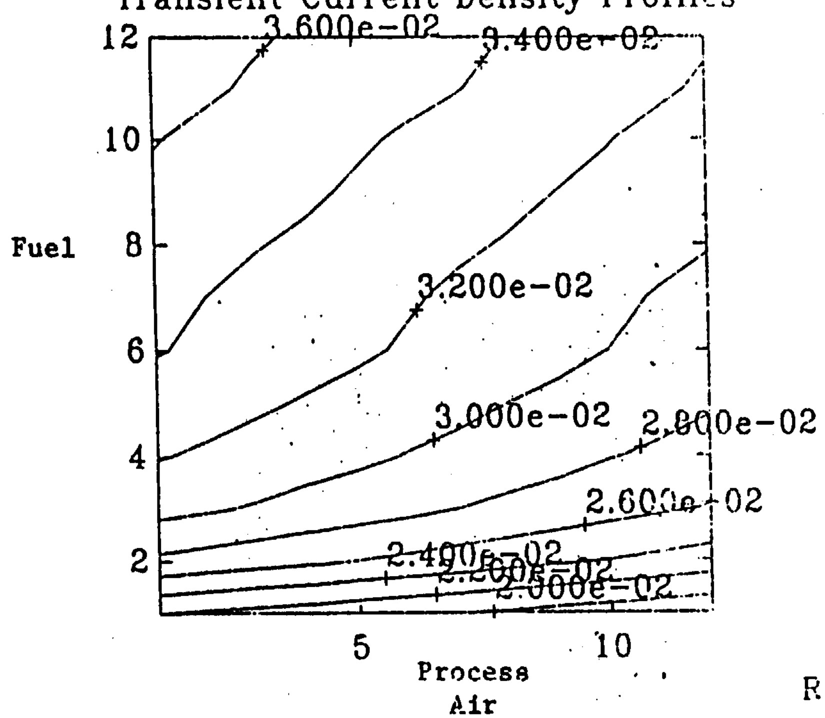
START--UP PROCESS

TIME INTERVAL NO.2

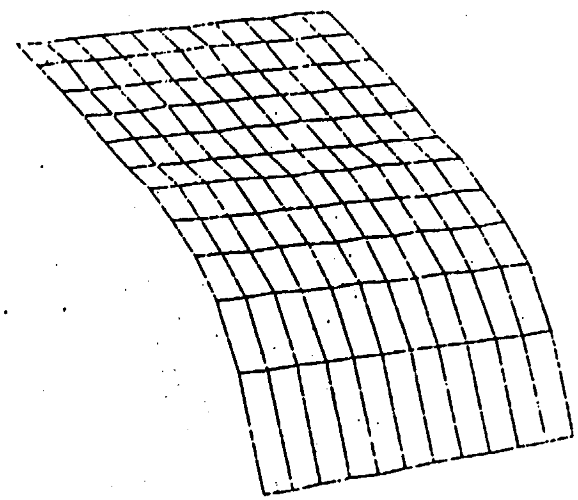
Table 122. Transient Current Density Distribution During a Start-Up Process (Water Coolant, P=0 KPa, Re=1250, T.I.=2).

TRANSIENT CURRENT DENSITY DISTRIBUTION

Transient Current Density Profiles



Transient Current Density 3D Contour



Re=1250,P=0 KPa

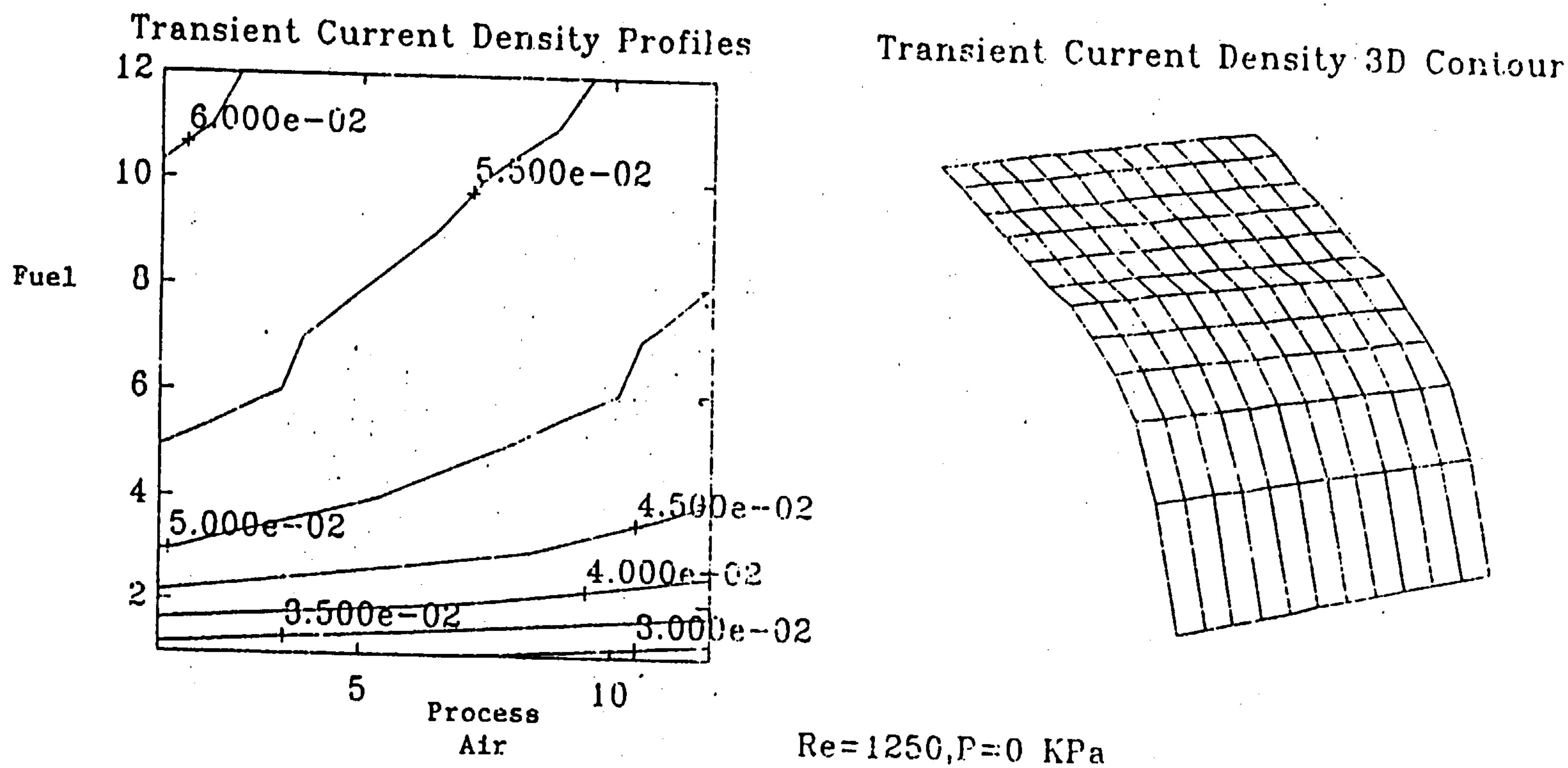
COOLING FLUID: WATER

START-UP PROCESS

TIME INTERVAL NO.3

Table 123. Transient Current Density Distribution During a Start-Up Process (Water Coolant, P=0 KPa, Re=1250, T.I.=3).

TRANSIENT CURRENT DENSITY DISTRIBUTION



Re=1250,P=0 KPa

COOLING FLUID: WATER

START-UP PROCESS

TIME INTERVAL NO.4

Figure 124. Transient Current Density Distribution During a Start-Up Process (Water Coolant, P=0 KPa, Re=1250, T.I.=4).

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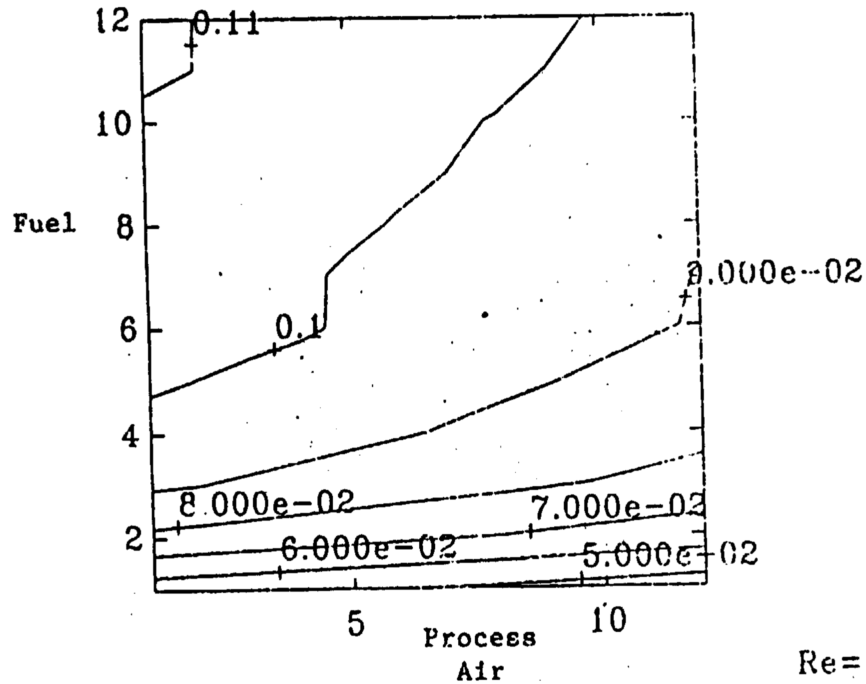
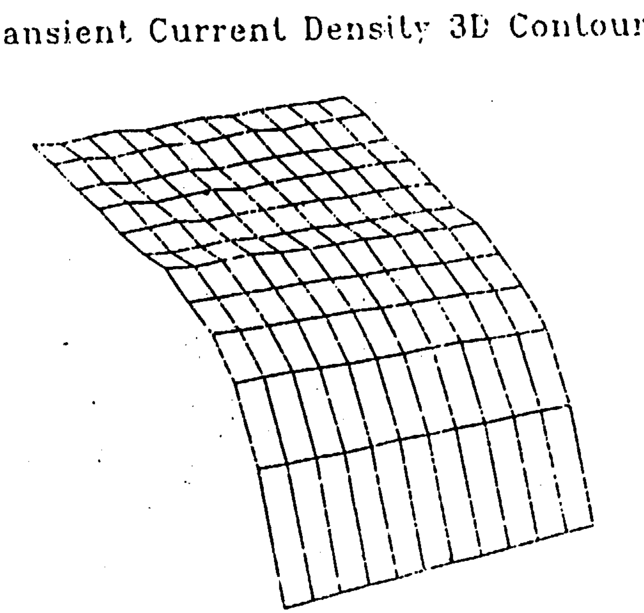
TRANSIENT CURRENT DENSITY DISTRIBUTION





Re=1250,P=0 KPa

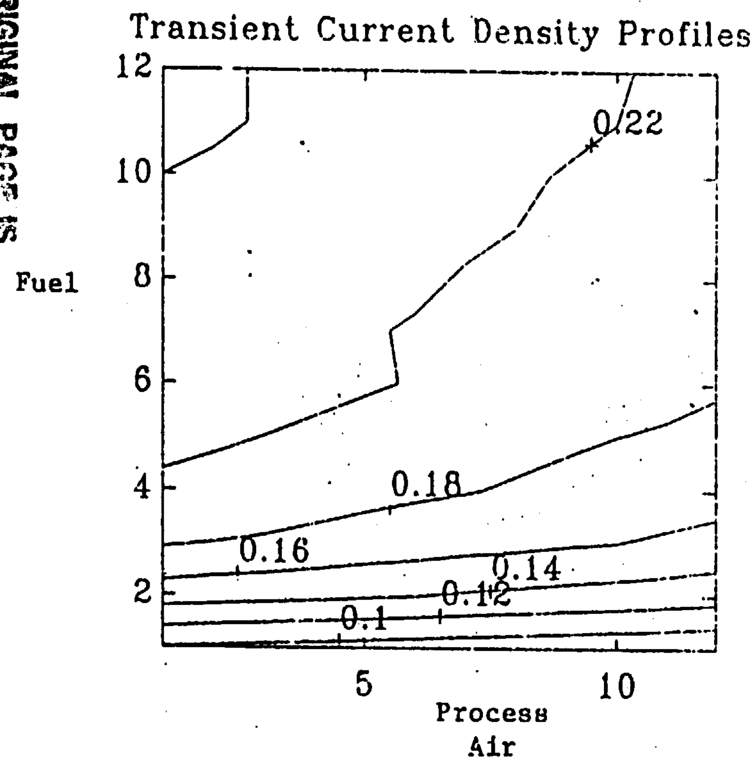
COOLING FLUID: WATER

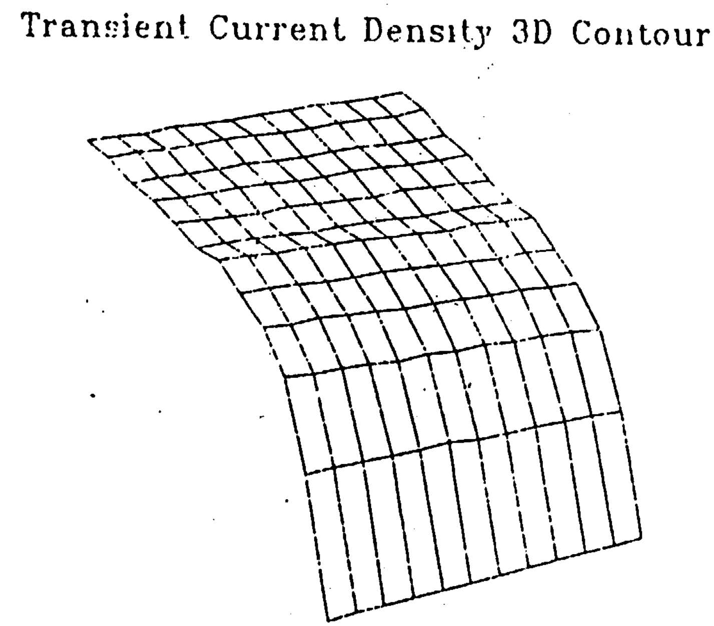
START-UP PROCESS

TIME INTERVAL NO.5

Figure 125. Transient Current Density Distribution During a Start-Up Process (Water Coolant, P=0 KPa, Re=1250, T.I.=5).

TRANSIENT CURRENT DENSITY DISTRIBUTION





Re=1250,P=0 KPa

COOLING FLUID: WATER

START-UP PROCESS

TIME INTERVAL NO.6

Figure 126. Transient Current Density Distribution During a Start-Up Process (Water Coolant. P=0 KPa, Re=1250, T.I.=6).

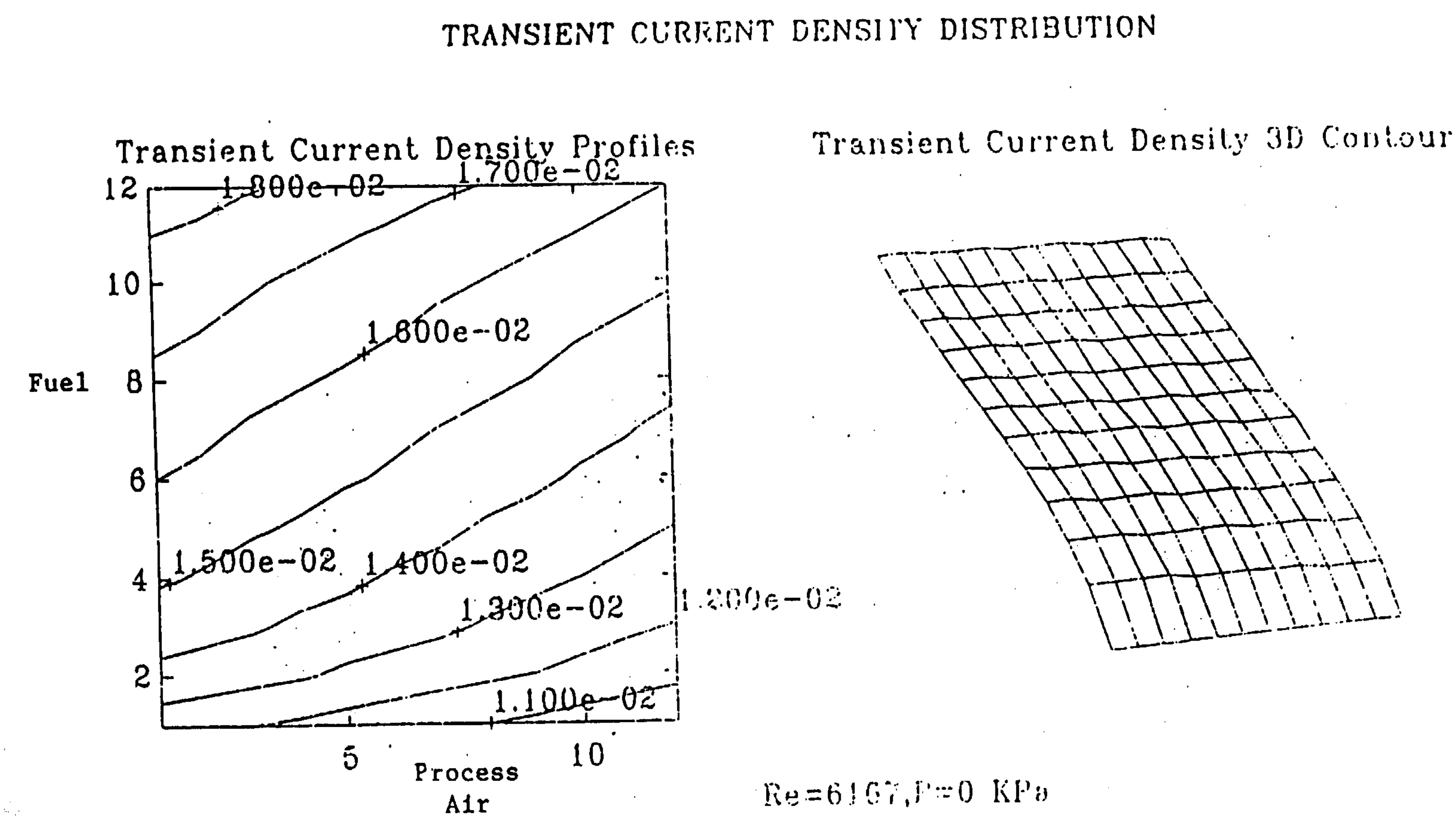


Figure 127. Transient Current Density Distribution During a Start-Up Process (Water Coolant, P=0 KPa, Re=6167, T.I.=1).

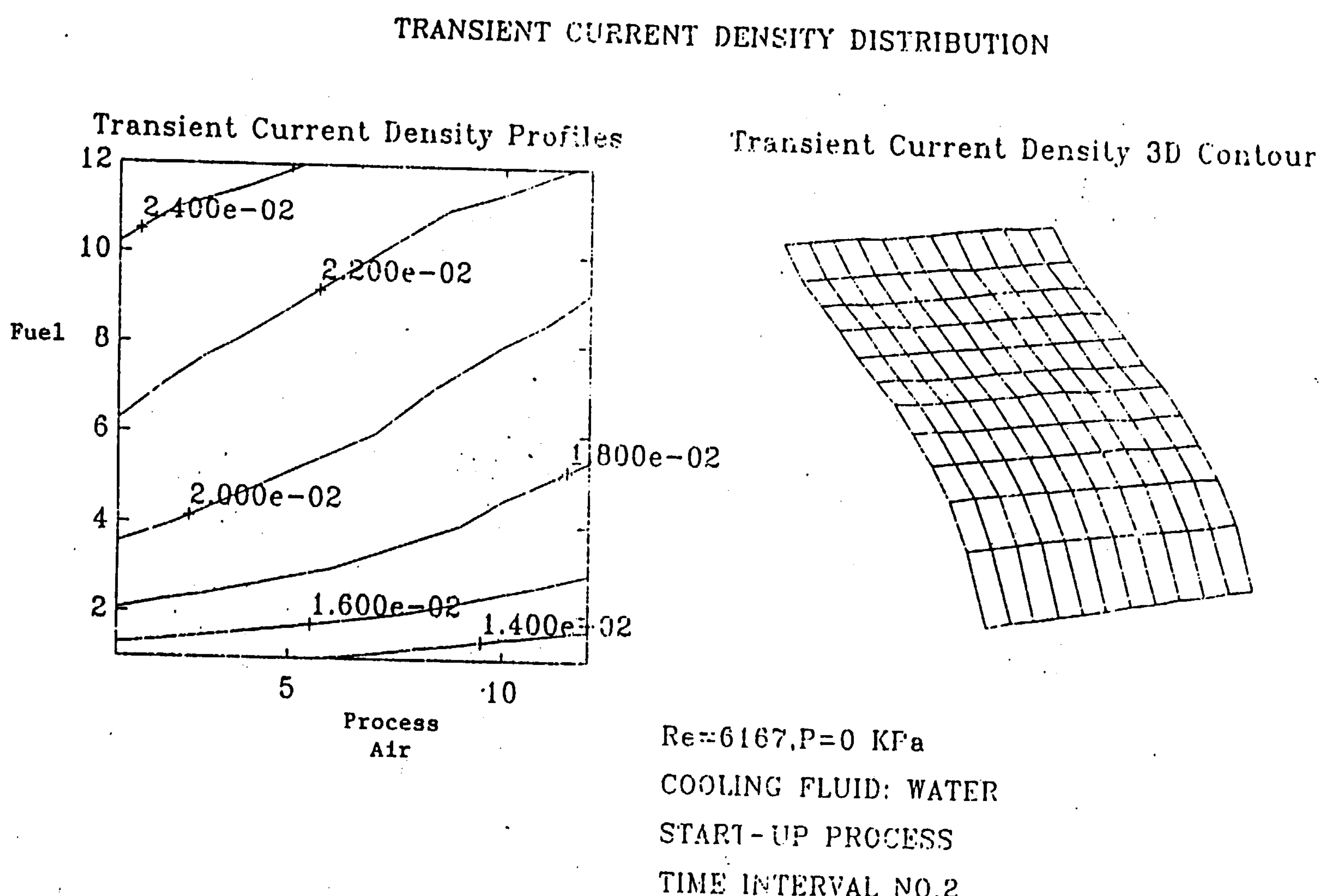
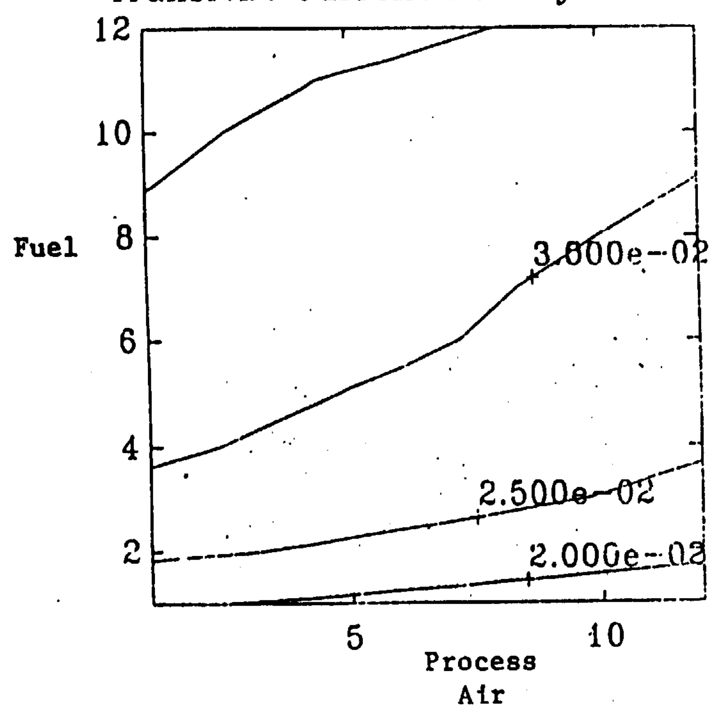
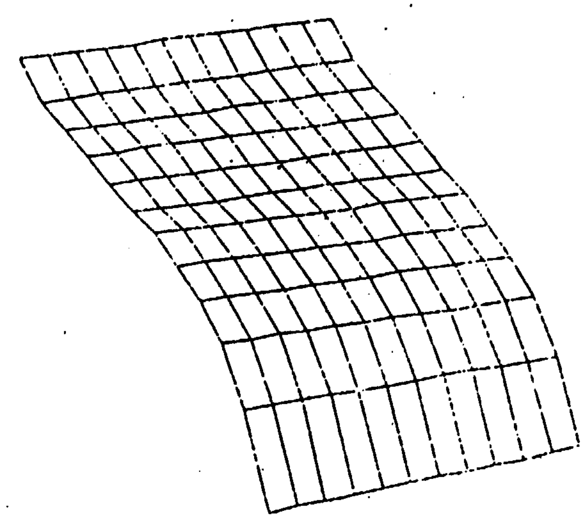


Figure 128. Transient Current Density Distribution During a Start-Up Process (Water Coolant, P=0 KPa, Re=6167, T.I.=2).

TRANSIENT CURRENT DENSITY DISTRIBUTION





Re=6167,P=0 KPa

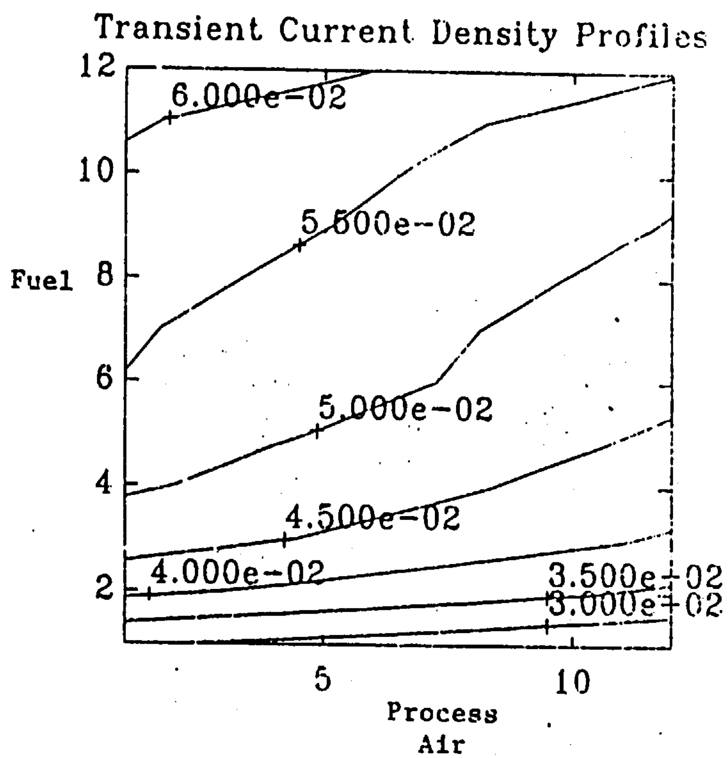
COOLING FLUID: WATER

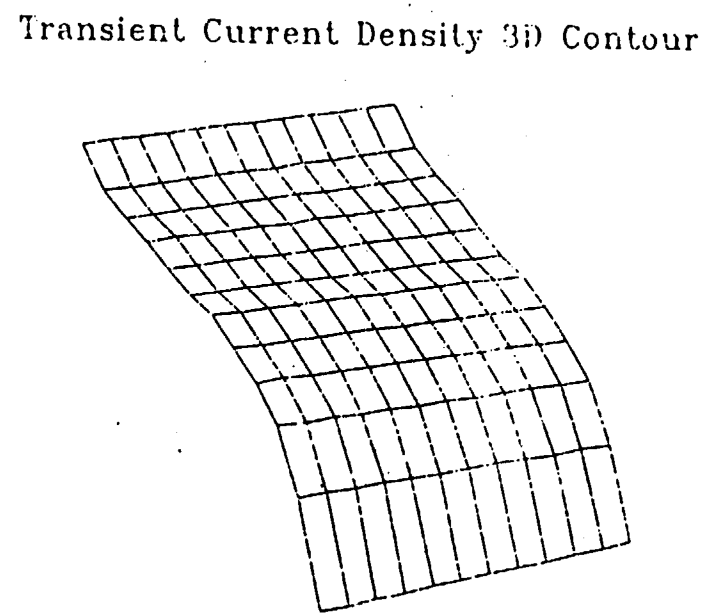
START-UP PROCESS

TIME INTERVAL NO.3

Figure 129. Transient Current Density Distribution During a Start-Up Process (Water Coolant, P=0 KPa, Re=6167, T.I.=3).

TRANSIENT CURRENT DENSITY DISTRIBUTION





Re=6167,P=0 KPa

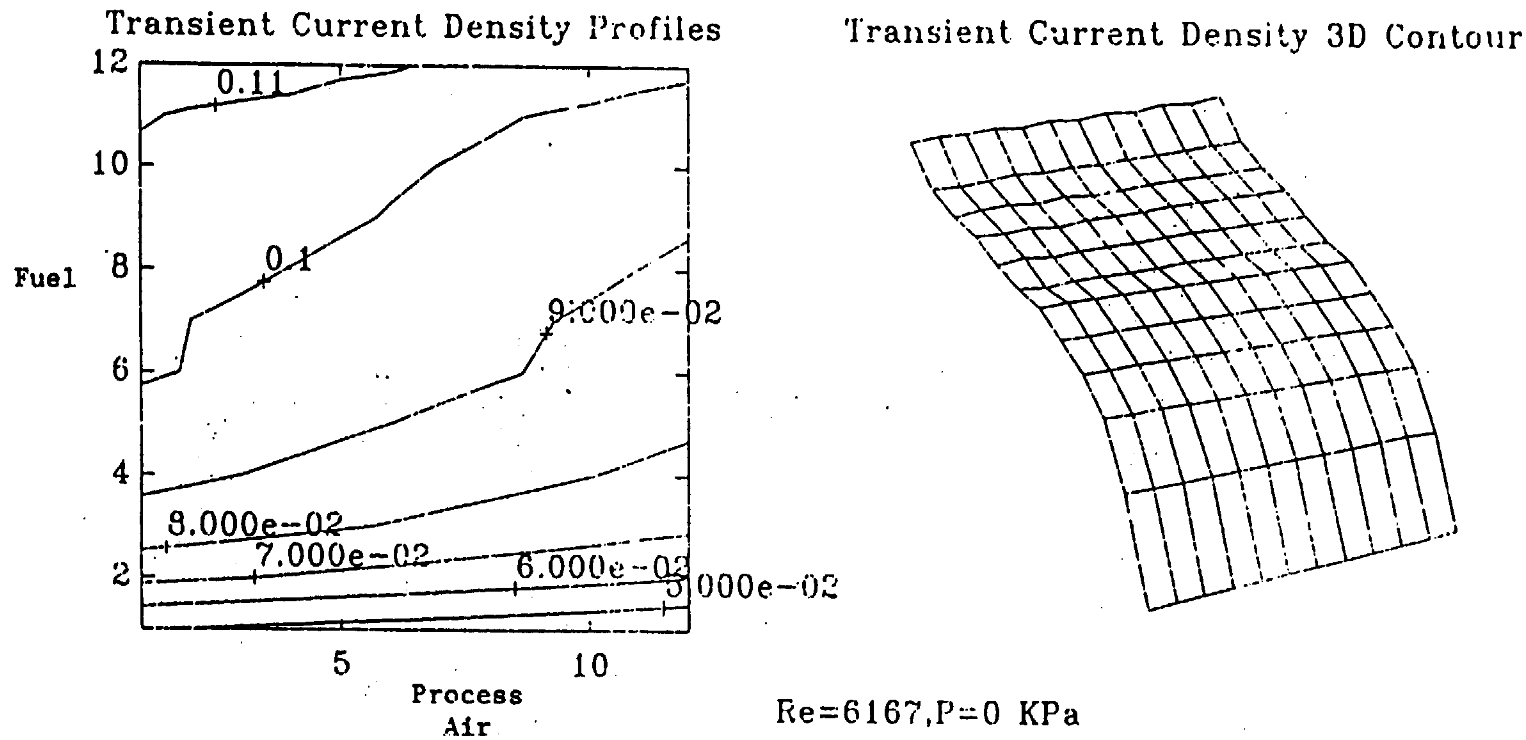
COOLING FLUID: WATER

START-UP PROCESS

TIME INTERVAL NO.4

Figure 130. Transient Current Density Distribution During a Start-Up Process (Water Coolant, P=0 KPa, Re=6167, T.I.=4).

TRANSIENT CURRENT DENSITY DISTRIBUTION



Re=6167,P=0 KPa

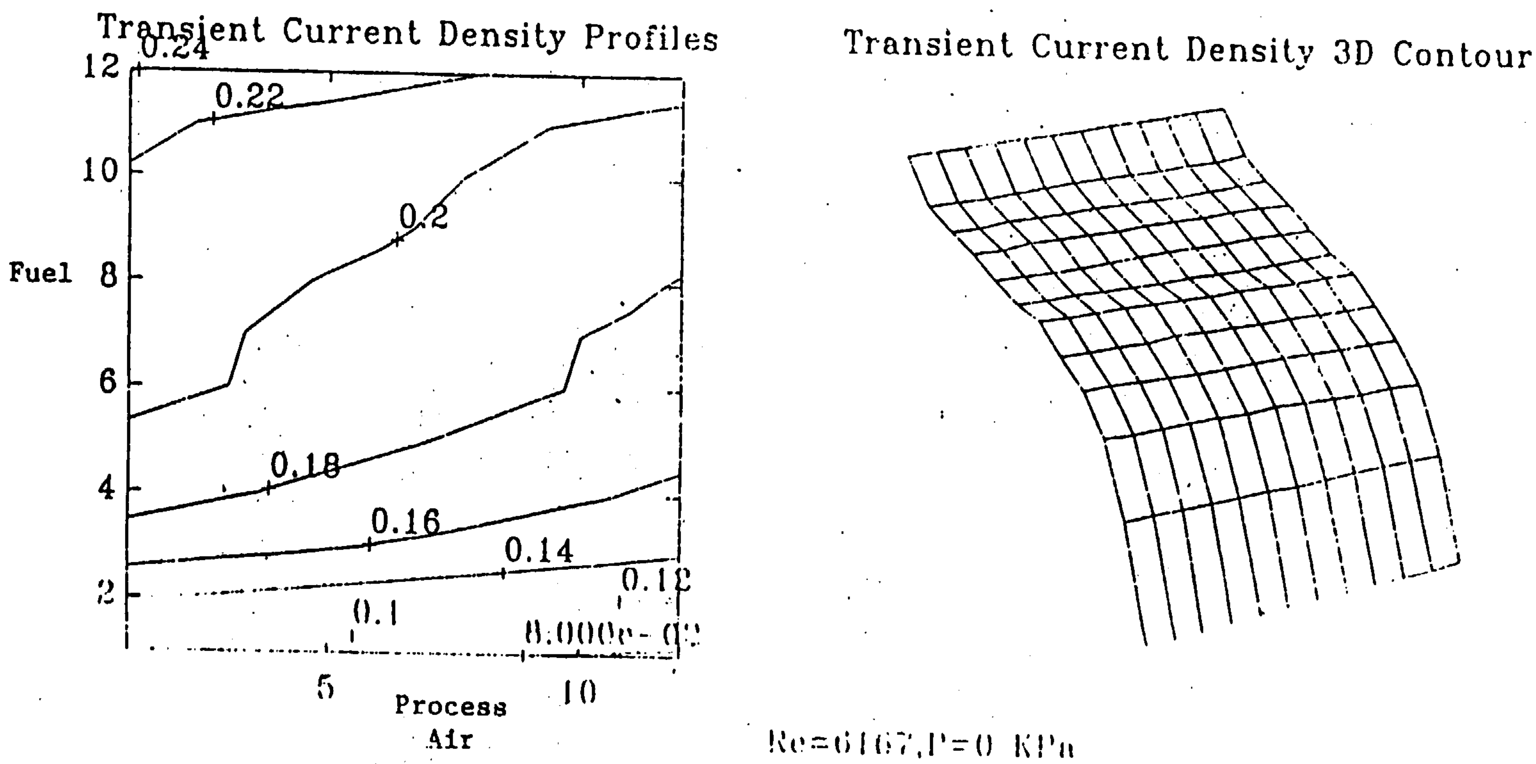
COOLING FLUID: WATER

START-UP PROCESS

TIME INTERVAL NO.5

Figure 131. Transient Current Density Distribution During a Start Up Process (Water Coolant, P=0 KPa, Re=6167, T.I.=5).

TRANSIENT CURRENT DENSITY DISTRIBUTION



Re=6167,P=0 KPa

COOLING FLUID: WATER

START-UP PROCESS

TIME INTERVAL NO.6

Figure 132. Transient Current Density Distribution During a Start-Up Process (Water Coolant, P=0 KPa, Re=6167, T.I.=6).

6.2 Transient Electrode Current Density Distribution During A Shut-Down Process

The same cases examined in the previous section are considered during a shut-down process in this section to determine the effect of the clamping pressure, coolant flow rate and thermophysical properties on the current density distributions. Referring to Figure D-1 to Figure D-13 in the Appendix, for water with Re=1250 and clamping pressure of 3500 KPa, and Figure D-14 to Figure D-27 for the same flow rate and cooling fluid but with zero applied stack pressure, the following can be observed:

1. The current density decrease rate is higher than the accompanied temperature decrease rate.
2. The peak areas of the current density shifted to the center of the plates and with maximum clamping pressure.
3. Figure 133 which exhibits the variation of the average current density of the plate, demonstrates the reduction of that value for the most extreme case considered, minimum flow rate and maximum clamping pressure, when compared to the minumum flow rate and zero applied stack pressure case. This can be related to the effect of the electrode plate temperature distribution.
4. The increase in the average current density when increasing the mass flow rate was not

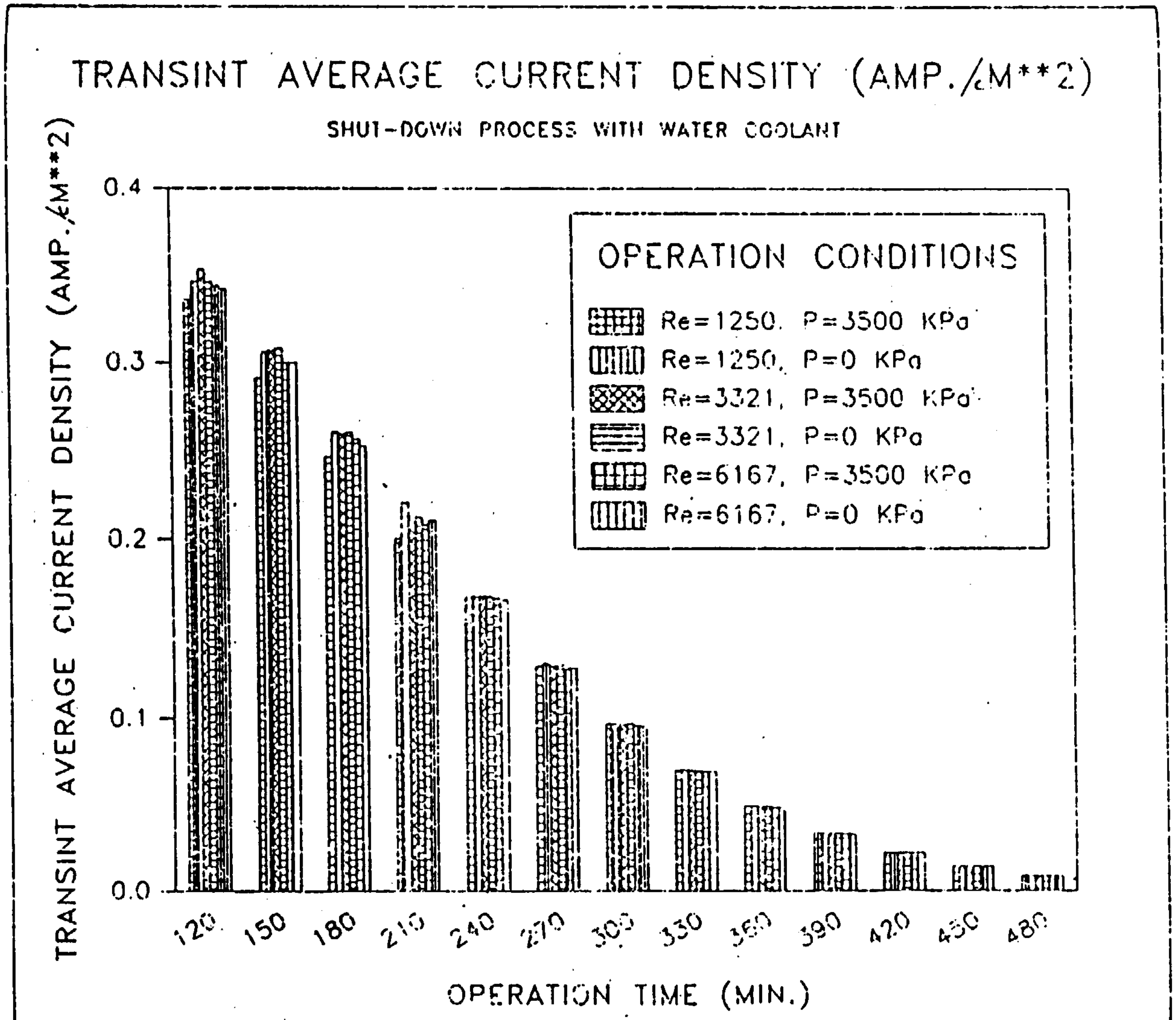


Figure 133. Transient Average Current Density During a Shut-Down Process (Water Coolant).

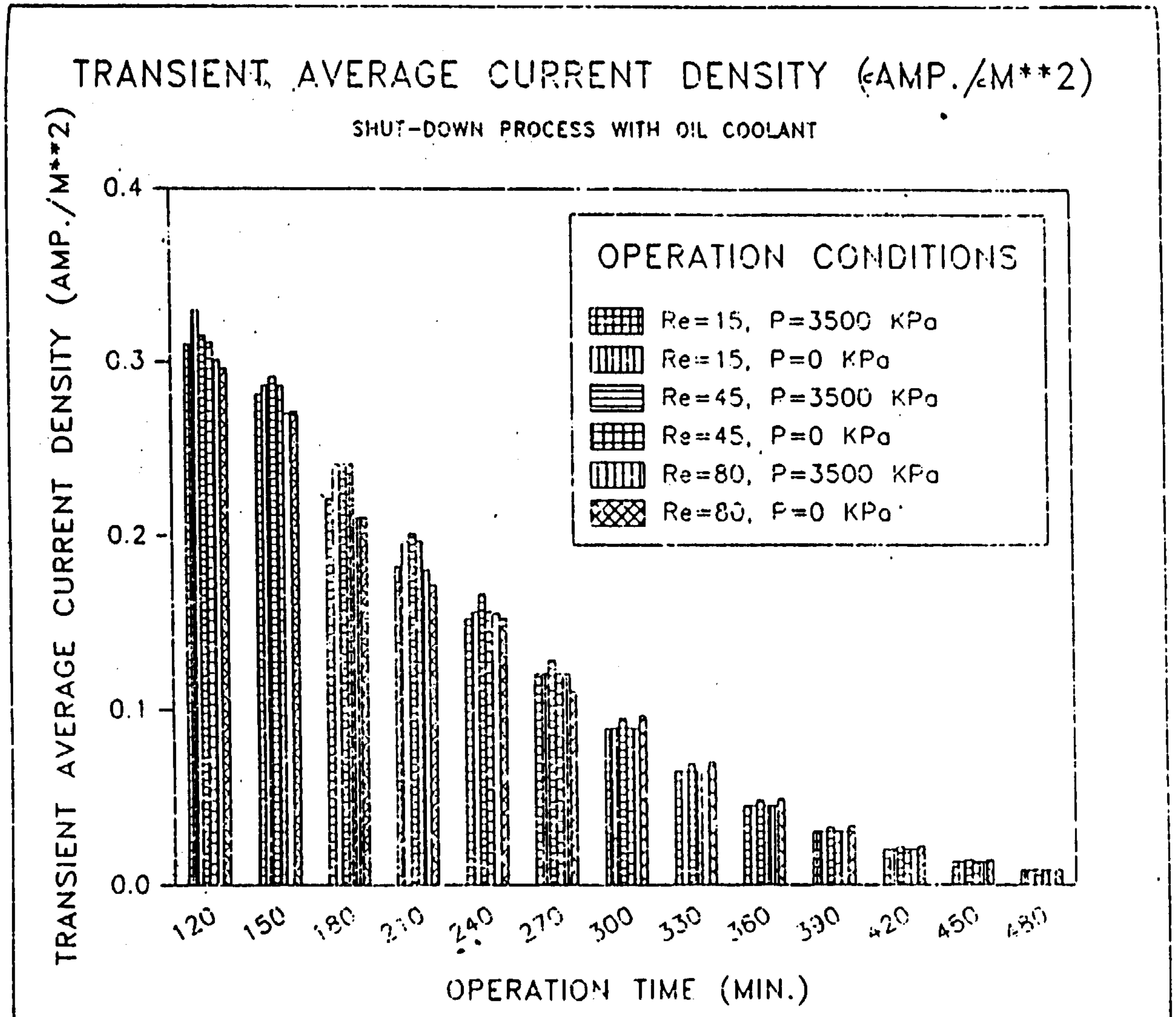


Figure 134. Transient Average Current Density During a Shut-Down Process (Oil Coolant).

as high as that when reducing the clamping pressure during the shut-down process.

5. Similar observations were recorded when oil was used as a cooling fluid. However, the average transient current density drop rate was higher than that when water was used as a coolant due to the coolant volumetric flow restriction which affected negatively the efficiency of the cooling system in heat removal during the shut-down process as shown in Figure 134.

CHAPTER VII

DISCUSSION OF RESULTS AND ACCURACY ANALYSIS

This chapter is devoted to the analysis and interpretation of the experimental and theoretical results obtained in the previous chapters. These analyses and interpretations will be mostly concerned with the effects of clamping pressures, cooling fluid flow characteristics, thermophysical properties and the transient heat transfer characteristic on the performance of a PAFC power plant operating under transient conditions.

A good method of presenting the gathered information and forming a clear picture of the effects of each considered parameter on the fuel cell transient heat transfer rates is experimental and analytical results comparison.

Figure 135 shows the overall heat transfer coefficient as a function of time for both cooling fluids for a start-up and shut-down cases respectively, with average (Re) number and stack pressure conditions. An obvious increase in the values of the overall heat transfer coefficient was noticed with higher applied stack pressure as mentioned in Chapter IV, however, that increase in the case of water was higher than that of oil. The average difference was 28.392%

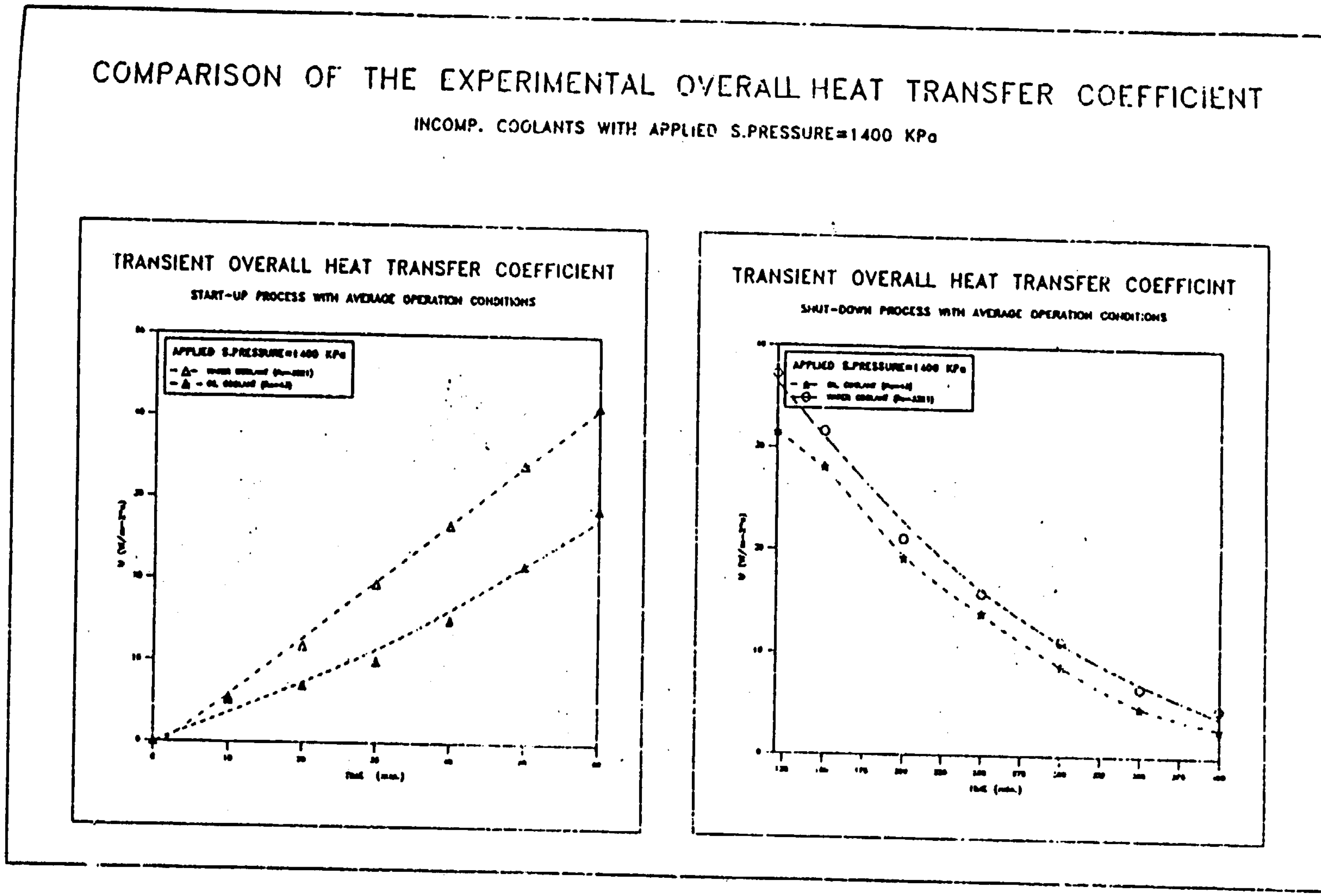


Figure 135. Comparisons of the Experimental Overall Heat Transfer Coefficient.

during a start-up process and approximately 16.524% during a shut-down process. The higher U value for water was not solely due to the different cooling fluid thermophysical properties but also due to the large difference of the fluid velocity. That difference affected the results since the transient overall heat transfer is a function of the convection heat transfer coefficient which is dependent on the flow characteristics. It should be noticed that the data obtained for water was for mass flow rates covering laminar and turbulent flows but only the laminar flow condition was considered in the oil case.

The effect of pressure on the reduction of the thermal contact resistance is significant for all the cases considered for each coolant, as demonstrated in Chapter IV. This reduction in the thermal resistance is mainly due to the increase of the contact common surface area between the fuel cell plate and the cooling plate which was caused by the plastic deformation of the two surfaces and the reduction of the air-occupied gaps due to surfaces roughness. The significant effect of the thermal contact resistance on the overall transient heat transfer coefficient can be demonstrated clearly by monitoring the variation of the ratio I(t) with time, where I(t) can be defined as:

$$I(t) = U(t)/V(t) = \frac{\text{transient overall heat transfer coefficient of the fuel cell model}}{\text{transient overall heat transfer coefficient neglecting the effect of the thermal contact resistance.}}$$

C-4.

or

$$I(t) = \frac{[(\frac{x_1}{K}) + (\frac{x_2}{K}) + (\frac{1}{h(t)})])}{[(\frac{x_1}{K}) + (r_c) + \frac{x_2}{K}) + (\frac{1}{h(t)})]}$$

Utilizing the experimental correlation to generate the results for both U-values a remarkable difference was noticed, as shown by Figure 136 and Figure 137 for water during start-up and shut-down process respectively, for several considered applied stack pressure. It was noticed that the difference reached a maximum of 10.383% for the considered start-up process and 10.109% for the considered shut-down process. In the case of oil coolant the maximum difference was 9.921% for start-up conditions and 9.844% for the shut-down conditions for the same pressure ranges.

An increase in the values of the Nusselt number was noticed for both cooling fluid with high applied stack pressure, (please refer to Appendix A and B). That is mainly due to the effect of the stack pressure on the surface temperature. Also, the Nusselt number increased with increasing the coolant volumetric flow rate for both coolants. However, the increase in the oil Nusselt number case was higher than that for water. This can be shown by dividing the average difference of the Nusselt number values measured during a start-up process for the maximum and minimum coolant volumetric flow rate by the total difference in the Re number. That non-dimensional ratio was $7.692*10^{-3}$

for oil and $9.152*10^{-6}$ for water. Figure 138 represents a comparison between the transient variation of the experimental Nusselt number for both coolants with average operation conditions during a start-up and shut-down process respectively.

This is because higher stack pressure results in decreasing the thermal contact resistance between the heating elements and the electrode plate. This in turn results in an increase in the electrode internal energy and electrode temperature. However, the rate of heat transfer electrode from the electrode plate to the coolant is not equivalent to the rate of increase of the electrode internal energy. This is because of a significant thermal contact resistance between the electrode plate and the cooling plate even after increasing the stack pressure. This results in the accumulation of internal energy in the electrode plate which results in an increase of the electrode plate temperature.

The increase in the average cell temperature rate was greater and the average temperature measured was higher in the case of oil coolant during the considered start-up process due to the lower Re number used in the case of oil as demonstrated in Chapter V. On the other hand during shut-down process the average transient temperature drop rate was slower for oil than that for water. That is basically due to the higher accumulation rates of the internally generated thermal energy when oil is used as a

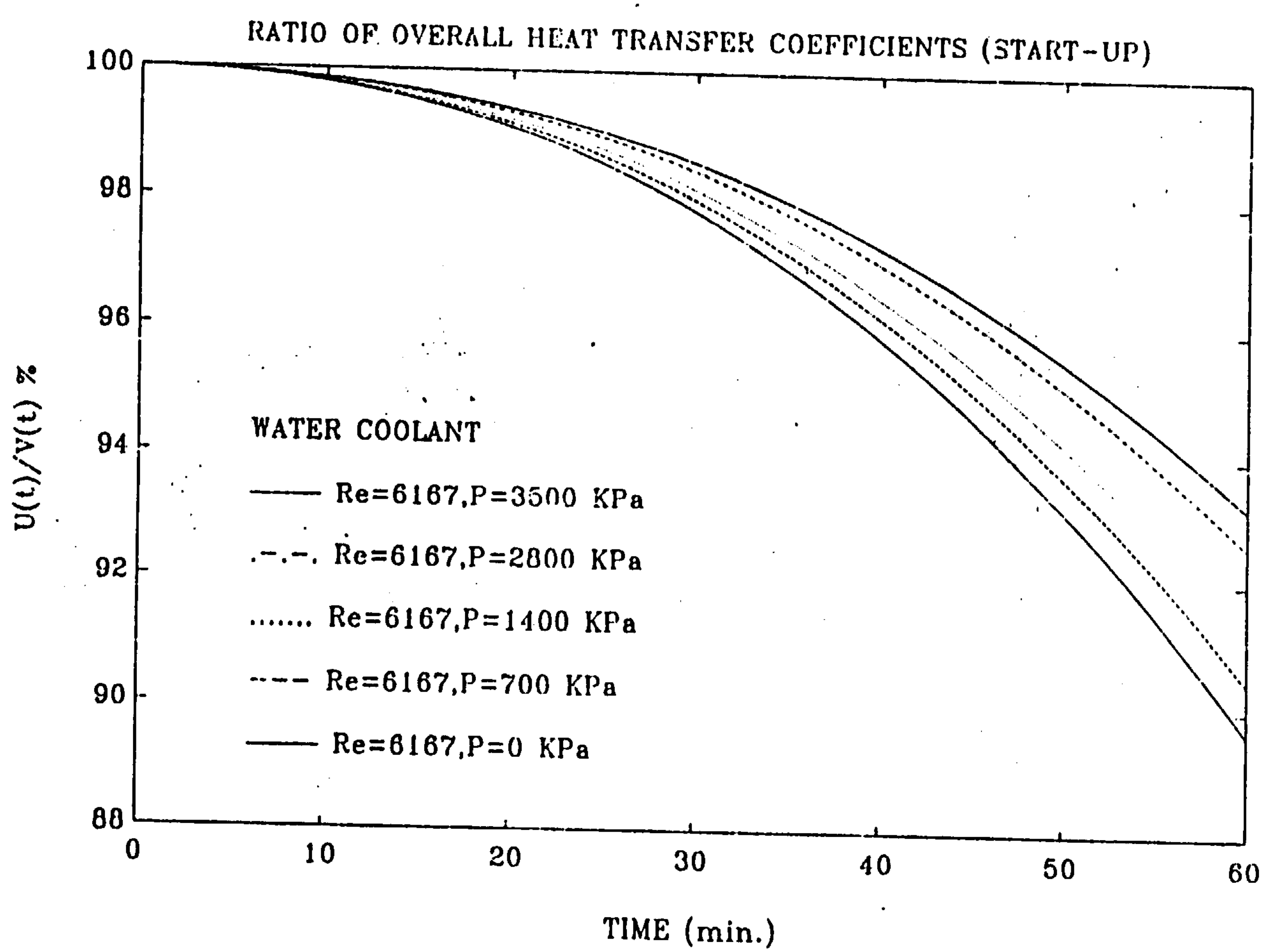


Figure 136. I(t) Ratio (Water, Start-Up).

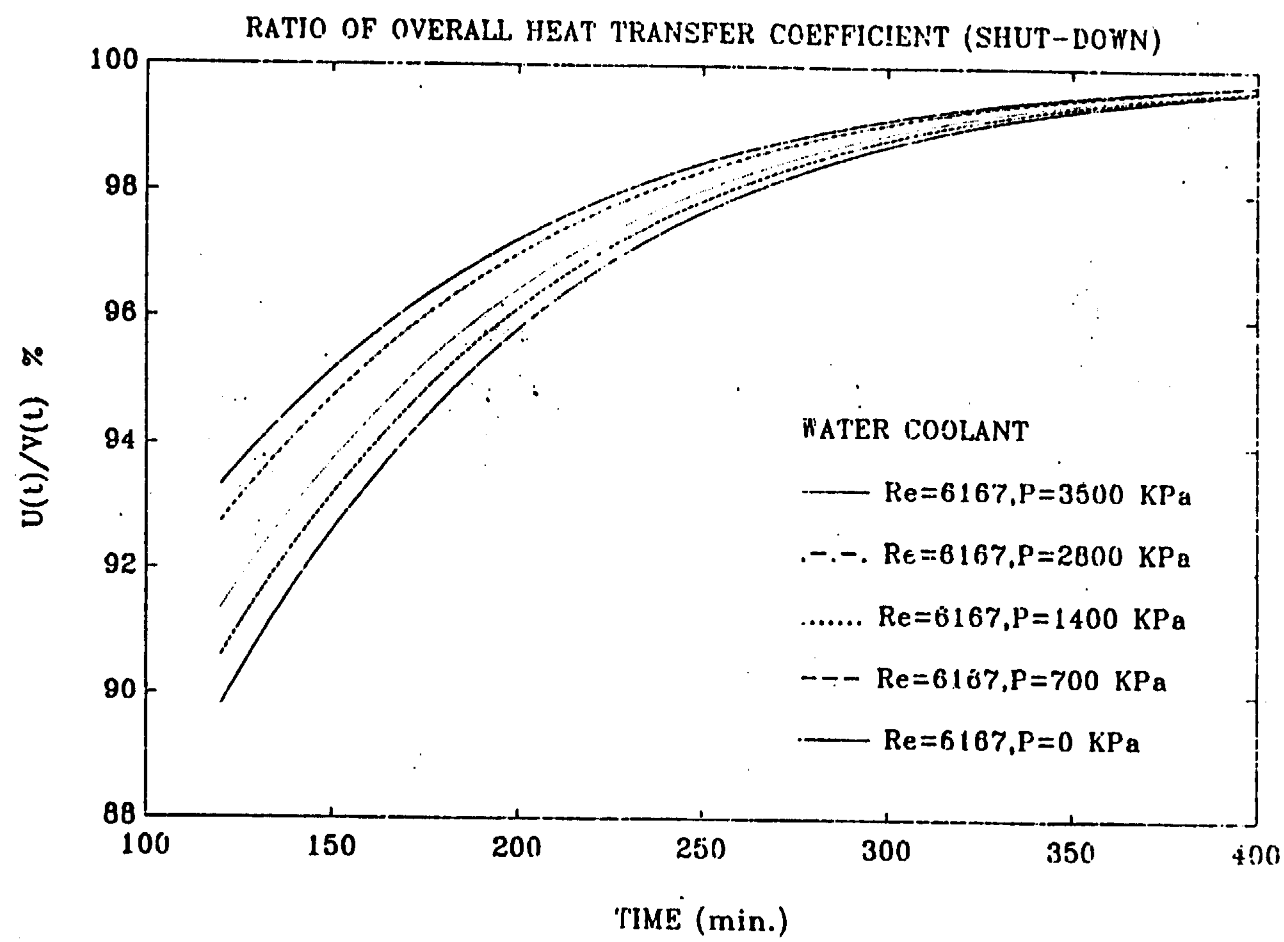


Figure 137. I(t) Ratio (Water, Shut-Down).

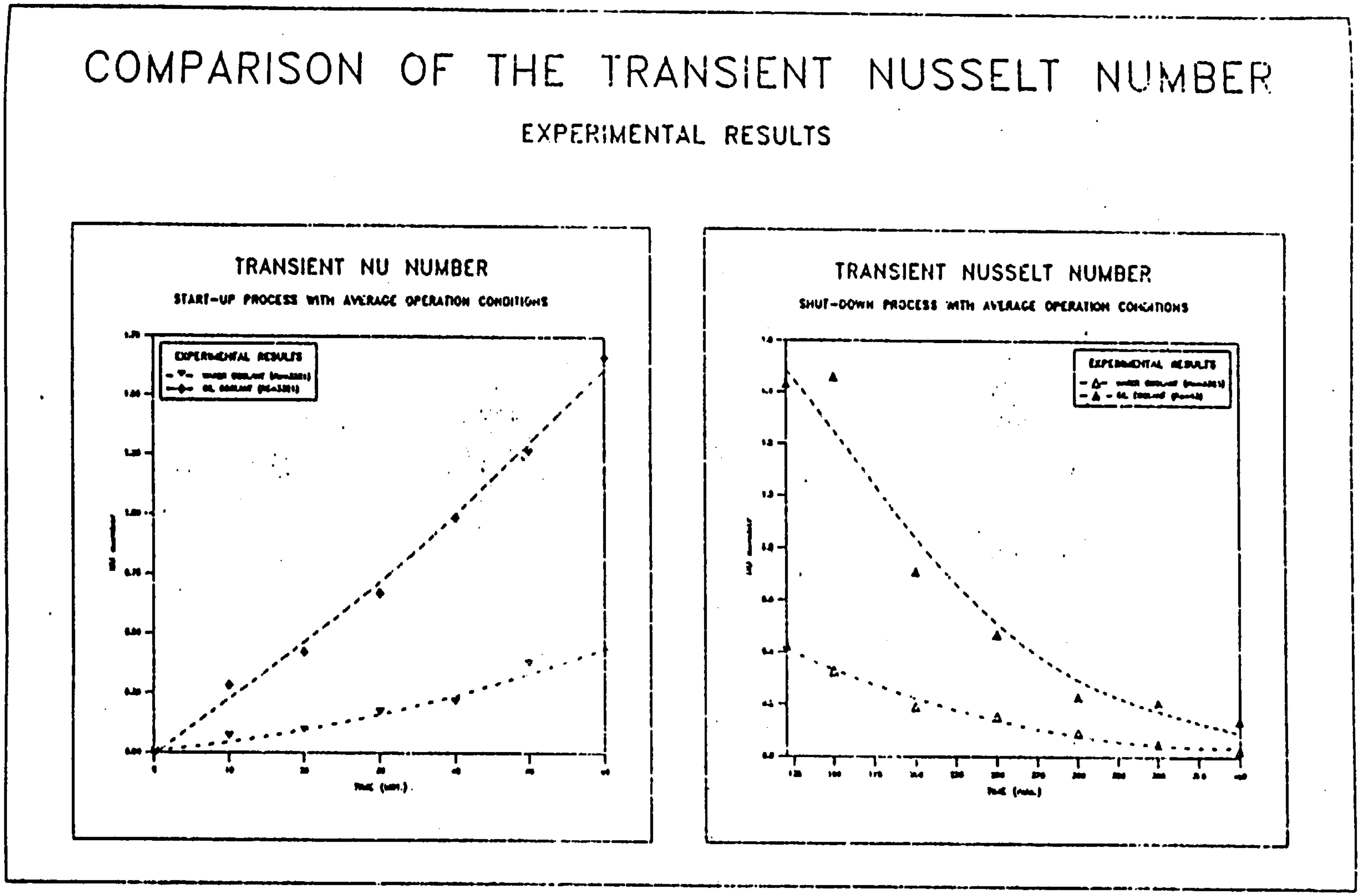


Figure 138. Comparisons of Experimental Nusselt Numbers.

coolant. Typically, as expected, the peak temperature areas were located in cell portions remote from the entrance side of the coolant during the start-up process. Considering the heat flux of the electrode, we notice that in general the heat flux is more uniform with higher stack pressure due to the homogeneous temperature distribution profiles of the electrode.

Considering the current density distribution, it is noticed that during the start-up process, the increase in the electrode temperature during the start-up process increased the fuel utilization rate and the chemical reaction between the reactants and consequently the production and travel of free electrons as demonstrated by the 2-D and 3-D contour profiles presented in Chapter VI. Also, the increase of the applied clamping pressure caused the electrode temperature to rise and that affected electron production rate while increasing the Re number will reduce the current density during a start-up process as shown in Figure 139. On the other hand, during the shut-down process three opposing factors were working against each other and affecting the transient current density distribution. The first factor, the thermal energy positive effect on the chemical reaction rate of the reactants, the second factor, effect of the temperature peak areas on the free electrons' travel ability and the third factor, the effect of the reduction of the fuel flow rate. Therefore, the effect of increasing the stack pressure and increasing the cooling

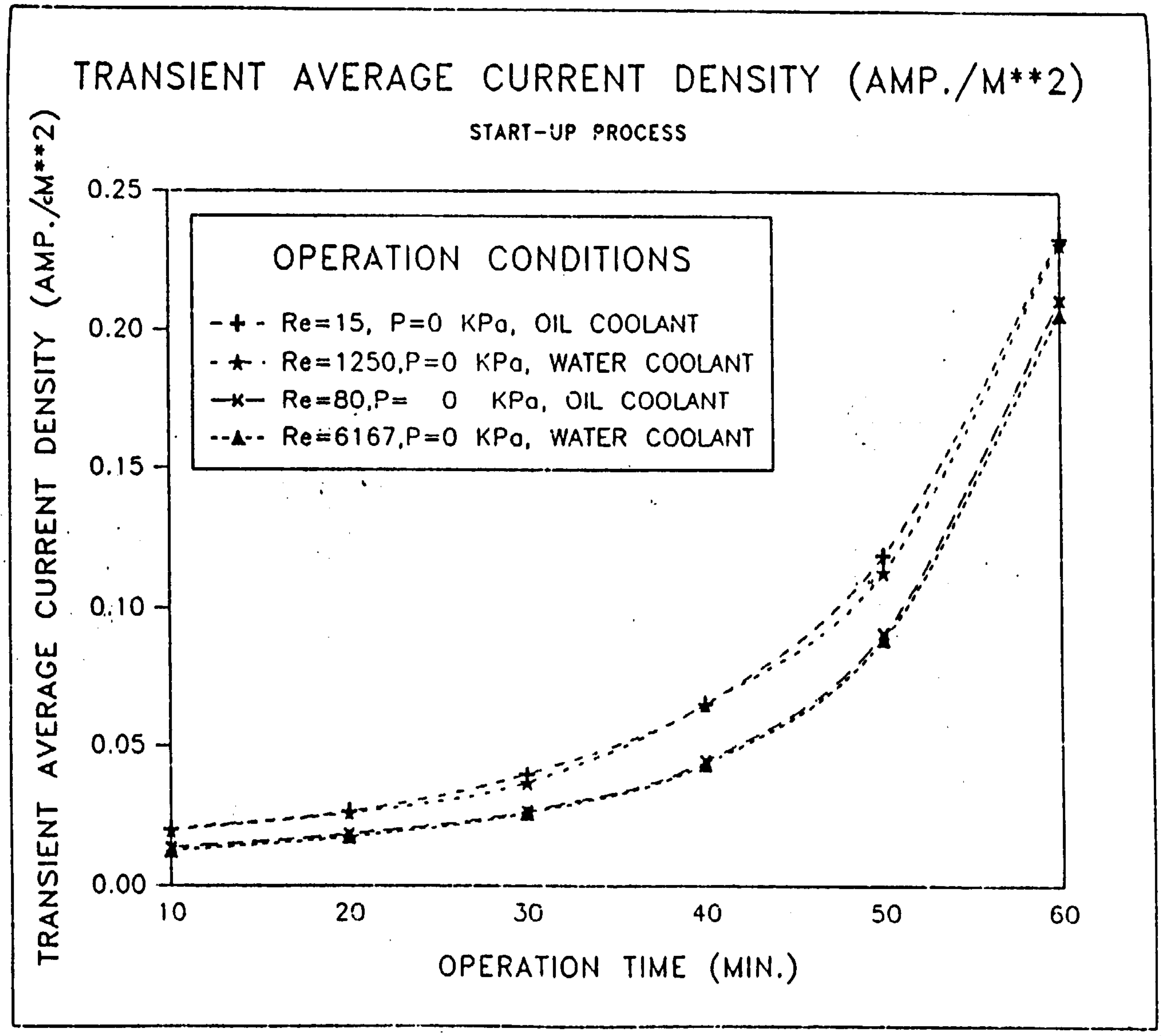


Figure 139. Transient Average Current Density (Start-Up).

fluid Re number and the fluid thermophysical properties effect could not be isolated, as shown in Chapter VI.

In comparing experimental results with results obtained analytically, the observed difference was found to be within acceptable range. Referring to Figure 140 we notice that differences between the reported experimental results and the analytical results of the transient overall heat transfer coefficient did not exceed the maximum of 8.25% and on the average the difference was 5.322% during the considered start-up and shut-down process for both coolant for the average operation condition, P = 1400 and Re = 3321 for water and Re=47 for oil. Also referring to Chapter V Figures we notice that the average deviation between the experimental and analytical transient average electrode temperature results was 6.351%.

By comparing the results of runs with identical conditions and considering the accuracy of the used equipment, the experimental results error should not exceed a maximum of 10%. The major source of errors in the experimental work, refer to Chapter III, can be summarized as follows.

(a) accuracy of the experimental instrumentation especially the thermocouples, flow meters and electrical power supply measurement equipment used.

(b) Cooling system configuration, the affect of this factor is important due to the fact that

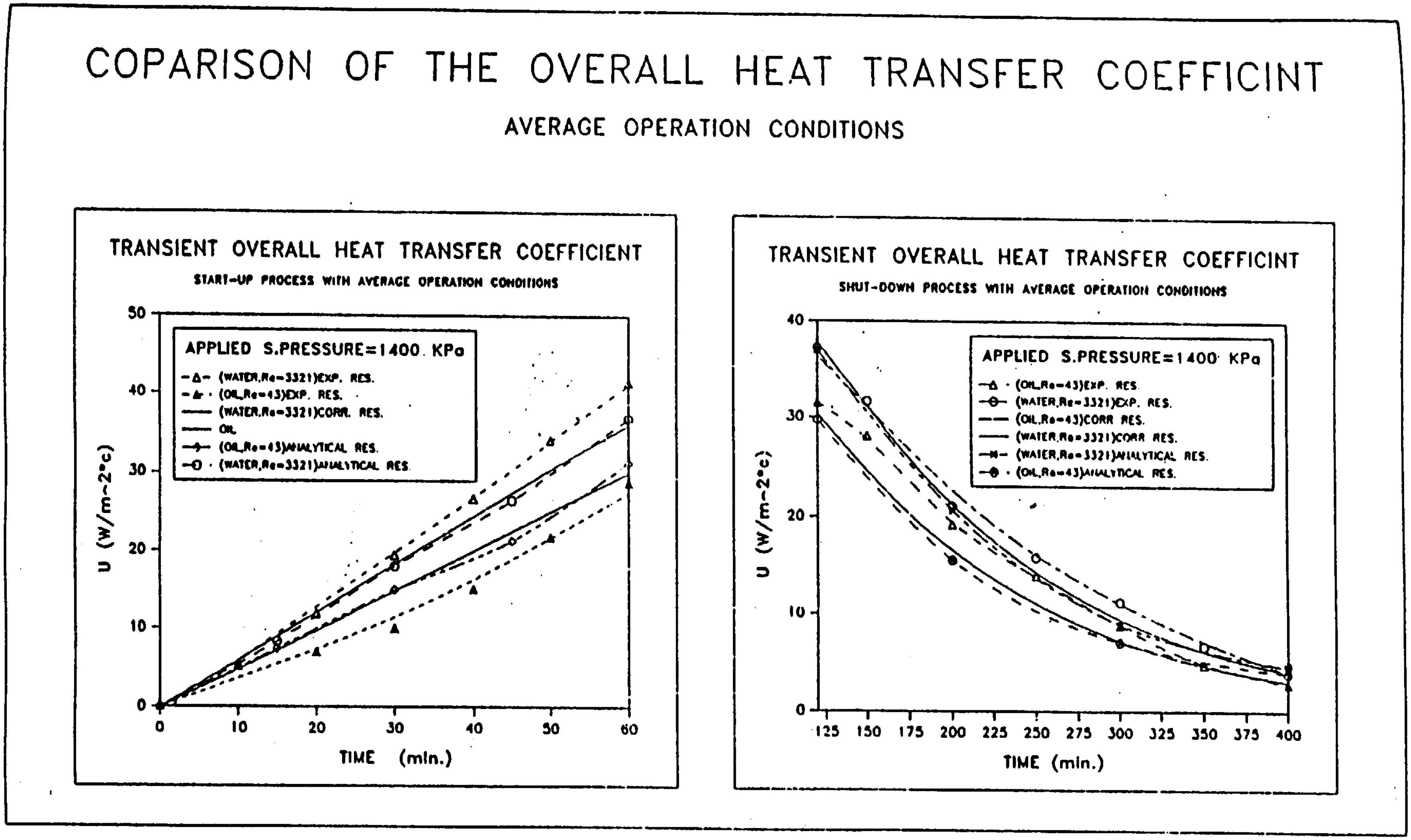


Figure 140. Comparisons of Experimental and Analytical U(t) Results.

the fitting of the serpentine cooling configurations and surface roughness of the internal areas of the tubes can cause turbulant flow and high pressure drop even with relatively low Re numbers. It was beyond the capability of the used instrumentation and scope of this study to determine how significant was the effect of such factor on the overall heat transfer coefficient. The observed influence of this factor on the accuracy of experimental results in similar experimental set-ups was mainly related to the relationship between convective heat transfer coefficient which is a function of the mixed bulk flow temperature (T_e) versus the friction coefficient which is a function of the mean flow velocity.

(c) Heat losses to the surrounding environment: Although additional insulation was used to reduce the heat transfer from the control volume, unavoided heat transfer by radiation and convection occurred during the lengthy experimental run time intervals.

(d) A correction factor was used when oil is used as a coolant to eliminate or reduce the error caused by the efficiency of the secondary cooling process for the closed cooling systems that affected the temperature of the return coolant.

(e) The effect of two-phase flow when water was used as a coolant was a contributor in the marginal error of the experimental results. The cooling tube temperature exceeded 100°C during several runs and that can easily cause the generation of the gaseous phase at least in the case of water.

(f) Human error factor should also be taken into account inspite of the fact that most of the monitoring process was done automatically. However, the gradual variations of the power supplied to the cell plate was controlled manually and checked by a secondary set of amperage and voltage measuring instrumentations.

CHAPTER VIII

CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

The following can be concluded from the experimental investigation and the comparison with the theoretical results.

(a) The effects of the clamping stack pressure on the surpentine cooling system performance: increasing pressure on the PAFC system will increase the transient overall heat transfer coefficient and consequently the heat transfer to the cooling fluid and this in turn improves the efficiency of the cooling system, whether it is an open system or a closed system with a secondary cooling system. This effect is mainly due to the plastic deformation of the cooling plate and cell plate that will cause the increase of the common contact surface and reduce the thermal contact resistance significantly.

(b) The general transient performance of the serpentine cooling system: the transient performance of both experimental serpentine cooling systems used can be described as reliable and effective provided that the electrode peak temperature is always kept below 210 degrees C to prevent any damages to thermocouples adhesive material or the resistive heating elements. This reasonably good performance is basically due to the fact that cooling fluids in their liquid phase have high heat capacity and can transfer additional thermal energy by means of the latent energy that is observed during the phase change process when pressurizing is not available as in the considered experimental setup. On the other hand, several serious problems were noticed with the use of such systems, which can be summarized as follows:

(a-1) Leaks from the cooling coil inside the control volume caused by corrosion, long fluid travel path inside the cooling coil, and high pressure difference through fittings. The cooling system leak can negatively influence the electrode chemical reaction and cause irreversible damages. But this risk can be reduced effectively by improving the cooling system design to reduce the number of fittings used and employing non corrosive materials with high thermal conductivity.

(1-2) Coolant effective contact area: This problem can be reduced by combining long travel paths with the flexibility of serpentine systems to be expanded on large cooling areas. But larger numbers of independent coils with shorter total travel distance should be used to compensate for reducing the tube diameters in order to maintain a reasonable pressure drop. This method will also improve the transient electrode temperature distribution uniformity.

(a-3) High initial cost and maintenance of the serpentine cooling systems: the high initial cost is usually due to the design complexity and the use of a non-corrosive tube material. The high maintenance cost is normally observed when a closed cooling system is used with a cooling tower as part of the cooling system.

(c) The transient current density distribution: Three factors will affect the transient current density profiles, the transient temperature distribution, the flow rate of the reactants and efficiency of the chemical reactions, and its relationship with the thermal energy. These factors will determine the phase density at a certain area.

(d) The accuracy of the modified computer code:

The comparison between the experimental and theoretical results generated by the modified computer code revealed a significant improvement in the accuracy of theoretical results because of the consideration of the effect of thermal contact resistance as a function of stack pressure and other important experimental conditions such as the return cooling fluid temperature.

8.2 Recommendations

In the light of the results obtained from the presented experimental and theoretical study, the following is recommended to enlarge the scope of the gained knowledge in this field for any further scientific work utilizing similar experimental methods or set-up:

(a) The effect of two-phase flow on the transient heat transfer should be recognized and studied carefully to modify the computer code to be sensible to that important factor.

(b) The effect of pressurizing the cooling system on the PAFC efficiency and cooling system performance should be studied carefully.

(c) The heat loss by radiation and convection can be reduced by containing the considered control volume in a sealed reflective space.

(d) The effect of the cooling tube roughness and the configuration on the cooling system performance, turbulant flow effect, and unaccounted for pressure drop, should be analyzed.

(e) More actual simulation of the temperature distribution can be created if the number of resistive heating element coils is increased and their center location is shifted toward the fuel entrance side. This should be done in conjunction with the suggested cooling system modifications described in the previous section.

(f) The closed cooling system should be modified to provide higher oil volumetric flow rates than it is presently capable of, Re=15 to Re=80. This can be done by eliminating the flexible joints and fittings and increasing the horsepower of the circulating pump.

(g) The C.S.U. experimental set-up should be connected to the VAX computer center utilizing the 1200 BUAD rated modum available to facilitate the time consuming monitoring process and obtain more accurate results. This modification will allow efficient testing of the transient performance of other cooling systems such as the gasious straight channeling cooling system utilizing a variety of compressible fluids.

(h) The existing PAFC experimental models should be modified to use Hydrogen as a fuel and a cooling system, including a cooling tower, or an air condensor, and tested as a practical co-generation prototype to reduce the KWH and KWD consumption that can be further developed for commercial applications such as hospitals and refrigeration warehouses.

(i) The effect of applying a perpendicular magnetic field on the cooling system's performance by influencing the flow and heat transfer characteristics of a magnetohydrodynamic, MHD, coolant such as hard and sea water is extremely important and should be tested for the considered PAFC model. Another advantage of using the magnetic will be to reduce the scaling factor which will consequently cause the increase of the thermal efficiency of the cooling system.

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APPENDIX A-1

WATER COOLANT

HEAT TRANSFER CHARACTERISTICS

Start-Up Process: Table (A-1-1) - (A-1-2)

Shut-Down Process: Table (A-1-3) - (A-1-4)

RE = 15.00
PRESSURE (KPa)= 0
FLUID :WATER

TIME	NU1	U1	% U1/V1
0.000E+00	0.000E+00	0.100E-09	0.100E+03
0.100E+01	0.336E-02	0.357E+00	0.100E+03
0.200E+01	0.674E-02	0.716E+00	0.100E+03
0.300E+01	0.102E-01	0.108E+01	0.100E+03
0.400E+01	0.136E-01	0.144E+01	0.100E+03
0.500E+01	0.171E-01	0.181E+01	0.100E+03
0.600E+01	0.206E-01	0.217E+01	0.999E+02
0.700E+01	0.241E-01	0.254E+01	0.999E+02
0.800E+01	0.276E-01	0.292E+01	0.999E+02
0.900E+01	0.312E-01	0.329E+01	0.999E+02
0.100E+02	0.348E-01	0.367E+01	0.998E+02
0.110E+02	0.385E-01	0.405E+01	0.998E+02
0.120E+02	0.422E-01	0.443E+01	0.998E+02
0.130E+02	0.459E-01	0.481E+01	0.997E+02
0.140E+02	0.496E-01	0.520E+01	0.997E+02
0.150E+02	0.534E-01	0.558E+01	0.996E+02
0.160E+02	0.572E-01	0.597E+01	0.996E+02
0.170E+02	0.610E-01	0.636E+01	0.995E+02
0.180E+02	0.649E-01	0.675E+01	0.994E+02
0.190E+02	0.687E-01	0.715E+01	0.994E+02
0.200E+02	0.727E-01	0.754E+01	0.993E+02
0.210E+02	0.766E-01	0.794E+01	0.992E+02
0.220E+02	0.806E-01	0.834E+01	0.991E+02
0.230E+02	0.846E-01	0.874E+01	0.990E+02
0.240E+02	0.887E-01	0.914E+01	0.989E+02
0.250E+02	0.928E-01	0.954E+01	0.988E+02
0.260E+02	0.969E-01	0.994E+01	0.987E+02
0.270E+02	0.101E+00	0.103E+02	0.986E+02
0.280E+02	0.105E+00	0.108E+02	0.985E+02
0.290E+02	0.109E+00	0.112E+02	0.984E+02
0.300E+02	0.114E+00	0.116E+02	0.982E+02
0.310E+02	0.118E+00	0.120E+02	0.981E+02
0.320E+02	0.122E+00	0.124E+02	0.980E+02
0.330E+02	0.127E+00	0.128E+02	0.978E+02
0.340E+02	0.131E+00	0.132E+02	0.977E+02
0.350E+02	0.136E+00	0.136E+02	0.975E+02
0.360E+02	0.140E+00	0.140E+02	0.974E+02
0.370E+02	0.145E+00	0.144E+02	0.972E+02
0.380E+02	0.149E+00	0.148E+02	0.970E+02
0.390E+02	0.154E+00	0.152E+02	0.968E+02
0.400E+02	0.158E+00	0.157E+02	0.966E+02
0.410E+02	0.163E+00	0.161E+02	0.964E+02
0.420E+02	0.168E+00	0.165E+02	0.962E+02
0.430E+02	0.172E+00	0.169E+02	0.960E+02
0.440E+02	0.177E+00	0.173E+02	0.958E+02
0.450E+02	0.182E+00	0.177E+02	0.956E+02
0.460E+02	0.187E+00	0.181E+02	0.953E+02
0.470E+02	0.192E+00	0.185E+02	0.951E+02
0.480E+02	0.197E+00	0.189E+02	0.949E+02
0.490E+02	0.202E+00	0.193E+02	0.946E+02
0.500E+02	0.207E+00	0.197E+02	0.943E+02
0.510E+02	0.212E+00	0.201E+02	0.941E+02
0.520E+02	0.217E+00	0.205E+02	0.938E+02
0.530E+02	0.222E+00	0.209E+02	0.935E+02
0.540E+02	0.227E+00	0.213E+02	0.932E+02
0.550E+02	0.232E+00	0.217E+02	0.929E+02
0.560E+02	0.238E+00	0.221E+02	0.926E+02
0.570E+02	0.243E+00	0.225E+02	0.923E+02
0.580E+02	0.248E+00	0.228E+02	0.920E+02
0.590E+02	0.254E+00	0.232E+02	0.917E+02

Table A-1-1. Heat Transfer Characteristics During Start-Up Process (Water Coolant, P=0 KPa, Re=15).

RE = 15.00
PRESSURE (KPa)= 3500.
FLUID :WATER

TIME	NU5	U5	% U5/V5
0.000E+00	0.000E+00	0.100E-09	0.100E+03
0.100E+01	0.517E-02	0.549E+00	0.100E+03
0.200E+01	0.104E-01	0.110E+01	0.100E+03
0.300E+01	0.156E-01	0.166E+01	0.100E+03
0.400E+01	0.209E-01	0.221E+01	0.100E+03
0.500E+01	0.263E-01	0.277E+01	0.100E+03
0.600E+01	0.317E-01	0.334E+01	0.100E+03
0.700E+01	0.371E-01	0.390E+01	0.999E+02
0.800E+01	0.426E-01	0.447E+01	0.999E+02
0.900E+01	0.481E-01	0.504E+01	0.999E+02
0.100E+02	0.537E-01	0.561E+01	0.999E+02
0.110E+02	0.593E-01	0.619E+01	0.999E+02
0.120E+02	0.650E-01	0.677E+01	0.998E+02
0.130E+02	0.707E-01	0.735E+01	0.998E+02
0.140E+02	0.764E-01	0.793E+01	0.998E+02
0.150E+02	0.822E-01	0.851E+01	0.997E+02
0.160E+02	0.881E-01	0.910E+01	0.997E+02
0.170E+02	0.940E-01	0.969E+01	0.997E+02
0.180E+02	0.999E-01	0.103E+02	0.996E+02
0.190E+02	0.106E+00	0.109E+02	0.996E+02
0.200E+02	0.112E+00	0.115E+02	0.995E+02
0.210E+02	0.118E+00	0.121E+02	0.995E+02
0.220E+02	0.124E+00	0.127E+02	0.994E+02
0.230E+02	0.130E+00	0.133E+02	0.994E+02
0.240E+02	0.137E+00	0.139E+02	0.993E+02
0.250E+02	0.143E+00	0.145E+02	0.992E+02
0.260E+02	0.149E+00	0.151E+02	0.992E+02
0.270E+02	0.156E+00	0.157E+02	0.991E+02
0.280E+02	0.162E+00	0.163E+02	0.990E+02
0.290E+02	0.169E+00	0.169E+02	0.989E+02
0.300E+02	0.175E+00	0.175E+02	0.988E+02
0.310E+02	0.182E+00	0.181E+02	0.987E+02
0.320E+02	0.189E+00	0.187E+02	0.987E+02
0.330E+02	0.195E+00	0.193E+02	0.986E+02
0.340E+02	0.202E+00	0.199E+02	0.985E+02
0.350E+02	0.209E+00	0.205E+02	0.984E+02
0.360E+02	0.216E+00	0.212E+02	0.982E+02
0.370E+02	0.223E+00	0.218E+02	0.981E+02
0.380E+02	0.230E+00	0.224E+02	0.980E+02
0.390E+02	0.237E+00	0.230E+02	0.979E+02
0.400E+02	0.244E+00	0.236E+02	0.978E+02
0.410E+02	0.251E+00	0.242E+02	0.976E+02
0.420E+02	0.258E+00	0.248E+02	0.975E+02
0.430E+02	0.266E+00	0.254E+02	0.974E+02
0.440E+02	0.273E+00	0.260E+02	0.972E+02
0.450E+02	0.281E+00	0.266E+02	0.971E+02
0.460E+02	0.288E+00	0.273E+02	0.969E+02
0.470E+02	0.296E+00	0.279E+02	0.968E+02
0.480E+02	0.303E+00	0.285E+02	0.966E+02
0.490E+02	0.311E+00	0.291E+02	0.964E+02
0.500E+02	0.319E+00	0.297E+02	0.963E+02
0.510E+02	0.326E+00	0.303E+02	0.961E+02
0.520E+02	0.334E+00	0.309E+02	0.959E+02
0.530E+02	0.342E+00	0.315E+02	0.957E+02
0.540E+02	0.350E+00	0.321E+02	0.955E+02
0.550E+02	0.358E+00	0.327E+02	0.953E+02
0.560E+02	0.366E+00	0.332E+02	0.951E+02
0.570E+02	0.375E+00	0.338E+02	0.949E+02
0.580E+02	0.383E+00	0.344E+02	0.947E+02
0.590E+02	0.391E+00	0.350E+02	0.945E+02

TABLE A-1-2.

Heat Transfer Characteristics During Start-Up Process (Water Coolant, P=3500 KPa Re=15).

RE = 15.00
PRESSURE (KPa)= 0
FLUID :WATER

TIME	NU1	U1	% U1/V1
0.120E+03	0.336E+00	0.249E+02	0.915E+02
0.125E+03	0.318E+00	0.240E+02	0.919E+02
0.130E+03	0.302E+00	0.232E+02	0.924E+02
0.135E+03	0.286E+00	0.224E+02	0.928E+02
0.140E+03	0.271E+00	0.216E+02	0.932E+02
0.145E+03	0.256E+00	0.208E+02	0.935E+02
0.150E+03	0.243E+00	0.200E+02	0.939E+02
0.155E+03	0.230E+00	0.193E+02	0.942E+02
0.160E+03	0.218E+00	0.186E+02	0.945E+02
0.165E+03	0.206E+00	0.179E+02	0.949E+02
0.170E+03	0.196E+00	0.172E+02	0.951E+02
0.175E+03	0.185E+00	0.166E+02	0.954E+02
0.180E+03	0.175E+00	0.159E+02	0.957E+02
0.185E+03	0.166E+00	0.153E+02	0.959E+02
0.190E+03	0.157E+00	0.147E+02	0.962E+02
0.195E+03	0.149E+00	0.141E+02	0.964E+02
0.200E+03	0.141E+00	0.136E+02	0.966E+02
0.205E+03	0.134E+00	0.131E+02	0.968E+02
0.210E+03	0.127E+00	0.125E+02	0.970E+02
0.215E+03	0.120E+00	0.120E+02	0.971E+02
0.220E+03	0.114E+00	0.116E+02	0.973E+02
0.225E+03	0.108E+00	0.111E+02	0.975E+02
0.230E+03	0.102E+00	0.106E+02	0.976E+02
0.235E+03	0.967E-01	0.102E+02	0.978E+02
0.240E+03	0.917E-01	0.980E+01	0.979E+02
0.245E+03	0.868E-01	0.940E+01	0.980E+02
0.250E+03	0.822E-01	0.902E+01	0.981E+02
0.255E+03	0.779E-01	0.865E+01	0.982E+02
0.260E+03	0.738E-01	0.829E+01	0.984E+02
0.265E+03	0.699E-01	0.795E+01	0.985E+02
0.270E+03	0.662E-01	0.762E+01	0.985E+02
0.275E+03	0.627E-01	0.730E+01	0.986E+02
0.280E+03	0.594E-01	0.700E+01	0.987E+02
0.285E+03	0.563E-01	0.671E+01	0.988E+02
0.290E+03	0.533E-01	0.643E+01	0.989E+02
0.295E+03	0.505E-01	0.616E+01	0.989E+02
0.300E+03	0.479E-01	0.590E+01	0.990E+02
0.305E+03	0.453E-01	0.565E+01	0.991E+02
0.310E+03	0.430E-01	0.541E+01	0.991E+02
0.315E+03	0.407E-01	0.518E+01	0.992E+02
0.320E+03	0.385E-01	0.497E+01	0.992E+02
0.325E+03	0.365E-01	0.476E+01	0.993E+02
0.330E+03	0.346E-01	0.455E+01	0.993E+02
0.335E+03	0.328E-01	0.436E+01	0.994E+02
0.340E+03	0.310E-01	0.418E+01	0.994E+02
0.345E+03	0.294E-01	0.400E+01	0.994E+02
0.350E+03	0.279E-01	0.383E+01	0.995E+02
0.355E+03	0.264E-01	0.366E+01	0.995E+02
0.360E+03	0.250E-01	0.351E+01	0.995E+02
0.365E+03	0.237E-01	0.336E+01	0.996E+02
0.370E+03	0.224E-01	0.321E+01	0.996E+02
0.375E+03	0.213E-01	0.308E+01	0.996E+02
0.380E+03	0.201E-01	0.294E+01	0.996E+02
0.385E+03	0.191E-01	0.282E+01	0.997E+02
0.390E+03	0.181E-01	0.270E+01	0.997E+02
0.395E+03	0.171E-01	0.258E+01	0.997E+02
0.400E+03	0.162E-01	0.247E+01	0.997E+02
0.405E+03	0.000E+00	0.000E+00	0.000E+00
0.000E+00	0.000E+00	0.000E+00	0.000E+00
0.000E+00	0.000E+00	0.000E+00	0.000E+00

TABLE A-1-3.

Heat Transfer Characteristics During Shut-Down Process (Water Coolant, P=0 KPa, Re=15).

RE = 15.00
PRESSURE (KPa)= 3500.
FLUID :WATER

TIME	NUS	US	% US/VS
0.120E+03	0.567E+00	0.375E+02	0.944E+02
0.125E+03	0.537E+00	0.362E+02	0.947E+02
0.130E+03	0.508E+00	0.349E+02	0.949E+02
0.135E+03	0.482E+00	0.337E+02	0.952E+02
0.140E+03	0.456E+00	0.325E+02	0.955E+02
0.145E+03	0.432E+00	0.314E+02	0.957E+02
0.150E+03	0.409E+00	0.302E+02	0.960E+02
0.155E+03	0.388E+00	0.291E+02	0.962E+02
0.160E+03	0.367E+00	0.281E+02	0.964E+02
0.165E+03	0.348E+00	0.270E+02	0.966E+02
0.170E+03	0.330E+00	0.260E+02	0.968E+02
0.175E+03	0.312E+00	0.250E+02	0.970E+02
0.180E+03	0.296E+00	0.241E+02	0.971E+02
0.185E+03	0.280E+00	0.232E+02	0.973E+02
0.190E+03	0.266E+00	0.223E+02	0.974E+02
0.195E+03	0.252E+00	0.214E+02	0.976E+02
0.200E+03	0.238E+00	0.206E+02	0.977E+02
0.205E+03	0.226E+00	0.198E+02	0.979E+02
0.210E+03	0.214E+00	0.190E+02	0.980E+02
0.215E+03	0.203E+00	0.183E+02	0.981E+02
0.220E+03	0.192E+00	0.176E+02	0.982E+02
0.225E+03	0.182E+00	0.169E+02	0.983E+02
0.230E+03	0.172E+00	0.162E+02	0.984E+02
0.235E+03	0.163E+00	0.155E+02	0.985E+02
0.240E+03	0.155E+00	0.149E+02	0.986E+02
0.245E+03	0.146E+00	0.143E+02	0.987E+02
0.250E+03	0.139E+00	0.137E+02	0.988E+02
0.255E+03	0.131E+00	0.132E+02	0.988E+02
0.260E+03	0.124E+00	0.126E+02	0.989E+02
0.265E+03	0.118E+00	0.121E+02	0.990E+02
0.270E+03	0.112E+00	0.116E+02	0.990E+02
0.275E+03	0.106E+00	0.111E+02	0.991E+02
0.280E+03	0.100E+00	0.107E+02	0.991E+02
0.285E+03	0.949E-01	0.102E+02	0.992E+02
0.290E+03	0.899E-01	0.981E+01	0.992E+02
0.295E+03	0.852E-01	0.940E+01	0.993E+02
0.300E+03	0.807E-01	0.901E+01	0.993E+02
0.305E+03	0.764E-01	0.864E+01	0.994E+02
0.310E+03	0.724E-01	0.827E+01	0.994E+02
0.315E+03	0.686E-01	0.793E+01	0.994E+02
0.320E+03	0.650E-01	0.759E+01	0.995E+02
0.325E+03	0.616E-01	0.728E+01	0.995E+02
0.330E+03	0.583E-01	0.697E+01	0.995E+02
0.335E+03	0.552E-01	0.667E+01	0.996E+02
0.340E+03	0.523E-01	0.639E+01	0.996E+02
0.345E+03	0.496E-01	0.612E+01	0.996E+02
0.350E+03	0.470E-01	0.586E+01	0.996E+02
0.355E+03	0.445E-01	0.561E+01	0.997E+02
0.360E+03	0.421E-01	0.538E+01	0.997E+02
0.365E+03	0.399E-01	0.515E+01	0.997E+02
0.370E+03	0.378E-01	0.493E+01	0.997E+02
0.375E+03	0.358E-01	0.472E+01	0.997E+02
0.380E+03	0.339E-01	0.452E+01	0.998E+02
0.385E+03	0.322E-01	0.432E+01	0.998E+02
0.390E+03	0.305E-01	0.414E+01	0.998E+02
0.395E+03	0.289E-01	0.396E+01	0.998E+02
0.400E+03	0.273E-01	0.379E+01	0.998E+02
0.405E+03	0.000E+00	0.000E+00	0.000E+00
0.000E+00	0.000E+00	0.000E+00	0.000E+00
0.000E+00	0.000E+00	0.000E+00	0.000E+00

TABLE A-1-4.

Heat Transfer Characteristics During Shut-Down Process (Water Coolant, P=3500 KPa, Re=15).

APPENDIX A-2

WATER COOLANT

THERMAL CONTACT RESISTANCE AND AFFECTIVE TEMPERATURE DROP

Start-Up Process: Table (A-2-1) - (A-2-2)

Shut-Down Process: Table (A-2-3) - (A-2-4)

RE = 15.
PRESSURE (KPa)= 0
FLUID :WATER

TIME	D1	R1
0.000E+00	0.000E+00	0.000E+00
0.100E+01	0.989E-01	0.423E-04
0.200E+01	0.199E+00	0.852E-04
0.300E+01	0.300E+00	0.129E-03
0.400E+01	0.403E+00	0.172E-03
0.500E+01	0.507E+00	0.217E-03
0.600E+01	0.612E+00	0.262E-03
0.700E+01	0.719E+00	0.307E-03
0.800E+01	0.826E+00	0.353E-03
0.900E+01	0.936E+00	0.400E-03
0.100E+02	0.105E+01	0.447E-03
0.110E+02	0.116E+01	0.494E-03
0.120E+02	0.127E+01	0.543E-03
0.130E+02	0.139E+01	0.591E-03
0.140E+02	0.150E+01	0.641E-03
0.150E+02	0.162E+01	0.691E-03
0.160E+02	0.174E+01	0.741E-03
0.170E+02	0.186E+01	0.792E-03
0.180E+02	0.198E+01	0.844E-03
0.190E+02	0.210E+01	0.897E-03
0.200E+02	0.223E+01	0.950E-03
0.210E+02	0.236E+01	0.100E-02
0.220E+02	0.248E+01	0.106E-02
0.230E+02	0.261E+01	0.111E-02
0.240E+02	0.274E+01	0.117E-02
0.250E+02	0.288E+01	0.122E-02
0.260E+02	0.301E+01	0.128E-02
0.270E+02	0.315E+01	0.134E-02
0.280E+02	0.329E+01	0.140E-02
0.290E+02	0.343E+01	0.146E-02
0.300E+02	0.357E+01	0.152E-02
0.310E+02	0.371E+01	0.158E-02
0.320E+02	0.386E+01	0.164E-02
0.330E+02	0.400E+01	0.170E-02
0.340E+02	0.415E+01	0.176E-02
0.350E+02	0.430E+01	0.182E-02
0.360E+02	0.445E+01	0.189E-02
0.370E+02	0.461E+01	0.195E-02
0.380E+02	0.476E+01	0.202E-02
0.390E+02	0.492E+01	0.208E-02
0.400E+02	0.508E+01	0.215E-02
0.410E+02	0.524E+01	0.222E-02
0.420E+02	0.541E+01	0.229E-02
0.430E+02	0.557E+01	0.236E-02
0.440E+02	0.574E+01	0.243E-02
0.450E+02	0.591E+01	0.250E-02
0.460E+02	0.608E+01	0.257E-02
0.470E+02	0.626E+01	0.264E-02
0.480E+02	0.643E+01	0.272E-02
0.490E+02	0.661E+01	0.279E-02
0.500E+02	0.679E+01	0.287E-02
0.510E+02	0.698E+01	0.294E-02
0.520E+02	0.716E+01	0.302E-02
0.530E+02	0.735E+01	0.310E-02
0.540E+02	0.754E+01	0.318E-02
0.550E+02	0.773E+01	0.326E-02
0.560E+02	0.792E+01	0.334E-02
0.570E+02	0.812E+01	0.342E-02
0.580E+02	0.832E+01	0.350E-02
0.590E+02	0.852E+01	0.359E-02

TABLE A-2-1.

Effective Temperature Drop and Thermal Contact Resistance During Start-Up Process (Water Collant, P=0 KPa, Re=15).

RE = 15.
PRESSURE (KPa)= 3500.
FLUID :WATER

TIME	D5	R5
----	--	--
0.000E+00	0.000E+00	0.000E+00
0.100E+01	0.573E-01	0.186E-04
0.200E+01	0.115E+00	0.374E-04
0.300E+01	0.174E+00	0.564E-04
0.400E+01	0.234E+00	0.756E-04
0.500E+01	0.294E+00	0.951E-04
0.600E+01	0.355E+00	0.115E-03
0.700E+01	0.416E+00	0.135E-03
0.800E+01	0.479E+00	0.155E-03
0.900E+01	0.542E+00	0.175E-03
0.100E+02	0.606E+00	0.196E-03
0.110E+02	0.671E+00	0.217E-03
0.120E+02	0.736E+00	0.238E-03
0.130E+02	0.803E+00	0.259E-03
0.140E+02	0.870E+00	0.281E-03
0.150E+02	0.938E+00	0.303E-03
0.160E+02	0.101E+01	0.325E-03
0.170E+02	0.108E+01	0.347E-03
0.180E+02	0.115E+01	0.370E-03
0.190E+02	0.122E+01	0.393E-03
0.200E+02	0.129E+01	0.416E-03
0.210E+02	0.136E+01	0.440E-03
0.220E+02	0.144E+01	0.464E-03
0.230E+02	0.151E+01	0.488E-03
0.240E+02	0.159E+01	0.512E-03
0.250E+02	0.167E+01	0.537E-03
0.260E+02	0.175E+01	0.562E-03
0.270E+02	0.182E+01	0.587E-03
0.280E+02	0.190E+01	0.612E-03
0.290E+02	0.198E+01	0.638E-03
0.300E+02	0.207E+01	0.664E-03
0.310E+02	0.215E+01	0.691E-03
0.320E+02	0.223E+01	0.717E-03
0.330E+02	0.232E+01	0.745E-03
0.340E+02	0.240E+01	0.772E-03
0.350E+02	0.249E+01	0.800E-03
0.360E+02	0.258E+01	0.828E-03
0.370E+02	0.267E+01	0.856E-03
0.380E+02	0.276E+01	0.885E-03
0.390E+02	0.285E+01	0.914E-03
0.400E+02	0.294E+01	0.943E-03
0.410E+02	0.304E+01	0.973E-03
0.420E+02	0.313E+01	0.100E-02
0.430E+02	0.323E+01	0.103E-02
0.440E+02	0.333E+01	0.106E-02
0.450E+02	0.342E+01	0.110E-02
0.460E+02	0.352E+01	0.113E-02
0.470E+02	0.362E+01	0.116E-02
0.480E+02	0.373E+01	0.119E-02
0.490E+02	0.383E+01	0.122E-02
0.500E+02	0.394E+01	0.126E-02
0.510E+02	0.404E+01	0.129E-02
0.520E+02	0.415E+01	0.132E-02
0.530E+02	0.426E+01	0.136E-02
0.540E+02	0.437E+01	0.139E-02
0.550E+02	0.448E+01	0.143E-02
0.560E+02	0.459E+01	0.146E-02
0.570E+02	0.471E+01	0.150E-02
0.580E+02	0.482E+01	0.154E-02
0.590E+02	0.494E+01	0.157E-02

TABLE A-2-2.

Effective Temperature Drop and Thermal Contact Resistance During Start-Up Process (Water Coolant, P=3500 KPa, Re=15).

RE = 15.
PRESSURE (KPa)= 0.
FLUID :WATER

TIME	D1	R1
0.120E+03	0.867E+01	0.360E-02
0.125E+03	0.848E+01	0.353E-02
0.130E+03	0.829E+01	0.346E-02
0.135E+03	0.810E+01	0.339E-02
0.140E+03	0.792E+01	0.333E-02
0.145E+03	0.774E+01	0.326E-02
0.150E+03	0.756E+01	0.320E-02
0.155E+03	0.739E+01	0.314E-02
0.160E+03	0.723E+01	0.308E-02
0.165E+03	0.706E+01	0.302E-02
0.170E+03	0.690E+01	0.296E-02
0.175E+03	0.675E+01	0.290E-02
0.180E+03	0.660E+01	0.285E-02
0.185E+03	0.645E+01	0.279E-02
0.190E+03	0.630E+01	0.274E-02
0.195E+03	0.616E+01	0.269E-02
0.200E+03	0.602E+01	0.263E-02
0.205E+03	0.589E+01	0.258E-02
0.210E+03	0.575E+01	0.253E-02
0.215E+03	0.562E+01	0.248E-02
0.220E+03	0.550E+01	0.244E-02
0.225E+03	0.537E+01	0.239E-02
0.230E+03	0.525E+01	0.234E-02
0.235E+03	0.513E+01	0.230E-02
0.240E+03	0.502E+01	0.225E-02
0.245E+03	0.491E+01	0.221E-02
0.250E+03	0.480E+01	0.217E-02
0.255E+03	0.469E+01	0.212E-02
0.260E+03	0.458E+01	0.208E-02
0.265E+03	0.448E+01	0.204E-02
0.270E+03	0.438E+01	0.200E-02
0.275E+03	0.428E+01	0.196E-02
0.280E+03	0.418E+01	0.193E-02
0.285E+03	0.409E+01	0.189E-02
0.290E+03	0.400E+01	0.185E-02
0.295E+03	0.391E+01	0.182E-02
0.300E+03	0.382E+01	0.178E-02
0.305E+03	0.373E+01	0.175E-02
0.310E+03	0.365E+01	0.171E-02
0.315E+03	0.357E+01	0.168E-02
0.320E+03	0.349E+01	0.165E-02
0.325E+03	0.341E+01	0.162E-02
0.330E+03	0.333E+01	0.158E-02
0.335E+03	0.326E+01	0.155E-02
0.340E+03	0.318E+01	0.152E-02
0.345E+03	0.311E+01	0.149E-02
0.350E+03	0.304E+01	0.147E-02
0.355E+03	0.297E+01	0.144E-02
0.360E+03	0.290E+01	0.141E-02
0.365E+03	0.284E+01	0.138E-02
0.370E+03	0.278E+01	0.136E-02
0.375E+03	0.271E+01	0.133E-02
0.380E+03	0.265E+01	0.130E-02
0.385E+03	0.259E+01	0.128E-02
0.390E+03	0.253E+01	0.125E-02
0.395E+03	0.248E+01	0.123E-02
0.400E+03	0.242E+01	0.121E-02
0.405E+03	0.000E+00	0.000E+00

TABLE A-2-3.

Effective Temperature Drop and Thermal Contact Resistance During Shut-Down Process (Water Coolant, P=0 KPa, Re=15).

RE = 15.
PRESSURE (KPa)= 3500
FLUID :WATER

TIME	D5	R5
0.120E+03	0.673E+01	0.158E-02
0.125E+03	0.658E+01	0.155E-02
0.130E+03	0.643E+01	0.152E-02
0.135E+03	0.628E+01	0.149E-02
0.140E+03	0.614E+01	0.146E-02
0.145E+03	0.600E+01	0.143E-02
0.150E+03	0.587E+01	0.140E-02
0.155E+03	0.574E+01	0.138E-02
0.160E+03	0.561E+01	0.135E-02
0.165E+03	0.548E+01	0.132E-02
0.170E+03	0.536E+01	0.130E-02
0.175E+03	0.524E+01	0.127E-02
0.180E+03	0.512E+01	0.125E-02
0.185E+03	0.500E+01	0.122E-02
0.190E+03	0.489E+01	0.120E-02
0.195E+03	0.478E+01	0.118E-02
0.200E+03	0.467E+01	0.115E-02
0.205E+03	0.457E+01	0.113E-02
0.210E+03	0.446E+01	0.111E-02
0.215E+03	0.436E+01	0.109E-02
0.220E+03	0.427E+01	0.107E-02
0.225E+03	0.417E+01	0.105E-02
0.230E+03	0.408E+01	0.103E-02
0.235E+03	0.398E+01	0.101E-02
0.240E+03	0.389E+01	0.988E-03
0.245E+03	0.381E+01	0.968E-03
0.250E+03	0.372E+01	0.950E-03
0.255E+03	0.364E+01	0.931E-03
0.260E+03	0.355E+01	0.913E-03
0.265E+03	0.347E+01	0.896E-03
0.270E+03	0.340E+01	0.878E-03
0.275E+03	0.332E+01	0.861E-03
0.280E+03	0.324E+01	0.845E-03
0.285E+03	0.317E+01	0.828E-03
0.290E+03	0.310E+01	0.812E-03
0.295E+03	0.303E+01	0.797E-03
0.300E+03	0.296E+01	0.781E-03
0.305E+03	0.290E+01	0.766E-03
0.310E+03	0.283E+01	0.751E-03
0.315E+03	0.277E+01	0.737E-03
0.320E+03	0.270E+01	0.723E-03
0.325E+03	0.264E+01	0.709E-03
0.330E+03	0.258E+01	0.695E-03
0.335E+03	0.253E+01	0.681E-03
0.340E+03	0.247E+01	0.668E-03
0.345E+03	0.241E+01	0.655E-03
0.350E+03	0.236E+01	0.643E-03
0.355E+03	0.231E+01	0.630E-03
0.360E+03	0.225E+01	0.618E-03
0.365E+03	0.220E+01	0.606E-03
0.370E+03	0.215E+01	0.594E-03
0.375E+03	0.210E+01	0.583E-03
0.380E+03	0.206E+01	0.572E-03
0.385E+03	0.201E+01	0.561E-03
0.390E+03	0.197E+01	0.550E-03
0.395E+03	0.192E+01	0.539E-03
0.400E+03	0.188E+01	0.529E-03
0.405E+03	0.000E+00	0.000E+00

TABLE A-2-4.

Effective Temperature Drop and Thermal Contact Resistance During Shut-Down Process (Water Coolant, P=3500 KPa, Re=15).

APPENDIX B-1

OIL COOLANT

HEAT TRANSFER CHARACTERISTICS

Start-Up Process: Table (B-1-1) - (B-1-2)

Shut-Down Process: Table (B-1-3) - (B-1-4)

RE = 1250.00
PRESSURE (KPa)= 0.
FLUID :OIL

TIME	NU1	U1	% U1/V1
0.000E+00	0.000E+00	0.100E-09	0.100E+03
0.100E+01	0.305E-01	0.750E+00	0.100E+03
0.200E+01	0.612E-01	0.150E+01	0.100E+03
0.300E+01	0.922E-01	0.226E+01	0.100E+03
0.400E+01	0.124E+00	0.302E+01	0.999E+02
0.500E+01	0.155E+00	0.378E+01	0.999E+02
0.600E+01	0.187E+00	0.454E+01	0.999E+02
0.700E+01	0.219E+00	0.530E+01	0.998E+02
0.800E+01	0.251E+00	0.607E+01	0.998E+02
0.900E+01	0.284E+00	0.683E+01	0.997E+02
0.100E+02	0.317E+00	0.760E+01	0.997E+02
0.110E+02	0.350E+00	0.837E+01	0.996E+02
0.120E+02	0.384E+00	0.914E+01	0.995E+02
0.130E+02	0.418E+00	0.991E+01	0.994E+02
0.140E+02	0.452E+00	0.107E+02	0.993E+02
0.150E+02	0.487E+00	0.114E+02	0.992E+02
0.160E+02	0.521E+00	0.122E+02	0.991E+02
0.170E+02	0.556E+00	0.130E+02	0.990E+02
0.180E+02	0.592E+00	0.137E+02	0.988E+02
0.190E+02	0.628E+00	0.145E+02	0.987E+02
0.200E+02	0.664E+00	0.153E+02	0.985E+02
0.210E+02	0.700E+00	0.160E+02	0.984E+02
0.220E+02	0.737E+00	0.168E+02	0.982E+02
0.230E+02	0.774E+00	0.176E+02	0.980E+02
0.240E+02	0.811E+00	0.183E+02	0.978E+02
0.250E+02	0.849E+00	0.191E+02	0.976E+02
0.260E+02	0.887E+00	0.198E+02	0.974E+02
0.270E+02	0.925E+00	0.206E+02	0.972E+02
0.280E+02	0.964E+00	0.213E+02	0.970E+02
0.290E+02	0.100E+01	0.221E+02	0.967E+02
0.300E+02	0.104E+01	0.228E+02	0.965E+02
0.310E+02	0.108E+01	0.235E+02	0.962E+02
0.320E+02	0.112E+01	0.242E+02	0.960E+02
0.330E+02	0.116E+01	0.250E+02	0.957E+02
0.340E+02	0.120E+01	0.257E+02	0.954E+02
0.350E+02	0.124E+01	0.264E+02	0.951E+02
0.360E+02	0.129E+01	0.271E+02	0.948E+02
0.370E+02	0.133E+01	0.278E+02	0.945E+02
0.380E+02	0.137E+01	0.285E+02	0.941E+02
0.390E+02	0.141E+01	0.292E+02	0.938E+02
0.400E+02	0.146E+01	0.298E+02	0.935E+02
0.410E+02	0.150E+01	0.305E+02	0.931E+02
0.420E+02	0.154E+01	0.312E+02	0.927E+02
0.430E+02	0.159E+01	0.318E+02	0.923E+02
0.440E+02	0.163E+01	0.325E+02	0.920E+02
0.450E+02	0.168E+01	0.331E+02	0.916E+02
0.460E+02	0.172E+01	0.337E+02	0.911E+02
0.470E+02	0.177E+01	0.344E+02	0.907E+02
0.480E+02	0.181E+01	0.350E+02	0.903E+02
0.490E+02	0.186E+01	0.356E+02	0.899E+02
0.500E+02	0.191E+01	0.361E+02	0.894E+02
0.510E+02	0.195E+01	0.367E+02	0.890E+02
0.520E+02	0.200E+01	0.373E+02	0.885E+02
0.530E+02	0.205E+01	0.378E+02	0.880E+02
0.540E+02	0.210E+01	0.384E+02	0.875E+02
0.550E+02	0.215E+01	0.389E+02	0.870E+02
0.560E+02	0.220E+01	0.394E+02	0.865E+02
0.570E+02	0.225E+01	0.400E+02	0.860E+02
0.580E+02	0.230E+01	0.405E+02	0.855E+02
0.590E+02	0.235E+01	0.409E+02	0.850E+02

TABLE B-1-1.

Heat Transfer Characteristics During Start-Up Process (Oil Coolant, P=0 KPa, Re=1250).

RE = 1250.00
PRESSURE (KPa)= 3500.
FLUID :OIL

TIME	NU5	U5	% U5/V5
0.000E+00	0.000E+00	0.100E-09	0.100E+03
0.100E+01	0.490E-01	0.120E+01	0.100E+03
0.200E+01	0.984E-01	0.241E+01	0.100E+03
0.300E+01	0.148E+00	0.361E+01	0.100E+03
0.400E+01	0.199E+00	0.481E+01	0.100E+03
0.500E+01	0.249E+00	0.602E+01	0.999E+02
0.600E+01	0.300E+00	0.722E+01	0.999E+02
0.700E+01	0.352E+00	0.842E+01	0.999E+02
0.800E+01	0.404E+00	0.962E+01	0.998E+02
0.900E+01	0.457E+00	0.108E+02	0.998E+02
0.100E+02	0.510E+00	0.120E+02	0.998E+02
0.110E+02	0.563E+00	0.132E+02	0.997E+02
0.120E+02	0.617E+00	0.144E+02	0.997E+02
0.130E+02	0.672E+00	0.156E+02	0.996E+02
0.140E+02	0.727E+00	0.168E+02	0.995E+02
0.150E+02	0.782E+00	0.179E+02	0.994E+02
0.160E+02	0.838E+00	0.191E+02	0.994E+02
0.170E+02	0.894E+00	0.203E+02	0.993E+02
0.180E+02	0.951E+00	0.215E+02	0.992E+02
0.190E+02	0.101E+01	0.226E+02	0.991E+02
0.200E+02	0.107E+01	0.238E+02	0.990E+02
0.210E+02	0.113E+01	0.250E+02	0.989E+02
0.220E+02	0.118E+01	0.261E+02	0.988E+02
0.230E+02	0.124E+01	0.272E+02	0.987E+02
0.240E+02	0.130E+01	0.284E+02	0.985E+02
0.250E+02	0.136E+01	0.295E+02	0.984E+02
0.260E+02	0.143E+01	0.306E+02	0.983E+02
0.270E+02	0.149E+01	0.318E+02	0.981E+02
0.280E+02	0.155E+01	0.329E+02	0.980E+02
0.290E+02	0.161E+01	0.340E+02	0.978E+02
0.300E+02	0.167E+01	0.351E+02	0.976E+02
0.310E+02	0.174E+01	0.362E+02	0.975E+02
0.320E+02	0.180E+01	0.373E+02	0.973E+02
0.330E+02	0.187E+01	0.383E+02	0.971E+02
0.340E+02	0.193E+01	0.394E+02	0.969E+02
0.350E+02	0.200E+01	0.405E+02	0.967E+02
0.360E+02	0.207E+01	0.415E+02	0.965E+02
0.370E+02	0.213E+01	0.425E+02	0.963E+02
0.380E+02	0.220E+01	0.436E+02	0.961E+02
0.390E+02	0.227E+01	0.446E+02	0.958E+02
0.400E+02	0.234E+01	0.456E+02	0.956E+02
0.410E+02	0.241E+01	0.466E+02	0.954E+02
0.420E+02	0.248E+01	0.476E+02	0.951E+02
0.430E+02	0.255E+01	0.486E+02	0.949E+02
0.440E+02	0.262E+01	0.495E+02	0.946E+02
0.450E+02	0.269E+01	0.505E+02	0.944E+02
0.460E+02	0.277E+01	0.514E+02	0.941E+02
0.470E+02	0.284E+01	0.524E+02	0.938E+02
0.480E+02	0.291E+01	0.533E+02	0.935E+02
0.490E+02	0.299E+01	0.542E+02	0.932E+02
0.500E+02	0.306E+01	0.551E+02	0.929E+02
0.510E+02	0.314E+01	0.559E+02	0.926E+02
0.520E+02	0.322E+01	0.568E+02	0.923E+02
0.530E+02	0.329E+01	0.577E+02	0.920E+02
0.540E+02	0.337E+01	0.585E+02	0.917E+02
0.550E+02	0.345E+01	0.593E+02	0.913E+02
0.560E+02	0.353E+01	0.601E+02	0.910E+02
0.570E+02	0.361E+01	0.609E+02	0.906E+02
0.580E+02	0.369E+01	0.617E+02	0.903E+02
0.590E+02	0.377E+01	0.625E+02	0.899E+02

TABLE B-1-2.

Heat Transfer Characteristics During Start-Up Process (Oil Coolant, P=3500 KPa, Re=1250).

RE = 1250.00
PRESSURE (KPa)= 0.
FLUID :OIL

TIME	NU1	U1	% U1/V1
0.120E+03	0.961E+00	0.421E+02	0.850E+02
0.125E+03	0.910E+00	0.409E+02	0.856E+02
0.130E+03	0.862E+00	0.397E+02	0.863E+02
0.135E+03	0.817E+00	0.386E+02	0.869E+02
0.140E+03	0.774E+00	0.374E+02	0.875E+02
0.145E+03	0.733E+00	0.363E+02	0.881E+02
0.150E+03	0.694E+00	0.352E+02	0.887E+02
0.155E+03	0.658E+00	0.341E+02	0.892E+02
0.160E+03	0.623E+00	0.330E+02	0.897E+02
0.165E+03	0.590E+00	0.319E+02	0.902E+02
0.170E+03	0.559E+00	0.308E+02	0.907E+02
0.175E+03	0.530E+00	0.298E+02	0.912E+02
0.180E+03	0.502E+00	0.288E+02	0.916E+02
0.185E+03	0.475E+00	0.278E+02	0.920E+02
0.190E+03	0.450E+00	0.269E+02	0.924E+02
0.195E+03	0.427E+00	0.259E+02	0.928E+02
0.200E+03	0.404E+00	0.250E+02	0.932E+02
0.205E+03	0.383E+00	0.241E+02	0.935E+02
0.210E+03	0.363E+00	0.232E+02	0.939E+02
0.215E+03	0.344E+00	0.224E+02	0.942E+02
0.220E+03	0.325E+00	0.216E+02	0.945E+02
0.225E+03	0.308E+00	0.208E+02	0.948E+02
0.230E+03	0.292E+00	0.200E+02	0.951E+02
0.235E+03	0.277E+00	0.193E+02	0.953E+02
0.240E+03	0.262E+00	0.185E+02	0.956E+02
0.245E+03	0.248E+00	0.178E+02	0.958E+02
0.250E+03	0.235E+00	0.171E+02	0.961E+02
0.255E+03	0.223E+00	0.165E+02	0.963E+02
0.260E+03	0.211E+00	0.158E+02	0.965E+02
0.265E+03	0.200E+00	0.152E+02	0.967E+02
0.270E+03	0.189E+00	0.146E+02	0.969E+02
0.275E+03	0.179E+00	0.140E+02	0.970E+02
0.280E+03	0.170E+00	0.135E+02	0.972E+02
0.285E+03	0.161E+00	0.129E+02	0.974E+02
0.290E+03	0.153E+00	0.124E+02	0.975E+02
0.295E+03	0.145E+00	0.119E+02	0.976E+02
0.300E+03	0.137E+00	0.114E+02	0.978E+02
0.305E+03	0.130E+00	0.110E+02	0.979E+02
0.310E+03	0.123E+00	0.105E+02	0.980E+02
0.315E+03	0.116E+00	0.101E+02	0.981E+02
0.320E+03	0.110E+00	0.969E+01	0.982E+02
0.325E+03	0.104E+00	0.930E+01	0.983E+02
0.330E+03	0.989E-01	0.891E+01	0.984E+02
0.335E+03	0.937E-01	0.855E+01	0.985E+02
0.340E+03	0.888E-01	0.819E+01	0.986E+02
0.345E+03	0.841E-01	0.785E+01	0.987E+02
0.350E+03	0.797E-01	0.753E+01	0.988E+02
0.355E+03	0.755E-01	0.721E+01	0.988E+02
0.360E+03	0.715E-01	0.691E+01	0.989E+02
0.365E+03	0.677E-01	0.662E+01	0.990E+02
0.370E+03	0.642E-01	0.634E+01	0.990E+02
0.375E+03	0.608E-01	0.608E+01	0.991E+02
0.380E+03	0.576E-01	0.582E+01	0.991E+02
0.385E+03	0.545E-01	0.558E+01	0.992E+02
0.390E+03	0.517E-01	0.534E+01	0.992E+02
0.395E+03	0.489E-01	0.511E+01	0.993E+02
0.400E+03	0.464E-01	0.490E+01	0.993E+02
0.405E+03	0.000E+00	0.000E+00	0.000E+00
0.000E+00	0.000E+00	0.000E+00	0.000E+00
0.000E+00	0.000E+00	0.000E+00	0.000E+00

TABLE B-1-3.

Heat Transfer Characteristics During Shut-Down Process (Oil Coolant, P=0 KPa, Re=1250).

RE = 1250.00
PRESSURE (KPa)= 3500.
FLUID :OIL

TIME	NUS	US	% US/VS
0.120E+03	0.219E+01	0.651E+02	0.901E+02
0.125E+03	0.208E+01	0.633E+02	0.905E+02
0.130E+03	0.197E+01	0.615E+02	0.909E+02
0.135E+03	0.186E+01	0.598E+02	0.913E+02
0.140E+03	0.176E+01	0.580E+02	0.917E+02
0.145E+03	0.167E+01	0.563E+02	0.921E+02
0.150E+03	0.158E+01	0.546E+02	0.925E+02
0.155E+03	0.150E+01	0.530E+02	0.928E+02
0.160E+03	0.142E+01	0.513E+02	0.932E+02
0.165E+03	0.135E+01	0.497E+02	0.935E+02
0.170E+03	0.128E+01	0.481E+02	0.938E+02
0.175E+03	0.121E+01	0.465E+02	0.941E+02
0.180E+03	0.114E+01	0.450E+02	0.944E+02
0.185E+03	0.108E+01	0.435E+02	0.947E+02
0.190E+03	0.103E+01	0.421E+02	0.949E+02
0.195E+03	0.973E+00	0.406E+02	0.952E+02
0.200E+03	0.922E+00	0.392E+02	0.954E+02
0.205E+03	0.873E+00	0.379E+02	0.957E+02
0.210E+03	0.827E+00	0.365E+02	0.959E+02
0.215E+03	0.783E+00	0.353E+02	0.961E+02
0.220E+03	0.742E+00	0.340E+02	0.963E+02
0.225E+03	0.703E+00	0.328E+02	0.965E+02
0.230E+03	0.666E+00	0.316E+02	0.967E+02
0.235E+03	0.631E+00	0.304E+02	0.969E+02
0.240E+03	0.598E+00	0.293E+02	0.970E+02
0.245E+03	0.566E+00	0.282E+02	0.972E+02
0.250E+03	0.536E+00	0.271E+02	0.973E+02
0.255E+03	0.508E+00	0.261E+02	0.975E+02
0.260E+03	0.481E+00	0.251E+02	0.976E+02
0.265E+03	0.456E+00	0.242E+02	0.977E+02
0.270E+03	0.432E+00	0.232E+02	0.979E+02
0.275E+03	0.409E+00	0.223E+02	0.980E+02
0.280E+03	0.388E+00	0.215E+02	0.981E+02
0.285E+03	0.367E+00	0.206E+02	0.982E+02
0.290E+03	0.348E+00	0.198E+02	0.983E+02
0.295E+03	0.329E+00	0.190E+02	0.984E+02
0.300E+03	0.312E+00	0.183E+02	0.985E+02
0.305E+03	0.296E+00	0.176E+02	0.986E+02
0.310E+03	0.280E+00	0.168E+02	0.986E+02
0.315E+03	0.265E+00	0.162E+02	0.987E+02
0.320E+03	0.251E+00	0.155E+02	0.988E+02
0.325E+03	0.238E+00	0.149E+02	0.989E+02
0.330E+03	0.226E+00	0.143E+02	0.989E+02
0.335E+03	0.214E+00	0.137E+02	0.990E+02
0.340E+03	0.202E+00	0.131E+02	0.990E+02
0.345E+03	0.192E+00	0.126E+02	0.991E+02
0.350E+03	0.182E+00	0.121E+02	0.992E+02
0.355E+03	0.172E+00	0.116E+02	0.992E+02
0.360E+03	0.163E+00	0.111E+02	0.992E+02
0.365E+03	0.154E+00	0.107E+02	0.993E+02
0.370E+03	0.146E+00	0.102E+02	0.993E+02
0.375E+03	0.139E+00	0.979E+01	0.994E+02
0.380E+03	0.131E+00	0.938E+01	0.994E+02
0.385E+03	0.124E+00	0.899E+01	0.994E+02
0.390E+03	0.118E+00	0.861E+01	0.995E+02
0.395E+03	0.112E+00	0.825E+01	0.995E+02
0.400E+03	0.106E+00	0.790E+01	0.995E+02
0.405E+03	0.000E+00	0.000E+00	0.000E+00
0.000E+00	0.000E+00	0.000E+00	0.000E+00
0.000E+00	0.000E+00	0.000E+00	0.000E+00

TABLE B-1-4.

Heat Transfer Characteristics During Shut-Down Process (Oil Coolant, P=3500 KPa, Re=1250).

APPENDIX B-2

OIL COOLANT

THERMAL CONTACT RESISTANCE AND AFFECTIVE TEMPERATURE DROP

Start-Up Process: Table (B-2-1) - (B-2-2)

Shut-Down Process: Table (B-2-3) - (B-2-4)

RE = 1250.
PRESSURE (KPa)= 0.
FLUID :OIL

TIME	D1	R1
0.000E+00	0.000E+00	0.000E+00
0.100E+01	0.966E-01	0.428E-04
0.200E+01	0.194E+00	0.861E-04
0.300E+01	0.293E+00	0.130E-03
0.400E+01	0.394E+00	0.174E-03
0.500E+01	0.495E+00	0.219E-03
0.600E+01	0.598E+00	0.265E-03
0.700E+01	0.702E+00	0.311E-03
0.800E+01	0.807E+00	0.358E-03
0.900E+01	0.914E+00	0.405E-03
0.100E+02	0.102E+01	0.452E-03
0.110E+02	0.113E+01	0.501E-03
0.120E+02	0.124E+01	0.550E-03
0.130E+02	0.135E+01	0.599E-03
0.140E+02	0.147E+01	0.650E-03
0.150E+02	0.158E+01	0.700E-03
0.160E+02	0.170E+01	0.752E-03
0.170E+02	0.181E+01	0.804E-03
0.180E+02	0.193E+01	0.856E-03
0.190E+02	0.205E+01	0.910E-03
0.200E+02	0.218E+01	0.964E-03
0.210E+02	0.230E+01	0.102E-02
0.220E+02	0.242E+01	0.107E-02
0.230E+02	0.255E+01	0.113E-02
0.240E+02	0.268E+01	0.119E-02
0.250E+02	0.281E+01	0.124E-02
0.260E+02	0.294E+01	0.130E-02
0.270E+02	0.307E+01	0.136E-02
0.280E+02	0.321E+01	0.142E-02
0.290E+02	0.334E+01	0.148E-02
0.300E+02	0.348E+01	0.154E-02
0.310E+02	0.362E+01	0.160E-02
0.320E+02	0.376E+01	0.167E-02
0.330E+02	0.390E+01	0.173E-02
0.340E+02	0.405E+01	0.179E-02
0.350E+02	0.419E+01	0.186E-02
0.360E+02	0.434E+01	0.192E-02
0.370E+02	0.449E+01	0.199E-02
0.380E+02	0.464E+01	0.206E-02
0.390E+02	0.480E+01	0.212E-02
0.400E+02	0.495E+01	0.219E-02
0.410E+02	0.511E+01	0.226E-02
0.420E+02	0.527E+01	0.233E-02
0.430E+02	0.543E+01	0.240E-02
0.440E+02	0.559E+01	0.248E-02
0.450E+02	0.576E+01	0.255E-02
0.460E+02	0.593E+01	0.262E-02
0.470E+02	0.609E+01	0.270E-02
0.480E+02	0.627E+01	0.278E-02
0.490E+02	0.644E+01	0.285E-02
0.500E+02	0.662E+01	0.293E-02
0.510E+02	0.679E+01	0.301E-02
0.520E+02	0.697E+01	0.309E-02
0.530E+02	0.716E+01	0.317E-02
0.540E+02	0.734E+01	0.325E-02
0.550E+02	0.753E+01	0.333E-02
0.560E+02	0.772E+01	0.342E-02
0.570E+02	0.791E+01	0.350E-02
0.580E+02	0.810E+01	0.359E-02
0.590E+02	0.830E+01	0.367E-02

TABLE B-2-1.

Effective Temperature Drop and Thermal Contact Resistance During Start-Up Process (Oil Coolant, P=0 KPa, Re=1250).

RE = 1250.
PRESSURE (KPa)= 3500.
FLUID :OIL

TIME	DS	RS
0.000E+00	0.000E+00	0.000E+00
0.100E+01	0.560E-01	0.188E-04
0.200E+01	0.113E+00	0.378E-04
0.300E+01	0.170E+00	0.570E-04
0.400E+01	0.228E+00	0.765E-04
0.500E+01	0.287E+00	0.962E-04
0.600E+01	0.346E+00	0.116E-03
0.700E+01	0.407E+00	0.136E-03
0.800E+01	0.468E+00	0.157E-03
0.900E+01	0.529E+00	0.177E-03
0.100E+02	0.592E+00	0.198E-03
0.110E+02	0.655E+00	0.220E-03
0.120E+02	0.719E+00	0.241E-03
0.130E+02	0.784E+00	0.263E-03
0.140E+02	0.849E+00	0.285E-03
0.150E+02	0.916E+00	0.307E-03
0.160E+02	0.983E+00	0.330E-03
0.170E+02	0.105E+01	0.352E-03
0.180E+02	0.112E+01	0.375E-03
0.190E+02	0.119E+01	0.399E-03
0.200E+02	0.126E+01	0.422E-03
0.210E+02	0.133E+01	0.446E-03
0.220E+02	0.140E+01	0.471E-03
0.230E+02	0.148E+01	0.495E-03
0.240E+02	0.155E+01	0.520E-03
0.250E+02	0.163E+01	0.545E-03
0.260E+02	0.170E+01	0.571E-03
0.270E+02	0.178E+01	0.596E-03
0.280E+02	0.186E+01	0.622E-03
0.290E+02	0.194E+01	0.649E-03
0.300E+02	0.202E+01	0.676E-03
0.310E+02	0.210E+01	0.703E-03
0.320E+02	0.218E+01	0.730E-03
0.330E+02	0.226E+01	0.758E-03
0.340E+02	0.234E+01	0.786E-03
0.350E+02	0.243E+01	0.814E-03
0.360E+02	0.252E+01	0.843E-03
0.370E+02	0.260E+01	0.872E-03
0.380E+02	0.269E+01	0.902E-03
0.390E+02	0.278E+01	0.931E-03
0.400E+02	0.287E+01	0.962E-03
0.410E+02	0.296E+01	0.992E-03
0.420E+02	0.305E+01	0.102E-02
0.430E+02	0.315E+01	0.105E-02
0.440E+02	0.324E+01	0.109E-02
0.450E+02	0.334E+01	0.112E-02
0.460E+02	0.343E+01	0.115E-02
0.470E+02	0.353E+01	0.118E-02
0.480E+02	0.363E+01	0.122E-02
0.490E+02	0.373E+01	0.125E-02
0.500E+02	0.383E+01	0.128E-02
0.510E+02	0.394E+01	0.132E-02
0.520E+02	0.404E+01	0.135E-02
0.530E+02	0.415E+01	0.139E-02
0.540E+02	0.425E+01	0.143E-02
0.550E+02	0.436E+01	0.146E-02
0.560E+02	0.447E+01	0.150E-02
0.570E+02	0.458E+01	0.154E-02
0.580E+02	0.469E+01	0.157E-02
0.590E+02	0.481E+01	0.161E-02

TABLE B-2-2.

Effective Temperature Drop and Thermal Contact Resistance During Start-Up Process (Oil Coolant, P=3500 KPa, Re=1250).

RE = 1250.
PRESSURE (KPa)= 0.
FLUID :OIL

TIME	D1	R1
0.120E+03	0.899E+01	0.375E-02
0.125E+03	0.880E+01	0.368E-02
0.130E+03	0.862E+01	0.362E-02
0.135E+03	0.844E+01	0.356E-02
0.140E+03	0.827E+01	0.350E-02
0.145E+03	0.810E+01	0.344E-02
0.150E+03	0.793E+01	0.338E-02
0.155E+03	0.777E+01	0.333E-02
0.160E+03	0.761E+01	0.327E-02
0.165E+03	0.745E+01	0.322E-02
0.170E+03	0.730E+01	0.316E-02
0.175E+03	0.715E+01	0.311E-02
0.180E+03	0.700E+01	0.306E-02
0.185E+03	0.686E+01	0.300E-02
0.190E+03	0.672E+01	0.295E-02
0.195E+03	0.658E+01	0.290E-02
0.200E+03	0.645E+01	0.286E-02
0.205E+03	0.631E+01	0.281E-02
0.210E+03	0.618E+01	0.276E-02
0.215E+03	0.606E+01	0.271E-02
0.220E+03	0.593E+01	0.267E-02
0.225E+03	0.581E+01	0.262E-02
0.230E+03	0.569E+01	0.258E-02
0.235E+03	0.557E+01	0.254E-02
0.240E+03	0.546E+01	0.249E-02
0.245E+03	0.535E+01	0.245E-02
0.250E+03	0.524E+01	0.241E-02
0.255E+03	0.513E+01	0.237E-02
0.260E+03	0.502E+01	0.233E-02
0.265E+03	0.492E+01	0.229E-02
0.270E+03	0.482E+01	0.225E-02
0.275E+03	0.472E+01	0.221E-02
0.280E+03	0.462E+01	0.218E-02
0.285E+03	0.453E+01	0.214E-02
0.290E+03	0.443E+01	0.210E-02
0.295E+03	0.434E+01	0.207E-02
0.300E+03	0.425E+01	0.203E-02
0.305E+03	0.417E+01	0.200E-02
0.310E+03	0.408E+01	0.197E-02
0.315E+03	0.400E+01	0.193E-02
0.320E+03	0.391E+01	0.190E-02
0.325E+03	0.383E+01	0.187E-02
0.330E+03	0.375E+01	0.184E-02
0.335E+03	0.368E+01	0.181E-02
0.340E+03	0.360E+01	0.178E-02
0.345E+03	0.353E+01	0.175E-02
0.350E+03	0.346E+01	0.172E-02
0.355E+03	0.338E+01	0.169E-02
0.360E+03	0.331E+01	0.166E-02
0.365E+03	0.325E+01	0.163E-02
0.370E+03	0.318E+01	0.160E-02
0.375E+03	0.311E+01	0.158E-02
0.380E+03	0.305E+01	0.155E-02
0.385E+03	0.299E+01	0.153E-02
0.390E+03	0.293E+01	0.150E-02
0.395E+03	0.287E+01	0.147E-02
0.400E+03	0.281E+01	0.145E-02
0.405E+03	0.000E+00	0.000E+00
0.000E+00	0.000E+00	0.000E+00
0.000E+00	0.000E+00	0.000E+00

TABLE B-2-3.

Effective Temperature Drop and Thermal Contact Resistance During Shut-Down Process (Oil Coolant, P=0 KPa, Re=1250).

RE = 1250.
PRESSURE (KPa)= 3600.
FLUID :OIL

TIME	DS	RS
----	--	--
0.120E+03	0.692E+01	0.160E-02
0.125E+03	0.677E+01	0.158E-02
0.130E+03	0.663E+01	0.155E-02
0.135E+03	0.650E+01	0.152E-02
0.140E+03	0.636E+01	0.150E-02
0.145E+03	0.623E+01	0.147E-02
0.150E+03	0.610E+01	0.145E-02
0.155E+03	0.598E+01	0.142E-02
0.160E+03	0.586E+01	0.140E-02
0.165E+03	0.574E+01	0.138E-02
0.170E+03	0.562E+01	0.135E-02
0.175E+03	0.550E+01	0.133E-02
0.180E+03	0.539E+01	0.131E-02
0.185E+03	0.528E+01	0.129E-02
0.190E-03	0.517E+01	0.126E-02
0.195E+03	0.506E+01	0.124E-02
0.200E+03	0.496E+01	0.122E-02
0.205E+03	0.486E+01	0.120E-02
0.210E+03	0.476E+01	0.118E-02
0.215E+03	0.466E+01	0.116E-02
0.220E+03	0.456E+01	0.114E-02
0.225E+03	0.447E+01	0.112E-02
0.230E+03	0.438E+01	0.110E-02
0.235E+03	0.429E+01	0.109E-02
0.240E+03	0.420E+01	0.107E-02
0.245E+03	0.411E+01	0.105E-02
0.250E+03	0.403E+01	0.103E-02
0.255E+03	0.395E+01	0.101E-02
0.260E+03	0.386E+01	0.998E-03
0.265E+03	0.379E+01	0.981E-03
0.270E+03	0.371E+01	0.964E-03
0.275E+03	0.363E+01	0.948E-03
0.280E+03	0.356E+01	0.932E-03
0.285E+03	0.348E+01	0.917E-03
0.290E+03	0.341E+01	0.901E-03
0.295E+03	0.334E+01	0.886E-03
0.300E+03	0.327E+01	0.871E-03
0.305E+03	0.321E+01	0.857E-03
0.310E+03	0.314E+01	0.842E-03
0.315E+03	0.308E+01	0.828E-03
0.320E+03	0.301E+01	0.814E-03
0.325E+03	0.295E+01	0.800E-03
0.330E+03	0.289E+01	0.787E-03
0.335E+03	0.283E+01	0.774E-03
0.340E+03	0.277E+01	0.761E-03
0.345E+03	0.271E+01	0.748E-03
0.350E+03	0.266E+01	0.735E-03
0.355E+03	0.260E+01	0.723E-03
0.360E+03	0.255E+01	0.711E-03
0.365E+03	0.250E+01	0.699E-03
0.370E+03	0.245E+01	0.687E-03
0.375E+03	0.240E+01	0.676E-03
0.380E+03	0.235E+01	0.664E-03
0.385E+03	0.230E+01	0.653E-03
0.390E+03	0.225E+01	0.642E-03
0.395E+03	0.221E+01	0.631E-03
0.400E+03	0.216E+01	0.621E-03
0.405E+03	0.000E+00	0.000E+00
0.000E+00	0.000E+00	0.000E+00
0.000E+00	0.000E+00	0.000E+00

TABLE B-2-4.

Effective Temperature Drop and Thermal Contact Resistance During Shut-Down Process (Oil Coolant, P=3500 KPa, Re=1250).

APPENDIX C

PART 1: EXAMPLES OF TEMPERATURE DISTRIBUTION DURING START-UP PROCESS WITH OIL COOLANT

TABLE (C-1) - TABLE (C-2)

TABLE C-1. Examples of Temperature Distribution During Start-Up Process with Oil Coolant (P=0 KPa, Re=15).

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 10.00
ENDING TIME = 20.00
AVERAGE TEMPERATURE = 72.456
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.15000E+02
COOLANT:OIL

91.029	89.919	88.810	87.701	86.592	85.483	84.374	83.264	82.155
89.009	87.897	86.785	85.673	84.562	83.450	82.338	81.226	80.114
86.839	85.726	84.614	83.501	82.388	81.276	80.163	79.050	77.937
84.756	83.641	82.527	81.412	80.297	79.182	78.067	76.953	75.838
82.622	81.506	80.389	79.273	78.157	77.040	75.924	74.808	73.692
80.588	79.468	78.349	77.230	76.111	74.991	73.872	72.753	71.634
78.346	77.227	76.107	74.988	73.868	72.749	71.630	70.510	69.391
75.310	74.202	73.094	71.986	70.878	69.771	68.663	67.555	66.447
73.040	71.933	70.826	69.718	68.611	67.504	66.397	65.289	64.182
70.741	69.635	68.529	67.423	66.317	65.210	64.104	62.998	61.892
67.414	66.326	65.238	64.149	63.061	61.972	60.884	59.795	58.707
62.700	61.654	60.608	59.561	58.515	57.469	56.422	55.376	54.330

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 20.00
ENDING TIME = 30.00
AVERAGE TEMPERATURE = 81.694
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.15000E+02
COOLANT:OIL

102.898	101.644	100.390	99.137	97.883	96.629	95.375	94.121	92.868
100.838	99.578	98.319	97.059	95.799	94.540	93.280	92.021	90.761
98.457	97.195	95.933	94.672	93.410	92.149	90.887	89.626	88.364
96.265	94.998	93.732	92.466	91.200	89.934	88.668	87.402	86.135
93.956	92.687	91.417	90.148	88.878	87.609	86.340	85.070	83.801
91.877	90.601	89.325	88.049	86.773	85.497	84.221	82.945	81.669
89.370	88.093	86.816	85.539	84.263	82.986	81.709	80.432	79.155
85.023	83.773	82.522	81.271	80.020	78.770	77.519	76.268	75.017

TABLE C-1. Continued.

82.417	81.167	79.918	78.668	77.419	76.170	74.920	73.671	72.421
79.744	78.497	77.250	76.003	74.756	73.509	72.262	71.015	69.768
74.767	73.560	72.353	71.146	69.939	68.732	67.525	66.317	65.110
66.855	65.739	64.623	63.508	62.392	61.276	60.161	59.045	57.929

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 30.00
ENDING TIME = 40.00
AVERAGE TEMPERATURE = 92.659
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.15000E+02
COOLANT:OIL

116.999	115.574	114.148	112.722	111.297	109.871	108.445	107.020	105.594
114.890	113.454	112.019	110.584	109.149	107.714	106.279	104.844	103.409
112.263	110.824	109.386	107.947	106.509	105.070	103.632	102.193	100.755
109.947	108.501	107.055	105.609	104.163	102.717	101.271	99.824	98.378
107.432	105.980	104.529	103.077	101.626	100.175	98.723	97.272	95.820
105.313	103.850	102.388	100.925	99.462	98.000	96.537	95.074	93.612
102.537	101.072	99.607	98.142	95.677	95.212	93.747	92.282	90.817
96.546	95.126	93.706	92.285	90.865	89.445	88.025	86.604	85.184
93.536	92.118	90.700	89.282	87.864	86.446	85.028	83.610	82.192
90.413	89.000	87.586	86.172	84.758	83.344	81.931	80.517	79.103
83.396	82.050	80.703	79.357	78.011	76.664	75.318	73.971	72.625
71.698	70.501	69.305	68.108	66.912	65.715	64.519	63.322	62.126

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 40.00
ENDING TIME = 50.00
AVERAGE TEMPERATURE =105.720
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.15000E+02
COOLANT:OIL

133.815	132.185	130.554	128.924	127.293	125.663	124.032	122.402	120.771
131.645	130.001	128.356	126.712	125.067	123.423	121.779	120.134	118.490
128.732	127.083	125.433	123.784	122.134	120.485	118.835	117.186	115.536
126.277	124.616	122.955	121.294	119.634	117.973	116.312	114.651	112.990

TABLE C-1. Continued.

123.515	121.847	120.178	118.509	116.840	115.172	113.503	111.834	110.16[illegible]
121.365	119.679	117.994	116.308	114.623	112.937	111.252	109.566	107.88[illegible]
118.325	116.635	114.944	113.253	111.563	109.872	108.182	106.491	104.800
110.267	108.645	107.023	105.400	103.778	102.156	100.534	98.912	97.290
106.771	105.153	103.534	101.915	100.297	98.678	97.059	95.441	93.822
103.105	101.493	99.880	98.268	96.656	95.044	93.431	91.819	90.207
93.553	92.043	90.532	89.022	87.511	86.001	84.490	82.980	81.469
77.337	76.047	74.756	73.466	72.175	70.884	69.594	68.303	67.013

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 50.00
ENDING TIME = 60.00
AVERAGE TEMPERATURE =121.337
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.15000E+02
COOLANT:OIL

153.949	152.073	150.197	148.321	146.446	144.570	142.594	140.818	138.942
151.703	149.809	147.913	146.019	144.124	142.229	140.334	138.439	136.544
148.457	146.555	144.652	142.750	140.848	138.946	137.043	135.141	133.239
145.844	143.925	142.007	140.089	138.171	136.252	134.334	132.416	130.495
142.787	140.858	138.929	137.000	135.070	133.141	131.212	129.283	127.35[illegible]
140.619	138.656	136.713	134.760	132.807	130.854	128.901	126.948	124.995
137.337	135.374	133.412	131.450	129.488	127.525	125.563	123.601	121.639
126.667	124.804	122.941	121.077	119.214	117.350	115.487	113.624	111.760
122.586	120.728	118.969	117.011	115.152	113.294	111.436	109.577	107.719
118.260	116.411	114.561	112.712	110.863	109.014	107.164	105.315	103.466
105.547	103.842	102.138	100.434	98.730	97.026	95.322	93.618	91.914
83.904	82.504	81.104	79.704	78.304	76.904	75.503	74.103	72.703

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 60.00
ENDING TIME = 70.00
AVERAGE TEMPERATURE =140.085
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.15000E+02
COOLANT:OIL

TABLE C-1. Continued.

178.154	175.983	173.812	171.641	169.470	167.300	165.129	162.958	160.767
175.814	173.618	171.422	169.225	167.029	164.833	162.637	160.441	158.245
172.177	169.971	167.765	165.559	163.352	161.146	158.940	156.734	154.528
169.384	167.156	164.928	162.701	160.473	158.245	156.017	153.789	151.561
165.972	163.730	161.487	159.245	157.002	154.760	152.518	150.275	148.033
163.806	161.531	159.256	156.981	154.706	152.431	150.156	147.881	145.606
160.327	158.036	155.745	153.455	151.164	148.873	146.583	144.292	142.001
146.351	144.198	142.045	139.892	137.739	135.586	133.433	131.280	129.127
141.559	139.413	137.267	135.121	132.975	130.829	128.683	126.537	124.391
136.429	134.295	132.162	130.029	127.895	125.762	123.629	121.495	119.362
119.758	117.825	115.891	113.958	112.024	110.091	108.157	106.224	104.290
91.557	90.029	88.501	86.973	85.445	83.917	82.390	80.862	79.334

TABLE C-2. Examples of Temperature Distribution During Start-Up Process with Oil Coolant (P=3500, Re=15).

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 10.00
ENDING TIME = 20.00
AVERAGE TEMPERATURE = 74.505
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.15000E+02
COOLANT:oil

91.029	90.107	89.186	88.264	87.343	86.421	85.500	84.578	83.657
89.197	88.273	87.350	86.426	85.502	84.578	83.655	82.731	81.807
87.216	86.291	85.367	84.442	83.518	82.594	81.669	80.745	79.820
85.322	84.396	83.470	82.544	81.617	80.691	79.765	78.839	77.913
83.377	82.450	81.522	80.595	79.668	78.740	77.813	76.886	75.958
81.534	80.605	79.675	78.745	77.815	76.385	75.955	75.025	74.096
79.482	78.552	77.622	76.692	75.762	74.832	73.902	72.972	72.043
76.622	75.702	74.781	73.861	72.940	72.020	71.100	70.179	69.259
74.539	73.619	72.699	71.779	70.859	69.939	69.020	68.100	67.180
72.426	71.507	70.588	69.669	68.750	67.831	66.912	65.993	65.074
69.256	68.352	67.447	66.543	65.639	64.735	63.830	62.926	62.022
64.648	63.778	62.909	62.040	61.171	60.301	59.432	58.563	57.693

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 20.00
ENDING TIME = 30.00
AVERAGE TEMPERATURE = 83.995
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.15000E+02
COOLANT:oil

102.898	101.856	100.815	99.773	98.731	97.690	96.648	95.606	94.565
101.051	100.004	98.958	97.912	96.865	95.819	94.772	93.726	92.679
98.883	97.835	96.787	95.739	94.691	93.643	92.595	91.547	90.499
96.907	95.855	94.803	93.752	92.700	91.648	90.596	89.544	88.492
94.815	93.760	92.706	91.651	90.597	89.542	88.487	87.433	86.378
92.956	91.896	90.836	89.776	88.716	87.656	86.596	85.536	84.475
90.666	89.606	88.545	87.484	86.423	85.362	84.301	83.241	82.180
86.505	85.466	84.427	83.387	82.348	81.309	80.270	79.231	78.192

TABLE C-2. Continued.

84.106	83.070	82.032	80.994	79.956	78.918	77.880	76.842	75.804
81.643	80.607	79.571	78.535	77.499	76.463	75.427	74.391	73.355
76.810	75.807	74.804	73.801	72.798	71.795	70.793	69.790	68.787
68.931	68.004	67,077	66.151	65.224	64.297	63.370	62.443	61.515

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 30.00
ENDING TIME = 40.00
AVERAGE TEMPERATURE = 95.257
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.15000E+02
COOLANT:oil

116.999	115.815	114.630	113.446	112.262	111.077	109.893	108.708	107.524
115.132	113.940	112.748	111.556	110.363	109.171	107.979	106.786	105.594
112.749	111.554	110.353	109.164	107.969	106.774	105.579	104.384	103.189
110.681	109.480	108.279	107.077	105.876	104.674	103.473	102.271	101.070
108.414	107.208	106.002	104.797	103.591	102.385	101.179	99.973	98.767
106.550	105.335	104.120	102.905	101.690	100.474	99.259	98.044	96.829
104.024	102.807	101.590	100.373	99.155	97.938	96.721	95.504	94.287
98.229	97.049	95.869	94.689	93.509	92.329	91.149	89.969	88.789
95.456	94.277	93.099	91.921	90.743	89.565	88.387	87.209	86.031
92.566	91.392	90.217	89.043	87.868	86.693	85.519	84.344	83.170
85.675	84.556	83.437	82.319	81.200	80.081	78.963	77.844	76.725
73.925	72.931	71.937	70.943	69.948	68.954	67.960	66.966	65.972

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 40.00
ENDING TIME = 50.00
AVERAGE TEMPERATURE =108.672
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.15000E+02
COOLANT:oil

133.815	132.461	131.106	129.752	128.397	127.042	125.688	124.333	122.978
131.923	130.557	129.191	127.825	126.459	125.092	123.726	122.360	120.994
129.290	127.920	126.550	125.179	123.809	122.438	121.068	119.697	118.327
127.120	125.740	124.360	122.981	121.601	120.221	118.841	117.461	116.081

TABLE C-2. Continued.

124.645	123.258	121.872	120.486	119.099	117.713	116.326	114.940	113.554
122.791	121.391	119.990	118.590	117.189	115.789	114.389	112.988	111.588
120.042	118.637	117.232	115.828	114.423	113.019	111.614	110.210	108.805
112.188	110.840	109.493	108.145	106.797	105.450	104.102	102.754	101.407
108.962	107.617	106.273	104.928	103.583	102.238	100.894	99.549	98.204
105.560	104.221	102.881	101.542	100.202	98.863	97.523	96.184	94.844
96.109	94.854	93.599	92.344	91.089	89.834	88.579	87.325	86.070
79.739	78.667	77.595	76.523	75.451	74.378	73.306	72.234	71.162

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 50.00
ENDING TIME = 60.00
AVERAGE TEMPERATURE =124.712
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.15000E+02
COOLANT:oil

153.949	152.391	150.832	149.274	147.715	146.157	144.598	143.040	141.481
152.024	150.450	148.875	147.301	145.727	144.152	142.578	141.004	139.429
149.101	147.520	145.940	144.359	142.779	141.199	139.618	138.038	136.458
146.817	145.224	143.630	142.036	140.443	138.849	137.255	135.662	134.068
144.093	142.490	140.887	139.284	137.682	136.079	134.476	132.674	131.271
142.271	140.648	139.026	137.403	135.781	134.158	132.536	130.913	129.291
139.329	137.698	136.068	134.438	132.808	131.178	129.547	127.917	126.287
128.874	127.326	125.778	124.230	122.682	121.134	119.586	118.038	116.489
125.101	123.557	122.013	120.470	118.926	117.382	115.838	114.294	112.750
121.076	119.539	118.003	116.467	114.930	113.394	111.858	110.321	108.785
108.430	107.014	105.598	104.183	102.767	101.351	99.935	98.520	97.104
86.510	85.347	84.184	83.021	81.857	80.694	79.531	78.368	77.204

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME = 60.00
ENDING TIME = 70.00
AVERAGE TEMPERATURE =143.966
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.15000E+02
COOLANT:oil

TABLE C-2. Continued.

178.154	176.350	174.547	172.743	170.940	169.136	167.333	165.529	163.729
176.185	174.361	172.536	170.712	168.887	167.063	165.238	163.414	161.589
172.924	171.091	169.258	167.425	165.592	163.759	161.926	160.093	158.252
170.515	168.664	166.813	164.962	163.111	161.260	159.410	157.559	155.708
167.490	165.627	163.764	161.901	160.038	158.175	156.312	154.449	152.586
165.731	163.841	161.951	160.061	158.171	156.280	154.390	152.500	150.610
162.652	160.749	158.846	156.943	155.040	153.137	151.234	149.331	147.427
148.901	147.112	145.323	143.535	141.746	139.957	138.169	136.380	134.591
144.464	142.681	140.898	139.115	137.332	135.549	133.766	131.983	130.201
139.677	137.905	136.133	134.360	132.588	130.815	129.043	127.271	125.498
123.030	121.423	119.817	118.211	116.604	114.998	113.392	111.785	110.179
94.401	93.131	91.862	90.592	89.323	88.054	86.784	85.515	84.246

PART 2: EXAMPLES OF TEMPERATURE DISTRIBUTION DURING SHUT-DOWN PROCESS WITH OIL COOLANT

TABLE (C-4) - TABLE (C-5)

TABLE C-5. Example of Temperature Distribution During Shut-Down Process with Oil Coolant (P=0 KPa, Re=15).

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME -120.00
ENDING TIME -150.00
AVERAGE TEMPERATURE -185.641
PRESURE- 0.0 KPa
REYNOLD'S NUMBER- 0.15000E+02
COOLANT:OIL

208.054	206.636	205.219	203.802	202.384	200.967	199.550	198.133	196.715
205.684	204.267	202.850	201.432	200.015	198.598	197.181	195.764	194.346
202.446	201.034	199.623	198.212	196.801	195.390	193.979	192.568	191.157
199.650	198.242	196.834	195.426	194.018	192.610	191.202	189.794	168.356
197.062	195.656	194.250	192.843	191.437	190.031	188.625	187.218	165.812
194.478	193.073	191.669	190.264	188.860	187.455	186.051	184.646	183.242
191.902	190.499	189.096	187.694	186.291	184.888	183.485	182.082	180.680
189.291	187.890	186.490	185.089	183.688	182.287	180.887	179.466	176.085
186.737	185.338	183.939	162.539	181.140	179.741	178.342	176.943	175.544
184.182	182.784	181.387	179.989	178.592	177.194	175.797	174.400	173.002
181.741	180.345	178.948	177.551	176.155	174.758	173.362	171.965	170.569
179.177	177.782	176.387	174.993	173.598	172.203	170.809	169.414	168.019

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME -150.00
ENDING TIME -180.00
AVERAGE TEMPERATURE -171.446
PRESURE- 0.0 KPa
REYNOLD'S NUMBER- 0.15000E+02
COOLANT:OIL

194.247	192.924	191.600	190.277	188.954	187.631	186.308	184.964	183.661
192.026	190.703	189.380	188.057	186.734	185.410	184.087	182.764	181.441
187.942	186.632	185.322	184.012	182.702	181.392	180.082	178.772	177.462
184.875	183.571	182.268	180.964	179.660	178.356	177.052	175.749	174.445
182.200	180.899	179.599	178.299	176.999	175.699	174.398	173.098	171.798
179.533	178.236	176.940	175.643	174.346	173.050	171.753	170.457	169.160
176.884	175.591	174.298	173.005	171.712	170.419	169.126	167.833	166.540
174.164	172.875	171.586	170.297	169.008	167.720	166.431	165.142	163.853

TABLE C-3. (Continued)

171.561	170.276	168.990	167.705	166.419	165.134	163.849	162.563	161.276
168.957	167.675	166.393	165.112	163.830	162.548	161.266	159.984	158.702
166.591	165.311	164.031	162.751	161.471	160.190	158.919	157.630	156.350
163.970	162.694	161.417	160.141	158.864	157.588	156.312	155.035	153.759

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =180.00
ENDING TIME =210.00
AVERAGE TEMPERATURE =156.126
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.15000E+02
COOLANT:OIL

179.207	177.986	176.765	175.544	174.324	173.103	171.882	170.661	169.441
177.148	175.927	174.707	173.486	172.266	171.045	169.825	168.604	167.383
172.182	170.982	169.782	168.582	167.382	166.182	164.982	163.781	162.581
168.886	167.695	166.504	165.313	164.122	162.931	161.740	160.549	159.358
166.137	164.951	163.766	162.580	161.395	160.209	159.024	157.838	156.652
163.402	162.222	161.042	159.862	158.682	157.501	156.321	155.141	153.961
160.696	159.521	158.346	157.172	155.997	154.822	153.648	152.473	151.298
157.883	156.715	155.546	154.378	153.210	152.041	150.873	149.705	148.536
155.250	154.086	152.923	151.760	150.597	149.434	148.270	147.107	145.944
152.616	151.458	150.300	149.142	147.984	146.826	145.668	144.510	143.352
150.340	149.185	148.030	146.875	145.719	144.564	143.409	142.253	141.098
147.682	146.533	145.383	144.233	143.084	141.934	140.785	139.635	138.486

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =210.00
ENDING TIME =240.00
AVERAGE TEMPERATURE =140.193
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.15000E+02
COOLANT:OIL

163.371	162.258	161.145	160.032	158.919	157.807	156.694	155.581	154.468
161.484	160.371	159.259	158.146	157.034	155.921	154.808	153.696	152.583
155.669	154.584	153.499	152.414	151.329	150.244	149.159	148.074	146.989
152.201	151.128	150.054	148.981	147.908	146.834	145.761	144.688	143.614

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TABLE C-3. (Continued).

149.403	148.337	147.271	146.204	145.138	144.072	143.006	141.940	140.874
146.626	145.567	144.508	143.449	142.390	141.331	140.272	139.213	138.154
143.889	142.837	141.785	140.734	139.682	138.630	137.578	136.526	135.474
141.015	139.971	138.926	137.884	136.841	135.797	134.754	133.710	132.667
138.378	137.341	136.304	135.267	134.230	133.194	132.157	131.120	130.083
135.742	134.712	133.682	132.652	131.622	130.592	129.562	128.532	127.502
133.575	132.548	131.522	130.495	129.469	128.443	127.416	126.390	125.363
130.910	129.891	128.872	127.853	126.834	125.815	124.796	123.777	122.758

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =240.00
ENDING TIME =270.00
AVERAGE TEMPERATURE =124.137
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.15000E+02
COOLANT:OIL

147.169	146.167	145.164	144.162	143.159	142.157	141.154	140.152	139.149
145.459	144.457	143.455	142.452	141.450	140.448	139.446	138.443	137.441
138.889	137.921	136.953	135.985	135.017	134.048	133.080	132.112	131.144
135.315	134.361	133.407	132.453	131.498	130.544	129.590	128.636	127.681
132.503	131.557	130.612	129.666	128.721	127.775	126.830	125.884	124.939
129.719	128.782	127.845	126.909	125.972	125.035	124.098	123.161	122.224
126.987	126.056	125.130	124.202	123.274	122.345	121.427	120.489	119.560
124.092	123.174	122.255	121.337	120.419	119.501	118.582	117.664	116.746
121.485	120.575	119.665	118.755	117.844	116.934	116.024	115.114	114.203
118.883	117.981	117.079	116.177	115.275	114.373	113.471	112.569	111.667
116.842	115.944	115.046	114.148	113.250	112.353	111.455	110.557	109.659
114.209	113.320	112.431	111.542	110.653	109.764	108.875	107.986	107.097

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =270.00
ENDING TIME =300.00
AVERAGE TEMPERATURE =108.397
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.15000E+02
COOLANT:OIL

TABLE C-3. (Continued).

131.003	130.110	129.218	128.325	127.433	126.541	125.648	124.756	123.863
129.470	128.578	127.686	126.794	125.901	125.009	124.117	123.225	122.333
122.287	121.435	120.583	119.730	118.878	118.025	117.173	116.321	115.468
118.682	117.845	117.008	116.171	115.334	114.497	113.660	112.823	111.986
115.896	115.069	114.242	113.414	112.587	111.760	110.933	110.106	109.279
113.145	112.328	111.511	110.694	109.877	109.060	108.243	107.426	106.608
110.457	109.650	108.843	108.035	107.228	106.420	105.613	104.805	103.998
107.591	106.794	105.998	105.202	104.406	103.610	102.813	102.017	101.221
105.052	104.265	103.478	102.691	101.904	101.117	100.329	99.542	98.755
102.522	101.744	100.966	100.188	99.410	98.632	97.854	97.077	96.299
100.623	99.850	99.076	98.303	97.530	96.757	95.984	95.210	94.437
98.064	97.301	96.537	95.774	95.011	94.247	93.484	92.721	91.957

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =300.00
ENDING TIME =330.00
AVERAGE TEMPERATURE = 93.345
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.15000E+02
COOLANT:OIL

115.230	114.445	113.660	112.875	112.090	111.305	110.520	109.735	108.950
113.871	113.086	112.302	111.517	110.733	109.948	109.163	108.379	107.594
106.254	105.513	104.773	104.032	103.291	102.551	101.810	101.069	100.329
102.690	101.966	101.242	100.518	99.793	99.069	98.345	97.621	96.897
99.973	99.259	98.546	97.833	97.119	96.406	95.692	94.979	94.266
97.299	96.597	95.894	95.191	94.489	93.786	93.083	92.381	91.678
94.698	94.005	93.313	92.621	91.929	91.237	90.544	89.852	89.160
91.908	91.228	90.548	89.868	89.188	88.508	87.828	87.147	86.467
89.476	88.806	88.136	87.465	86.795	86.124	85.454	84.784	84.113
87.057	86.396	85.736	85.075	84.415	83.754	83.094	82.433	81.773
85.314	84.658	84.003	83.347	82.692	82.036	81.381	80.725	80.069
82.871	82.225	81.580	80.935	80.290	79.645	79.000	78.355	77.710

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =330.00

TABLE C-3. (Continued).

ENDING TIME =360.00
AVERAGE TEMPERATURE = 79.277
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.15000E+02
COOLANT:OIL

100.154	99.472	98.790	98.107	97.425	96.743	96.061	95.378	94.696
98.964	98.282	97.600	96.918	96.236	95.554	94.872	94.190	93.509
91.108	90.473	89.838	89.203	88.568	87.933	87.298	86.663	86.028
87.656	87.038	86.419	85.801	85.183	84.565	83.947	83.329	82.710
85.050	84.443	83.836	83.229	82.622	82.015	81.408	80.801	80.194
82.494	81.898	81.303	80.707	80.111	79.515	78.920	78.324	77.728
80.019	79.434	78.849	78.264	77.679	77.094	76.509	75.924	75.339
77.355	76.782	76.210	75.637	75.065	74.493	73.920	73.348	72.775
75.065	74.502	73.940	73.377	72.815	72.253	71.690	71.128	70.565
72.792	72.240	71.687	71.135	70.583	70.030	69.478	68.926	68.374
71.215	70.667	70.120	69.573	69.026	68.478	67.931	67.384	66.837
68.924	68.388	67.851	67.315	66.778	66.242	65.705	65.169	64.632

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =360.00
ENDING TIME =390.00
AVERAGE TEMPERATURE = 66.407
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.15000E+02
COOLANT:OIL

86.019	85.433	84.847	84.261	83.675	83.089	82.503	81.917	81.331
84.987	84.402	83.816	83.231	82.645	82.060	81.474	80.888	80.303
77.094	76.556	76.019	75.482	74.944	74.407	73.870	73.332	72.795
73.814	73.293	72.773	72.252	71.732	71.211	70.691	70.170	69.650
71.357	70.848	70.338	69.829	69.320	68.811	68.302	67.792	67.283
68.957	68.459	67.961	67.463	66.965	66.467	65.969	65.471	64.973
66.642	66.155	65.668	65.181	64.694	64.206	63.719	63.232	62.745
64.146	63.671	63.197	62.722	62.247	61.772	61.298	60.823	60.348
62.028	61.563	61.098	60.634	60.169	59.704	59.239	58.775	58.310
59.931	59.477	59.022	58.567	58.112	57.658	57.203	56.748	56.294

TABLE C-3. (Continued).

58.525	58.075	57.626	57.176	56.726	56.277	55.827	55.377	54.927
56.419	55.980	55.541	55.102	54.662	54.223	53.784	53.345	52.906

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =390.00
ENDING TIME =420.00
AVERAGE TEMPERATURE = 54.867
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.15000E-02
COOLANT:OIL

73.003	72.506	72.009	71.511	71.014	70.517	70.019	69.522	69.025
72.119	71.622	71.125	70.628	70.132	69.635	69.138	68.641	68.144
64.377	63.928	63.480	63.031	62.582	62.133	61.685	61.236	60.787
61.320	60.888	60.455	60.023	59.590	59.158	58.726	58.293	57.861
59.044	58.622	58.201	57.780	57.358	56.937	56.516	56.094	55.673
56.829	56.419	56.008	55.598	55.187	54.777	54.367	53.956	53.546
54.703	54.304	53.904	53.504	53.104	52.704	52.304	51.904	51.504
52.409	52.021	51.633	51.245	50.857	50.469	50.082	49.694	49.306
50.485	50.106	49.728	49.350	48.972	48.593	48.215	47.837	47.459
48.587	48.218	47.849	47.481	47.112	46.743	46.375	46.006	45.638
47.352	46.989	46.625	46.261	45.897	45.533	45.169	44.805	44.441
45.453	45.099	44.745	44.391	44.038	43.684	43.330	42.976	42.622

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =420.00
ENDING TIME =450.00
AVERAGE TEMPERATURE = 44.717
PRESURE= 0.0 KPa
REYNOLD'S NUMBER= 0.15000E+02
COOLANT:OIL

61.222	60.805	60.388	59.971	59.554	59.137	58.720	58.303	57.886
60.473	60.057	59.640	59.223	58.807	58.390	57.973	57.557	57.140
53.051	52.681	52.311	51.942	51.572	51.202	50.832	50.462	50.093
50.255	49.900	49.546	49.191	48.837	48.483	48.128	47.774	47.419
48.182	47.838	47.494	47.151	46.807	46.463	46.119	45.775	45.431
46.175	45.841	45.508	45.174	44.841	44.507	44.174	43.840	43.507

TABLE C-3. (C ontinued).

44.256	43.934	43.611	43.287	42.964	42.640	42.316	41.993	41.669
42.188	41.876	41.563	41.251	40.939	40.627	40.315	40.002	39.690
40.472	40.169	39.866	39.562	39.259	38.956	38.653	38.349	38.046
38.786	38.491	38.197	37.903	37.609	37.314	37.020	36.726	36.431
37.719	37.430	37.140	36.850	36.560	36.270	35.980	35.691	35.401
36.040	35.759	35.478	35.198	34.917	34.637	34.356	34.076	33.795

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME -450.00
ENDING TIME -480.00
AVERAGE TEMPERATURE - 35.953
PRESURE- 0.0 KPa
REYNOLD'S NUMBER- 0.15000E+02
COOLANT:OIL

50.734	50.388	50.043	49.697	49.352	49.006	48.660	48.315	47.965
50.107	49.761	49.416	49.071	48.726	48.380	48.035	47.690	47.345
43.142	42.842	42.541	42.240	41.939	41.639	41.338	41.037	40.737
40.631	40.344	40.058	39.771	39.485	39.198	38.912	38.625	38.339
38.777	38.500	38.223	37.947	37.670	37.393	37.116	36.840	36.563
36.989	36.722	36.455	36.188	35.921	35.654	35.387	35.119	34.851
35.291	35.033	34.775	34.517	34.259	34.001	33.743	33.485	33.227
33.460	33.212	32.964	32.717	32.469	32.222	31.974	31.726	31.479
31.958	31.718	31.479	31.239	31.000	30.760	30.521	30.282	30.042
30.487	30.256	30.024	29.793	29.562	29.331	29.099	28.868	28.637
29.581	29.354	29.126	28.899	28.672	28.445	28.217	27.990	27.763
28.124	27.905	27.686	27.467	27.248	27.029	26.811	26.592	26.373

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME -480.00
ENDING TIME -510.00
AVERAGE TEMPERATURE - 28.519
PRESURE- 0.0 KPa
REYNOLD'S NUMBER- 0.15000E+02
COOLANT:OIL

41.544	41.261	40.978	40.695	40.412	40.129	39.846	39.563	39.280
41.024	40.742	40.459	40.176	39.894	39.611	39.328	39.046	38.763

TABLE C-3. (Continued).

34.623	34.362	34.140	33.899	33.658	33.416	33.175	32.934	32.692
32.407	32.179	31.950	31.722	31.493	31.265	31.036	30.807	30.579
30.777	30.558	30.338	30.118	29.899	29.679	29.460	29.240	29.020
29.214	29.003	28.792	28.581	28.370	28.159	27.948	27.737	27.526
27.737	27.534	27.331	27.128	26.926	26.723	26.520	26.317	26.115
26.146	25.953	25.759	25.566	25.372	25.179	24.985	24.792	24.598
24.855	24.669	24.483	24.297	24.110	23.924	23.738	23.552	23.365
23.597	23.418	23.243	23.060	22.881	22.702	22.523	22.344	22.165
22.840	22.664	22.489	22.313	22.138	21.962	21.787	21.611	21.435
21.600	21.432	21.264	21.096	20.928	20.760	20.591	20.423	20.255

TABLE C-4. Example of Temperature Distribution During Shut-Down Process with Oil Coolant (P=0 KPa, Re=15).

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =120.00
ENDING TIME =150.00
AVERAGE TEMPERATURE =187.700
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.15000E+02
COOLANT:OIL

208.054	206.920	205.786	204.652	203.518	202.385	201.251	200.117	198.983
205.779	204.645	203.511	202.377	201.243	200.110	198.976	197.842	196.708
202.634	201.505	200.376	199.247	198.118	196.989	195.860	194.732	193.603
199.932	198.805	197.679	196.553	195.426	194.300	193.173	192.047	190.921
197.437	196.312	195.187	194.062	192.937	191.812	190.687	189.562	188.437
194.946	193.822	192.699	191.575	190.452	189.328	188.204	187.081	185.957
192.463	191.341	190.219	189.096	187.974	186.852	185.730	184.507	183.485
189.945	188.824	187.704	186.583	185.462	184.342	183.221	182.101	180.980
187.483	186.364	185.244	184.125	183.006	181.887	180.767	179.648	178.529
185.020	183.902	182.784	181.666	180.548	179.430	178.312	177.194	176.077
182.672	181.555	180.438	179.321	178.203	177.086	175.969	174.852	173.734
180.200	179.084	177.968	176.852	175.737	174.621	173.505	172.389	171.274

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =150.00
ENDING TIME =180.00
AVERAGE TEMPERATURE =173.345
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.15000E+02
COOLANT:OIL

194.247	193.188	192.130	191.071	190.013	188.954	187.895	186.837	185.778
192.114	191.056	189.997	188.939	187.880	186.822	185.763	184.705	183.646
188.117	187.069	186.021	184.973	183.925	182.877	181.829	180.781	179.733
185.136	184.093	183.050	182.007	180.964	179.921	178.878	177.835	176.792
182.546	181.506	180.466	179.426	178.386	177.346	176.305	175.265	174.225
179.965	178.928	177.890	176.853	175.816	174.779	173.741	172.704	171.667
177.401	176.367	175.332	174.298	173.264	172.229	171.195	170.160	169.126
174.765	173.734	172.703	171.672	170.641	169.610	168.579	167.548	166.517

TABLE C-4. (Continued).

172.247	171.218	170.190	169.162	168.133	167.105	166.077	165.048	164.020
169.727	168.701	167.675	166.650	165.624	164.599	163.573	162.548	161.522
167.445	166.421	165.396	164.372	163.348	162.324	161.300	160.276	159.252
164.906	163.885	162.864	161.843	160.822	159.801	158.779	157.758	156.737

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =180.00
ENDING TIME =210.00
AVERAGE TEMPERATURE =157.852
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.15000E+02
COOLANT:OIL

179.207	178.230	177.253	176.277	175.300	174.324	173.347	172.370	171.394
177.229	176.253	175.276	174.300	173.324	172.347	171.371	170.394	169.418
172.342	171.382	170.422	169.462	168.502	167.542	166.582	165.622	164.661
169.124	168.172	167.219	166.266	165.313	164.360	163.408	162.455	161.502
166.453	165.505	164.556	163.608	162.659	161.711	160.762	159.814	158.865
163.795	162.851	161.907	160.963	160.019	159.075	158.131	157.187	156.243
161.166	160.226	159.286	158.346	157.407	156.467	155.527	154.587	153.648
158.428	157.494	156.559	155.624	154.690	153.755	152.820	151.886	150.951
155.870	154.940	154.009	153.078	152.148	151.217	150.287	149.356	148.426
153.311	152.384	151.458	150.532	149.605	148.679	147.752	146.826	145.900
151.111	150.186	149.262	148.338	147.414	146.490	145.565	144.641	143.717
148.525	147.606	146.686	145.766	144.847	143.927	143.007	142.088	141.168

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =210.00
ENDING TIME =240.00
AVERAGE TEMPERATURE =141.741
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.15000E+02
COOLANT:OIL

163.371	162.481	161.590	160.700	159.810	158.919	158.029	157.139	156.249
161.558	160.668	159.778	158.888	157.998	157.108	156.218	155.327	154.437
155.814	154.946	154.078	153.210	152.342	151.474	150.606	149.738	148.870
152.416	151.557	150.698	149.840	148.981	148.122	147.264	146.405	145.546

TABLE C-4. (Continued).

149.687	148.834	147.981	147.128	146.276	145.423	144.570	143.717	142.854
146.979	146.132	145.285	144.437	143.590	142.743	141.896	141.049	140.202
144.310	143.468	142.527	141.785	140.944	140.102	139.261	138.420	137.579
141.502	140.667	139.832	138.997	138.162	137.328	136.493	135.658	134.823
138.931	138.101	137.272	136.442	135.613	134.783	133.954	133.124	132.295
136.360	135.536	134.712	133.888	133.064	132.240	131.416	130.592	129.768
134.259	133.438	132.617	131.796	130.975	130.153	129.332	128.511	127.690
131.658	130.842	130.027	129.212	128.397	127.581	126.766	125.951	125.136

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =240.00
ENDING TIME =270.00
AVERAGE TEMPERATURE =125.505
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.15000E+02
COOLANT:OIL

147.169	146.367	145.565	144.763	143.961	143.159	142.357	141.555	140.753
145.526	144.724	143.922	143.120	142.319	141.517	140.715	139.913	139.111
139.018	138.244	137.469	136.695	135.920	135.146	134.371	133.597	132.822
135.506	134.743	133.980	133.216	132.453	131.689	130.926	130.162	129.399
132.755	131.999	131.242	130.486	129.729	128.973	128.217	127.460	126.704
130.031	129.282	128.532	127.783	127.034	126.284	125.535	124.785	124.036
127.358	126.615	125.873	125.130	124.387	123.645	122.902	122.160	121.417
124.521	123.786	123.051	122.317	121.582	120.847	120.113	119.378	118.644
121.971	121.243	120.514	119.786	119.058	118.330	117.602	116.873	116.145
119.424	118.702	117.981	117.259	116.537	115.816	115.094	114.373	113.651
117.440	116.722	116.004	115.286	114.567	113.849	113.131	112.412	111.694
114.861	114.150	113.439	112.727	112.016	111.305	110.594	109.883	109.171

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =270.00
ENDING TIME =300.00
AVERAGE TEMPERATURE =109.588
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.15000E+02
COOLANT:OIL

TABLE C-4. (Continued).

131.003	130.289	129.575	128.861	128.147	127.433	126.719	126.005	125.291
129.529	128.816	128.102	127.388	126.675	125.961	125.247	124.534	123.820
122.401	121.719	121.037	120.355	119.673	118.991	118.310	117.628	116.946
118.849	118.180	117.510	116.841	116.171	115.501	114.832	114.162	113.493
116.116	115.455	114.793	114.131	113.470	112.808	112.146	111.485	110.823
113.418	112.764	112.110	111.457	110.803	110.149	109.496	108.842	108.188
110.780	110.135	109.489	108.843	108.197	107.551	106.905	106.259	105.613
107.962	107.325	106.688	106.051	105.414	104.777	104.140	103.504	102.867
105.472	104.842	104.213	103.583	102.953	102.323	101.694	101.064	100.434
102.988	102.366	101.744	101.121	100.499	99.877	99.255	98.632	98.010
101.138	100.520	99.901	99.283	98.664	98.046	97.427	96.808	96.190
98.624	98.013	97.402	96.792	96.181	95.570	94.960	94.349	93.738

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =300.00
ENDING TIME =330.00
AVERAGE TEMPERATURE = 94.368
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.15000E+02
COOLANT:OIL

115.230	114.602	113.974	113.346	112.718	112.090	111.462	110.834	110.206
113.923	113.296	112.668	112.040	111.413	110.785	110.157	109.530	108.902
106.353	105.760	105.168	104.575	103.983	103.390	102.798	102.205	101.613
102.835	102.256	101.676	101.097	100.518	99.938	99.359	98.780	98.200
100.163	99.592	99.022	98.451	97.880	97.310	96.739	96.168	95.597
97.534	96.972	96.409	95.847	95.285	94.723	94.161	93.599	93.036
94.975	94.421	93.867	93.313	92.759	92.206	91.652	91.098	90.544
92.226	91.682	91.138	90.593	90.049	89.505	88.961	86.417	87.873
89.834	89.298	88.761	88.225	87.689	87.152	86.616	86.080	85.543
87.453	86.925	86.396	85.868	85.340	84.811	84.283	83.754	83.226
85.751	85.227	84.702	84.178	83.653	83.129	82.604	82.080	81.555
83.344	82.828	82.311	81.795	81.279	80.763	80.247	79.731	79.215

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =330.00

TABLE C-4. (Continued).

ENDING TIME =360.00
AVERAGE TEMPERATURE = 80.144
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.15000E+02
COOLANT:OIL

100.154	99.608	99.063	98.517	97.971	97.425	96.879	96.334	95.788
99.009	98.464	97.918	97.373	96.827	96.282	95.736	95.191	94.645
91.193	90.685	90.177	89.669	89.161	88.653	88.145	87.637	87.129
87.779	87.285	86.790	86.296	85.801	85.307	84.812	84.318	83.823
85.211	84.726	84.240	83.755	83.269	82.784	82.298	81.813	81.327
82.693	82.216	81.740	81.263	80.786	80.310	79.833	79.357	76.880
80.253	79.785	79.317	78.849	78.381	77.913	77.445	76.977	76.509
77.622	77.164	76.706	76.248	75.790	75.332	74.874	74.416	73.958
75.365	74.915	74.465	74.015	73.565	73.115	72.665	72.215	71.765
73.123	72.681	72.240	71.798	71.356	70.914	70.472	70.030	69.589
71.580	71.142	70.704	70.266	69.828	69.391	68.953	68.515	68.077
69.318	68.889	68.459	68.030	67.601	67.172	66.742	66.313	65.884

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =360.00
ENDING TIME =390.00
AVERAGE TEMPERATURE = 67.130
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.15000E+02
COOLANT:OIL

86.019	85.550	85.082	84.613	84.144	83.675	83.207	82.738	82.269
85.026	84.558	84.090	83.621	83.153	82.684	82.216	81.747	81.279
77.165	76.736	76.306	75.876	75.446	75.016	74.586	74.156	73 726
73.918	73.502	73.085	72.669	72.252	71.836	71.419	71.003	70.587
71.493	71.085	70.678	70.271	69.863	69.456	69.048	68.641	68.234
69.123	68.724	68.326	67.928	67.529	67.131	66.732	66.334	65.936
66.837	66.447	66.058	65.668	65.278	64.888	64.499	64.109	63.719
64.367	63.988	63.608	63.228	62.848	62.469	62.089	61.709	61.329
62.276	61.904	61.532	61.160	60.788	60.417	60.045	59.673	59.301
60.204	59.840	59.477	59.113	58.749	58.385	58.022	57.658	57.294

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TABLE C-4. (Continued).

58.825	58.465	58.106	57.746	57.386	57.026	56.666	56.307	55.947
56.741	56.390	56.038	55.687	55.336	54.984	54.633	54.282	53.930

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME -390.00
ENDING TIME -420.00
AVERAGE TEMPERATURE - 55.463
PRESURE- 3500.0 KPa
REYNOLD'S NUMBER- 0.15000E+02
COOLANT:OIL

73.003	72.605	72.208	71.810	71.412	71.014	70.616	70.218	69.821
72.152	71.755	71.357	70.960	70.562	70.165	69.767	69.370	68.972
64.437	64.078	63.719	63.360	63.001	62.642	62.283	61.924	61.565
61.407	61.061	60.715	60.369	60.023	59.677	59.331	58.985	58.639
59.156	58.819	58.482	58.145	57.808	57.471	57.134	56.797	56.459
56.966	56.638	56.309	55.981	55.653	55.324	54.996	54.668	54.339
54.863	54.544	54.224	53.904	53.584	53.264	52.944	52.624	52.304
52.590	52.279	51.969	51.659	51.348	51.038	50.728	50.418	50.107
50.686	50.384	50.081	49.779	49.476	49.173	48.871	48.568	48.266
48.808	48.513	48.218	47.923	47.628	47.333	47.038	46.743	46.448
47.595	47.304	47.013	46.722	46.431	46.139	45.849	45.557	45.266
45.712	45.429	45.146	44.863	44.580	44.297	44.014	43.731	43.448

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME -420.00
ENDING TIME -450.00
AVERAGE TEMPERATURE - 45.201
PRESURE- 3500.0 KPa
REYNOLD'S NUMBER- 0.15000E+02
COOLANT:OIL

61.222	60.889	60.555	60.221	59.888	59.554	59.221	58.887	58.553
60.501	60.168	59.835	59.501	59.168	58.834	58.501	58.168	57.834
53.100	52.804	52.509	52.213	51.917	51.621	51.325	51.029	50.734
50.326	50.042	49.759	49.475	49.191	48.908	48.624	48.341	48.057
48.274	47.999	47.724	47.449	47.173	46.898	46.623	46.348	46.073
46.286	46.019	45.752	45.485	45.219	44.952	44.685	44.418	44.152

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OF POOR QUALITY

TABLE C-4. (Continued).

44.387	44.128	43.869	43.611	43.352	43.093	42.834	42.575	42.31[illegible]
42.333	42.084	41.834	41.564	41.334	41.085	40.835	40.585	40.33[illegible]
40.634	40.391	40.149	39.906	39.663	39.421	39.178	36.936	38.69[illegible]
38.962	38.727	38.491	38.256	38.021	37.785	37.550	37.314	37.079
37.913	37.681	37.449	37.217	36.985	36.753	36.521	36.290	36.058
36.245	36.021	35.796	35.572	35.348	35.123	34.899	34.674	34.450

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =450.00
ENDING TIME =480.00
AVERAGE TEMPERATURE = 36.340
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.15000E+02
COOLANT:OIL

50.734	50.458	50.181	49.905	49.628	49.352	49.075	48.799	48.522
50.130	49.853	49.577	49.301	49.025	48.749	48.472	48.196	47.92[illegible]
43.182	42.942	42.701	42.461	42.220	41.980	41.739	41.498	41.258
40.688	40.459	40.230	40.000	39.771	39.542	39.313	39.084	38.854
38.851	38.629	38.408	38.186	37.965	37.744	37.522	37.301	37.080
37.078	36.865	36.651	36.437	36.224	36.010	35.796	35.582	35.369
35.394	35.188	34.982	34.775	34.569	34.363	34.156	33.950	33.74[illegible]
33.575	33.377	33.179	32.981	32.783	32.585	32.387	32.189	31.990
32.085	31.894	31.702	31.511	31.319	31.128	30.936	30.744	30.553
30.626	30.441	30.256	30.071	29.886	29.701	29.516	29.331	29.145
29.733	29.551	29.369	29.187	29.005	28.823	28.642	28.460	28.278
28.285	28.109	27.934	27.759	27.584	27.409	27.234	27.059	26.884

ELECTRODE TEMPERATURE DISTRIBUTION
STARTING TIME =480.00
ENDING TIME =510.00
AVERAGE TEMPERATURE = 28.825
PRESURE= 3500.0 KPa
REYNOLD'S NUMBER= 0.15000E+02
COOLANT:OIL

41.544	41.318	41.091	40.865	40.639	40.412	40.186	39.959	39.733
41.043	40.817	40.591	40.365	40.139	39.913	39.686	39.460	39.234

TABLE C-4. (Continued).

34.655	34.462	34.269	34.076	33.883	33.690	33.497	33.304	33.111
32.453	32.270	32.087	31.904	31.722	31.539	31.356	31.173	30.990
30.836	30.660	30.485	30.309	30.133	29.957	29.782	29.606	29.430
29.284	29.115	28.947	28.778	28.609	28.440	28.272	28.103	27.934
27.818	27.656	27.493	27.331	27.169	27.007	26.845	26.682	26.520
26.236	26.082	25.927	25.772	25.617	25.462	25.308	25.153	24.998
24.955	24.806	24.657	24.508	24.359	24.210	24.061	23.912	23.763
23.704	23.561	23.418	23.275	23.131	22.988	22.845	22.702	22.558
22.957	22.816	22.676	22.535	22.395	22.255	22.114	21.974	21.833
21.724	21.589	21.455	21.320	21.186	21.051	20.916	20.782	20.647

APPENDIX D

CURRENT DENSITY DISTRIBUTION DURING SHUT-DOWN PROCESS FOR:

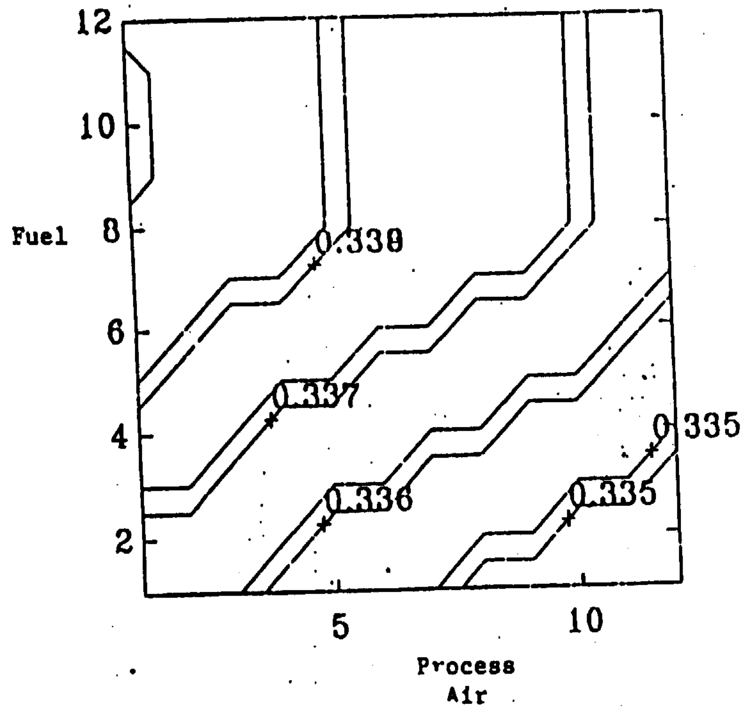
(D-1) THROUGH (D-13): WATER COOLANT (P=3500 KPa, Re = 1250)

(D-14) THROUGH (D-26): WATER COOLANT (P=0 KPa, Re = 1250)

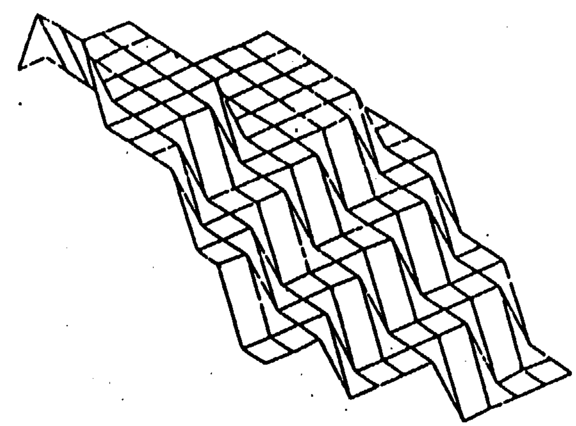
(D-27) THROUGH (D-39): WATER COOLANT (P=0 KPa, Re = 6167)

TRANSIENT CURRENT DENSITY DISTRIBUTION

Transient Current Density Profiles



Transient Current Density 3D Contour



Re=1250,P=3500 KPa

COOLING FLUID: WATER

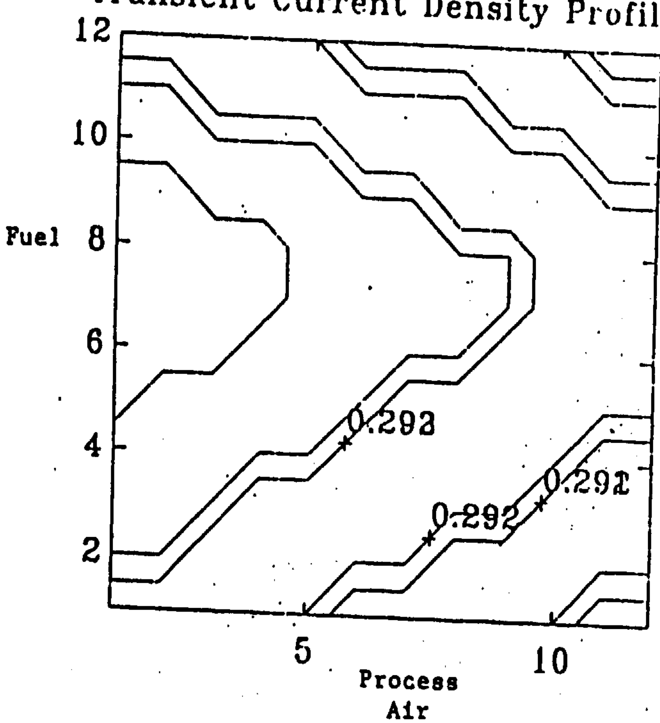
SHUT-DOWN PROCESS

TIME INTERVAL NO.1

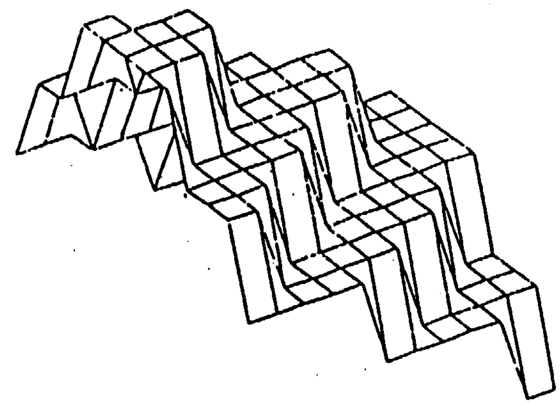
TABLE D-1. Transient Current Density Distribution During a Shut-Down Prcess (Water Coolant, P=3500 KPa, Re = 1250, T.I. = 1).

TRANSIENT CURRENT DENSITY DISTRIBUTION

Transient Current Density Profiles



Transient Current Density 3D Contour



Re=1250.P=3500 KPa

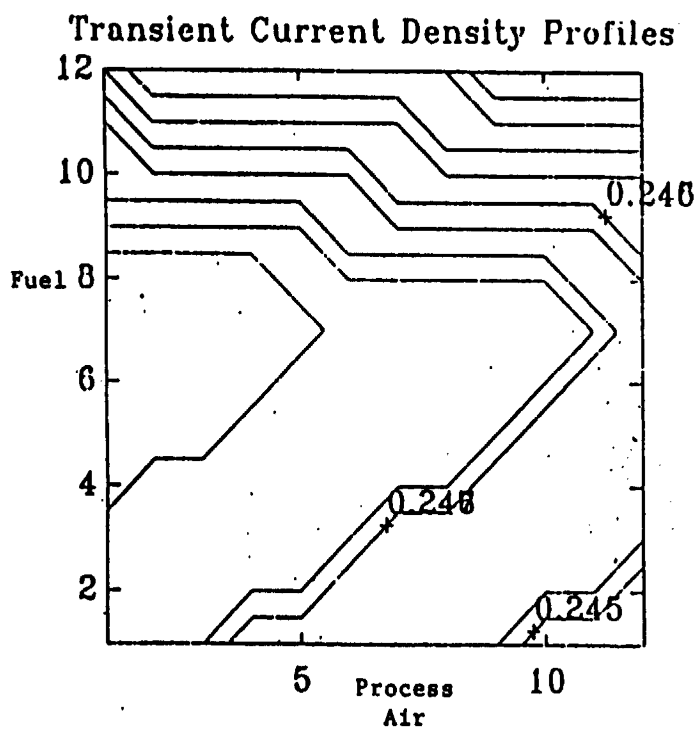
COOLING FLUID: WATER

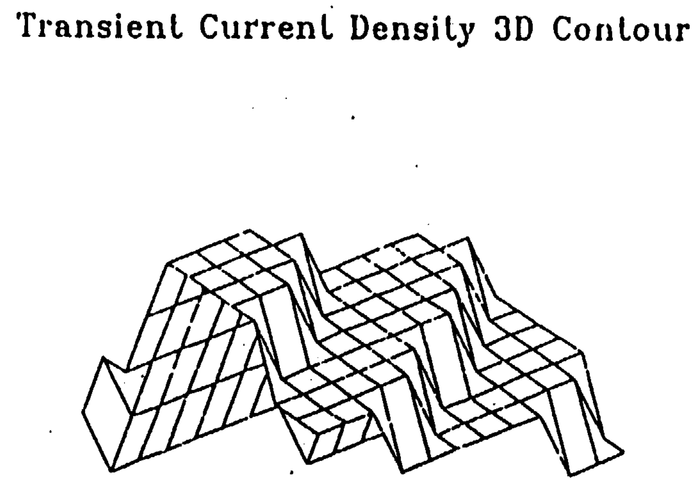
SHUT-DOWN PROCESS

TIME INTERVAL NO.2

TABLE D-2. Transient Current Density Distribution During a Shut-Down Process (Water Coolant, P = 3500 KPa, Re = 1250, T.I. = 2).

TRANSIENT CURRENT DENSITY DISTRIBUTION





Re=1250,P=3500 KPa

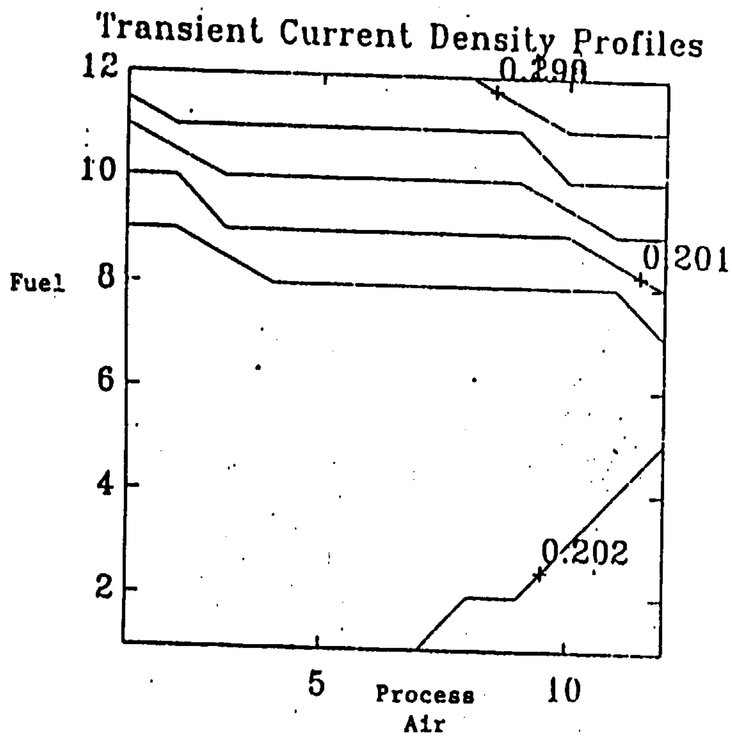
COOLING FLUID: WATER

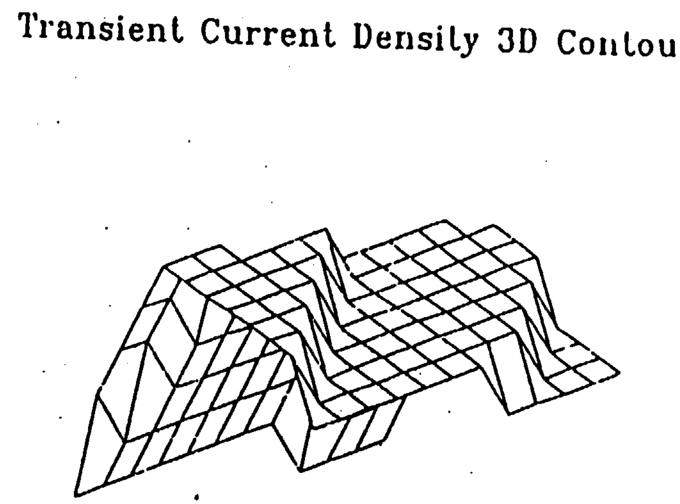
SHUT-DOWN PROCESS

TIME INTERVAL NO.3

TABLE D-3. Transient Current Density Distribution During a Shut-Down Process (Water Coolant, P = 3500 KPa, Re = 1250, T.I. = 3).

TRANSIENT CURRENT DENSITY DISTRIBUTION





Re=1250,P=3500 KPa

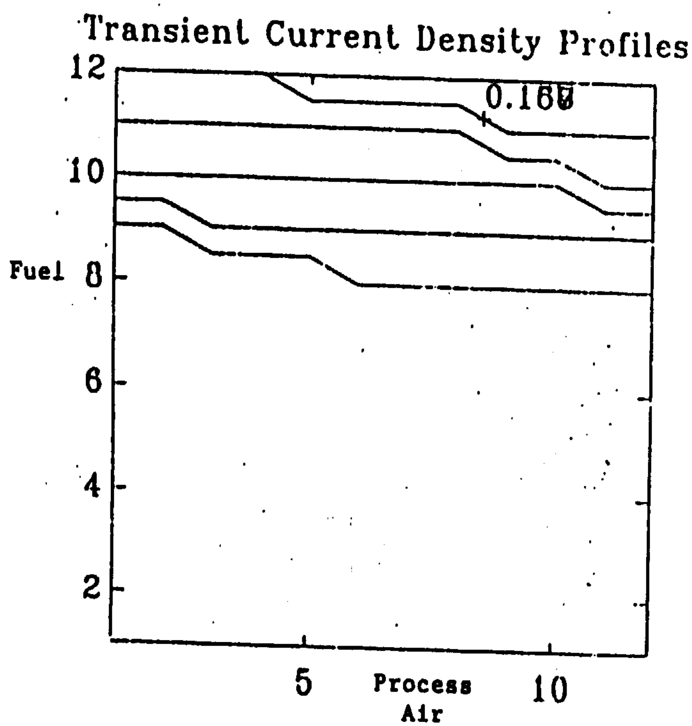
COOLING FLUID: WATER

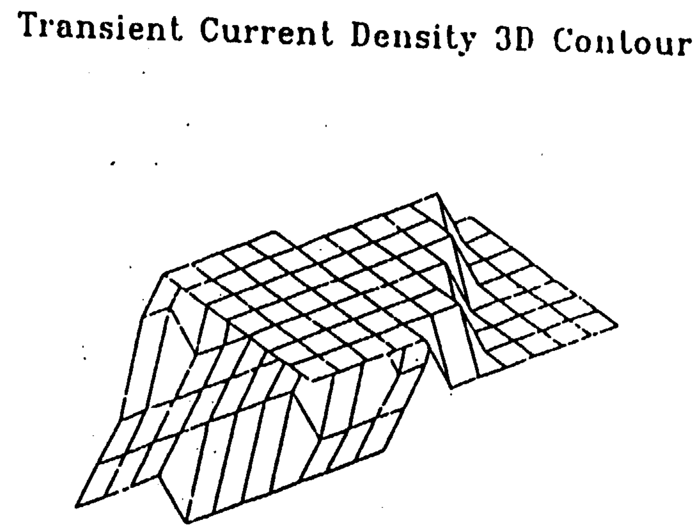
SHUT-DOWN PROCESS

TIME INTERVAL NO.4

TABLE D-4. Transient Current Density Distribution During a Shut-Down Process (Water Coolant, P = 3500, KPa, Re = 1250, T.I. = 4).

TRANSIENT CURRENT DENSITY DISTRIBUTION





Re=1250,P=3500 KPa

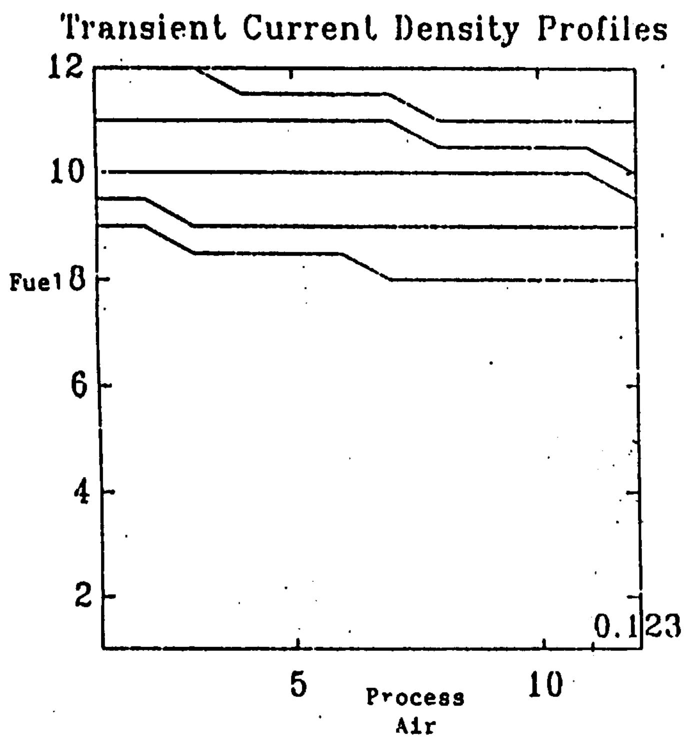
COOLING FLUID: WATER

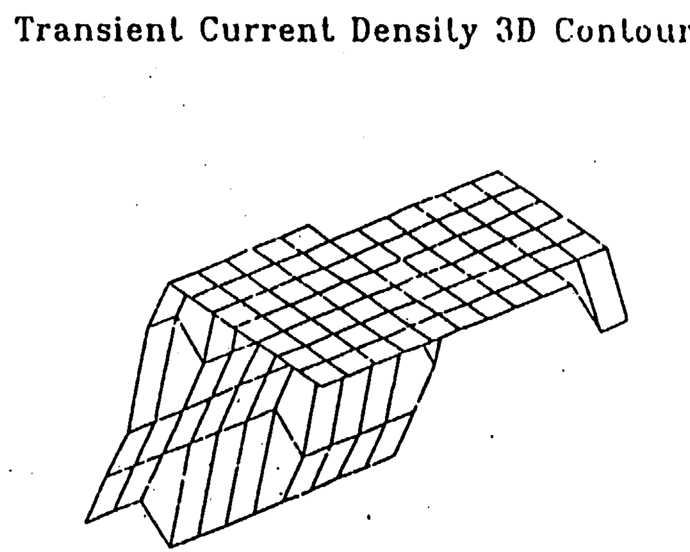
SHUT-DOWN PROCESS

TIME INTERVAL NO.5

TABLE D-5. Transient Current Density Distribution During a Shut-Down Process (Water Coolant, P = 3500 KPa, Re = 1250, T.I. = 5).

TRANSIENT CURRENT DENSITY DISTRIBUTION





Re=1250,P=3500 KPa

COOLING FLUID: WATER

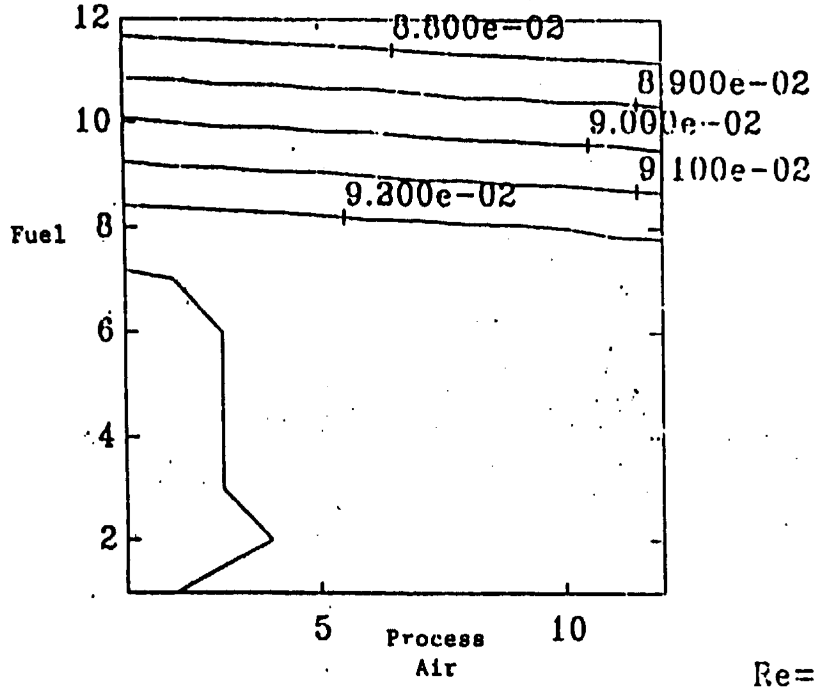
SHUT-DOWN PROCESS

TIME INTERVAL NO:6

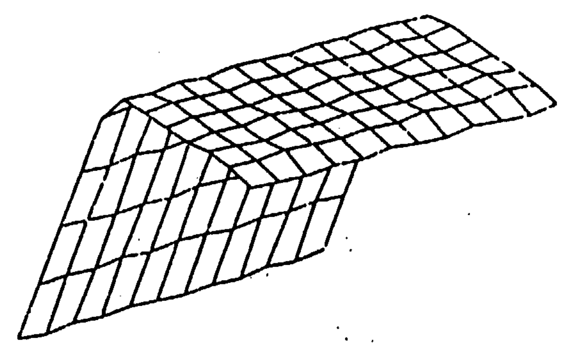
TABLE D-6. Transient Current Density Distribution During a Shut-Down Process (Water Coolant, P = 3500 KPa, Re = 1250, T.I. = 6).

TRANSIENT CURRENT DENSITY DISTRIBUTION

Transient Current Density Profiles



Transient Current Density 3D Contour



Re=1250,P=3500 KPa

COOLING FLUID: WATER

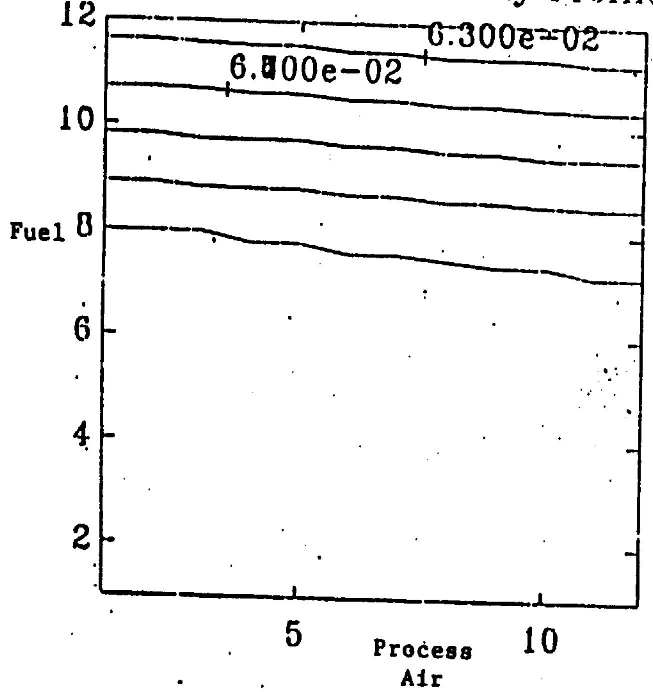
SHUT-DOWN PROCESS

TIME INTERVAL NO.7

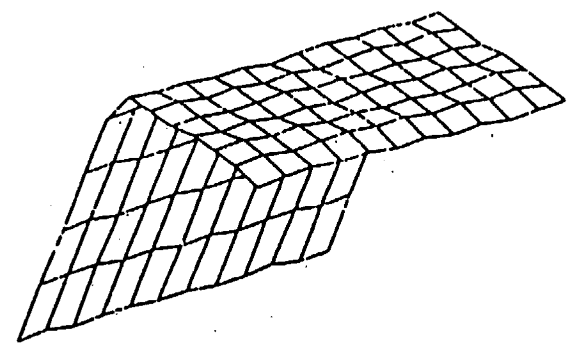
TABLE D-7. Transient Current Density Distribution During a Shut-Down Process (Water Coolant, P = 3500 KPa, Re = 1250, T.I. = 7).

TRANSIENT CURRENT DENSITY DISTRIBUTION

Transient Current Density Profiles



Transient Current Density 3D Contour



Re=1250,P=3500 KPa

COOLING FLUID: WATER

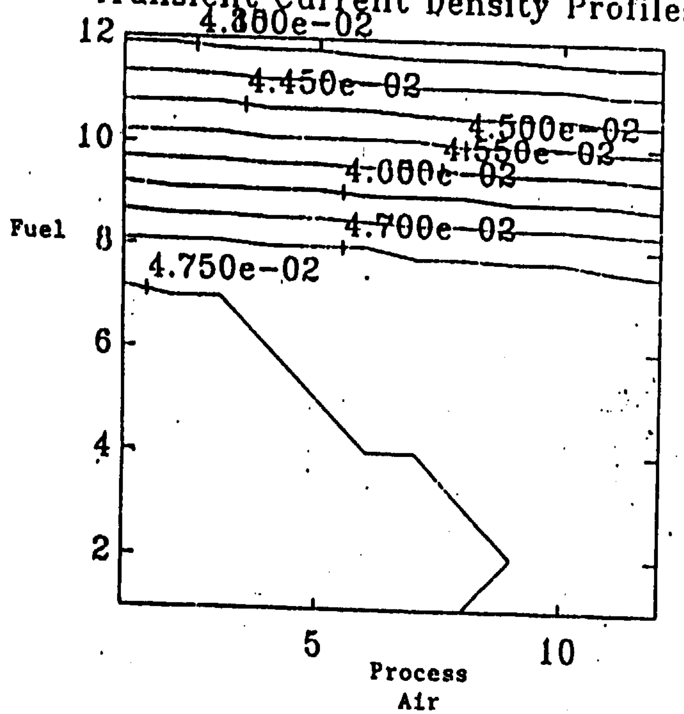
SHUT-DOWN PROCESS

TIME INTERVAL NO.8.

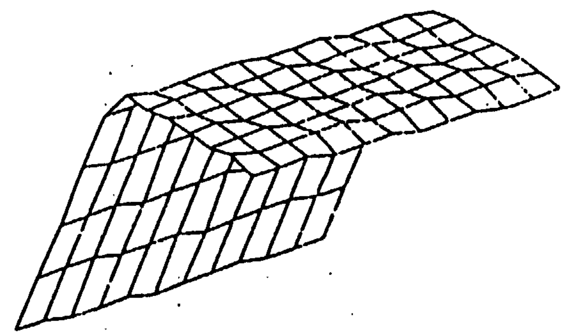
TABLE D-8. Transient Current Density Distribution During a Shut-Down Process (Water Coolant, P = 3500 KPa, Re = 1250, T.I. = 8).

TRANSIENT CURRENT DENSITY DISTRIBUTION

Transient Current Density Profiles



Transient Current Density 3D Contour



Re=1250,P=3500 KPa

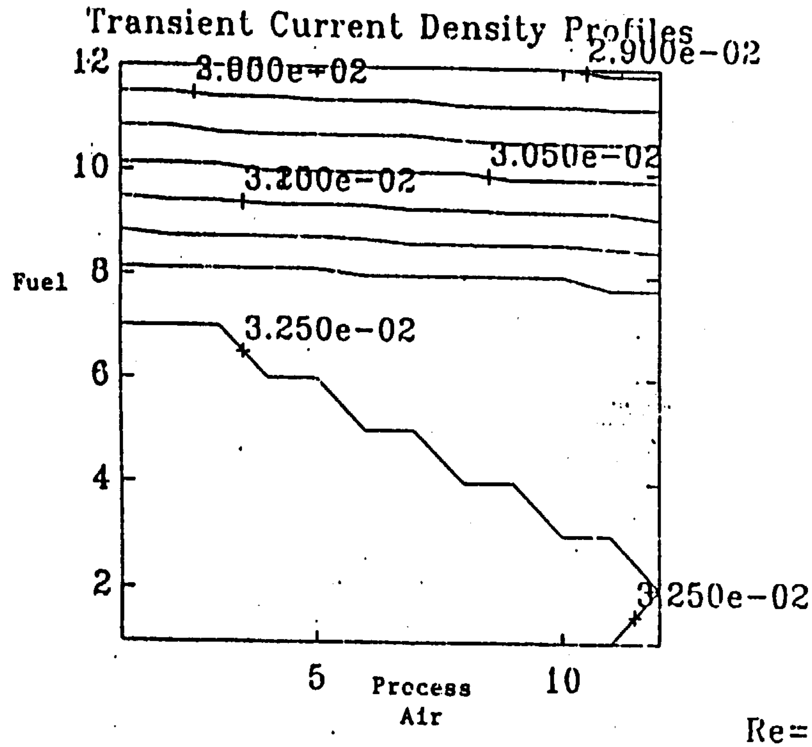
COOLING FLUID: WATER

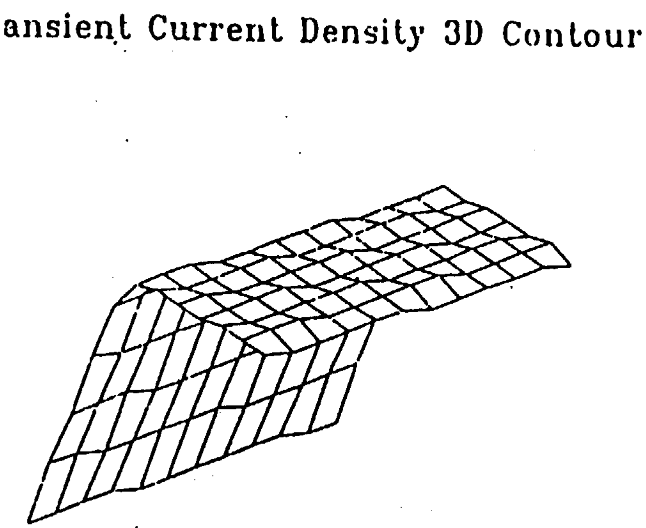
SHUT-DOWN PROCESS

TIME INTERVAL NO.9

TABLE D-9. Transient Current Density Distribution During a Shut-Down Process (Water Coolant, P = 3500 KPa, Re = 1250, T.I. = 9).

TRANSIENT CURRENT DENSITY DISTRIBUTION





Re=1250,P=3500 KPa

COOLING FLUID: WATER

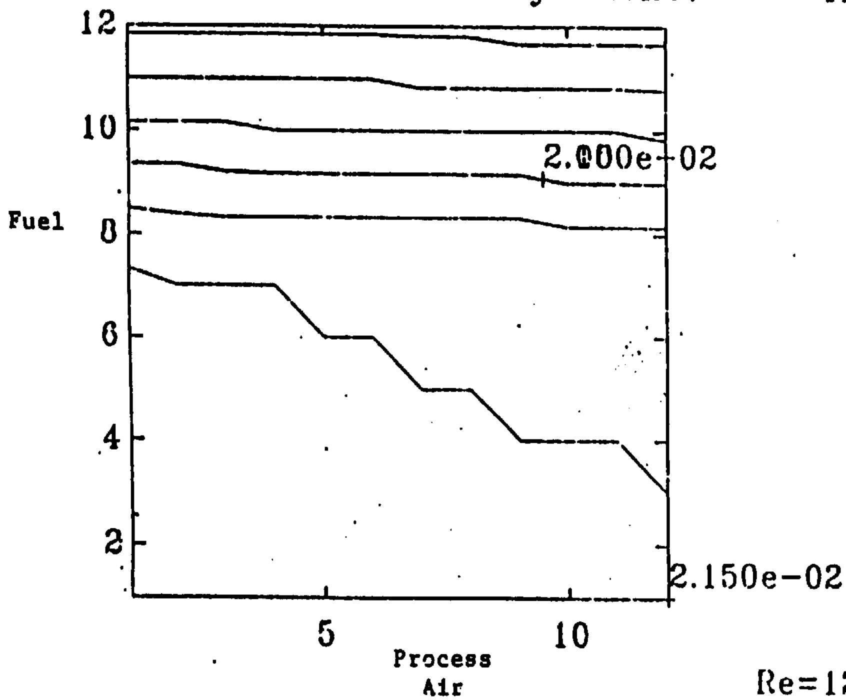
SHUT-DOWN PROCESS

TIME INTERVAL NO.10

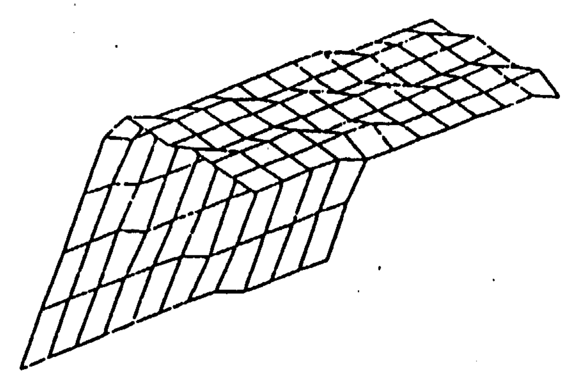
TABLE D-10. Transient Current Density Distribution DUring a Shut-Down Process (Water Coolant, P = 3500 KPa, Re = 1250, T.I. = 10).

TRANSIENT CURRENT DENSITY DISTRIBUTION

Transient Current Density Profiles



Transient Current Density 3D Contour



Re=1250,P=3500 KPa

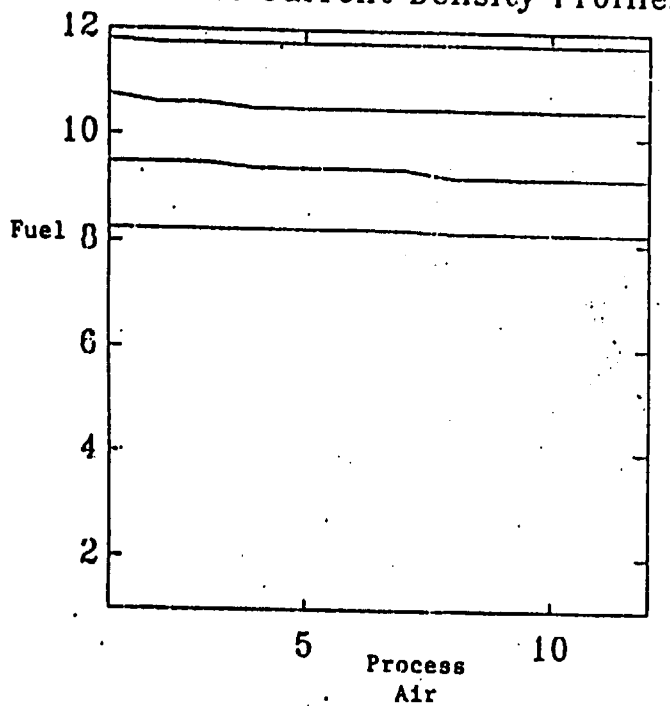
COOLING FLUID: WATER

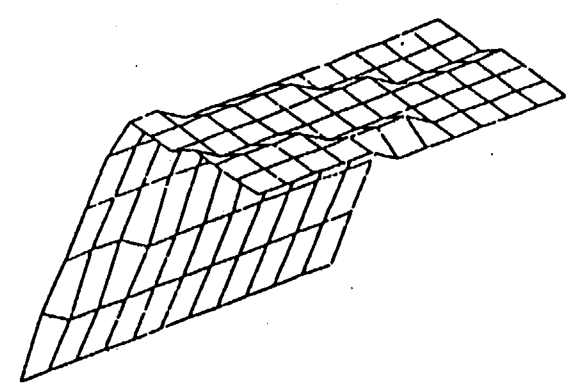
SHUT-DOWN PROCESS

TIME INTERVAL NO.11

TABLE D-11. Transient Current Density Distribution During a Shut-Down Process (Water Coolant, P = 3500 KPa, Re = 1250, T.I. = 11).

TRANSIENT CURRENT DENSITY DISTRIBUTION





Re=1250,P=3500 KPa

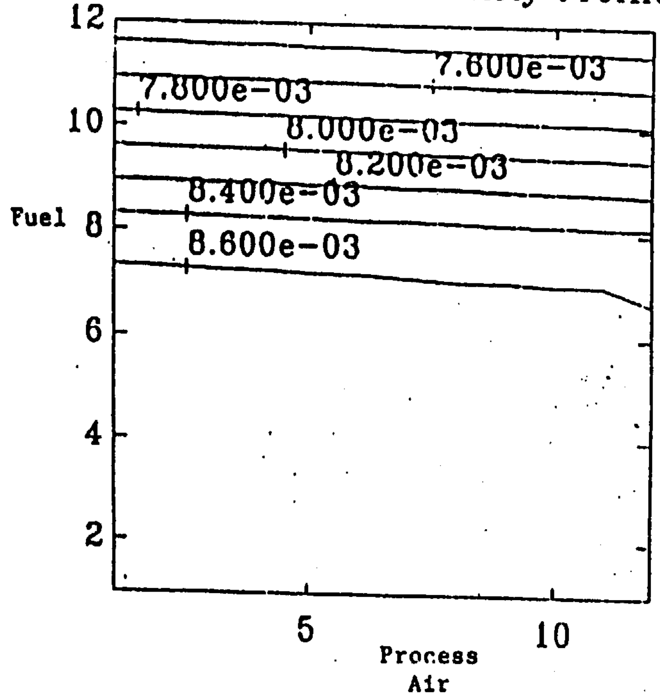
COOLING FLUID: WATER

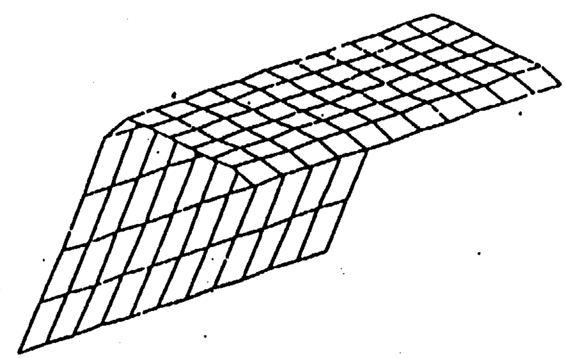
SHUT-DOWN PROCESS

TIME INTERVAL NO.12

TABLE D-12. Transient Current Density Distribution During a Shut-Down Process (Water Coolant, P = 3500 KPa, Re = 1250, T.I. = 12).

TRANSIENT CURRENT DENSITY DISTRIBUTION





Re=1250,P=3500 KPa

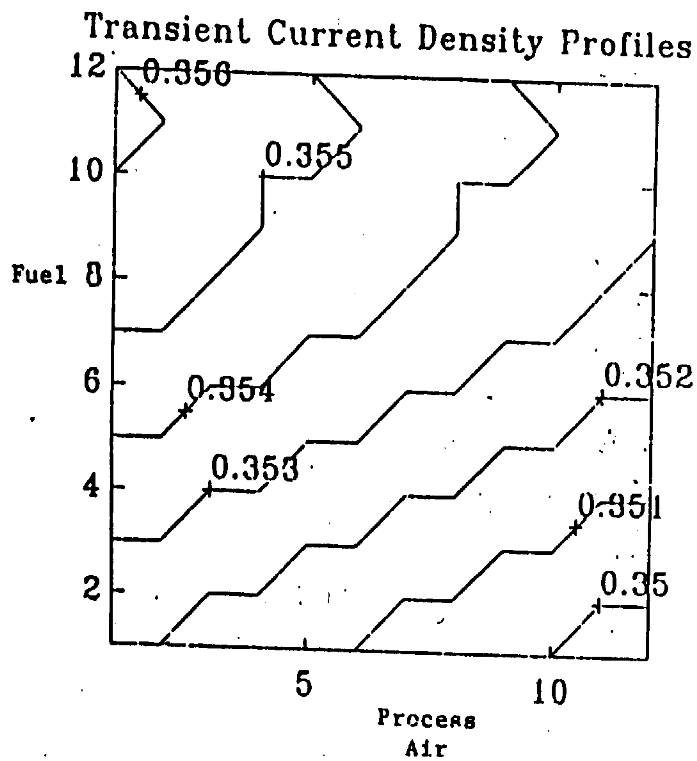
COOLING FLUID: WATER

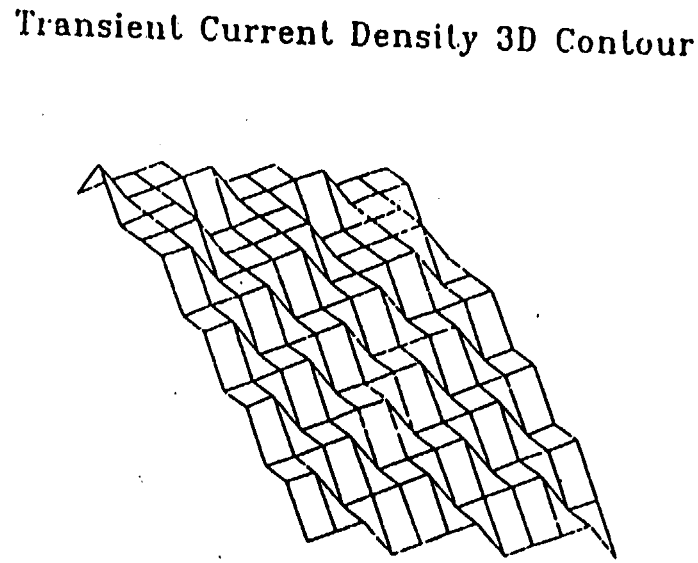
SHUT-DOWN PROCESS

TIME INTERVAL NO.13

TABLE D-13. Transient Current Density Distribution During a Shut-Down Process (Water Coolant, P = 3500 kPa, Re = 1250, T.I. = 13).

TRANSIENT CURRENT DENSITY DISTRIBUTION





Re=1250,P=0 KPa

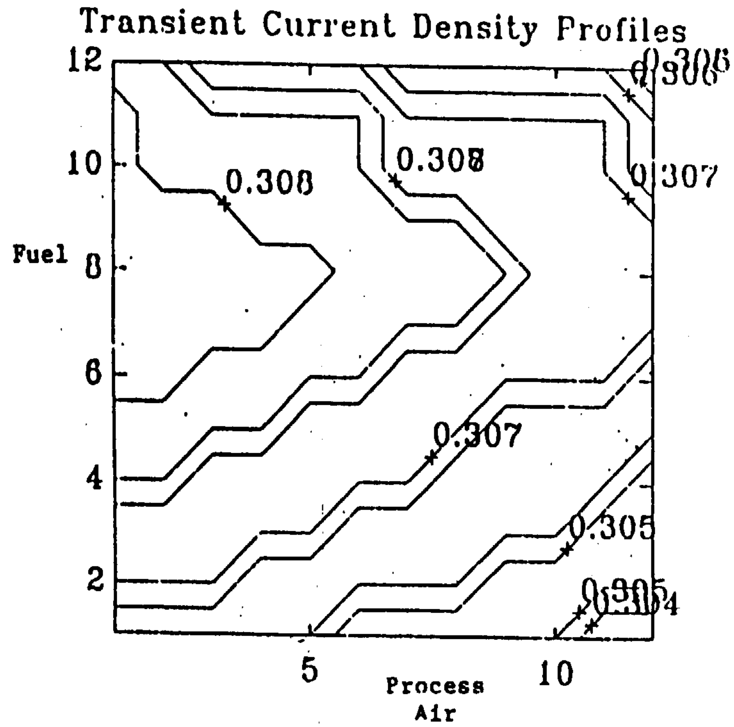
COOLING FLUID: WATER

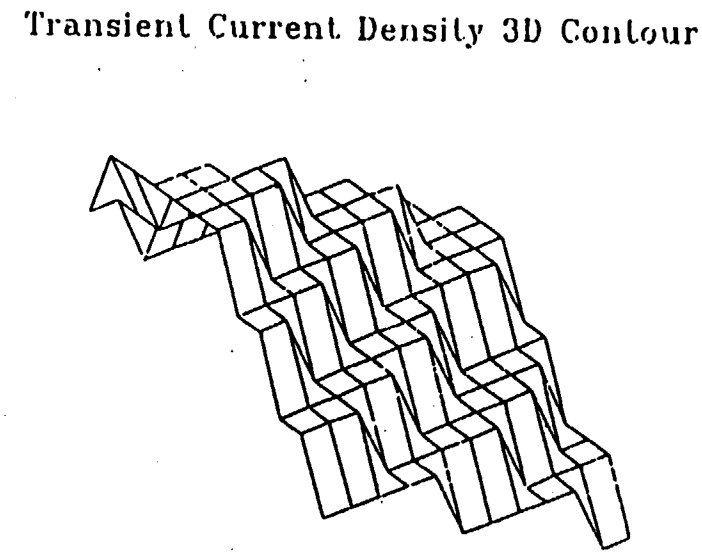
SHUT-DOWN PROCESS

TIME INTERVAL NO.1

TABLE D-14. Transient Current Density Distribution During a Shut-Down Process (Water Coolant, P = 0 KPa, Re = 1250, T.I. = 1).

TRANSIENT CURRENT DENSITY DISTRIBUTION





Re=1250,P=0 KPa

COOLING FLUID: WATER

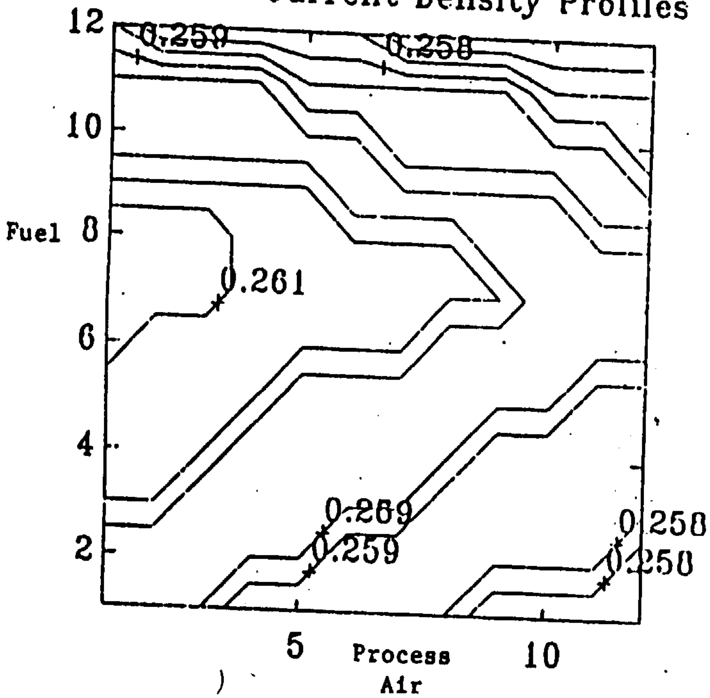
SHUT-DOWN PROCESS

TIME INTERVAL NO.2

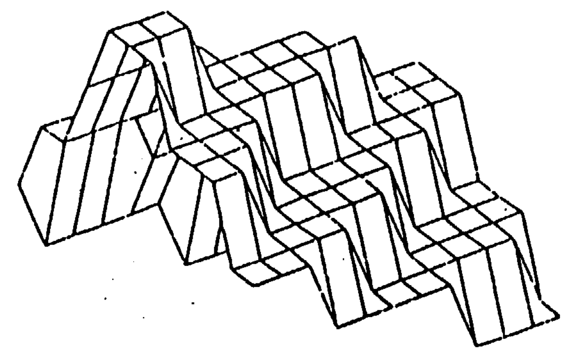
TABLE D-15. Transient Current Density Distribution During a Shut-Down Process (Water Coolant, P = 0 KPa, Re = 1250, T.I. = 2.

TRANSIENT CURRENT DENSITY DISTRIBUTION

Transient Current Density Profiles



Transient Current Density 3D Contour



Re=1250,P=0 KPa

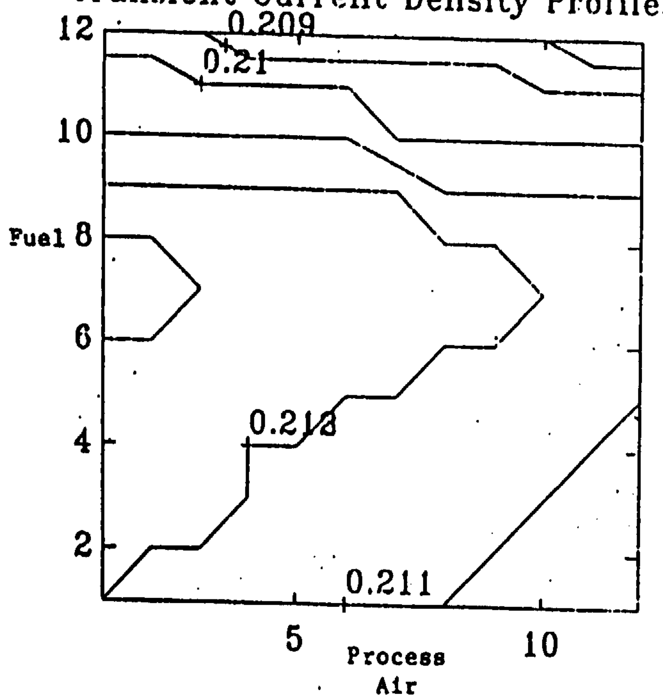
COOLING FLUID: WATER

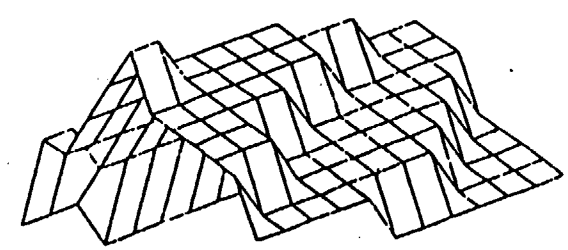
SHUT-DOWN PROCESS

TIME INTERVAL NO.3

TABLE D-16. Transient Current Density Distribution During a Shut-Down Process (Water Coolant, P = 0 KPa, Re = 1250, T.I. = 3).

TRANSIENT CURRENT DENSITY DISTRIBUTION





Re=1250,P=0 KPa

COOLING FLUID: WATER

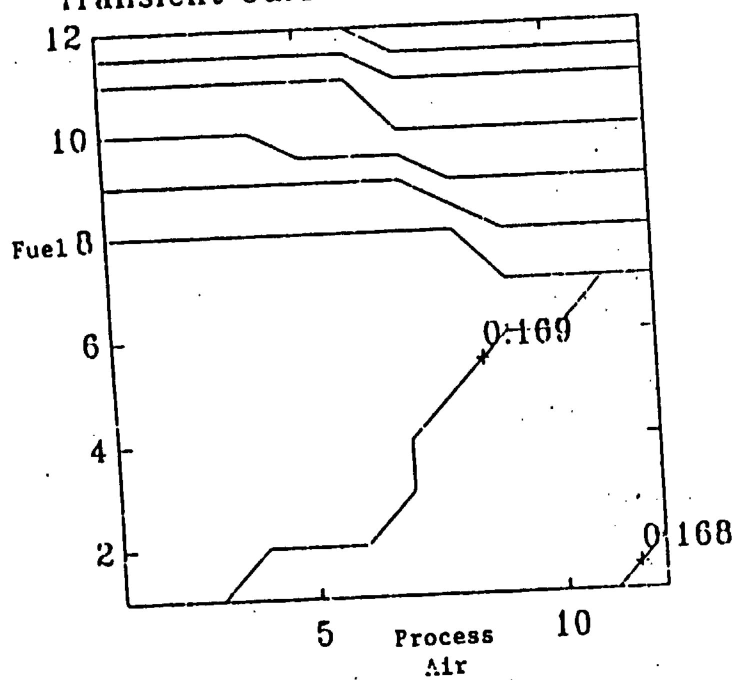
SHUT-DOWN PROCESS

TIME INTERVAL NO.4

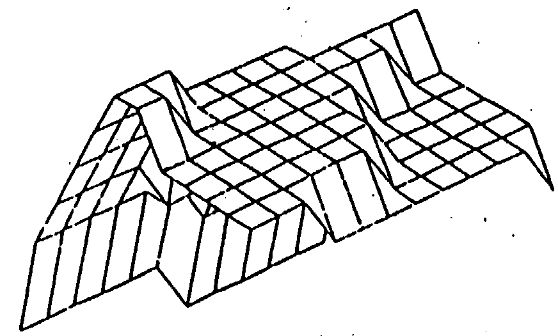
TABLE D-17. Transient Current Density Distribution During a Shut-Down Process (Water Coolant, P = 0 KPa, Re = 1250, T.I. = 4).

TRANSIENT CURRENT DENSITY DISTRIBUTION

Transient Current Density Profiles



Transient Current Density 3D Contour



Re=1250,P=0 KPa

COOLING FLUID: WATER

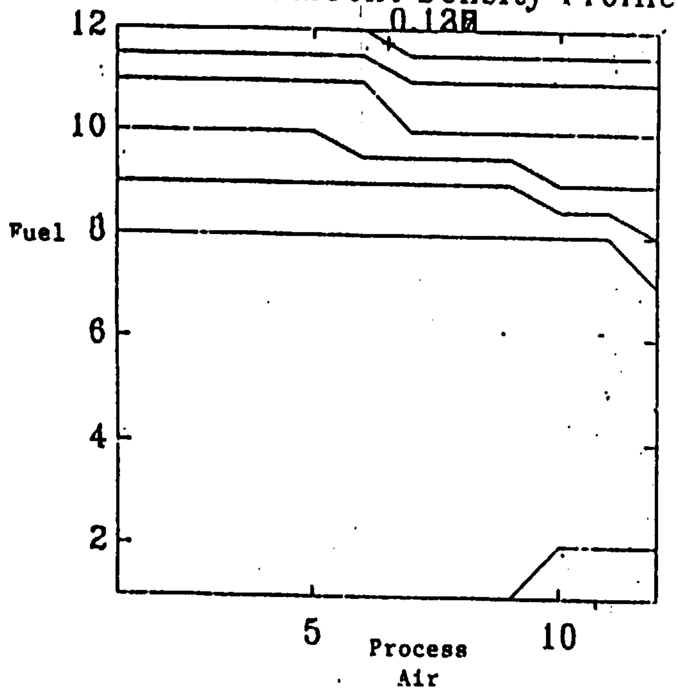
SHUT-DOWN PROCESS

TIME INTERVAL NO.5

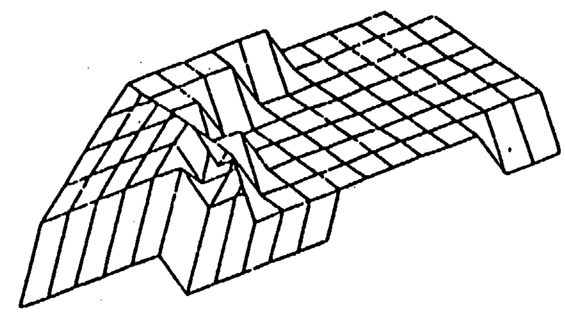
TABLED-18. Transient Current Density Distribution During a Shut-Down Process (Water Coolant, P = 0 KPa, Re = 1250, T.I. = 5).

TRANSIENT CURRENT DENSITY DISTRIBUTION

Transient Current Density Profiles



Transient Current Density 3D Contour



Re=1250,P=0 KPa

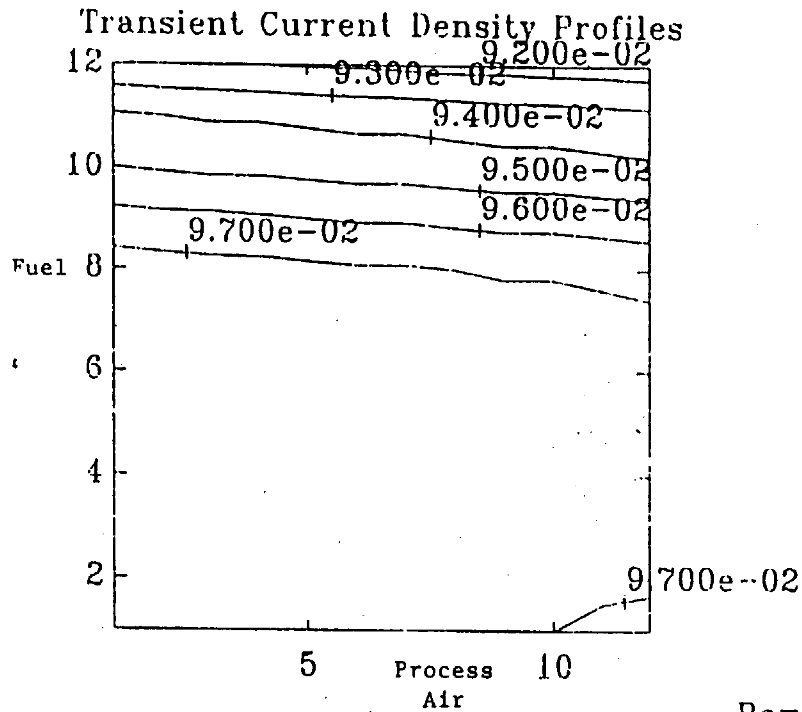
COOLING FLUID: WATER

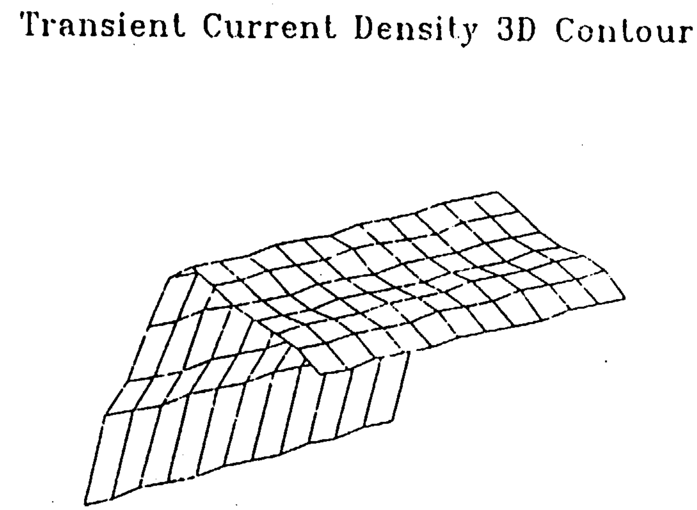
SHUT-DOWN PROCESS

TIME INTERVAL NO.6

TABLE D-19. Transient Current Density Distribution During a Shut-Down Process (Water Coolant, P = 0 KPa Re = 1250, T.I. = 6).

TRANSIENT CURRENT DENSITY DISTRIBUTION





Re=1250,P=0 KPa

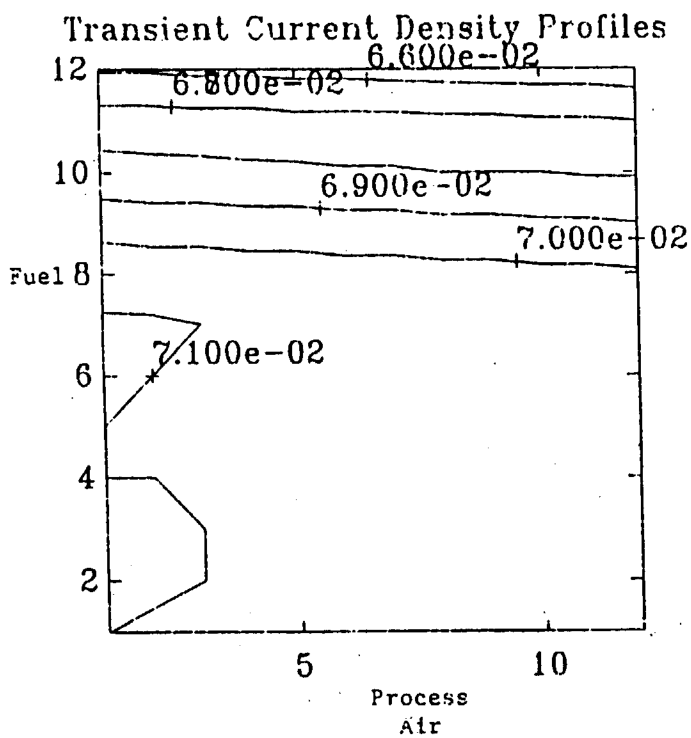
COOLING FLUID: WATER

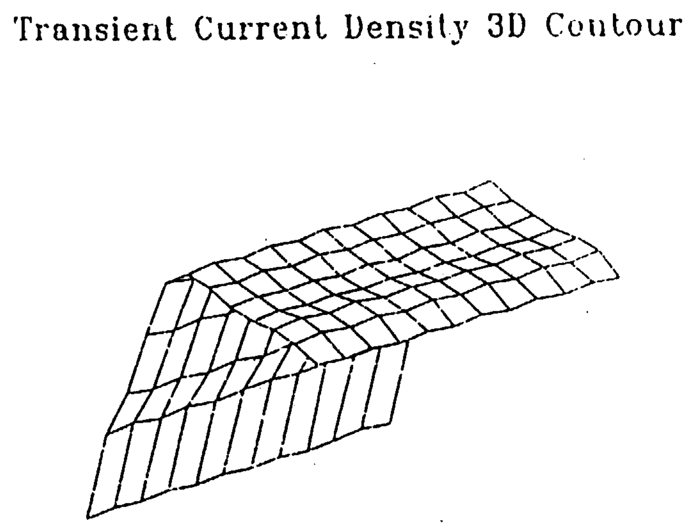
SHUT-DOWN PROCESS

TIME INTERVAL NO.7

TABLE D-20. Transient Current Density Distribution During a Shut-Down Process (Water Coolant, P = 0 KPa, Re = 1250, T.I. = 7).

TRANSIENT CURRENT DENSITY DISTRIBUTION





Re=1250,P=0 KPa

COOLING FLUID: WATER

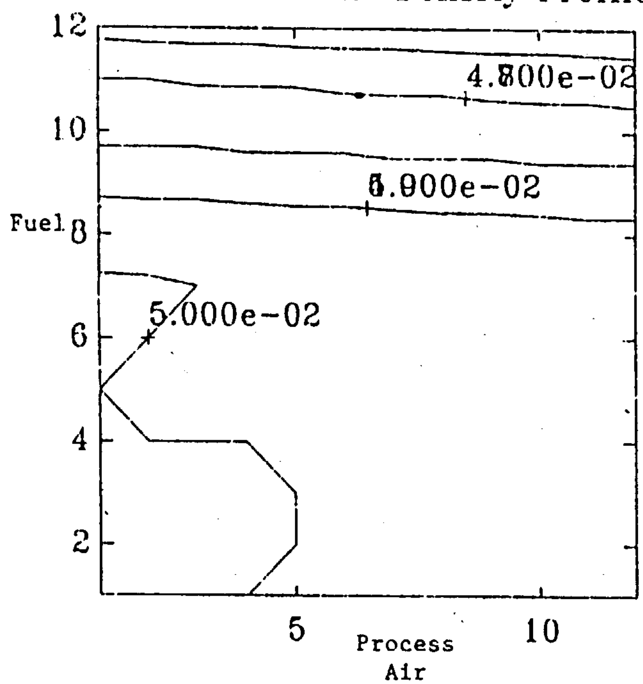
SHUT-DOWN PROCESS

TIME INTERVAL NO.8

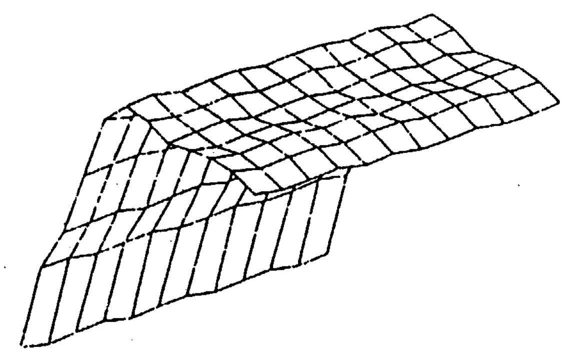
TABLE D-21. Transient Current Density Distribution During a Shut-Down Process (Water Coolant, P = 0 KPa, Re = 1250, T.I. = 8).

TRANSIENT CURRENT DENSITY DISTRIBUTION

Transient Current Density Profiles



Transient Current Density 3D Contour



Re=1250,P=0 KPa

COOLING FLUID: WATER

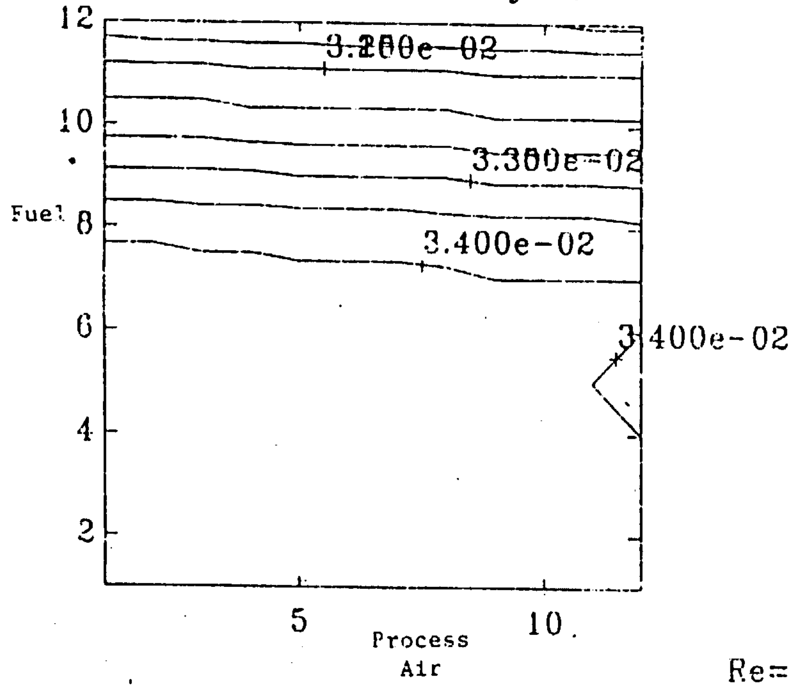
SHUT-DOWN PROCESS

TIME INTERVAL NO.9

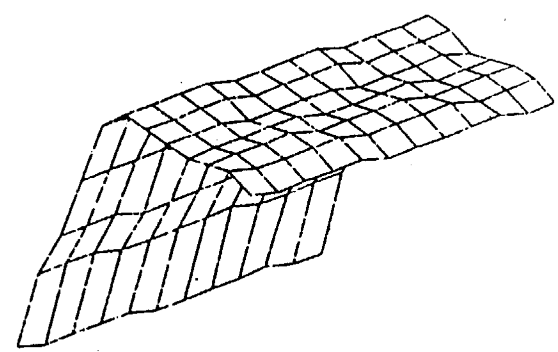
TABLE D-22. Transient Current Density Distribution During a Shut-Down Process (Water Coolant, P = 0 KPa, Re = 1250, T.I. = 9).

TRANSIENT CURRENT DENSITY DISTRIBUTION

Transient Current Density Profiles



Transient Current Density 3D Contour



Re=1250,P=0 KPa

COOLING FLUID: WATER

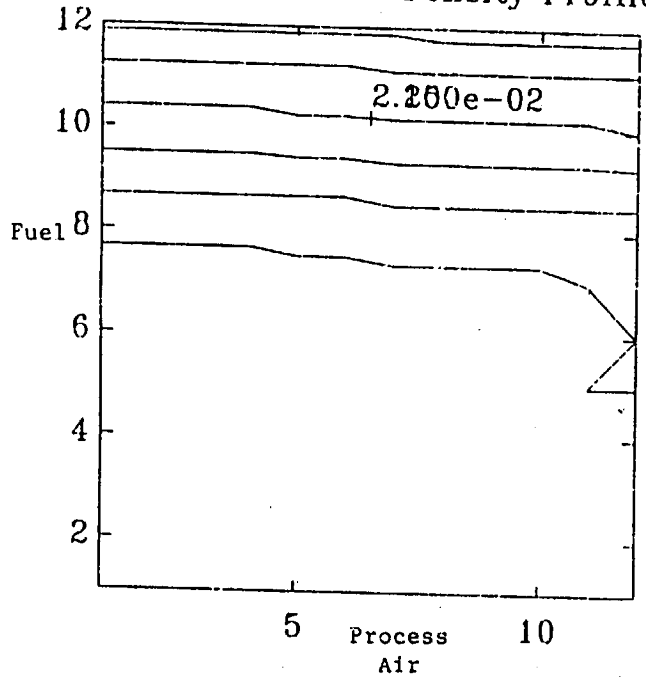
SHUT-DOWN PROCESS

TIME INTERVAL NO.10

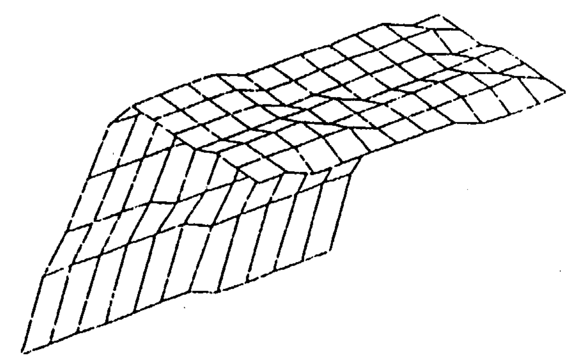
TABLE D-23. Transient Current Density Distribution During a Shut-Down Process (Water Coolant, P = 0 KPa, Re = 1250, T.I. = 10).

TRANSIENT CURRENT DENSITY DISTRIBUTION

Transient Current Density Profiles



Transient Current Density 3D Contour



Re=1250,P=0 KPa

COOLING FLUID: WATER

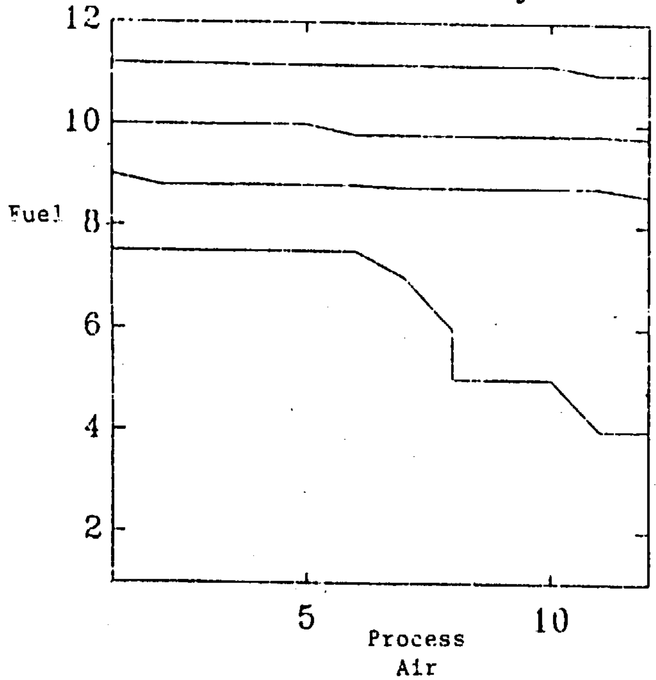
SHUT-DOWN PROCESS

TIME INTERVAL NO.11

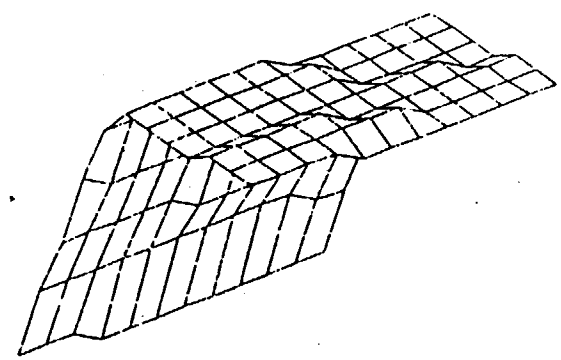
TABLE D-24. Transient Current Density Distribution During a Shut-Down Process (Water Coolant, P = 0 KPa, Re = 1250, T.I. = 11).

TRANSIENT CURRENT DENSITY DISTRIBUTION

Transient Current Density Profiles



Transient Current Density 3D Contour



Re=1250,P=0 KPa

COOLING FLUID: WATER

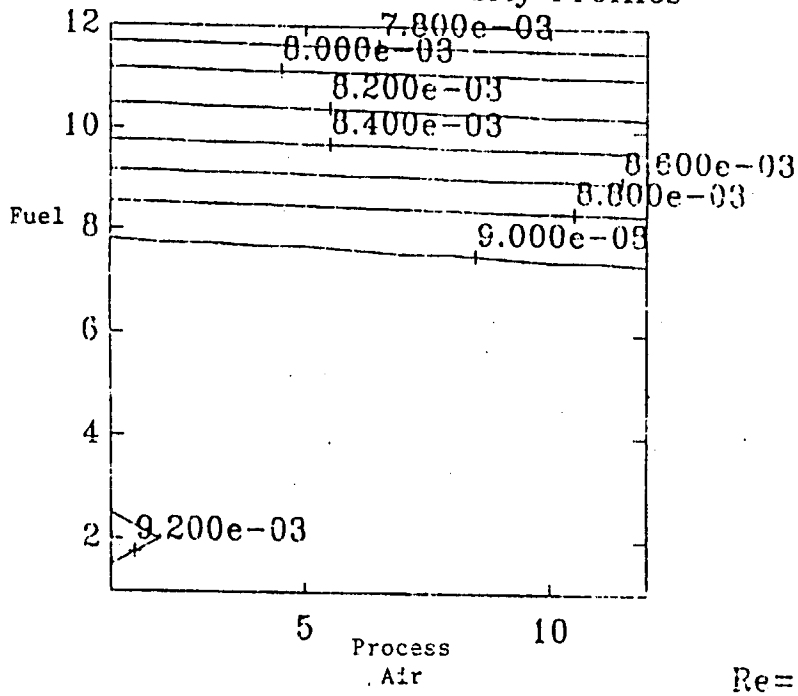
SHUT-DOWN PROCESS

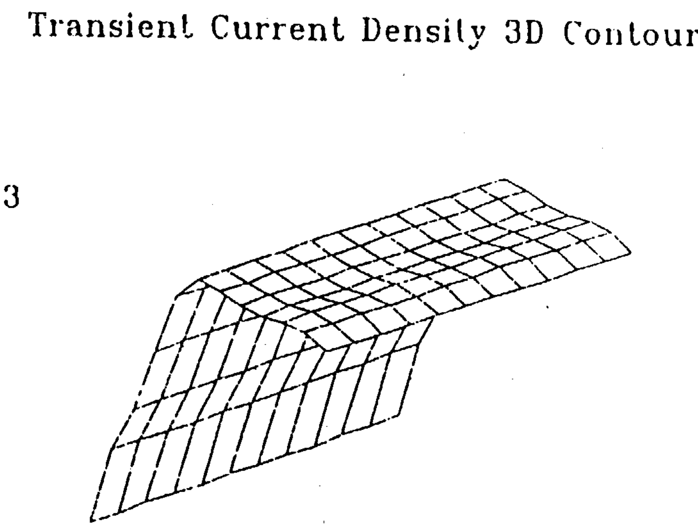
TIME INTERVAL NO.12

TABLE D-25. Transient Current Density Distribution During a Shut-Down Process (Water Coolant, P = 0 KPa, Re = 1250, T.I. = 12).

D-5.

TRANSIENT CURRENT DENSITY DISTRIBUTION





Re=1250,P=0 KPa

COOLING FLUID: WATER

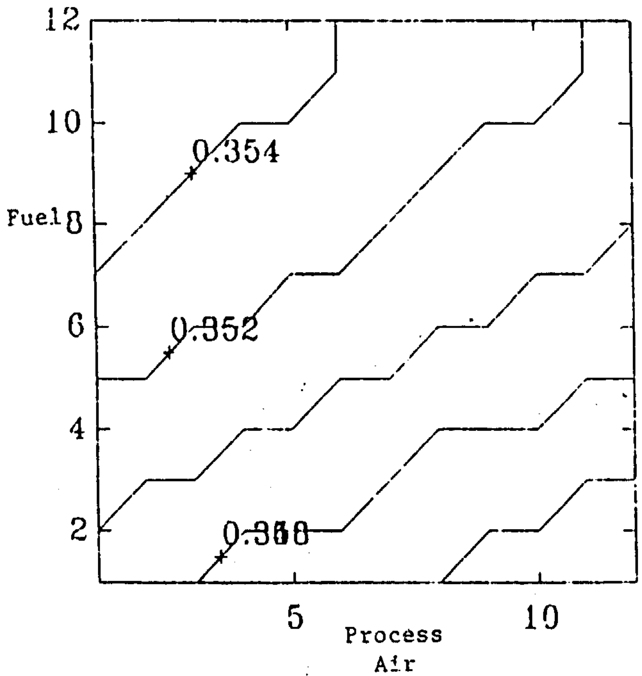
SHUT-DOWN PROCESS

TIME INTERVAL NO.13

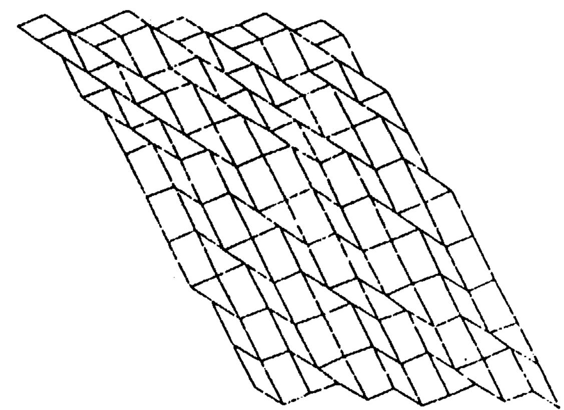
TABLE D-26. Transient Current Density Distribution During a Shut-Down Process (Water Coolant, P = 0 KPa, Re = 1250, T.I. = 13).

TRANSIENT CURRENT DENSITY DISTRIBUTION

Transient Current Density Profiles



Transient Current Density 3D Contour



Re=6167,P=0 KPa

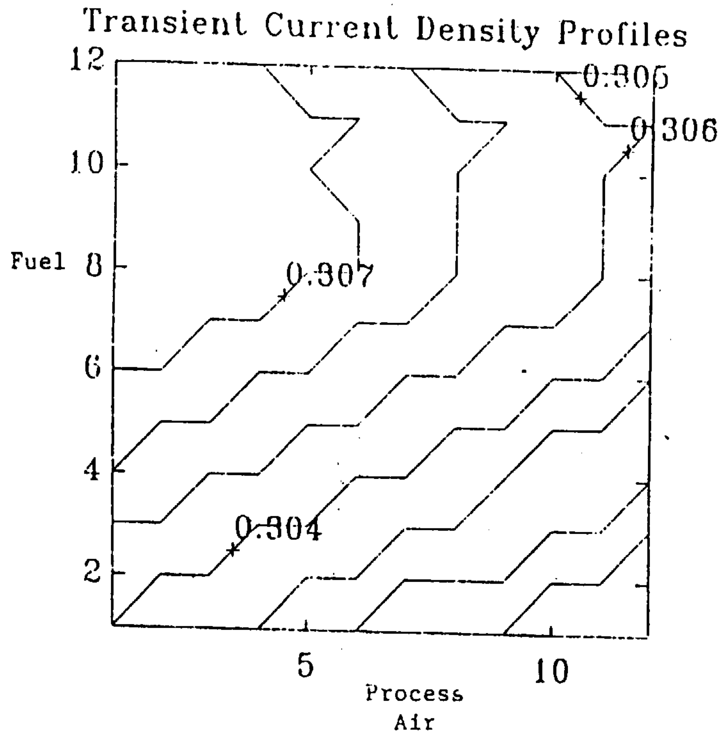
COOLING FLUID: WATER

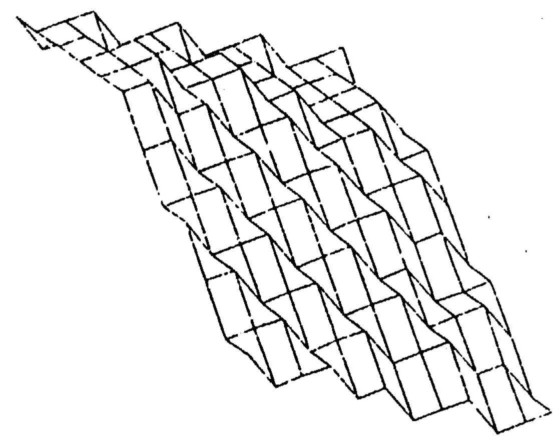
SHUT-DOWN PROCESS

TIME INTERVAL NO.1

TABLE D-27. Transient Current Density Distribution During a Shut-Down Process (Water Coolant, P = 0 KPa, Re = 6167, T.I. = 1).

TRANSIENT CURRENT DENSITY DISTRIBUTION





Re=6167,P=0 KPa

COOLING FLUID: WATER

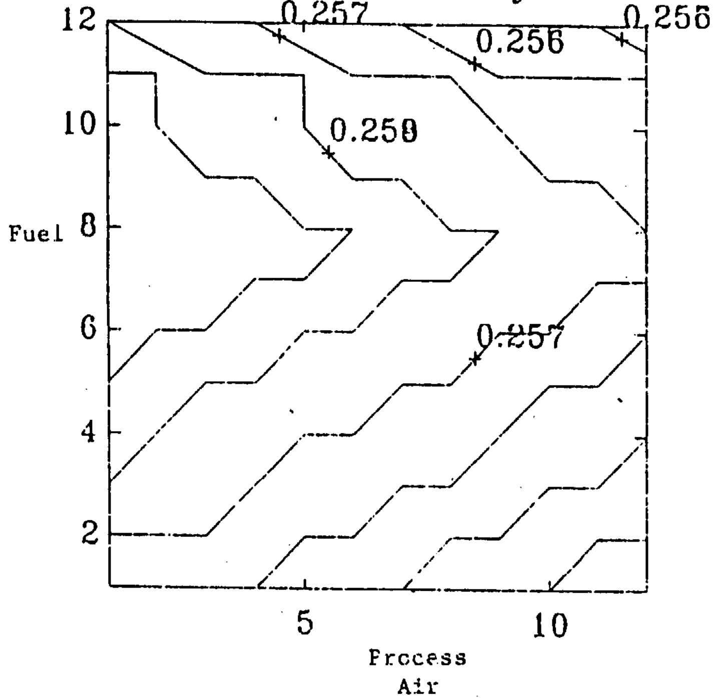
SHUT-DOWN PROCESS

TIME INTERVAL NO.2

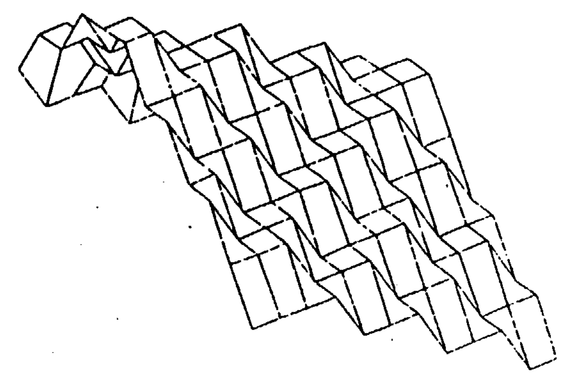
TABLE D-28. Transient Current Density Distribution During a Shut-Down Process (Water Coolant, P = 0 KPa, Re = 6167, T.I. = 2).

TRANSIENT CURRENT DENSITY DISTRIBUTION

Transient Current Density Profiles



Transient Current Density 3D Contour



Re=6167,P=0 KPa

COOLING FLUID: WATER

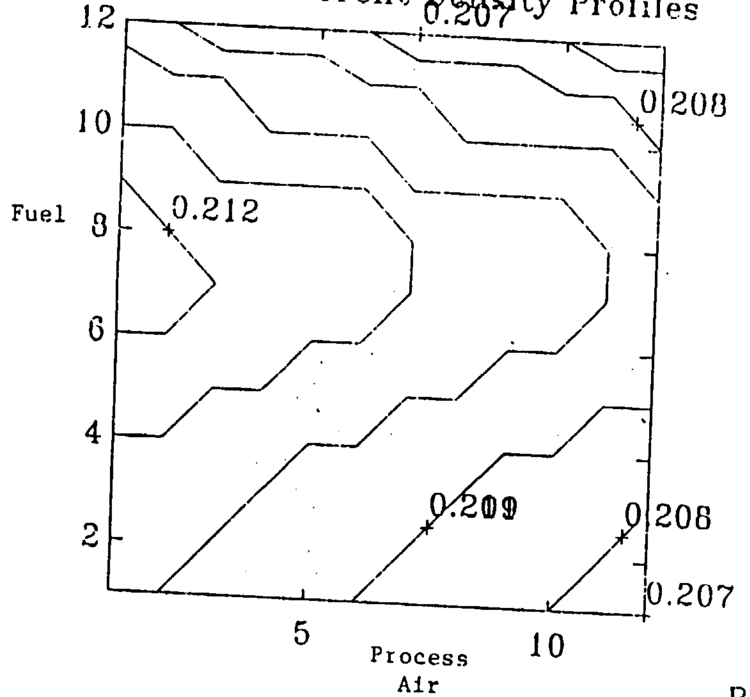
SHUT-DOWN PROCESS

TIME INTERVAL NO.3

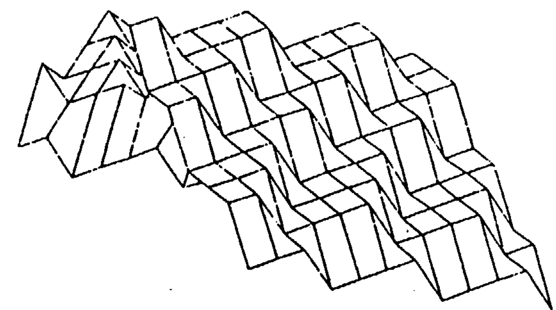
TABLE D-29. Transient Current Density Distribution During a Shut-Down Process (Water Coolant, P = 0 KPa, Re = 6167, T.I. = 3).

TRANSIENT CURRENT DENSITY DISTRIBUTION

Transient Current Density Profiles



Transient Current Density 3D Contour



Re=6167,P=0 KPa

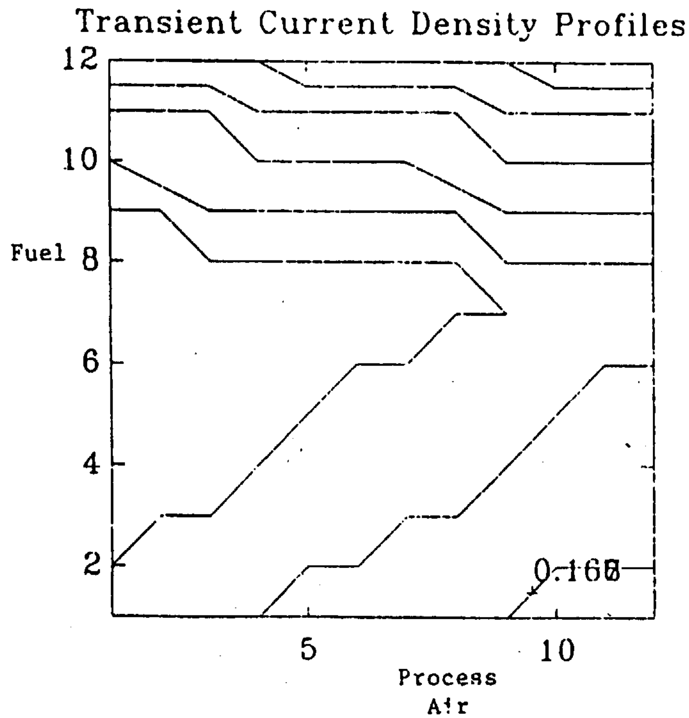
COOLING FLUID: WATER

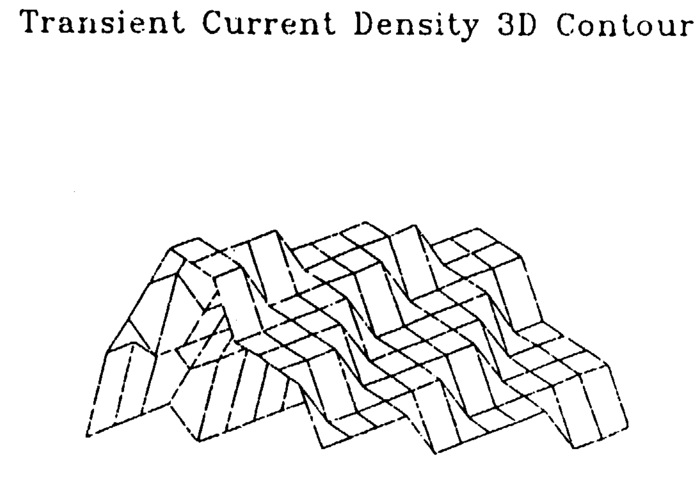
SHUT-DOWN PROCESS

TIME INTERVAL NO.4

TABLE D-30. Transient Current Density Distribution During a Shut-Down Process (Water Coolant, P = 0 KPa, Re = 6167, T.I. = 4).

TRANSIENT CURRENT DENSITY DISTRIBUTION





Re=6167,P=0 KPa

COOLING FLUID: WATER

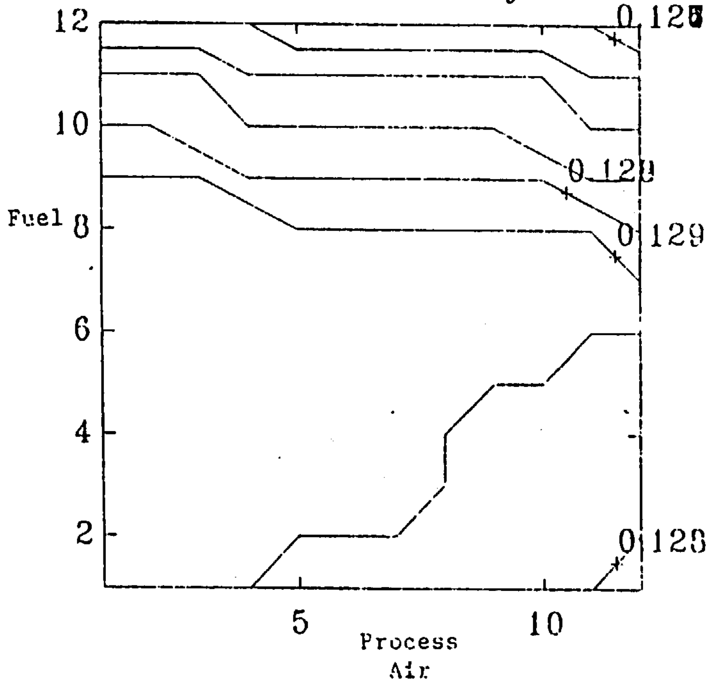
SHUT-DOWN PROCESS

TIME INTERVAL NO.5

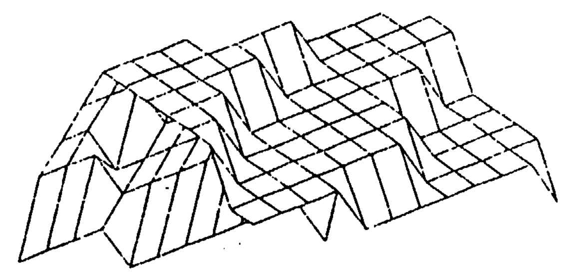
TABLE D-31. Transient Current Density Distribution During a Shut-Down Process (Water Coolant, P = 0 KPa, Re = 6167, T.I. = 5).

TRANSIENT CURRENT DENSITY DISTRIBUTION

Transient Current Density Profiles



Transient Current Density 3D Contour



Re=6167,P=0 KPa

COOLING FLUID: WATER

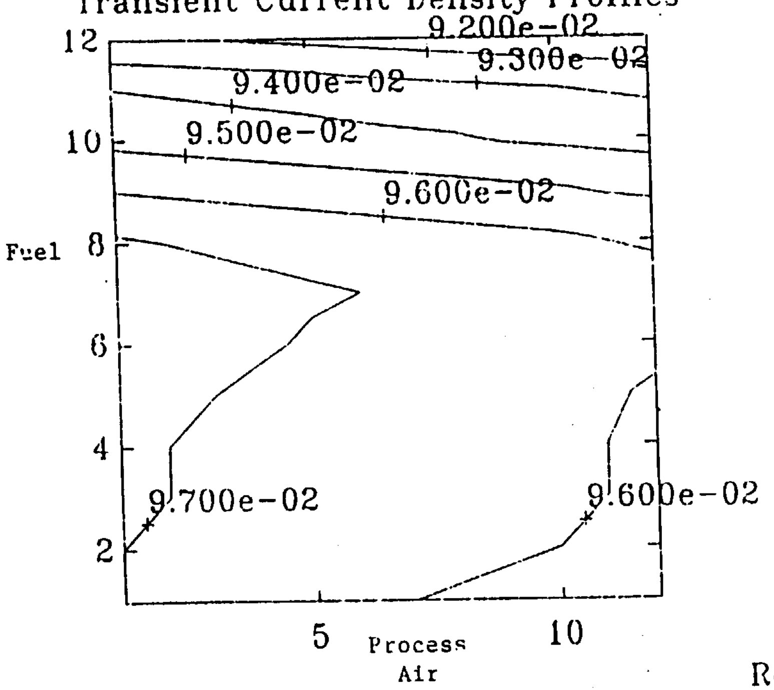
SHUT-DOWN PROCESS

TIME INTERVAL NO.6

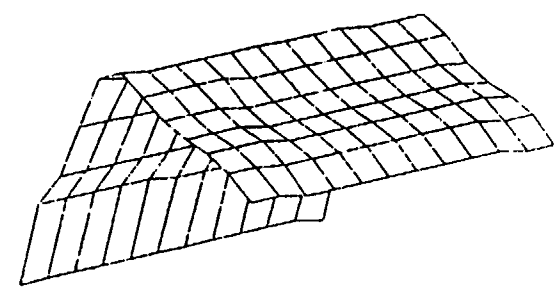
TABLE D-32. Transient Current Density Distribution During a Shut-Down Process (Water Coolant, P = 0 KPa, Re = 6167, T.I. = 6).

TRANSIENT CURRENT DENSITY DISTRIBUTION

Transient Current Density Profiles



Transient Current Density 3D Contour



Re=6167,P=0 KPa

COOLING FLUID: WATER

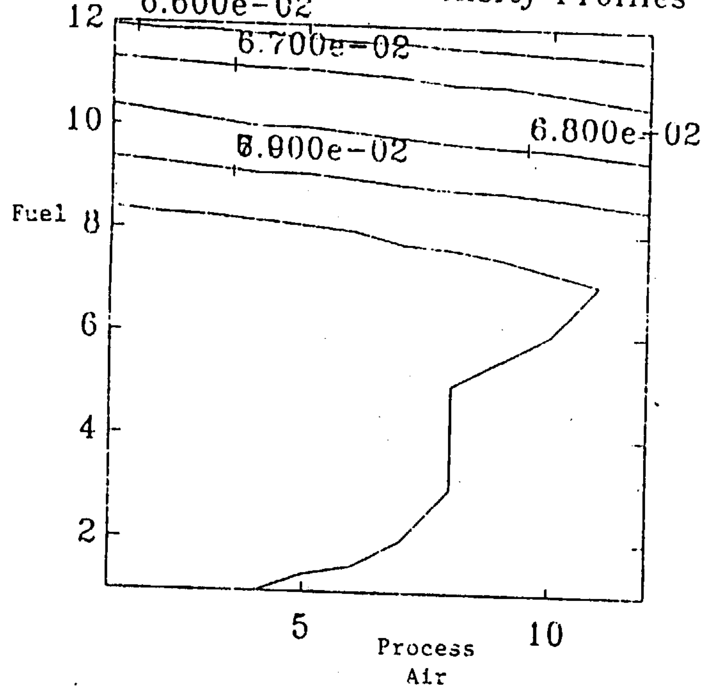
SHUT-DOWN PROCESS

TIME INTERVAL NO.7

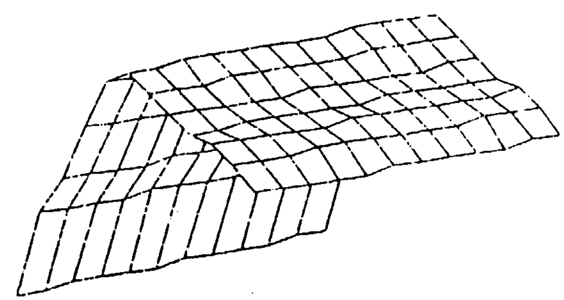
TABLE D-33. Transient Current Density Distribution During a Shut-Down Process (Water Coolant, P = 0 KPa, Re = 6167, T.I. = 7).

TRANSIENT CURRENT DENSITY DISTRIBUTION

Transient Current Density Profiles



Transient Current Density 3D Contour



Re=6167,P=0 KPa

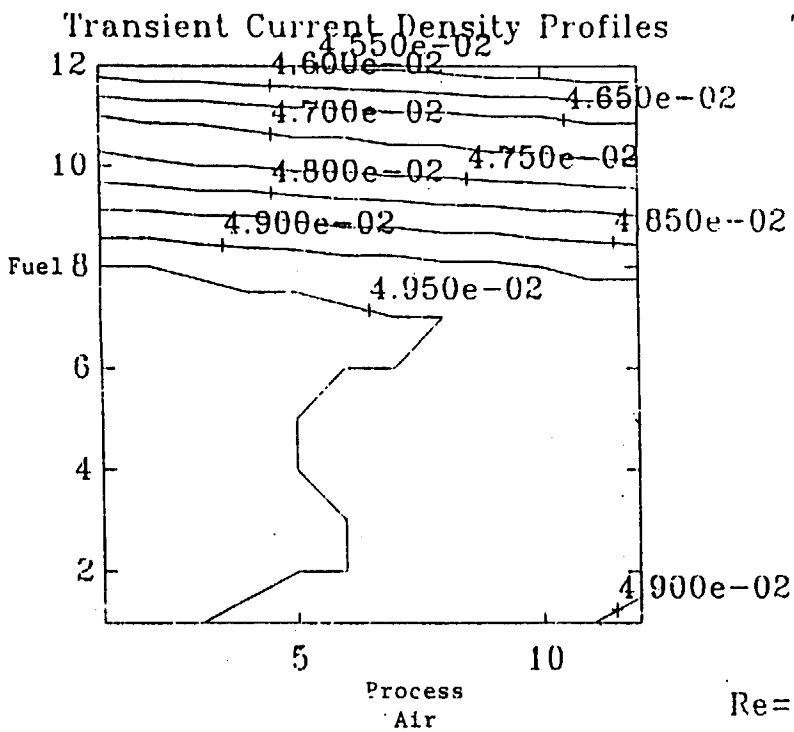
COOLING FLUID: WATER

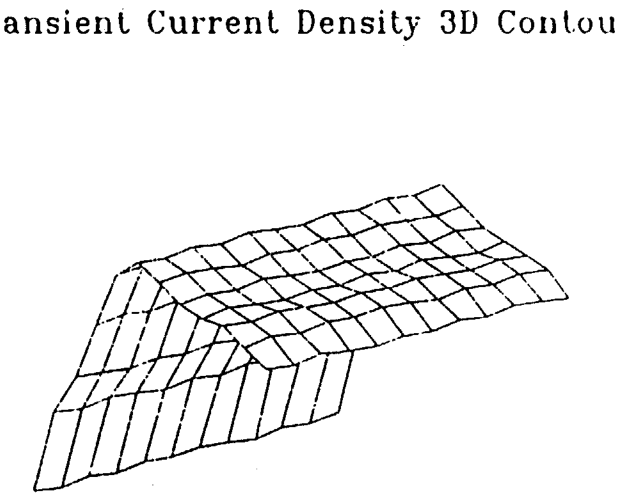
SHUT-DOWN PROCESS

TIME INTERVAL NO.8

TABLE D-34. Transient Current Density Distribution During a Shut-Down Process (Water Coolant, P = 0 KPa, Re = 6167, T.I. = 8).

TRANSIENT CURRENT DENSITY DISTRIBUTION





Re=6167,P=0 KPa

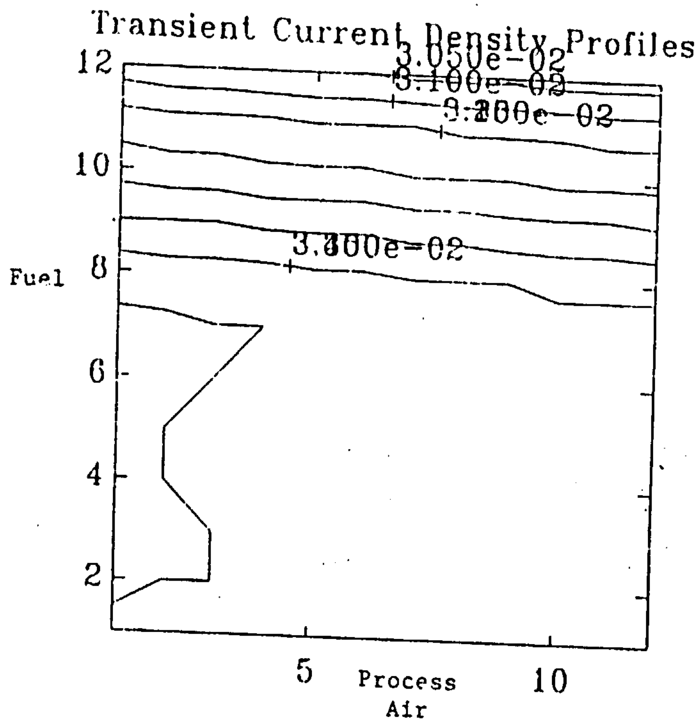
COOLING FLUID: WATER

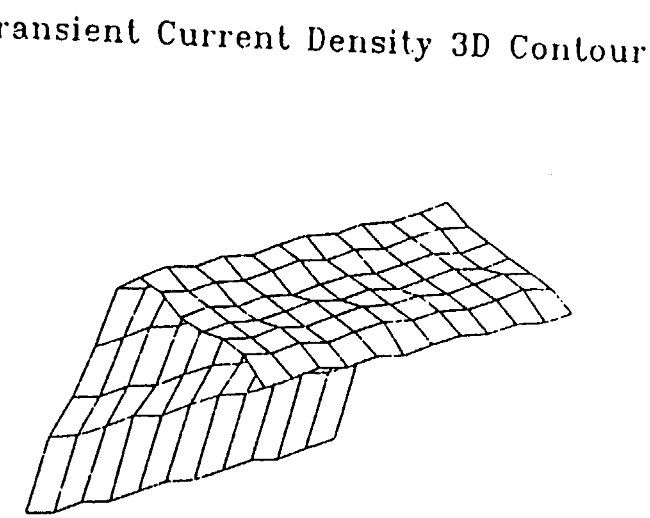
SHUT-DOWN PROCESS

TIME INTERVAL NO.9

TABLE D-35. Transient Current Density Distribution During a Shut-Down Process (Water Coolant, P = 0 KPa, Re = 6167, T.I. = 9).

TRANSIENT CURRENT DENSITY DISTRIBUTION





Re=6167,P=0 KPa

COOLING FLUID: WATER

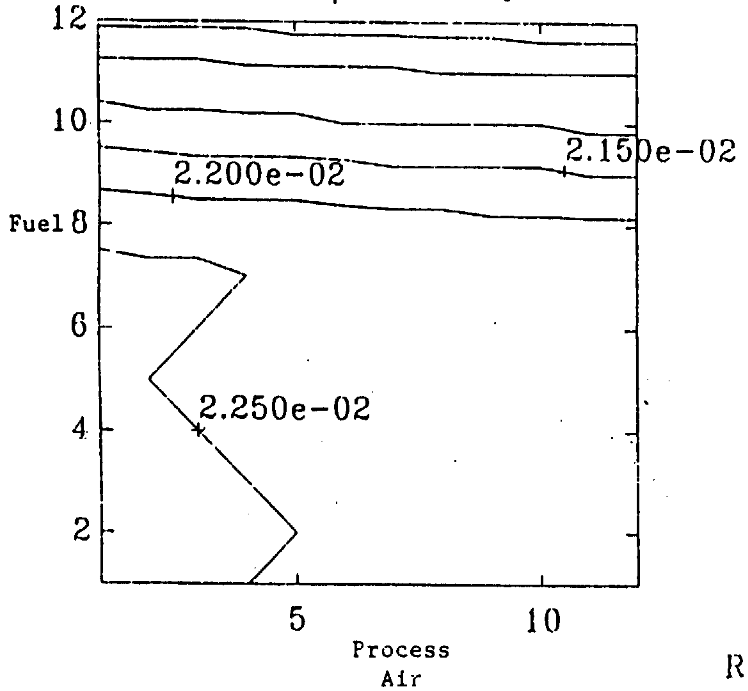
SHUT-DOWN PROCESS

TIME INTERVAL NO.10

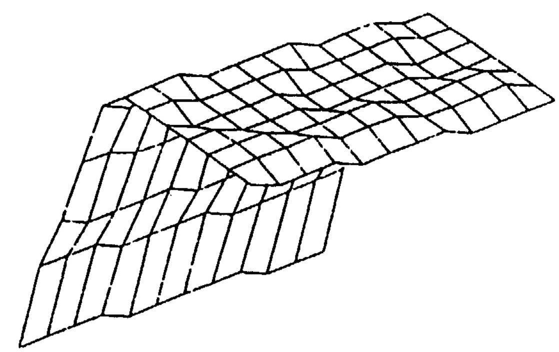
TABLE D-36. Transient Current Density Distribution During a Shut-Down Process (Water Coolant, P = 0, KPa, Re = 6167, T.I. = 10).

TRANSIENT CURRENT DENSITY DISTRIBUTION

Transient Current Density Profiles



Transient Current Density 3D Contour



Re=6167,P=0 KPa

COOLING FLUID: WATER

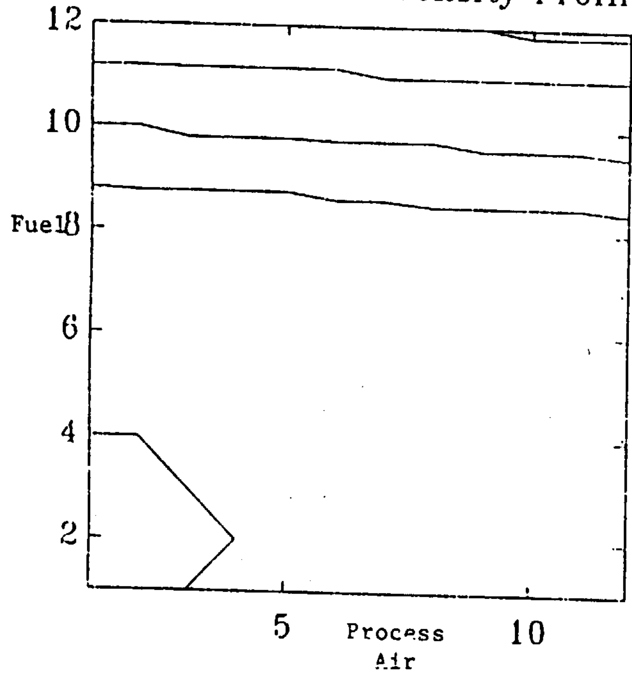
SHUT-DOWN PROCESS

TIME INTERVAL NO.11

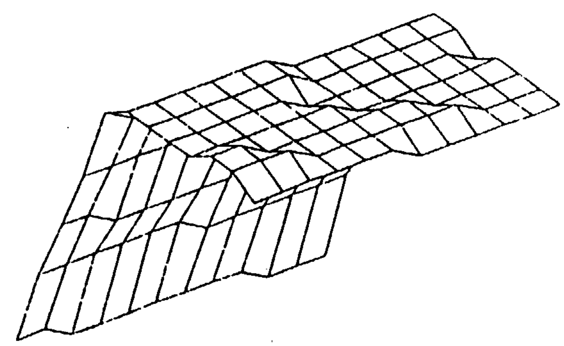
TABLE D-37. Transient Current Density Distribution During a Shut-Down Process (Water Coolant, P = 0 KPa, Re = 6167, T.I. = 11).

TRANSIENT CURRENT DENSITY DISTRIBUTION

Transient Current Density Profiles



Transient Current Density 3D Contour



Re=6167,P=0 KPa

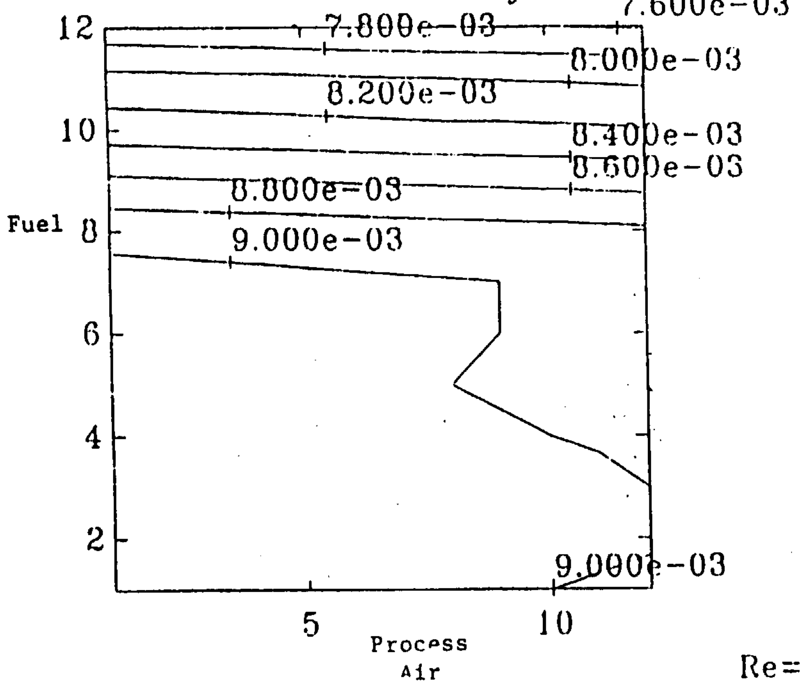
COOLING FLUID: WATER

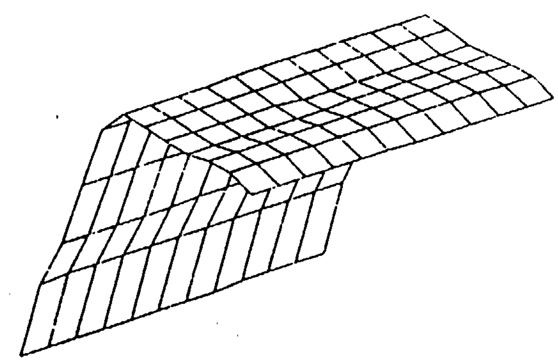
SHUT-DOWN PROCESS

TIME INTERVAL NO.12

TABLE D-38. Transient Current Density Distribution During a Shut-Down Process (Water Coolant, P = 0 KPa, Re = 6167, T.I. = 12).

TRANSIENT CURRENT DENSITY DISTRIBUTION





Re=6167,P=0 KPa

COOLING FLUID: WATER

SHUT-DOWN PROCESS

TIME INTERVAL NO.13

TABLE D-39. Transient Current Density Distribution During a Shut-Down Process (Water Coolant, P = 0 KPa, Re = 6167, T.I. = 13).

APPENDIX E

EXPERIMENTAL (T_w) TEMPERATURES

TABLE (E-1) WATER COOLANT AT (t=120 MIN)

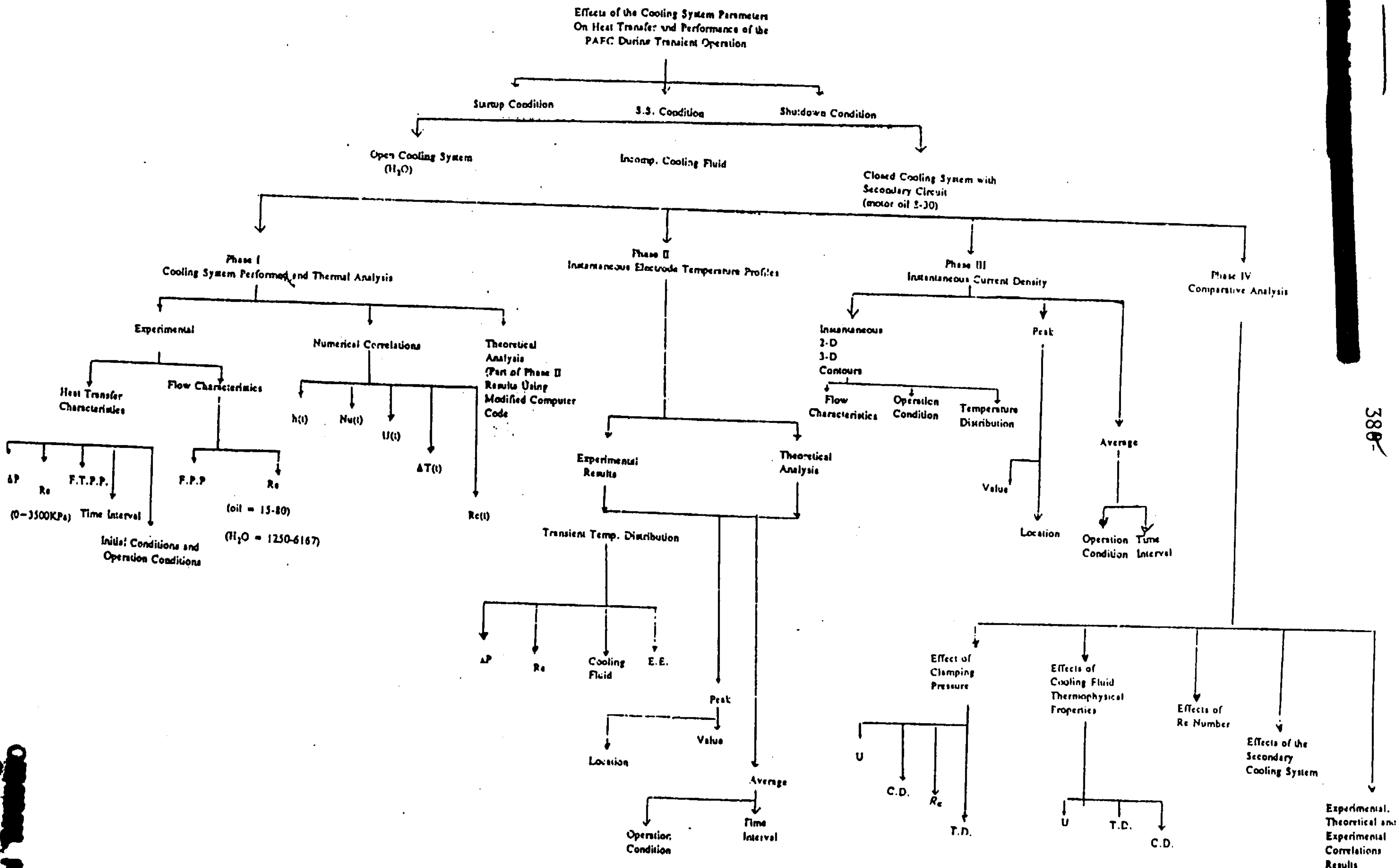
TABLE (E-2) OIL COOLANT AT (t=120 MIN)

WATER COOLANT (t = 120 min)

OPERATION CONDITION	T_3 C°	T_2 C°	T_x C°
Re = 1250 E.E. = 3000 W/m² P = 0 KPa	92.11	90.46	88.71
Re = 3321 E.E. = 3000 W/m₂ P = 0 KPa	89.98	87.61	84.91
Re = 6167 E.E. = 3000 W/m₂ P = 0 KPa	82.31	79.11	76.91
Re = 1250 E.E. = 3000 W/m₂ P = 1400 KPa	97.25	94.51	91.01
Re = 3321 E.E. = 3000 W/m₂ P = 14 KPa	88.25	85.71	82.71
Re = 6167 E.E. = 3000 W/m₂ P = 1400 KPa	84.11	80.44	78.91
Re = 1250 E.E. = 3000 W/m₂ P = 2800 KPa	97.01	94.98	92.12
Re = 3321 E.E. = 3000 W/m₂ P = 2800 KPa	88.24	86.98	83.91
Re = 6167 E.E. = 3000 W/m₂ P = 2800 KPa	86.91	89.11	81.91
Re = 1250 E.E. = 3000 W/m₂ P = 3500 KPa	83.87	81.91	78.98
Re = 3321 E.E. = 3000 W/M₂ P = 3500 KPa	73.01	71.81	68.01
Re = 6167 E.E. = 3000 W/m₂ P = 3500 KPa	73.02	70.10	67.23

OIL COOLANT (t = 120 min)

OPERATION CONDITION	T_3 C°	T_2 C°	T_1 C°
Re = 15 E.E. = 3000 W/m_2 P = 0 KPa	129.01	128.77	126.99
Re = 43 E.E. = 3000 W/m_2 P = 0 KPa	122.04	122.10	120.9
Re = 80 E.E. = 3000 W/m_2 P = 0 KPa	119.81	118.34	117.01
Re = 15 E.E. = 3000 W/m_2 P = 1400 KPa	186.10	184.71	183.16
Re = 43 E.E. = 3000 W/m_2 P = 1400 KPa	121.05	119.87	118.1
Re = 80 E.E. = 3000 W/m_2 P = 1400 KPa	116.13	114.81	113.71
Re = 15 E.E. = 3000 W/m_2 P = 2800 KPa	168.33	165.87	162.71
Re = 43 E.E. = 3000 W/m_2 P = 2800 KPa	141.01	139.89	138.00
Re = 80 E.E. = 3000 W/m_2 P = 3500 KPa	113.01	111.82	108.11
Re = 15 E.E. = 3000 W/m_2 P = 3500 KPa	113.01	111.87	108.11
Re = 43 E.E. = 3000 W/m_2 P = 3500 KPa	136.1	134.89	131.98
Re = 80 E.E. = 3000 W/m_2 P = 3500 KPa	104.07	102.11	99.89


Effects of the Cooling System Parameters On Heat Transfer and Performance of the PAFC During Transient Operation
Startup Condition
S.S. Condition
Shutdown Condition
Open Cooling System (H_2O)
Incomp. Cooling Fluid
Closed Cooling System with Secondary Circuit (motor oil 5-30)
Phase I Cooling System Performance and Thermal Analysis
Phase II Instantaneous Electrode Temperature Profiles
Phase III Instantaneous Current Density
Phase IV Comparative Analysis
Experimental
Numerical Correlations
Theoretical Analysis (Part of Phase II Results Using Modified Computer Code
Heat Transfer Characteristics
Flow Characteristics
ΔP
Re
F.T.P.P.
Time Interval
Initial Conditions and Operation Conditions
(0–3500KPa)
F.P.P
Re
(oil = 15-80)
(H_2O = 1250-6167)
h(t)
Nu(t)
U(t)
ΔT(t)
Re(t)
Experimental Results
Theoretical Analysis
Transient Temp. Distribution
ΔP
Re
Cooling Fluid
E.E.
Peak
Location
Value
Average
Operation Condition
Time Interval
Instantaneous 2-D 3-D Contours
Flow Characteristics
Operation Condition
Temperature Distribution
Peak
Value
Location
Average
Operation Condition
Time Interval
Effect of Clamping Pressure
U
C.D.
Re
T.D.
Effects of Cooling Fluid Thermophysical Properties
U
T.D.
C.D.
Effects of Re Number
Effects of the Secondary Cooling System
Experimental, Theoretical and Experimental Correlations Results