A FINITE ELEMENT THERMAL HYDRAULIC ANALYSIS OF A PLATE TYPE FUEL ELEMENT

by

Ş. NEJAT KAZAN

B.S. in Ch. E.

İ.T.Ü. , 1982

Submitted to the Institute for Graduate Studies in Science and Engineering in partial fulfillment of the Requirements for the degree of

Master of Science

in

Chemical Engineering

BOĞAZİÇİ UNIVERSITY

1986

A FINITE ELEMENT THERMAL HYDRAULIC

ANALYSIS OF A PLATE TYPE FUEL ELEMENT

APPROVED BY:

Doç. Dr. Fahir Borak

(Thesis Advisor)

Doç. Dr. Öner Hortaçsu

(Thesis Advisor)

Dr. Emre Aksan

DATE OF APPROVAL: June 23, 1986

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my thesis advisors Doç. Dr. Fahir Borak and Doç. Dr. Öner Hortaçsu for their continual guidance and helpfull criticism throughout the whole work.

I would like to express my thanks also, in the presence of Chairman of Chemical Engineering Department Doç. Dr. Fahir Borak to other members of the Chemical Engineering Department for their valuable assistance.

I wish to convey my sincere appreciation to all staff of the Computer Center for their help

Special thanks are due to Ali Ayla for his invaluable help and encouragements

I am also deeply indebted to Dilek Kıral for her efforts in preparing the graphs and tables

Last but not the least, I owe much to my aunt and father . . .

ABSTRACT

In this work a mathematical model and a Computer program developed to perform thermo-hydraulic analysis of a plate type fueled, water cooled nuclear core is presented.

A finite element numerical solution was obtained for the two dimensional heat conduction model developed. For the transient case, the finite difference method was chosen to approximate the time derivative. In the early stages of this work a lot of time and effort were necessary for the preparation and entering of the needed data for calculations. This difficulty was overcome later after using a grid generating subroutine.

In the determination of coolant temperature and pressure change mass, energy and momentum balance equations were evaluated for a control volume.

The computer program NEKA developed, throughout this work is used for the steady state calculations. If desired, subcooled boiling and transient calculations can also be performed using NEKA. In all cases the program may be used either interactively or using data file.

Two sample reactor cores were analyzed for various operating conditions such as the steady state analysis for a given power level, transient analysis with the change of power, coolant inflow temperature, inflowing mass flowrate as a function of time.

In the 1MW power generating core, the Reactor I in Çekmece Nükleer Araştırma ve Eğitim Merkezi, showed to have a maximum fuel temperature of 76.7°C under normal operating conditions for 37°C coolant input temperature This temperature reached to 66.8°C if coolant enters at 23°C. In the transient analysis, for a given step change 90 per cent of the total change was observed to complete within 5.2 seconds.

In the case of Reactor II which produces 5MW, the maximum fuel temperature reached to 69.2^{o}C under normal operating conditions for 30^{o}C coolant input temperature. If the coolant flowrate is decreased to 0.065 kg/s from 0.31 kg/s or power level is increased to 17.5 MW subcooled boiling occurance was predicted.

For both reactors, the operating conditions were found to be safe.

ÖZET

Bu çalışmada, plaka yakıt elemanlı, su soğutmalı nükleer reaktör kalbi için termo-hidrolik hesaplamalar yapmak üzere geliştirilen matematiksel model ve bir bilgisayar programı sunulmuştur.

Geliştirilen modelde ısı iletiminin iki yönde olduğu kabul edilmiş ve sayısal çözüm için sonlu elemanlar metodu kullanılmıştır. Kararsız durum hesaplamalarında zaman türevi için sonlu farklar yaklaşımı metodu kullanılmıştır. Bu çalışmanın başlarında hesaplamalar için gerekli olan verilerin hazırlanması ve programa girilmesinde çok fazla zamana ve çalışmaya gerek duyulmuştur. Daha sonra bir eleman oluşturan alt program kullanımıyla bu güçlük bertaraf edilmiştir.

Soğutucu sıcaklık ve basınç değişimini hesap etmek maksadıyla bir kontrol hacmi için kütle, enerji ve hareket miktarı denklemleri uygulanmıştır.

Bilgisayar programı NEKA görüşmeli veya bir veri kütüğünden veri girdisi ile kararlı durum ve isteğe bağlı olarak aşırı soğutulmuş kaynama ve kararsız durum hesaplamalarını yapmak üzere geliştirilmiştir.

Verilen bir güç seviyesi için kararlı durum, soğutucu giriş sıcaklığı, giriş debisi veya gücün zamana bağlı değişiklikleri için kararsız durum gibi çeşitli çalışma şartları altında iki örnek kalb bu çalışmada incelenmiştir.

Normal çalışma şartları ve 37°C soğutma suyu giriş sıcaklığı için Çekmece Nükleer Araştırma ve Eğitim Merkezin'deki 1MW güç üreten reaktörün yakıt plakasının maksimum sıcaklığı 76,8°C olarak hesaplanmıştır. Soğutma suyu giriş sıcaklığı 23°C olduğunda yapılan hesaplamalar bu sıcaklığın 66,8°C indiğini göstermiştir. Verilen bir adım değişimi için, kararsız

durum hesaplamalarında, toplam değişimin yüzde 90'nın 5.2 saniyede tamamlandığı gözlenmiştir. 30°C soğutma suyu giriş sıcaklığı ve normal çalışma şartlarında 5MW güç üreten reaktörde ise maksimum yakıt sıcaklığının 69.2° C olduğu bulunmuştur. Eğer soğutma suyu debisi 0.31 kg/s ' den 0.065 kg/s'ye indirilir veya güç seviyesi 17,5 MW'a çıkarılırsa aşırı soğutulmuş kaynamanın başlıyacağı gözlenmiştir.

Her iki reaktör için çalışma şartlarının tehlikesiz olduğu saptanmıştır.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

A_i	Coolant channel cros sectional area (m^2)
[B]	Gradient matrix
[C]	Capacitance matrix
de	Equivalent diameter (m)
{f}	Force vector
f	Friction coefficient
F_i	Frictional lost per unit length (N/m)
h	Convection heat transfer coefficient ($W/m^{2\,o}C$)
h_i	Coolant enthalpy (J/kg)
$h_{i_{old}}$	Coolant enthalpy one time step ago (J/kg)
[k]	Conduction matrix
m_i	Coolant flow rate (kg/s)
[N]	Shape function
P_i	Pressure (N/m^2)
Q	Heat generation rate per plate (w)
q_i	Heat flux (W/m^2)
t	Time (s)
T_f	Coolant temperature (^oC)
V_i	Coolant flow velocity (m/s)
z	Fuel width (m)

I- INTRODUCTION

In this work, thermal-hyraulic behaviour of water cooled plate type nuclear reactor core is examined. The finite element method is used as a numerical solution procedure for the mathematical models developed. The introduction chapter consists of four parts. In the first part, the importance of thermo-hyraulic analysis in nuclear reactor design is explained. The second part gives a short explanation of the finite element method related to its application areas and, the method's advantages and disadvantages. Computer codes which perform thermo-hyraulic analysis are presented in the third part of the introduction. The last part gives a short description of the contants of the thesis work.

A- THERMO-HYDRAULICS OF NUCLEAR REACTORS

Nuclear power is one of the sources of energy in either stationary power plants for the generation of electricity or for the propulsion of mobile systems. The application of nuclear energy is not confined only to nuclear power systems. Radioactive isotopes, which are produced in nuclear reactors, have been found to have a wide range of important applications [1] .

In the design of nuclear reactors except for the zero power reactors, the process of heat generation in the fuel element, heat transfer and thermal transport parameters are the most important factors. The thermal-transport path proceeds from a point of fission energy deposition within a fuel through layers of fuel, cladding and then through the cladding to the interface with a fluid coolent. The heat transported into the body of the flowing coolant causes a rise in the temperature of the coolant. The coolant transports the absorbed energy to the heat exchanger in which steam is generated, and the steam is then expanded in a turbine generator to produce electricity. However in some research reactors useful energy is not produced.

In general the temperature in an operating reactor varies from point to point within the system. The power level of the reactor, design of the coolant system, and the nature of the fuel determine the maximum fuel temperature to which a fuel element can safely be raised. Above this temperature there is a danger that the fuel may melt, which can lead to the rupture of the cladding and the release of the fission products. One of the major objectives in the design of a reactor cooling system is to provide for the removal of the heat produced at the desired power level, while keeping the maximum fuel temperature below a predetermined value. The power of the reactor could be increased by removing control rods and placing a reactor on a positive period, Therefore its power could be increased indefinitely. Eventually a point would be reached at which coolant can no langer remove all of the heat produced. After this point the temperature of the fuel will rise to its melting point, and a portion of it will start to melt down. To avoid this situation power is maintained at a desired level by the position of the control rods. Thus the amount of power generation in a given reactor is limited by thermal rather than by nuclear considerations. The reactor core must be operated at such a power level that with the best available coolant system, the temperature of fuel and cladding anywhere in the core must not exceed safe limits.

In the thermal design of a fuel element the following points must be taken into consideration [2] :

- The maximum temperature must not lead to the deterioration of the materials
- Thermal stresses from the effects of thermal gradients and

accumulated fission gases should not lead to the cladding creep and embrittlement.

- Thermal heat flux must be below the so called critical heat flux in which coolant boiling instabilities occur.

- The change in the core dimensions because of maximum temperature can also cause the failure of the coolant system plugging the coolant channel.

Therefore, from the view point of safety of a nuclear power plant, the thermal hydraulic analysis is the most important and complex part of the reactor design.

Thermo-hyraulic analysis is also the basic consideration in the case of an accident, such as LOCA (loss of coolant accident) ; a major pipe break leading to loss of coolant completely or partially from the core. In this case if cooling is not provided in sufficient quantity in a short time cladding, fuel and core melt down may take place with the relaase of considerable amounts of radioactive isotopes.

B- FINITE ELEMENT METHOD

During the past two decades, the finite element method has become a widely used numerical procedure for the computer oriented solution of complex problems in engineering. The method is applied to the problems governed by Laplace or Poisson equations which are closely related to the minimization of a functional. After a weighted residual procedure such as Galerkin's method have been used for the derivation of the element equations related to structural mechanizm, heat transfer, and fluid mechanics application range of the finite element method was enlarged [3]. Since the Galerkin's method allows the finite element method to be applied to all differential equation. This knowledge eliminated the need for a functional formulation of the physical problem.

The success of the finite element method is largely based on the basic finite element procedures used : the formulation of the problem in variational or weighted residual form, the finite element discretization of this formulation, and the effective solution of the resulting finite element equations. These basic steps are the same for all types of problem considered.

The fundemental concept of the finite element method is that any continuous quantity, such as temperature or pressure can be approximated by a discrete model composed of a set of piecewise continuous functions defined over a finite number of subdomains. The discrete model is constructed as follows.

1- A finite number of points called nodal points or nodes in the domain are identified

2- The domain is divided into a finite number of sub-domains called elements which are connected at common nodal points and collectively approximate the shape of the domain.

3- The value of the condinuous quantity at each nodal point is denoted as a variable which is to be determined.

4- The continuous quantity is approximated over each element by a polynomial that is defined using the nodal values of the continous quantity.

The equations for the individual elements are then assembled to give approximate equations for the domain as a whole and the solution of these equations represents an approximate solution to the problem as a whole.

The present-day applications of the finite element method are very extensive. Several advantages properties of the finite element method have contributed to its extensive use. Some of the main advantages of the method are as follows [3].

1- The material properties in adjacent elements do not have to be the same. This means that the method can be applied to bodies composed of several materials

2- Irreqularly shaped boundaries can be approximated using elements with straight sides or matched using elements with curved boundaries . The method, therefore, is not limited to regular shapes with easily defined boundaries.

3- The size of the elements can be varied. This property allows the element qrid to be expanded or refined as the need exists.

4- Boundary conditions such as discontinous surface loading present no difficulties for the method.

The primary disadvantage of the finite element method is the need for computer programs and computer facilities. The digital computer is a necessity, and computers with large memories are needed to solve large complicated problems.

C- THERMO-HYRAULIC COMPUTER CODES

For a long time, a great deal of effort has been devoted to the development of techniques that would allow the analysis and prediction of the thermal and hydraulic behavior of reactor fuel assemblies.

The code TERHID [4] performs the thermal hydraulic analysis for steady state and unsteady state conditions of water-cooled reactors. The fuel heat transfer model included in TERHID considers plate type fuel elements and allows the calculation of the fuel and cladding temperature for a specified power level. The fuel and cladding temperatures are calculated by using a lumped parameter technique and assuming one dimensional heat transfer model.

The code COBRA-3 C/KF KI [5] calculates the steady state and unsteady state flow and enthalpy transport in rod-bundle in both boiling and non-boiling conditions. A semi-explicit finite difference scheme is used to perform a boundary-value solution where the boundary conditions are the inlet enthalpy, inlet flowrate and exit pressure.

RODCON and HOTTEL [6] are two computational codes used to calculate thermal and radiation heat transfer for the Core Flow Test Loop (CFTL) analysis efforts. RODCON was developed to calculate the internal temperature distribution of the fuel rod simulator (FRS) for the CFTL in two-dimension. The governing elliptic, partial differential heat equation is cast into a fully implicit, finite-difference form by approximating the derivatives with a forward differencing scheme with variable mesh spacing. HOTTEL is used in calculating radiation heat transfer in a rod bundle. HOTTEL uses geometric view factors, surface emissivities, and surface areas to culculate the gray-body or composite view factors in an enclosure having multiple reflections in a nonparticipating medium.

The code RAT-3 D [7] using a two step iteration procedure performs the calculation of two and three-dimensional transient heat transfer. The set of heat-conduction equations are solved by the alternating-direction method. The two dimensional steady-state program, RAT-2DS is simple to use than the transient program, in that no time history is required. Radiation between solid regions and to the outside environment is allowed for in all the programs.

THAC-SIP-3 D [8] is a transient heat analysis code designed to use the Strongly Implicit Procedure to calculate temperature distributions for problems that can be modeled in the three dimensional cartesian coordinate system. The code uses a finite difference scheme to generate the system of equations solved by the Strongly Implicit Procedure to obtain the transient temperature distribution.

The code BIOT 2 [9] is a three dimensional steady-state and transient heat conduction code for a given geometry. The code calculates temperature distribution in fuel elements.

The code FEM [10] is used for the solution of two-dimensional transient heat conduction equation. The time derivation is approximated by use of Saul'ev ADE method which is motified for FEM. The realization of the method is based on a modified version of the program DIFGEN which solves the neutron diffusion equation.

The computer program HT2D [11] performs finite element, two dimensional, conduction heat transfer analysis in either Cartesian or cylindrical coordinates. In time domain a backward difference implicit integration scheme is used the user needs to supply only initial temperatures to restart the program.

The UNCLE [12] finite element system provides routines to carry out the operations which are common to all finite element programs.

In the code TEMPEL [13] finite element method in two dimensions, using linear triangular finite elements is used. Variational principle is used to produce the set of finite element equations for heat conduction.

HETRAP [13] is a heat transfer analysis program developed for use in the evaluation of LOCA experiments. The code can be used to calculate the steady-state and transient temperature field in fuel rods and electrically heated rods. The code uses finite element method to calculate the transient temperature field within the rods.

The other computer codes published between the years 1980-1985 are all given in table (1-1)

TABLE 1-1 List of Computer Codes

Program-name (s). Description	Abs-Id *
GHT, 3-D steady-state and transient heat conduction	NEA 0073
HEATING-5 , steady-state or transient heat conduction,3-D X-Y-Z,1-D Sph. geom.	NESC 0517
ORTHAT, transient heat conduction in 2-D X-Y,R-Z and R-Theta geom.	NESC 0525
ORTHIS, steady-state heat conduction in 2-D X-Y,R-Z and R-Theta geom.	NESC 0525
TAFE , 2-D steady-state heat conduction for struc with gas gaps	NEA 0532
TAFEST, 2-D transient heat conduction	NEA 0531
TEMP, steady-state and transient heat conduction in pl.or cyl. geom.	NEA 0570
ARGUS , transient temp. distr. cyl. geom, space dep. or time-dep heatgen.	NESC 0152
STRZ - 2 -F4, steady-state temp. distr. in inhomog. cyl. with heat srce and radn srce	NEA 0056
6- KILER, core heat transf, ZR-steam reactn, decay heat during bwr loca	NESC 0636
AIROS-2 A , space indep reactor kinetics and space-dep heat transf, mass transf.	NESC 0326
AXFLU, heat transf fuel elem cluster to coolant, slug flow or laminar flow	NESC 0182
AXTHRM, heat transf fuel elem cluster to coolant, slug flow or laminar flow	NESC 0183
BEACON/MOD3, 1-D and 2-D 2 phase flow and heat transf in containment, Lwr loca	NESC 0767
BLOOST-6 , space-indep reactor kinetics and 2-D heat transf in R-Z geom.	NESC 0303
CEDRAZAL, steady-state heat transfer in htr with multifuel reg.	NEA 0553
CLUS, heat transf and fuel power in liquid cooled 7 rod fuel elem cluster	NEA 0255
ENERGY, Lmfbr wire wrapped fuel assembly heat transf and coolant temp distr	NESC 0696

* Abs-Id : Abstract name and identification number

TABLE 1-1 List of Computer Codes (continued)

Program-name (s). Description	Abs-Id
EXCURS, heat transf transients in cyl reactor channel loca	NEA 0424
EXCURS,3, reactor kinetics and heat transf in cyl channel during accident	NEA 0228
HEATMESH, geom data gen for heat transf calc in axisym sys.	NESC 0434
LOCK, steady-state and transient heat transf, temp in FBR with blocked channels	NESC 0732
MANTA, heat transf fuel elem cluster to single-phase steady-state fluid flow	NESC 0256
REFLUX, time-dep heat transf and therm anal of fuel elem during loca reflood	NESC 0763
REFLUX-GRS, time-dep heat transf and press of fuel elem during loca reflood	NESC 0763
REPP, heat transf and temp anal of triangl or squ fuel elem lattice in lfr	NESC 0483
SAS-1A, lmfbr transient anal with heat transf, fuel deformation and feedback	NESC 0400
SCALE-1, modular sys for critlty, shielding, heat transf calc	CCC-0424
SCALE-2, modular sys for critlty, shielding, heat transf calc	CCC-0450
SCALE-3, modular sys for critlty, shielding, heat transf calc	CCC-0466
SIEX, steady-state heat transf, swelling,mixed oxide fuel pin in fast N flux	NESC 0673
SPARK, time-dep 1-D 2-D , 3-D diffn with heat transf and feedback	NEA 0468
TAC-2D, steady-state and transient heat transf in X-Y,R-Z or R-theta geom	NESC 0408

TABLE 1-1 List of Computer Codes (continued)

Program-name (s). Description	Abs-Id
TAC-3D, 3- D steady-state and transient heat transf in X-Y-Z and R-theta-Z geom	NESC 0414
TACO-3D, 3-D lin or nonlin, steady-state or transient heat transf	NESC 9838
THETA-1B, fuel rod temp distr by 2-D diffn, heat transf to coolant, LWR loca	NESC 0512
TRANS-FUGUE-1, single channel 2 phase flow heat transf after boiling	NESC 0268
VARR2 VARRLXSG, 2-D transient fluid flow and heat transf in X-Y and cyl geom	NESC 0755
VELVET-2, heat transf for triangl spaced fuel elem clusters in Lmfbr	NESC 0458

Technical assessment of accident conditions in nuclear reactors, and many problems in other fields, require the solution of the transient temperature distribution in solid regions usually cooled by a flowing fluid.

The purpose of the present work is to establish a realistic approach to the thermo-hydraulic behaviour of a nuclear reactor under normal operating conditions and similar structures where thermal and hydraulic problems are of interest. The computer code NEKA resulting from this work performs the calculation of steady state and transient temperature distribution in cartesian coordinate in two-dimensions. In this situation the flowing fluid temperatures are dependent on heat transfer between fluid and solid, and so these temperatures cannot be supplied as preset boundary conditions. The finite element procedure is used for the solution of heat-conduction equations, and finite-difference approach is applied to heat balance equations for coolant fluid so that a new set of boundary conditions are achieved for the next iteration. The program contains a grid generator which is used to construct triangular elements and to number nodal points. Furhermore, using this program it is possible to calcule the pressure change in coolant channel and to perform subcooled boiling calculation.

Following chapters give more detailed explanation of the code. In chapter 2, a description of physical system is given. Heat transfer and heat transport models are developed and application of finile element method to these equations is presented. The resultant equations of the second chapter are transformed into a computer program in the third chapter. In the fourth chapter, steady-state and unsteady-state numerical application of the program is given. In the fifth chapter, conlusions of the work are presented.

II. MATHEMATICAL MODELLING

This chapter mainly consists of three parts : description of the physical system, finite element formulation of heat conduction model together with the boundary conditions and, heat, mass and momentum transfer models.

A- DESCRIPTION OF PHYSICAL SYSTEM

The nuclear reactor core generally is rod or plate typed. In this work, a plate type fueled nuclear reactor core is analysed. The core consists of many fuel elements as shown in figure (2.1). The fuel element also includes the fuel which is a 20 per cent uranium-aluminium mixture, and aluminium cladding around the fuel. The coolant fluid is passed through the channels between fuel elements in downward direction. The energy produced in fuel element is removed by two fundamentally different heat transfer process, conduction and convection. Heat produced is first transferred to the surface of the element. The heat conducted to the surface of the fuel element is carried into the coolant and out of the system by convection. As the coolant moves along the fuel, because of absorbed heat its temperature contiunually increases. However, the temperature does not increase at a constant rate since the heat released nonuniformly from the fuel.

B- FINITE ELEMENT FORMULATION OF HEAT CONDUCTION IN NUCLEAR FUEL PLATE

The governing differential equation for heat conduction in solids is

$$K_x \frac{\partial^2 T}{\partial x^2} + K_y \frac{\partial^2 T}{\partial y^2} + K_z \frac{\partial^2 T}{\partial z^2} + Q = \rho c \frac{\partial T}{\partial t} \qquad (2.1)$$

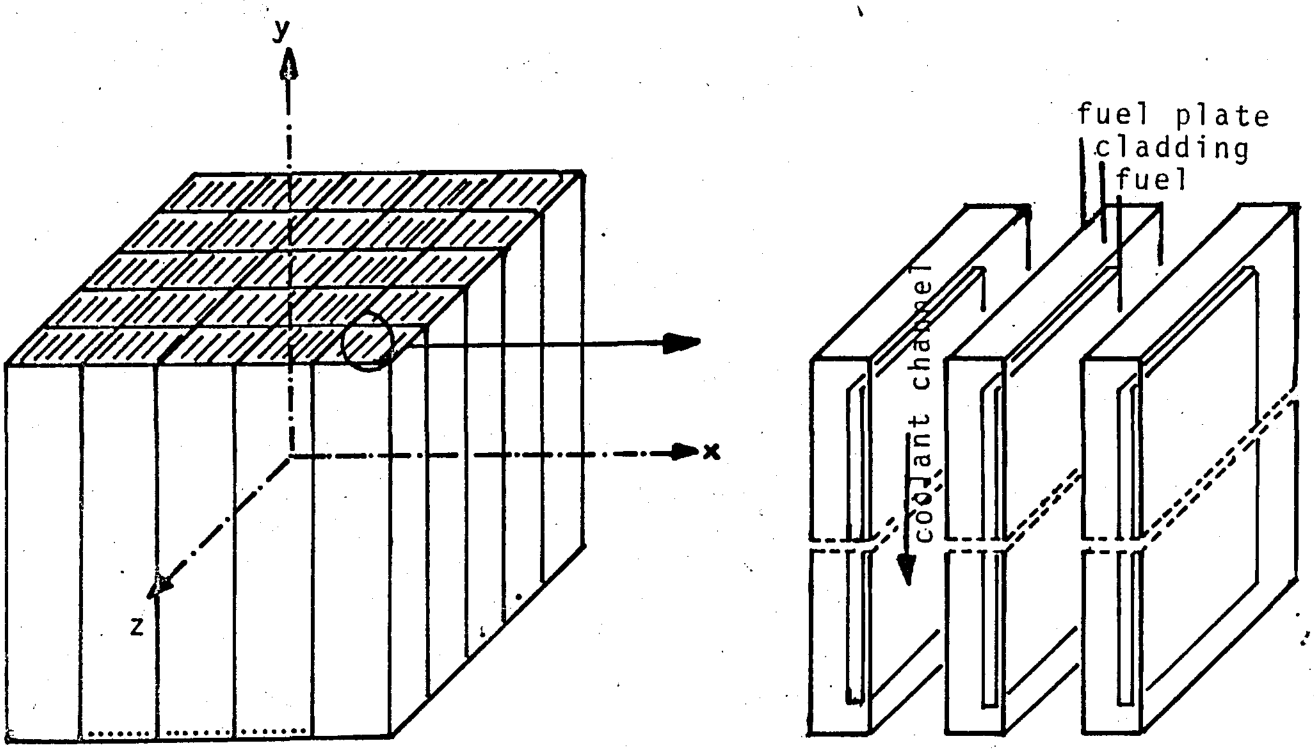

FIGURE 2-1 Reactor Core and Fuel Plates

where T is the temperature

K_x, K_y and K_z are the conductivities in the x,y, and z direction

Q is the heat generated within the body

ρ and c are the density and heat capacity of the solid.

Equation (2.1) can be applied to a two-dimensional problem simply by deleting the term associated with the coordinate in the direction of which there is no heat conduction. The governing equation for the two-dimensional (figure 2-2) case is

$$K_x \frac{\partial^2 T}{\partial x^2} + K_y \frac{\partial^2 T}{\partial y^2} + Q - \rho c \frac{\partial T}{\partial t} = 0 \qquad (2.2)$$

The most popular of the finite element formulations is the Galerkin method. The Galerkin method is a means of obtaining an approximate solution to a differential equation. It does this by requiring that the error between the approximate solution and true solution be orthogonal to the functions used in the approximation. If the solution of a differential equation of the form $L\bar{u}-f=0$ (where L is a differential operator), is assumed to be $\bar{u}$ then the solution is $L\bar{u} - f = \varepsilon$ where ε is a residual or error because the solution is only approximate. One way of making ε as small as possible is to require the integral $\int_R W_p \varepsilon \, dR = 0$ for the interpolation function W_p. This integral states that the interpolation function must be orthogonal to the error over the region R.

The application of the Galerkin method with the finite element approach yields the equation [3] ,

$$\int_R W_p L(\phi) \, dR = 0$$

where ϕ is an unknown parameter and approximated by

$$\phi = [N_i, N_j, N_k \ldots] \{\phi\}$$

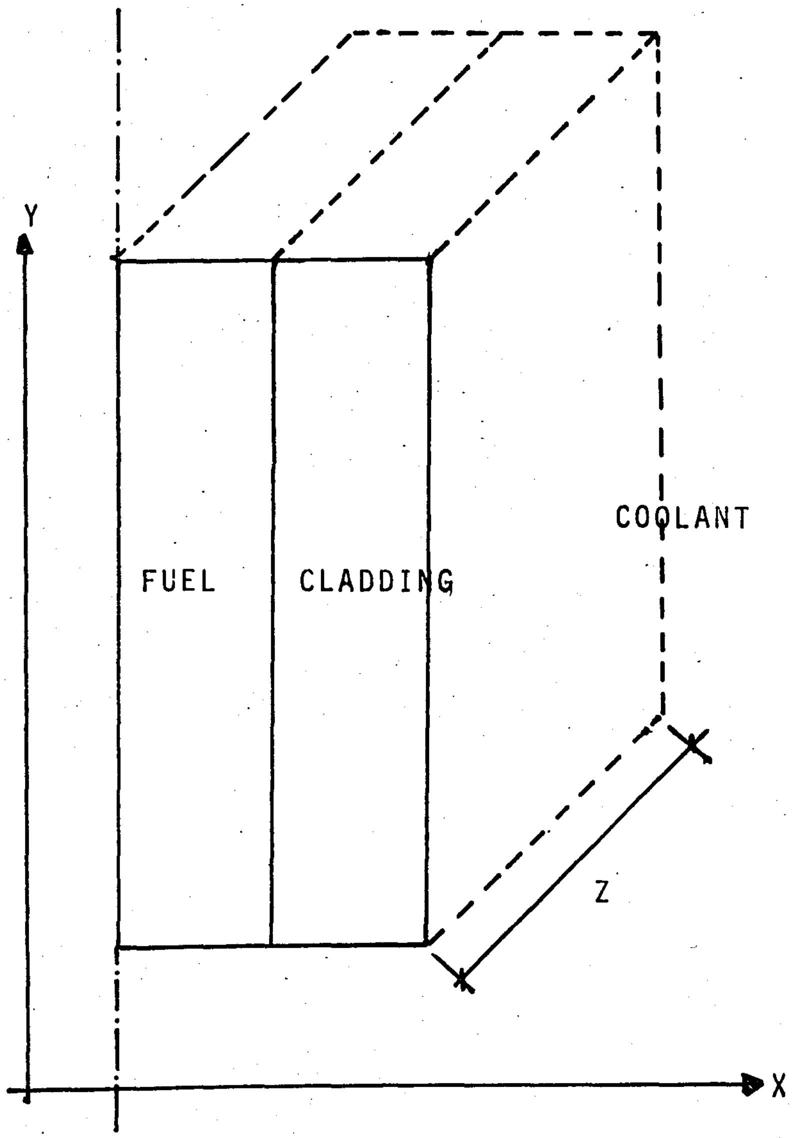

FIGURE 2-2 Fuel and Cladding Design

and w_p is equal to the shape function N_β ($\beta = i,j,k,\ldots$) .

Application of the Galerkin method to (2-2) yields

$$\int_v [N]^T \left(K_x \frac{\partial^2 T}{\partial x^2} + K_y \frac{\partial^2 T}{\partial y^2} + Q - \rho c \frac{\partial T}{\partial t}\right) d\,V = 0$$

or term by term

$$\int_v [N]^T K_x \frac{\partial^2 T}{\partial x^2} dV + \int_v [N]^T K_y \frac{\partial^2 T}{\partial y^2} dV + \int_v [N]^T Q\, dV$$

$$- \int_v [N]^T \rho c \frac{\partial T}{\partial t} dV = 0 \qquad (2.3)$$

second derivatives in this equation have to be transformed into first derivatives noting that

$$\frac{\partial}{\partial u}\left([N]^T \frac{\partial \phi}{\partial u}\right) = [N]^T \frac{\partial^2 \phi}{\partial u^2} + \frac{\partial [N]^T}{\partial u} \cdot \frac{\partial \phi}{\partial u}$$

This can be rearranged to yield

$$[N]^T \frac{\partial^2 \phi}{\partial u^2} = \frac{\partial}{\partial u}\left([N]^T \frac{\partial \phi}{\partial u}\right) - \frac{\partial [N]^T}{\partial u} \cdot \frac{\partial \phi}{\partial u} \qquad (2.4)$$

and the first volume integral of (2-3) becomes

$$\int_v [N]^T K_x \frac{\partial^2 T}{\partial x^2} dV = \int_v K_x \frac{\partial}{\partial x}\left([N]^T \frac{\partial T}{\partial x}\right) dV$$

$$- \int_v K_x \frac{\partial [N]^T}{\partial x} \frac{\partial T}{\partial x} dV \qquad (2.5)$$

Application of Gauss's theorem to the first integral on the right side gives

$$\int_v K_x \frac{\partial}{\partial x}\left([N]^T \frac{\partial T}{\partial x}\right) dV = \int_s K_x [N]^T \frac{\partial T}{\partial x} \ell_x \, dS \qquad (2.6)$$

the same kind of equation can be obtained for

$$\int_V K_y \frac{\partial}{\partial y}\left([N]^T \frac{\partial T}{\partial y}\right) dV = \int_S K_y\, [N]^T \frac{\partial T}{\partial y}\, \ell y\, dS \qquad (2.7)$$

Combining the results of equations (2.5) (2.6) (2.7) with equation (2-3) yields.

$$\int_S K_x\, [N]^T \frac{\partial T}{\partial x}\, \ell x\, dS - \int_V K_x \frac{\partial [N]^T}{\partial x} \cdot \frac{\partial T}{\partial x}\, dV$$

$$+ \int_S K_y\, [N]^T \frac{\partial T}{\partial y}\, \ell y\, dS - \int_V K_y \frac{\partial [N]^T}{\partial y} \cdot \frac{\partial T}{\partial y}\, dV + \int_V [N]^T Q\, dV$$

$$- \int_V [N]^T \rho c \frac{\partial T}{\partial t}\, dV = 0 \qquad (2.8)$$

Assuming the width of the plate is unity, and that the surface integral in equation (2-8) can be written as $\partial T/\partial n$ along the boundary where n is the outward normal to the surface, and also that in one element there is no change of the conductivity in x and y directions, Equation (2-8) becomes.

$$\int_A k\left(\frac{\partial [N]^T}{\partial x} \cdot \frac{\partial T}{\partial x} + \frac{\partial [N]^T}{\partial y} \cdot \frac{\partial T}{\partial y}\right) dA + \int_{\mathcal{L}} [N]^T \frac{\partial T}{\partial n}\, d\mathcal{L}$$

$$- \int_A [N]^T Q\, dA + \int_A [N]^T \rho c \frac{\partial T}{\partial t}\, dA = 0 \qquad (2.9)$$

1- MODEL FORMULATION FOR STEADY STATE

In the case of steady state the last integral in the equation (2.9) drops and the equation becomes

$$\int_A k\left(\frac{\partial [N]^T}{\partial x} \cdot \frac{\partial T}{\partial x} + \frac{\partial [N]^T}{\partial y} \cdot \frac{\partial T}{\partial y}\right) dA + \int_{\mathcal{L}} [N]^T \frac{\partial T}{\partial n}\, d\mathcal{L}$$

$$- \int_A [N]^T Q\, dA = 0 \qquad (2.10)$$

a. Finite Element Formulation For Elements in the Fuel

Boundary conditions for these elements are

$$\frac{\partial T}{\partial x} = 0 \qquad \text{at} \qquad x=0$$

$$\frac{\partial T}{\partial y} = 0 \qquad \text{at} \qquad y=0 \quad \text{and } y=Y \tag{2.11}$$

Thus flux term in equation (2-10) drops, and expressing the displacement function T by

$$T = [N]\{T\} \tag{2.12}$$

and noting that

$$\frac{\partial T}{\partial x} = \frac{\partial [N]}{\partial x}\{T\}$$

$$\frac{\partial T}{\partial y} = \frac{\partial [N]}{\partial y}\{T\} \tag{2.13}$$

equation (2.10) becomes

$$\int_A k\left(\frac{\partial [N]^T}{\partial x}\cdot\frac{\partial [N]}{\partial x} + \frac{\partial [N]^T}{\partial y}\cdot\frac{\partial [N]}{\partial y}\right) dA\,\{T\}$$

$$- \int_A [N]^T\, Q\, dA = 0 \tag{2.14}$$

which can be rewritten as

$$\int_A k\,[B]^T[B]\, dA\,\{T\} - \int_A [N]^T Q\, dA = 0 \tag{2.15}$$

This equation in matrix natation becomes

$$[k^e]\{T\} - \{f^e\} = 0 \tag{2.16}$$

Here $[k^e]$ is known as the element conduction matrix and $\{f^e\}$ is the element force vector

b. <u>Finite Element Formulation For Elements in the Cladding</u>

Boundary conditions for these elements are

$$\frac{\partial T}{\partial x} = h(T-T_F) \qquad \text{at} \qquad x=X \tag{2.17}$$

$$\frac{\partial T}{\partial y} = 0 \qquad \text{at} \qquad y=0 \quad \text{and} \quad y=Y \tag{2.18}$$

Since there is no heat generation in cladding heat generation related term in equation (2.10) drops, and substitution of equation (2.12) into equation (2.10) gives

$$\int_A k\left(\frac{\partial [N]^T}{\partial x} \cdot \frac{\partial [N]}{\partial x} + \frac{\partial [N]^T}{\partial y} \cdot \frac{\partial [N]}{\partial y}\right) dA \, \{T\}$$

$$+ \int_{\mathcal{L}} [N]^T h([N] \{T\} - T_F) \, d\mathcal{L} = 0 \tag{2.19}$$

which is also written as

$$\int_A k \, [B]^T [B] \, dA \, \{T\} + \int_{\mathcal{L}} h \, [N]^T [N] \, d\mathcal{L} \, \{T\} - \int_{\mathcal{L}} h \, [N]^T T_F \, d\mathcal{L} = 0 \tag{2.20}$$

and in matrix notation equation (2.20) written as

$$[k^e] \{T\} - [f^e] = 0 \tag{2.21}$$

2- MODEL FORMULATION FOR UNSTEADY STATE

Equation (2.9) is also applicable for unsteady state case

a. <u>Finite Element Formulation For Elements in the Fuel</u>

Since the boundary conditions are the same in both cases (steady-state and unsteady) , flux term in equation (2.9) drops. Differentiation of the displacement function T with respect to time yields

$$\frac{\partial T}{\partial t} = [N] \frac{\partial \, T}{\partial \, t} \qquad (2.22)$$

since $[N]$ is a function of the coordinate system and not of the time. substitution of these into equation (2.9) yields

$$\int_A k\left(\frac{\partial [N]^T}{\partial x} \cdot \frac{\partial [N]}{\partial x} + \frac{\partial [N]^T}{\partial y} \cdot \frac{\partial [N]}{\partial y}\right) dA \, \{T\} - \int_A \partial [N]^T Q \; dA$$

$$+ \int_A \rho \, c \; [N]^T [N] \frac{\partial \{T\}}{\partial t} dA = 0 \qquad (2.23)$$

which can also be written as

$$\int_A k \, [B]^T [B] \, dA \, \{T\} - \int_A [N]^T Q \, dA + \int_A \rho \, c \, [N]^T [N] \, dA \frac{\partial \{T\}}{\partial t} = 0$$

(2.24)

and in matrix notation this equation becomes

$$[c^e] \frac{\partial \{T\}}{\partial t} + [k^e]\{T\} - \{f^e\} = 0 \qquad (2.25)$$

Transient problem gives a new matrix. $[c]$, called the capacitance matrix.

b. Finite Element Formulation For Elements in the Cladding

Equation (2.9) can be written by means of equation (2.19) and (2.22) as

$$\int_A k \, [B]^T [B] \, dA \, \{T\} + \int_{\mathcal{L}} h \, [N]^T [N] \, d\mathcal{L} \, \{T\} - \int_{\mathcal{L}} h \, [N]^T T_F \; d\mathcal{L}$$

$$+ \int_A \rho c \, [N]^T [N] \, dA \frac{\partial \{T\}}{\partial t} = 0 \qquad (2.26)$$

In matrix notation this equation can be rewritten as

$$[c^e] \frac{\partial\{T\}}{\partial t} + [k^e]\{T\} - \{f^e\} = 0 \qquad (2.27)$$

3- FINITE DIFFERENCE SOLUTION OF THE EQUATIONS IN THE TIME DOMAIN

One of the popular procedures for solving the differential equation in the form of (2.25) or (2.27) is to approximete the time derivative using a central difference scheme. Derivate of the nodal values between two time points is given as

$$\frac{d\{T\}}{dt} = \frac{1}{\Delta t}(\{T\}_1 - \{T\}_o) \qquad (2.28)$$

since derivative is evaluated at the midpoint of the time interval. $\{T\}$, $[k]$ and $\{f\}$ values must also be evaluated at this point (point A in fig (2.3))

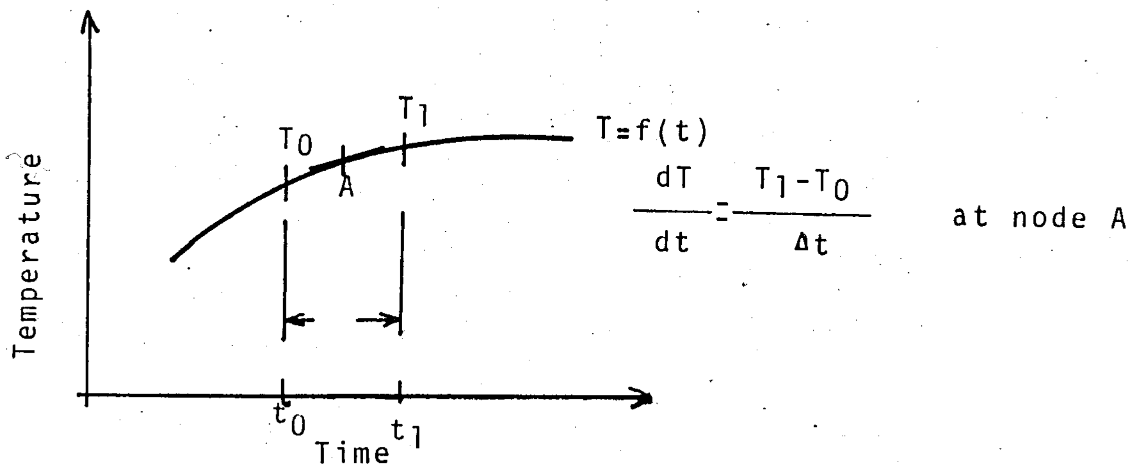

FIGURE 2-3 Numerical Approximation of the First Derivative

These quantities are

$$\{T\} = 1/2\ (\{T\}_1 + \{T\}_o)$$

$$[k] = 1/2\ ([k]_1 + [k]_o) \qquad (2.29)$$

$$\{f\} = 1/2\ (\{f\}_1 + \{f\}_o)$$

substitution of (2.28) and (2.29) into the equation of the form

(2.25) and (2.27) yields

$$(1/2\,(\,[k]_1 + [k]_o\,) + 2/\Delta t\,[c]\,)\ \{T\}_1 =$$

$$(2/\Delta t\,[c] - 1/2(\,[k]_1 + [k]_o\,)\ \{T\}_o + (\,\{f\}_1 + \{f\}_o\,) \qquad (2.30)$$

this equation can be written in a general form as

$$[EQ]\ \{T\}_{new} = [EP]\ \{T\}_{old} + (\,\{f\}_{new} + \{f\}_{old}\,) \qquad (2.31)$$

C. MODELLING OF THERMO-HYDRAULIC BEHAVIOUR OF THE COOLANT

The equation of mass, energy, and momentum conservation are written for a control volume to obtain the temperature distribution in coolant channel.

1- Equation of mass

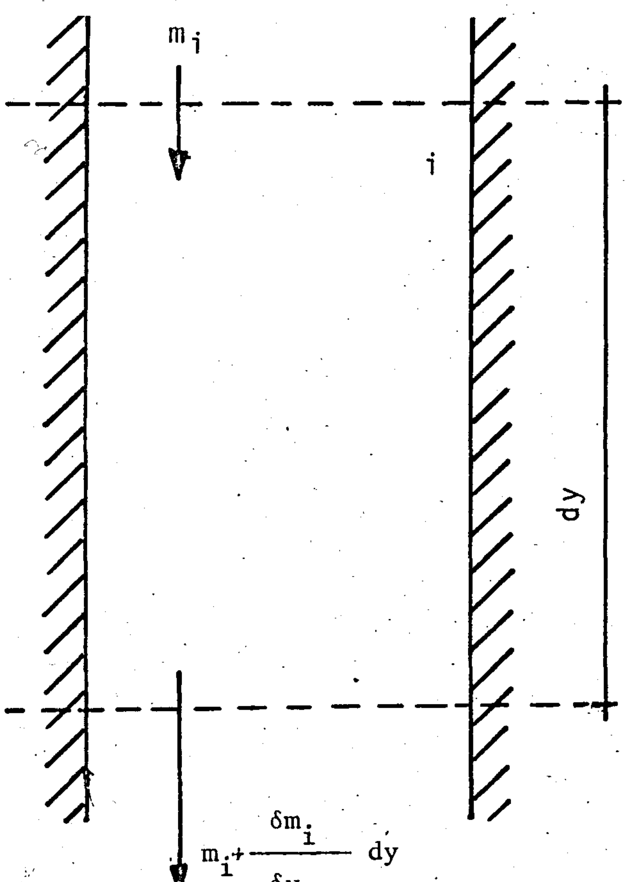

FIGURE 2-4 Control Volume for Equation of Mass

Input - Output = Accumulation

$$\frac{\partial \rho_i A_i}{\partial t} dy = m_i - (m_i + \frac{\partial m_i}{\partial y} dy) \qquad (2.32)$$

where

ρ_i, and m_i are coolant density and mass velocity respectively A_i is the cross-sectional area of the coolant channel. Equation (2.32), since A_i is constant, can be written as

$$A_i \frac{\partial \rho_i}{\partial t} + \frac{\partial m_i}{\partial y} = 0 \qquad (2.33)$$

2- Equation of Energy

Conservation of energy can be written for the control volume as

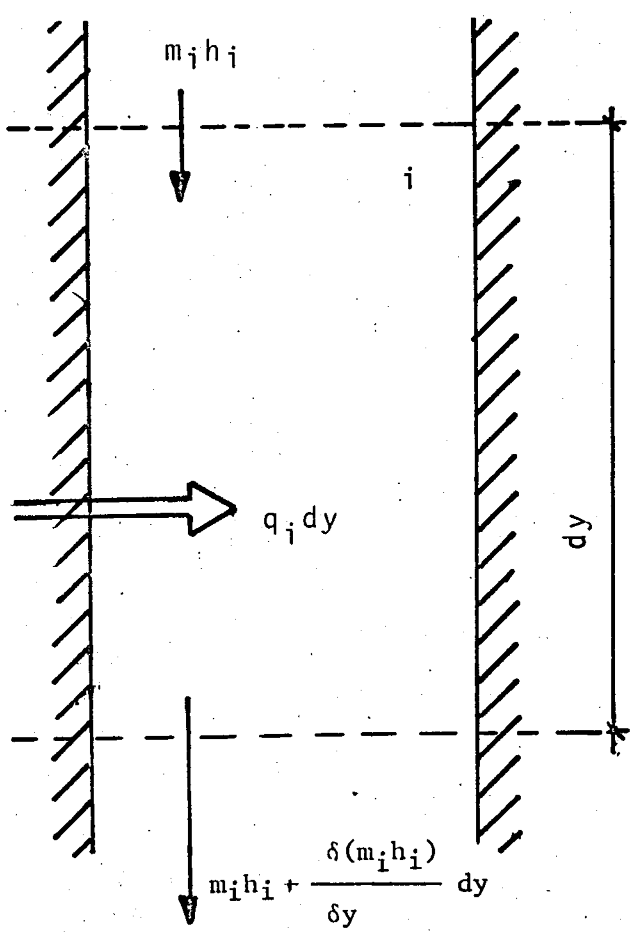

FIGURE 2-5 Control Volume for Equation of Energy

$$\frac{\partial}{\partial t}(\rho_i U_i A_i) dy = m_i h_i - (m_i h_i + \frac{\partial (m_i h_i)}{\partial y} dy) + q_i dy \qquad (2.34)$$

where

U_i and h_i are the coolant internal energy and enthalpy respectively and q_i is the heat flux in equation (2.34) U_i term is replaced by

$$U_i = h_i - P_i / \rho_i$$

$$A_i \frac{\partial}{\partial t} (\rho_i h_i - P_i) = - m_i \frac{\partial h_i}{\partial y} - h_i \frac{\partial m_i}{\partial y} + q_i \qquad (2.35)$$

assuming that $\partial P_i / \partial t = 0$ equation becomes

$$A_i \rho_i \frac{\partial h_i}{\partial t} + A_i h_i \frac{\partial \rho_i}{\partial t} + m_i \frac{\partial h_i}{\partial y} + h_i \frac{\partial m_i}{\partial y} - q_i = 0 \qquad (2.36)$$

substitution of equation (2.33) into equation (2.36) yields

$$\frac{1}{V_i} \quad \frac{\partial h_i}{\partial t} + \frac{\partial h_i}{\partial y} \quad \frac{q_i}{m_i} = 0 \qquad (2.37)$$

3- Equation of Momentum

For i th control volume conservation of momentum equation is

$$\frac{\partial m_i}{\partial t} dy + m_i V_i + P_i A_i + g A_i \rho_i dy - (m_i V_i + \frac{\partial m_i V_i}{\partial y} dy)$$

$$- (P_i A_i + \frac{\partial P_i A_i}{\partial y} dy) - F_i dy \qquad (2.38)$$

Where F_i is friction loss per unit length by rearranging the equation (2.38), it becomes

$$\frac{\partial m_i}{\partial t} = g A_i \rho_i - \frac{\partial m_i v_i}{\partial y} - A_i \frac{\partial P_i}{\partial y} - F_i \qquad (2.39)$$

where $v_i = \dfrac{m_i}{A_i \rho_i}$ (2.40)

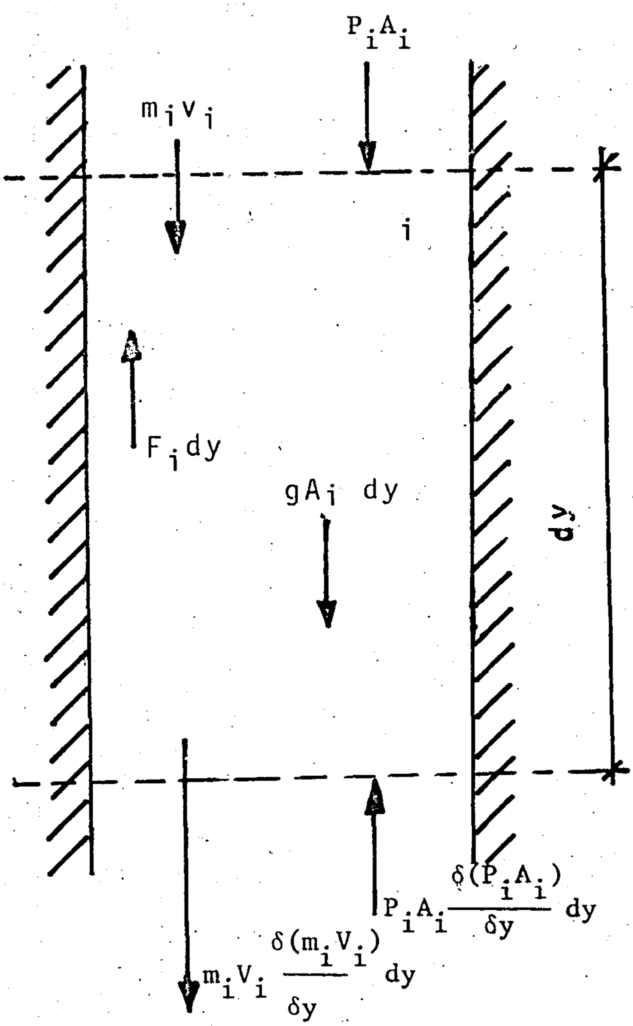

FIGURE 2-6 Control Volume for Equation of Momentum

substitution of equation (2.40) into equation (2.39) and, taking the derivative equation (2.39) becomes

$$\frac{\partial m_i}{\partial t} = g A_i \rho_i - \frac{1}{A_i}\left(\frac{2 m_i}{\rho_i}\frac{\partial m_i}{\partial y} + m^2{}_i \frac{\partial(1/\rho_i)}{\partial y}\right) - A_i \frac{\partial p_i}{\partial y} - F_i \tag{2.41}$$

substitution of equation (2.33) into equation (2.4)

$$\frac{\partial m_i}{\partial t} = g A_i \rho_i + 2v_i A_i \frac{\partial \rho_i}{\partial t} - \frac{m^2{}_i}{A_i}\frac{\partial(1/\rho_i)}{\partial y} - A_i \frac{\partial p_i}{\partial y} - F_i \tag{2.42}$$

rearranging the last equation to obtain pressure change, one obtains

$$\frac{\partial p_i}{\partial y} = g \rho_i + 2v_i \frac{\partial \rho_i}{\partial t} - \frac{m^2{}_i}{A_i^2}\frac{\partial(1/\rho_i)}{\partial y} - \frac{F_i}{A_i} - \frac{1}{A_i}\frac{\partial m_i}{\partial t} \tag{2.43}$$

III. THE COMPUTER PROGRAM NEKA

Mathematical models and solution procedure developed in the preceeding chapter are formulated into a computer program to perform steady state and transient calculations.

Flow chart of the computer program, interaction between the main program and the subnoutines, and also the capabilities of this program are given in section A. In the following section, a full description of the main program the subroutines and the function routines are given. Transformation of differential equation into computer program is also given in the related subroutine description.

A- PROGRAM DESCRIPTION

Program NEKA consists of one main, 17 subroutines and 7 function routines. The flowchart of program is given in figure (3-1). Interaction between main program and sub programs is also given in figure (3-2). The input parameters are introduced into the program in one of two ways: through a data file or interactively. First, two dimensional mesh generation is performed for a maximum 20 subregions meaning that 20 different dimensioned group of triangles, and 400 elements. The element numbers, nodel points, the coordinates of the elements, and bandwith quantity are written. When the numbers of elements, and bandwith are determined, physical properties of each element are calculated and combined into one global matrix. Solution of this matrix for unknown values gives the result. After this step, if desired the subcooled boiling calculation and the unsteady state calculation are performed for any change in heat generation, coolant flowrate and coolant input temperature.

In program NEKA, water is assumed to be the coolant and the temperature dependency of physical properties of water are taken into

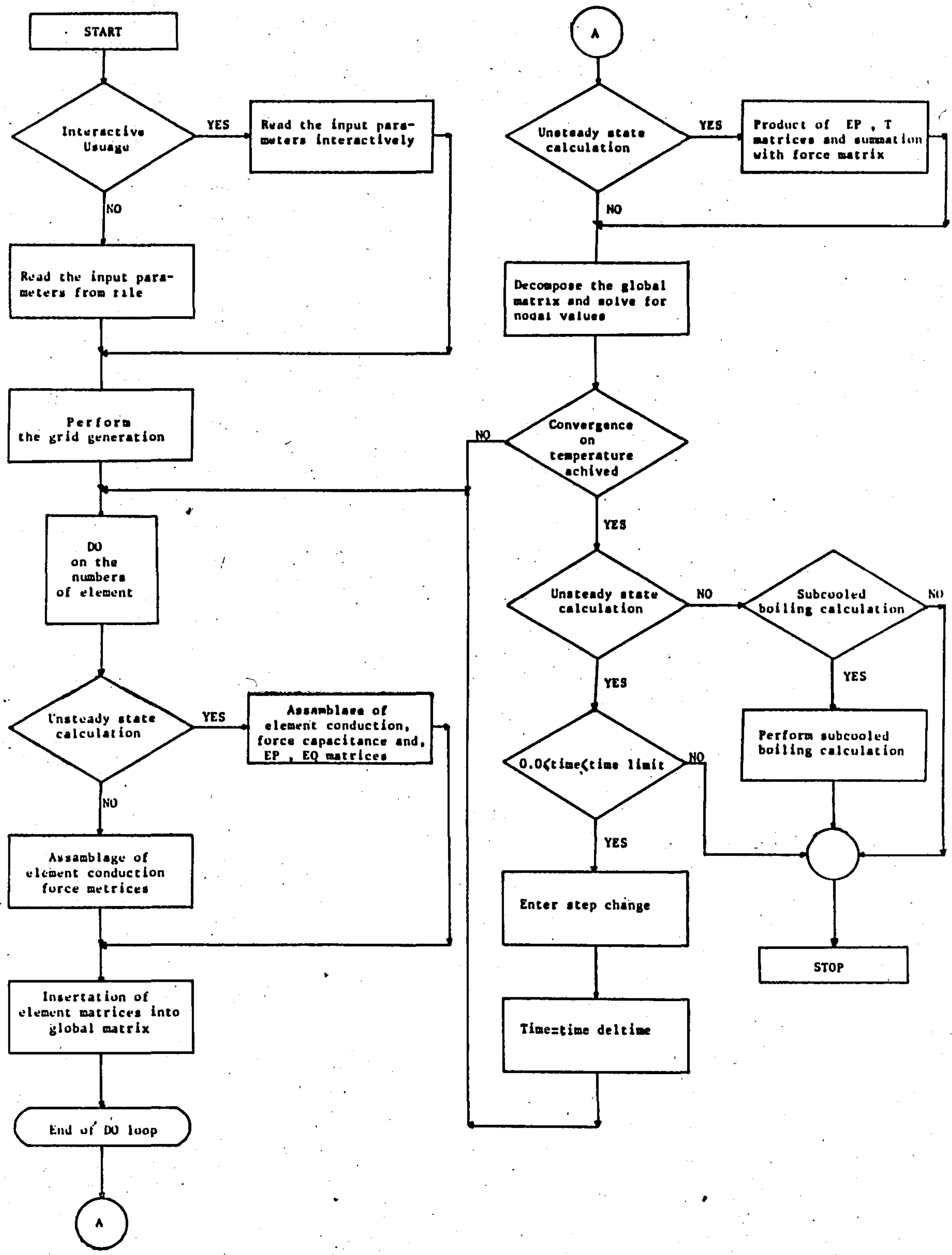

FIGURE 3-1 Flowchart of The Program NEKA

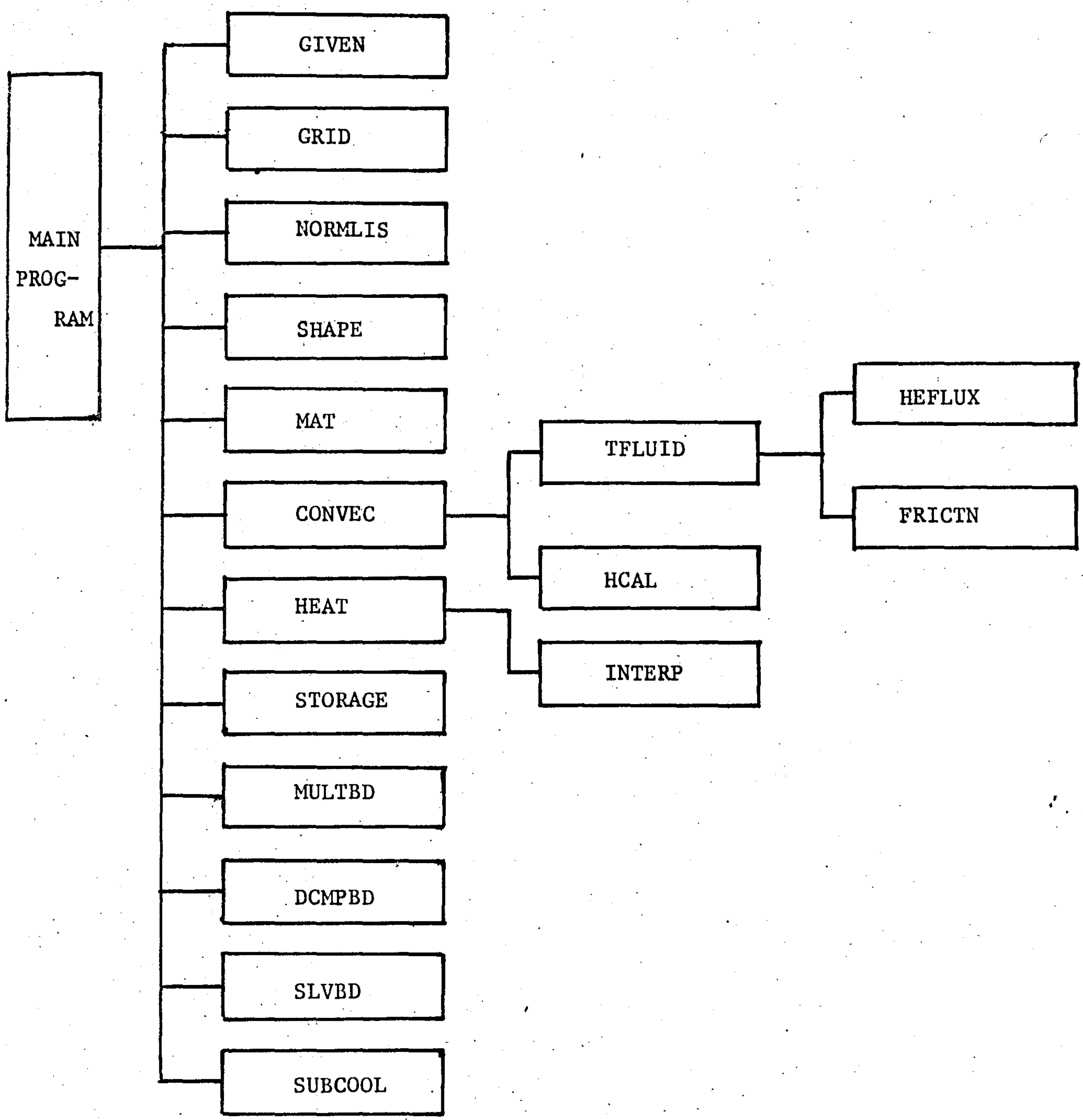

FIGURE 3-2 Main Program and Subroutines of NEKA

consideration.

The computer language of the program is FORTRAN, and the SI units have been used.

B- THE MAIN PROGRAM AND THE SURROUTINES

The main program of NEKA is a driver program which reads the input parameters by calling the subrautine GIVEN and performs the mesh generation calling the subroutime GRID. After the intialization of global matrix, it starts to determine the element matrices and then stores the values into global matrix making use of the related subroutine actions. Finally solutions for nodal values are printed.

SUBROUTINE GIVEN

GIVEN enters the necessary input data to the program by means of a data file (NEKADAT) or interactively, and also reprints these data for an echo check. These data are, in the order of, thermal conductivity of fuel and cladding (W/m ^{o}C), densities of fuel and cladding (kg/$_{m}$^{3}), heat capacity of fuel and cladding (J /kg ^{o}C), the power generated (W) in one plate which is under consideration, and the dimensions of the core, fuel length (mm), fuel half thickness (mm), fuel width (mm), channel width (mm), channel thickness (mm), and then the coolant inlet temperature (^{o}C) and mass flowrate (kg /s). Tabulated axial heat flux distribution data is read from the data file RELDATA which is called by subroutine GIVEN. The other data which are required for grid generation are read by subroutine GRID from the data file (NEKADAT) or supplied interactively to the program.

SUBROUTINE NORMLIS

This subroutine performs the unit conversions. Unit of coordinates of elements which are generated in subroutine GRID, and of dimensions of fuel is transformed into meter. Also intialization of FLOW and TEMF matrices is performed in this subroutine.

SUBROUTINE GRID

The preparation of element data is a time-consuming task. This subroutine automatically generates the element data. Subroutine GRID uses a group of eight-node quadrilateral regions to define the body under consideration. GRID is capable of modelling two-dimensional domains that are composed of triangles. Element nodes are numbered and bandwidth is also calculated by the subroutine. The expension contraction option is of special interest, this option makes it possible to change an existing mesh such that some regions are refined and other are made coarser than the original mesh.

SUBROUTINE INTERP

This subroutine calculates the ordinate value for a given absissa value. The input to this subroutine is a tabulated ordinate and absissa values. Searched value is calculated by linear interpolation between two values around that value.

SUBROUTINE SHAPE

This subroutine calculates the element area using the equction (3-1)

$$A= (X_jY_k- X_kY_j+ Y_jX_i- Y_kX_i+ X_kY_i- X_jY_i) /2 \quad (3\text{-}1)$$

where X_β and Y_β are the coordinates of element, A is the element area and, b_β on c_β values are calculated using the equation (A-6)

SUBROUTINE MAT

In the subroutine MAT element conduction matrix ESM(KK,I,J) is calculated by means of the equation (A-8) , where KK is element number, and element capacitance matrix ECM (I,J) using the equation (A-16). EP(I,J) and EQ (I,J) matrices which are the combination of conduction and capacitence matrices in equations (2-30) and (2-31) are also calculated using the following equations.

$$[EP] = \frac{2}{\Delta t}[c] - 1/2([k]_1 + [k]_0) \qquad (3.2)$$

$$[EP] = 1/2([k]_1 + [k]_0) + 2/\Delta t[c] \qquad (3.3)$$

SUBROUTINE CONVEC

This subroutine is devised to introduce the boundary condition to the element equations. First it calls the subroutine TFLUID to calculate fluid temperature and then the subroutine HCAL to calculate the convection coefficient. After these valves are calculated, contributions to element conduction matrix are introduced using equation (A-11). The force vector EF (I) is calculated by means of the equation (A-12) and, EP (I,J) and EQ (I,J) matrices are renewed because of the change in element conduction matrix.

SUBROUTINE HEAT

This subroutine performs the calculations for the elements in which heat generation occurs. The value of heat generation rate Q in equation (A-14) , for the coordinates of each element is determined using the heat flux distribution tabulated values by subroutine INTERP which is called at the very begining of this subroutine. So the element force vector EF(I) is calculated by equation (A-14). Then the element conduction matrix ESM (KK, I , J) , EP (I,J) and EQ (I,J) matrices are calculated by means of the equations (A-8) , (3-2) and (3-3) respectively.

SUBROUTINE TFLUID

Fluid temperature change in the axial direction is calculated in this subroutine. After calling the subroutine HEFLUX the change in enthalpy is first determined by using the equation (3-4) which is the modified version of the equation (2-37). The temperature is then calculated by means of the function routine TWA.

$$\frac{1}{v_i} \cdot \frac{h_i - h_{i\,old}}{\Delta t} + \frac{h_i - h_{i-1}}{\Delta y} = \frac{q_i}{m_i} \qquad (3.4)$$

where

h_{i-1} : enthalpy one axial step ago

$h_{i\,old}$: enthalpy one time step ago

and also pressure drop for steps and overall pressure differential are calculated after subroutine friction is called, by the equation (2-43). Using the finite difference method equation (2-43) can be written as

$$\frac{P_i - P_{i-1}}{\Delta y} = g\,\rho_i + 2\,v_i\,\frac{\rho_i - \rho_{i\,old}}{\Delta t} - \frac{m_i^2}{A_i^2} \cdot \frac{1/\rho_i - 1/\rho_{i-1}}{\Delta y}$$

$$- \frac{F_i}{A_i} - \frac{1}{A_i}\,\frac{m_i - m_{i\,old}}{\Delta t} \qquad (3.5)$$

where

A_i : channel area , m^2

m_i : water flowrate, kg/s

F_i : frictional lost per unit length,

SUBROUTINE HCAL

In this subroutine convection heat transfer coefficient h is calculated using the Dittus- Boelter correlation [4].

$$H = (0.023 \times k \times RE^{0.8} \times PR^{0.4} / de) \times (\mu / \mu_W)^{0.14} \qquad (3.6)$$

where

k : thermal conductivity , W/m ^{o}C

RE : Reynolds number

PR : Prandtly number

de : equvalent diameter, m

μ : viscosity at the fluid bulk temperature, kg/ms

μ_W : viscosity at the wall temperature, kg/ms

SUBROUTINE FRICTN

The fanning friction factor is calculated using [4]

$$f = 0.047 \times RE^{-0.2} \quad (3.7)$$

and frictional last per unit length of channel is calculated by the following equation [4]

$$F = 2 \times f \times mi^2 \;/\; (de \times \rho_i \times Ai) \quad (3.8)$$

where

RE : Reynolds number

m_i : fluid mass flowrate , kg/s

de : equivalent diameter of flow area, m

ρ_i : fluid density , kg / m^3

A_i : flow area, m^2

SUBROUTINE HEFLUX

In this subroutine heat flux in the cladding-fluid interface is calculated by the equation

$$q = h\,(Tw - Tf) \quad (3.9)$$

where

q : heat flow , w/m^2

h : convection heat transfer coefficient, $w/m^2\ {}^oC$

Tw : wall temperature , ^oC

Tf : fluid bulk temperature , ^oC

SUBROUTINE MULTB

By the use of this subroutine, the matrix product between a banded matrix and a rectangular array is performed. The product is [RF] = [GSM] [GF] when it is written using the variable names of the program.

SUBROUTINE STORAGE

This subroutine stores the global conduction matrix and the global force vector and the solution vector in one-dimensional column array. The main reason for the usage of the column array is to eliminate the dimensioning errors and allows the storage requirements for the stiffness (conduction) matrix to be deleted once the system of equations has been solved.

SUBROUTINE DCMPBD

The subroutine DCMPBD decomposes the banded matrix. Using the Gaussian elimination method, elements of the matrix are transformed into a triangular form that is easily being solved.

SUBROUTINE SLVBD

The subroutine SLVBD is the second part of the solution process and is used with DCMPBD to obtain a solution to $|k|\{T\} = \{F\}$. SLVBD first decomposes $\{F\}$ and then solves for $\{T\}$ using the method of backward substitution.

SUBROUTINE SUBCOOL

In this subroutine, using the Bernath's subcooled boiling correlation [14]

$$q_c = \alpha_c (Two - T_b) \tag{3.10}$$

$$Two = 57 \ln (14.503p) - 54 \frac{P}{P + 1.034} - 0.82\, v \tag{3.11}$$

$$\alpha_c = 61840 \frac{De}{De + Di} + 438.4 \frac{v}{De^{0.6}} \tag{3.12}$$

where

T_b : bulk temperature , ^{o}C

p : absolute pressure , kg/cm^2

De : equvalent diameter , m

Di : heated perimeter devided by , m

v : coolant velocity , m/s

critical heat flux q_c is first calculated then the ratio between critical heat flux and heat flux is calculated. If this ratio is less or equal to two , subcooled boiling is predicted.

FUNCTION VISCWA

This function routine calculates the water viscosity (kg/m s) for a given temperature (20^oC - 125 ^oC) from the equation. [4]

$$\mu = 0.148237 \times 10^{-2} - 0.295743 \times 10^{-4} T + 0.258156 \times 10^{-6} T^2 - 0.822939 \times 10^{-9} T^3 \quad (3.13)$$

FUNCTION VISCWA1

This function routine also calculates the water viscosity in the temperature range of 125^oC to 160^oC using the equation (3-14) which was obtained using least square approach from the tabulated data 16

$$\mu = - 6.896276 \times 10^{-9} + 6.853976 \times 10^{-6} T -5.680827 + 10^{-8} T^2 + 1.299773 \times 10^{-10} T^3 \quad (3.14)$$

FUNCTION CONDWA

This routine calculates the conductivity of water (w/m^oC) for a given temperature (^oC) from the equation. [4]

$$k = 0.570671 + 0.178690 \times 10^{-2} T - 0.684359 \times 10^{-5} T^2 \quad (3.15)$$

FUNCTION SPEHEAT

This routine calculates the heat capacity of water ($J/kg\ ^oC$) for a given temperature (^oC) from the equation. [4]

$$Cp : 0.419318 \times 10^{-4} - 0.744678\ T + 0.100875 \times 10^{-1}\ T^2 \quad (3.16)$$

FUNCTION TWA

This routine calculates the water temperature (^oC) for a given enthalpy (J /kg) from the equation. [4]

$$T = -\ 0.121704 + 0.240234 \times 10^{-3}\ H - 0.682278 \times 10^{-11}\ H^2 + 0.230918 \times 10^{-16}\ H^3 - 0.344210 \times 10^{-22}\ H^4 \quad (3.17)$$

FUNCTION ENTWA

This routine calculates the enthalpy of water (J /kg) for a given temperature (^oC) from the equation. [4]

$$H = 0.166564 \times 10^3 + 0.419253 \times 10^4\ T - 0.386479\ T^2 + 0.352709 \times 10^{-2}\ T^3 \quad (3.18)$$

FUNCTION RHOWA

This routine calculates the water density (kg/m^3) for a given temperature (^oC) from the equation. [4]

$$\rho = \left[0.997426 \times 10^{-3} + 0.135802 \times 10^{-6}\ T + 0.325184 \times 10^{-8}\ T^2\right]^{-1} \quad (3.19)$$

IV. RESULTS AND DISCUSSION

The application of the program NEKA to thermo-hydraulic analysis of a plate type fueled nuclear power core is examined in three parts: the application of the program to the steady state conditions; and application to the transient conditions (the responces to a given step change) together with the results obtained from TERHID ; and also application to subcooled boiling calculations.

A- STEADY STATE CALCULATIONS

The steady state calculations were based on to the two possible reactor configurations at Çekmece Nükleer Araştırma ve Eğitim Merkezi : Reactor I (TRI) and Reactor II (TRII). The Reactor I has 10 fuel elements, each one containing 20 fuel plates. The Reactor II consists of 10 standart and 4 control fuel elements which have 23 and 17 fuel plate respectively.

The input parameters for the Reactor I are given in table (4.1). As seen from the table, to obtain 1MW power, the central plate which generates maximum power produces 8929 W at mid point of the plate. Since power generation shows a cosine distribution, it is not the same throughout the plate, the avarage value is 6268 W. The heat flux distribution is also included in the table. The usage of tabulated heat flux distribution instead of the cosine function enables the program to be applicable for different heat flux distributions. To have a comparison to the results of the program TERHID, 30 axial steps were used. Results of calculations for 37 ^{o}C and 23^{o}C coolant inlet temperature are given in tables (4.2) and (4.3) respectively, and the tabulated results of the program TERHID are also given in tables (4.4) and (4.5). As seen from the tables, the difference of the temperatures calculated by two codes are in the range of 0.1^{o}C

TABLE 4-1 Input Parameters for Reactor-I

Fuel conductivity	167.0	w/m °C
Cladding conductivity	210.0	w/m °C
Fuel density	19000.0	kg/m^3
Cladding density	2707.0	kg/m^3
Fuel specific heat	740.0	kg/ °C
Cladding specific heat	896.0	J/kg °C
Fuel witdh	69.698	mm
Fuel thickness	0.508	mm
Fuel length	596.138	mm
Cladding thickness	.0.381	mm
Channel width	69.9	mm
Channel thickness	6.476	mm
Coolant mass flowrate	0.189	kg/s
Coolant input temperature	37°C and 23°C	
Plate power generation	8929.0	w
Heat flux distribution	Y/H	Q (n.) / Q (O.)
	0.0	0.165
	0.1	0.432
	0.2	0.665
	0.3	0.846
	0.4	0.960
	0.5	1.000
	0.6	0.960
	0.7	0.846
	0.8	0.665
	0.9	0.432
	1.0	0.165

TABLE 4-2 Thermo-Hydraulic Calcullation for T_f(in)=37^{o}C

DISTANCE (MM)	FUEL CENTER (C)	TEMPERATURES OF FUEL CLAD INTERFACE (C)	CLADDING SURFACE (C)	COOLING WATER (C)	PRESSURE DIFFERENCE (N/M**2)
.0	43.0	43.0	42.9	37.0	.0
19.9	47.0	47.0	46.9	37.1	188.9
39.7	50.4	50.4	50.3	37.2	377.8
59.6	53.9	53.8	53.7	37.3	566.7
79.5	56.8	56.8	56.7	37.5	755.5
99.4	59.8	59.7	59.6	37.7	944.4
119.2	62.8	62.7	62.6	38.0	1133.2
139.1	65.1	65.0	64.9	38.2	1322.0
159.0	67.4	67.3	67.2	38.5	1510.8
178.8	69.8	69.7	69.6	38.8	1699.6
198.7	71.3	71.2	71.0	39.1	1888.4
218.6	72.8	72.8	72.6	39.5	2077.1
238.5	74.5	74.4	74.2	39.8	2265.9
258.3	75.1	75.0	74.8	40.2	2454.6
278.2	75.8	75.7	75.6	40.6	2643.2
298.1	76.6	76.6	76.4	40.9	2831.9
317.9	76.4	76.3	76.1	41.3	3020.5
337.8	76.2	76.1	75.9	41.7	3209.1
357.7	76.1	76.0	75.8	42.1	3397.7
377.6	75.0	75.0	74.8	42.4	3586.3
397.4	74.0	73.9	73.8	42.7	3774.8
417.3	73.1	73.0	72.8	43.1	3963.3
437.2	71.2	71.2	71.0	43.4	4151.8
457.0	69.4	69.3	69.2	43.7	4340.3
476.9	67.6	67.6	67.4	43.9	4528.8
496.8	65.1	65.1	65.0	44.2	4717.2
516.7	62.6	62.6	62.5	44.4	4905.7
536.5	60.1	60.1	60.0	44.6	5094.1
556.4	57.1	57.1	57.0	44.7	5282.5
576.3	54.1	54.1	54.0	44.8	5471.0
596.1	50.4	50.4	50.4	44.9	5659.4

TABLE 4-3 Thermo-Hydraulic Calculation for T_f(in)=23^{o}C

DISTANCE (MM)	FUEL CENTER (C)	TEMPERATURES OF FUEL CLAD INTERFACE (C)	CLADDING SURFACE (C)	COOLING WATER (C)	PRESSURE DIFFERENCE (N/M**2)
.0	30.0	30.0	29.9	23.0	.0
19.9	34.3	34.3	34.2	23.1	189.5
39.7	38.1	38.1	38.1	23.2	379.1
59.6	42.0	42.0	41.9	23.3	568.6
79.5	45.3	45.2	45.1	23.5	758.1
99.4	48.6	48.5	48.4	23.7	947.7
119.2	51.9	51.8	51.7	24.0	1137.2
139.1	54.4	54.3	54.2	24.2	1326.7
159.0	56.9	56.8	56.7	24.5	1516.1
178.8	59.5	59.4	59.2	24.8	1705.6
198.7	61.1	61.0	60.8	25.1	1695.1
218.6	62.7	62.7	62.5	25.5	2084.5
238.5	64.5	64.4	64.2	25.8	2273.9
258.3	65.2	65.1	64.9	26.2	2463.3
278.2	65.9	65.8	65.6	26.6	2652.7
298.1	66.7	66.6	66.4	26.9	2842.1
317.9	66.4	66.3	66.1	27.3	3031.5
337.8	66.2	66.1	65.9	27.7	3220.8
357.7	66.0	65.9	65.7	28.1	3410.1
377.6	64.8	64.7	64.5	28.4	3599.4
397.4	63.6	63.6	63.4	28.7	3788.7
417.3	62.5	62.5	62.3	29.1	3978.0
437.2	60.5	60.4	60.3	29.4	4167.3
457.0	58.5	58.4	58.3	29.7	4356.6
476.9	56.5	56.4	56.3	29.9	4545.8
496.8	53.7	53.6	53.5	30.2	4735.1
516.7	50.9	50.8	50.7	30.4	4924.3
536.5	48.1	48.0	48.0	30.6	5113.5
556.4	44.7	44.7	44.6	30.7	5302.7
576.3	41.3	41.3	41.2	30.8	5492.0
596.1	37.3	37.3	37.3	30.9	5681.2

TABLE 4-4 Thermo-Hydraulic Calculation for T_f(in)=37°C [4]

DISTANCE (mm)	FUEL TEMPERATURE (°C)	CLADDING TEMPERATURE (°C)	COOLING WATER (°C)	PRESSURE DIFFERENCE (N/m²)
00.0	43.6	43.6	37.0	000.0
19.9	47.0	47.0	37.1	188.8
39.7	50.5	50.4	37.2	377.5
59.6	53.9	53.9	37.3	566.2
79.5	56.9	56.8	37.5	755.0
99.4	59.9	59.8	37.7	943.7
119.2	62.8	62.7	37.9	1132.4
139.1	65.1	65.0	38.1	1321.1
159.0	67.5	67.4	38.4	1509.8
178.8	69.8	69.7	38.7	1698.4
198.7	71.3	71.2	39.0	1887.1
218.6	72.9	72.7	39.4	2075.7
238.5	74.4	74.3	39.7	2264.3
258.3	75.1	75.0	40.1	2452.9
278.2	75.8	75.7	40.4	2641.4
298.1	76.6	76.4	40.8	2829.9
317.9	76.3	76.2	41.2	3018.5
337.8	76.2	76.0	41.6	3206.9
357.7	76.0	75.8	41.9	3395.4
377.6	74.9	74.8	42.3	3583.8
397.4	73.9	73.8	42.6	3772.3
417.3	72.9	72.8	43.0	3960.7
437.2	71.1	71.0	43.3	4149.0
457.0	69.3	69.2	43.6	4337.4
476.9	67.5	67.4	43.9	4525.7
496.8	65.0	64.9	44.1	4714.1
516.7	62.5	62.4	44.3	4902.4
536.5	60.0	59.9	44.5	5090.7
556.4	57.0	57.0	44.7	5279.0
576.3	54.0	54.0	44.8	5467.2
596.1	50.9	50.9	44.9	5655.5

TABLE 4-5 Thermo-Hydraulic Calculation for T_f(in)=23°C [4]

DISTANCE (mm)	FUEL TEMPERATURE (°C)	CLADDING TEMPERATURE (°C)	COOLANT WATER (°C)	PRESSURE DIFFERENCE (N/m²)
00.0	30.5	30.5	23.0	000.0
19.9	34.4	34.4	23.1	189.4
39.7	38.3	38.3	23.2	378.8
59.6	42.2	42.1	23.3	568.2
79.5	45.5	45.4	23.5	757.6
99.4	48.8	48.7	23.7	946.9
119.2	52.1	52.0	24.0	1136.3
139.1	54.6	54.5	24.2	1325.7
159.0	57.1	57.0	24.5	1515.0
178.8	59.7	59.5	24.8	1704.3
198.7	61.3	61.1	25.1	1893.7
218.6	62.9	62.8	25.5	2083.0
238.5	64.6	64.5	25.8	2272.3
258.3	65.3	65.1	26.2	2461.5
278.2	66.0	65.9	26.6	2650.8
298.1	66.8	66.6	27.0	2840.0
317.9	66.5	66.3	27.3	3029.3
337.8	66.2	66.1	27.7	3218.5
357.7	66.0	65.8	28.1	3407.7
377.6	64.8	64.6	28.4	3596.8
397.4	63.6	63.5	28.8	3786.0
417.3	62.5	62.3	29.1	3975.2
437.2	60.4	60.3	29.4	4164.3
457.0	58.4	58.3	29.7	4353.4
476.9	56.3	56.2	29.9	4542.5
496.8	53.6	53.5	30.2	4731.6
516.7	50.8	50.7	30.4	4920.7
536.5	47.9	47.9	30.6	5109.8
556.4	44.6	44.5	30.7	5298.9
576.3	41.2	41.1	30.8	5488.0
596.1	37.7	37.7	30.9	5677.1

except for the end points. In both works maximum fuel and cladding temperatures are at the midpoint of the plate length. Coolent temperature increase from inlet to outlet is also the same (7.9^{o}c) in these results. This states that the amount of power generated in plate is the same.

If more then 11 points for heat flux distribution are used to fit the cosine function more accurate results are obtained, if heat generation changes exatly as the cosine function. Results obtained using 51 points (table 4-6) for heat generation distribution are given in tables (4-7) and (4-8) for 37 ^{o}C and 23 ^{o}C coolant input temperatures. Graphs of coolant and fuel center temperatures along fuel length are given in figures (4-1) and (4-2). As seen from tables and graphs fuel and cladding temperatures increase up to well below the mid point of fuel height and then decreases. However, coolant temperature shows a continuous increase and at the exit point reachs to a maximum of 44.9 ^{o}C and 30.9 ^{o}C for 37^{o}C and 23^{o}C coolant input temperatures respectively

The pressure change is also given in the tables. Two factors generally determined the pressure difference : 1. Because of the calumn of water, an increase in pressure. 2. Pressure drops, because of frictional loss. Pressure last at inlet and outlet sections of coolant channel are not taken into consideration in the pressure change calculations.

Usually, a smaller qrid gives more accurate results in numerical methods. This is also valid for the finite element method. So more than 30 axial steps were tested to see whether 30 steps are sufficient for the calculations in the range of occuracy required. Results of Reactor I for 37 ^{o}C water input temperature with 60 and 90 axial steps are given in tables (C-1) and (C-2). Tables (4-7) , (C-1) and (C-2) show that there is an agreement between among them. Only fluctiation occurs at the end points.

Another example was based on the Reactor II. The input parameters

TABLE 4-6 Heat Flux Distribution

0.000	0.165	0.520	0.998
0.020	0.220	0.540	0.994
0.040	0.275	0.560	0.986
0.060	0.328	0.580	0.975
0.080	0.381	0.600	0.961
0.100	0.432	0.620	0.944
0.120	0.482	0.640	0.924
0.140	0.531	0.660	0.901
0.160	0.577	0.680	0.875
0.180	0.622	0.700	0.846
0.200	0.665	0.720	0.815
0.220	0.706	0.740	0.781
0.240	0.745	0.760	0.745
0.260	0.781	0.780	0.706
0.280	0.815	0.800	0.665
0.300	0.846	0.820	0.622
0.320	0.875	0.840	0.577
0.340	0.901	0.860	0.531
0.360	0.924	0.880	0.482
0.380	0.944	0.900	0.432
0.400	0.961	0.920	0.381
0.420	0.975	0.940	0.328
0.440	0.986	0.960	0.275
0.460	0.994	0.980	0.220
0.480	0.998	1.000	0.165
0.500	1.000		

TABLE 4-7 Thermo-Hydraulic Calculation for $T_f(in)=37^oC$

DISTANCE (MM)	FUEL CENTER (C)	FUEL CLAD INTERFACE (C)	CLADDING SURFACE (C)	COOLING WATER (C)	PRESSURE DIFFERENCE (N/M**2)
	TEMPERATURES OF				
.0	43.0	43.0	42.9	37.0	.0
19.9	47.1	47.1	47.0	37.1	186.9
39.7	50.5	50.5	50.4	37.2	377.8
59.6	53.8	53.8	53.7	37.3	566.7
79.5	57.0	57.0	56.9	37.5	755.5
99.4	60.0	59.9	59.8	37.7	944.4
119.2	62.8	62.7	62.6	38.0	1133.2
139.1	65.3	65.3	65.1	38.2	1322.0
159.0	67.7	67.6	67.4	38.5	1510.8
178.8	69.8	69.7	69.5	38.8	1699.6
198.7	71.6	71.5	71.4	39.2	1888.4
218.6	73.2	73.1	72.9	39.5	2077.1
238.5	74.5	74.4	74.2	39.9	2265.8
258.3	75.5	75.4	75.2	40.2	2454.5
278.2	76.2	76.1	75.9	40.6	2643.2
298.1	76.6	76.5	76.3	41.0	2831.9
317.9	76.7	76.6	76.4	41.3	3020.5
337.8	76.6	76.5	76.3	41.7	3209.1
357.7	76.1	76.0	75.9	42.1	3397.7
377.6	75.4	75.3	75.1	42.4	3586.2
397.4	74.4	74.3	74.1	42.8	3774.8
417.3	73.1	73.0	72.8	43.1	3963.3
437.2	71.5	71.4	71.3	43.4	4151.8
457.0	69.7	69.6	69.5	43.7	4340.3
476.9	67.6	67.6	67.4	44.0	4528.7
496.8	65.3	65.3	65.2	44.2	4717.2
516.7	62.9	62.8	62.7	44.4	4905.6
536.5	60.2	60.1	60.0	44.6	5094.1
556.4	57.3	57.2	57.2	44.7	5282.5
576.3	54.3	54.2	54.2	44.9	5470.9
596.1	50.5	50.4	50.4	44.9	5659.3

TABLE 4-8 Thermo-Hydraulic Calculation for $T_f(in)=23^oC$

DISTANCE (MM)	FUEL CENTER (C)	FUEL CLAD INTERFACE (C)	CLADDING SURFACE (C)	COOLING WATER (C)	PRESSURE DIFFERENCE (N/M**2)
	TEMPERATURES OF				
.0	30.0	30.0	29.9	23.0	.0
19.9	34.4	34.4	34.4	23.1	189.5
39.7	38.3	38.2	38.2	23.2	379.1
59.6	42.0	41.9	41.9	23.3	568.6
79.5	45.5	45.5	45.4	23.5	758.1
99.4	48.8	48.7	48.6	23.7	947.7
119.2	51.8	51.8	51.6	24.0	1137.2
139.1	54.6	54.6	54.4	24.2	1326.6
159.0	57.2	57.1	57.0	24.5	1516.1
178.8	59.4	59.4	59.2	24.8	1705.6
198.7	61.4	61.4	61.2	25.2	1895.0
218.6	63.1	63.0	62.8	25.5	2084.5
238.5	64.5	64.4	64.2	25.9	2273.9
258.3	65.5	65.4	65.2	26.2	2463.3
278.2	66.3	66.2	66.0	26.6	2652.7
298.1	66.7	66.6	66.4	27.0	2842.1
317.9	66.8	66.7	66.5	27.3	3031.4
337.8	66.5	66.5	66.3	27.7	3220.8
357.7	66.0	65.9	65.8	28.1	3410.1
377.6	65.2	65.1	64.9	28.4	3599.4
397.4	64.0	63.9	63.8	28.8	3788.7
417.3	62.5	62.5	62.3	29.1	3978.0
437.2	60.8	60.7	60.6	29.4	4167.3
457.0	58.8	58.7	58.6	29.7	4356.5
476.9	56.5	56.4	56.3	30.0	4545.8
496.8	53.9	53.8	53.7	30.2	4735.0
516.7	51.1	51.1	51.0	30.4	4924.3
536.5	48.1	48.1	48.0	30.6	5113.5
556.4	44.8	44.8	44.7	30.7	5302.7
576.3	41.4	41.4	41.4	30.9	5491.9
596.1	37.3	37.3	37.3	30.9	5681.1

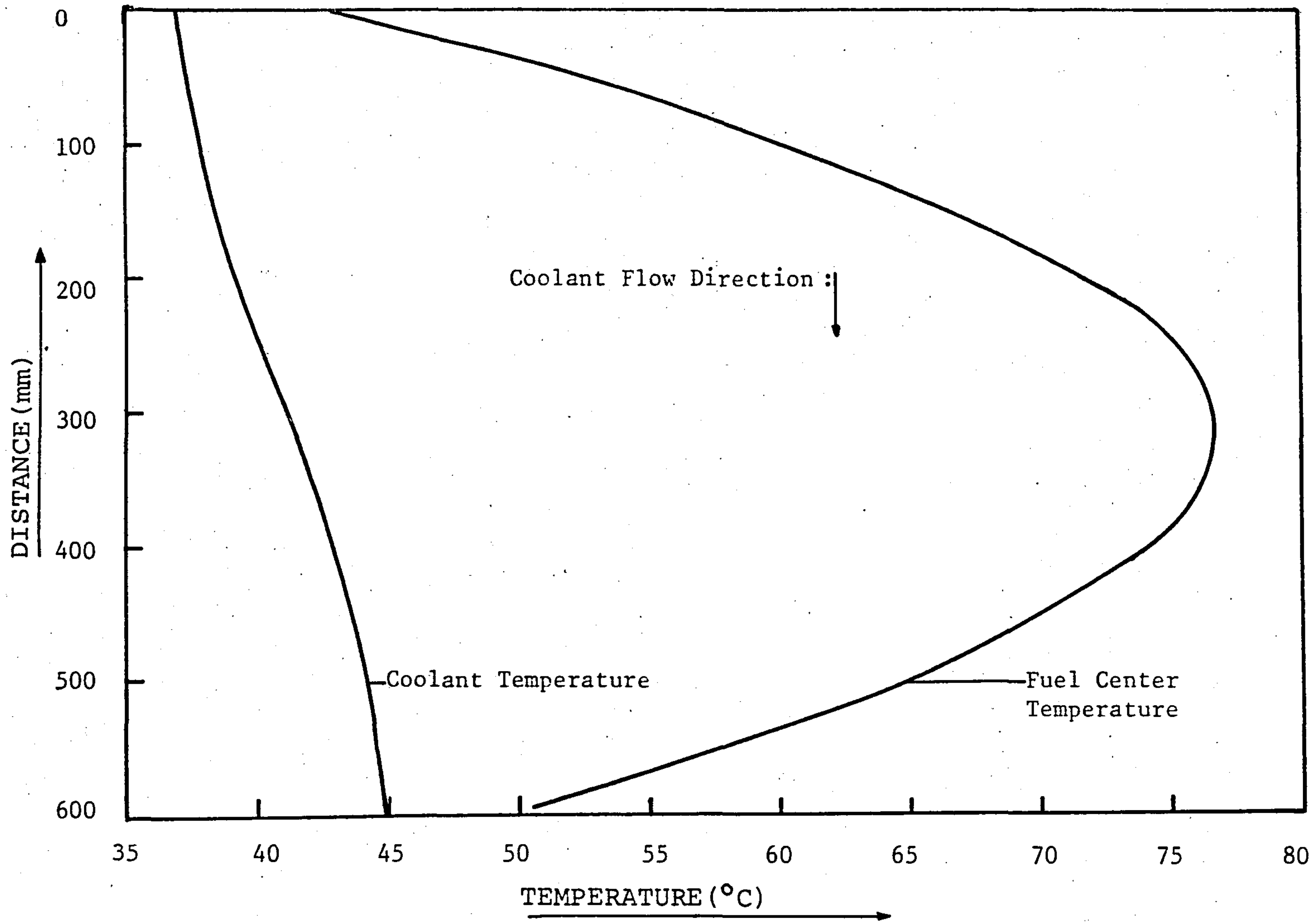

FIGURE 4-1 Temperature Distribution: $T_f(in)=37^{\circ}C$

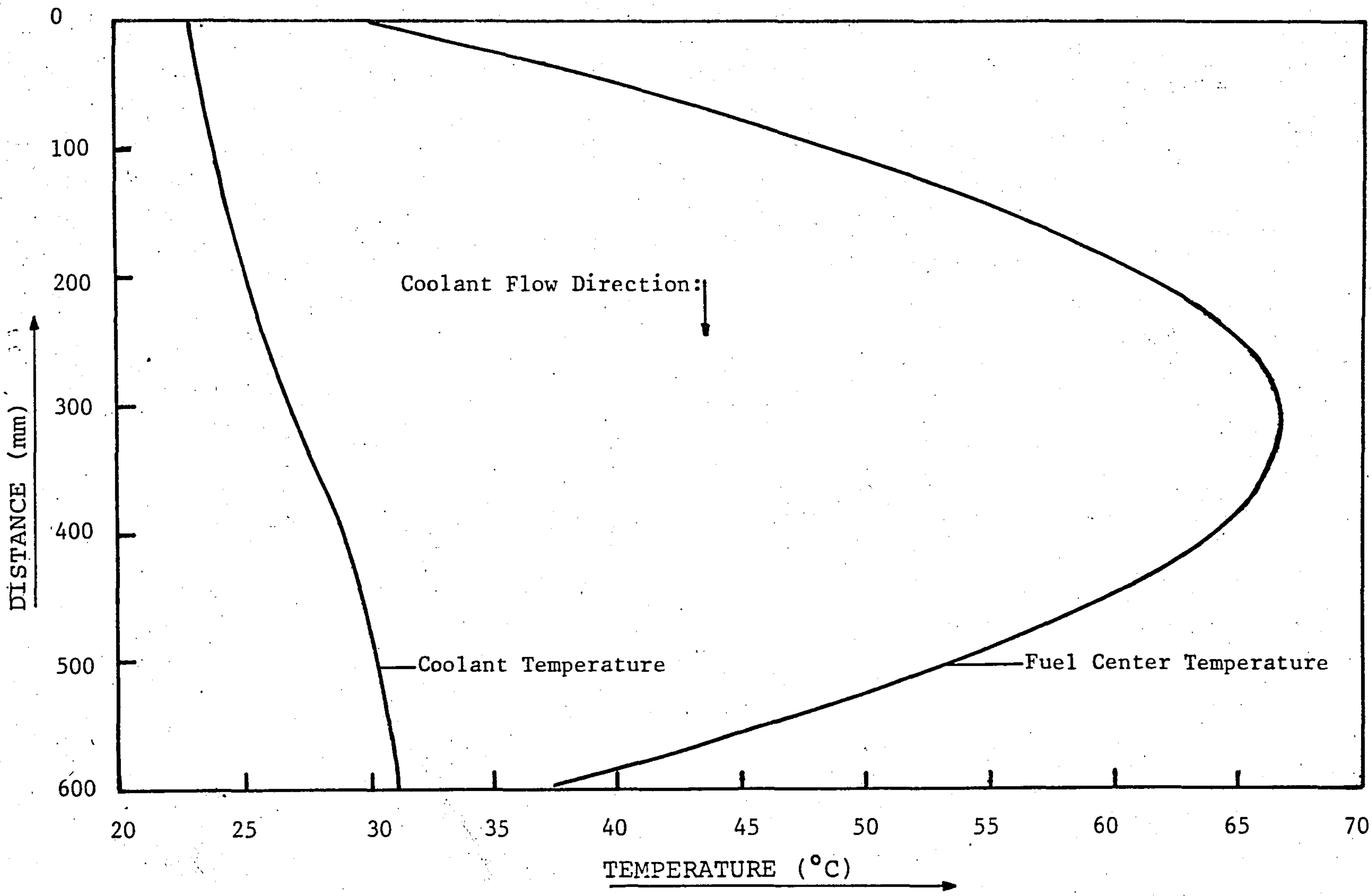

FIGURE 4-2 Temperature Distribution- $T_f(in)=23^{\circ}C$

for Reactor II are given in table (4-9). The maximum power generation in the plate, in this case, is 30201W and the channel thickness is much smaller than the TRI. Flowrate of coolant is about 1.6 times that of TRI. For the case of axial heat flux distribution same as TRI and for coolant input temperature of 30^{o}C , temperature distribution and pressure change

TABLE 4-9 Input Parameters for Reactor-II

Fuel conductivity	167.0	w/m °c
Cladding conductivity	210.0	w/m °c
Fuel density	3336.0	kg/m^3
Cladding density	2707.0	kg/m^3
Fuel specific heat	740.0	J/kg °c
Cladding specific heat	896.0	J/kg °c
Fuel witdhness	62.3	mm
Fuel thickness	0.51	mm
Fuel length	598.0	mm
Cladding thickness	0.38	mm
Channel witdness	66.6	mm
Channel thickness	2.1	mm
Coolant mass flowrate	0.31	kg/s
Coolant input temperature	30 ^{o}c	°c
Plate power generation	30201	W

in channel is given in table (4-10). The graph of coolant and fuel center temperatures versus fuel height are given in figure (4-3). The maximum temperature difference between cladding and coolant is 29.0 ^{o}C , whereas this difference was 35.3 ^{o}C in TRI. This is because of the change in the

TABLE 4-10 Thermo-Hydraulic Calculation for Reactor-II

DISTANCE (MM)	FUEL CENTER (C)	TEMPERATURES OF FUEL CLAD INTERFACE (C)	TEMPERATURES OF CLADDING SURFACE (C)	COOLING WATER (C)	PRESSURE DIFFERENCE (N/M**2)
.0	34.2	34.2	34.1	30.0	.0
19.9	39.2	39.2	39.0	30.2	-157.2
39.9	42.0	41.9	41.7	30.4	-314.2
59.8	45.2	45.0	44.7	30.7	-470.9
79.7	48.1	48.0	47.6	31.1	-627.4
99.7	50.9	50.8	50.3	31.5	-783.3
119.6	53.6	53.4	52.9	32.0	-938.8
139.5	56.2	55.9	55.4	32.5	-1093.8
159.5	58.5	58.2	57.6	33.1	-1246.1
179.4	60.6	60.3	59.7	33.8	-1401.7
199.3	62.5	62.2	61.6	34.4	-1554.6
219.5	64.2	63.9	63.2	35.1	-1706.8
239.2	65.6	65.3	64.6	35.9	-1858.1
259.1	66.8	66.5	65.8	36.6	-2008.6
279.1	67.8	67.5	66.8	37.4	-2158.3
299.0	68.5	68.2	67.5	38.2	-2307.1
318.9	69.0	68.7	68.0	39.0	-2455.0
338.9	69.2	68.9	68.2	39.7	-2602.1
358.8	69.2	68.9	68.2	40.5	-2748.4
378.7	68.9	68.6	68.0	41.2	-2893.8
398.7	68.4	68.1	67.5	41.9	-3038.4
418.6	67.7	67.4	66.8	42.6	-3182.2
438.5	66.7	66.4	65.8	43.2	-3325.3
458.5	65.4	65.2	64.7	43.8	-3467.6
478.4	64.0	63.8	63.3	44.4	-3609.3
498.3	62.3	62.2	61.7	44.9	-3750.4
518.3	60.5	60.4	60.0	45.3	-3890.9
538.2	58.5	58.4	58.0	45.7	-4030.9
558.1	56.2	56.1	55.8	46.0	-4170.5
578.1	54.2	54.1	53.9	46.2	-4309.7
598.0	50.1	50.0	49.9	46.4	-4448.5

value of the convective heat transfer coefficient which is directly related to the coolant velocity.

Some changes in the dimension of fuel core is encountered. In the Reactor II, fuel length changes between 586 mm and 610 mm, fuel width between 59.2 mm and 65.4 mm, and channel thickness between 1.85 mm and 2.35 mm. For this reason, the effect of dimensional differences on the temperature distribution was examined. Two per cent increase in the length of fuel (610 mm) caused the maximum fuel temperature to fall down to 68.7^{o}c from 69.2^{o}c , and two per cent decrease in this dimension (586 mm) caused the maximum fuel temperature to rise to 69.8^{o}c, this is due to the area exposed to cooling increase and decrease respectively.

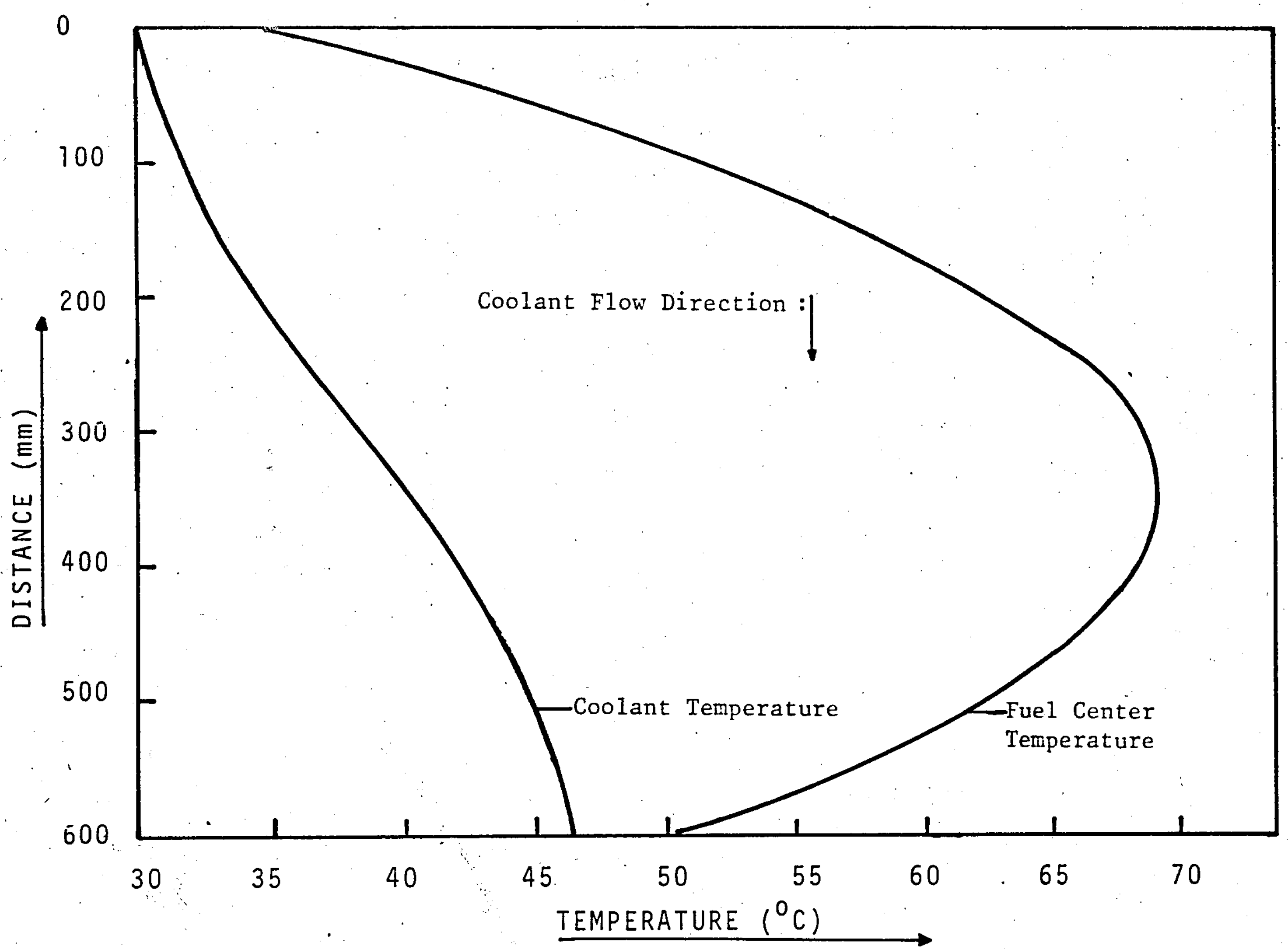

FIGURE 4-3 Temperature Distribution for Reactor-II

In the case of the change of fuel witdh between 65.4 mm and 59.2mm, the corresponding maximum fuel temperatures were 67.9 °C and 70.7 °C. That is, five per cent increase in fuel width results in 1.9 per cent decrease in the temperature, whereas five per cent decrease causes 2.1 per cent increase in the temperature. The previous reasoning for temperature change is also valid in this case. An increase of 12 per cent in the thickness of channel (2.35 mm) caused the maximum temperature to rise to 72.4 °C from 69.2 °C , and the same per cent decrease caused 3.1 °C decrease, this is because of the increase in channel thickness reducing the convective heat transfer coefficient and viceversa.

Another point which is observed in this parametic analysis is the change of the position of the maximum fuel temperature. In the case of 610 mm fuel length, 65.4 mm fuel widthness, and 1.85 mm channell thickness maximum fuel temperature were found at one axial step below that of reference system table (4-10). In cylindrical coordinates, the distance from the mid-plane of fuel length at which maximum fuel temperature occurs for the cosine axial heat flux distribution is calculated using the equation (4-1) [15]

$$Z_m = \frac{He}{\pi} \tan^{-1} \frac{He}{Cp\ \dot{m}\left[\frac{1}{4\,kf} + \frac{1}{2}\left[\frac{1}{k_c}\ \ln\frac{R+c}{R} + \frac{1}{h(R+c)}\right]\right]} \qquad (4.1)$$

where

Z_m = The distance from mid plane of fuel length, ft

He = Extrapolated deight, ft

Cp = Specific heat of coolant fluid, Bu/ ℓ_m °F

m = Mass-flow rate of coolant fluid, ℓbm /hr

R = Fuel radius, ft

c = Cladding thickness, ft

k_f = Thermal conductivity of fuel, Btu/hr ft ^oF

k_c = Thermal conductivity of cladding Btu/hr ft ^oF

h = Convective heat transfer coefficient, Btu/hr ft^2 ^oF

There is an agreement between the result of NEKA and this equation the increase in fuel length that is, the increase in extrapolated height cause the maximum fuel temperature to occur further from the fuel element mid-plane. Also the increase in (R+c) term in equation (4-1), that is, an increase in fuel width causes the maximum fuel temperature point to be further away . The other effect, the decrease in channel thickness resulting in the increase in convective heat transfer coefficient (h) , increases this distance.

B- UNSTEADY STATE CALCULATIONS

Unsteady state thermo-hydraulic calculations were examined for time rate of change of temperatures, after a step change, in coolant inflow temperature, coolant flowrate or heat generation is encountered in the reference system. The properties of the reference system is of Reactor I which has the temperature distribution as given in the table (4-7). The responce of the system to these step changes will be examined below using a time step (Δt) of 0.0473 seconds which is the time required for coolant to pass through one axial step.

a. The first calculation was carried out for the step change of coolant flowrate. The flowrate was changed with the factor of 0.8 and 1.2. Thus the reference coolant input flowrate was changed to 0.1511 kg/s and 0.2267 kg/s respectively. Tabulated results for 0.8 flowrate factor are in tables (C-3) through (C-8) for the times 0.473 , 0.946 , 1.419 , 1.892 3.311 and 5.203 seconds respectively. The maximum fuel temperature reaches 83.9 ^oC and coolant outflow temperature reaches 46.9 ^oC asymptotically (figure 4.4). The time required for 50 percent change of the total coolant outlet temperature change ($2^{o}C$) is 2.0 seconds, and for 90 per cent change is 5.2 seconds. For the same change,the time requirements calculated by TERHID are 2.2 and 5.0 seconds. The total change in the maximum fuel temperature is 7.2 ^{o}C . The 50 per cent and 90 per cent of this change are reached in 1.3 and 4.3 seconds. The corresponding time requirement in TERHID are 1.2 and 4.2 seconds.

In the case of the reference coolant flowrate increasing with factor of 1.2 the time requirement for 50 per cent change of the total coolant exit temperature change (Figure 4.4) is 1.4 seconds, and for 90 per cent is 3.7 seconds. The resuts of TERHID for these changes are 1.3 and 3.3 seconds. The same changes for the maximum fuel temperature require 1.0 and 3.2 seconds respectively and in TERHID these are 1.0 and 2.4 seconds.

b. Two step changes application were exemined on the coolant input temperature. These changes were made with the factor of 0.622 and 0.811 , corresponding to coolant input temperatures of 23 ^{o}C and $30^{o}C$. The maximum fuel and coolant temperature change with time is given in figure (4.5). When coolant input temperature is 23 ^{o}C , it takes 2.0 and 4.7 seconds for 50 and 90 per cent change of the maximum fuel temperature. In the case $30^{o}C$ these values become 2.0 and 4.6 seconds. TERHID results for these values are 1.9 and 4.5 , 1.9 and 4.7 seconds respectively. Fifty and 90 per cent changes in the coolant output temperatures are completed in 1.5 and 2.8 seconds for 23 ^{o}C input temperature, and 1.5 and 2.9 seconds for 30 ^{o}C input temperature. The corresponding values obtained in TERHID are 1.6 and 2.8 , 1.5 and 2.8 seconds.

c. The response of the reference system to step changes in plate

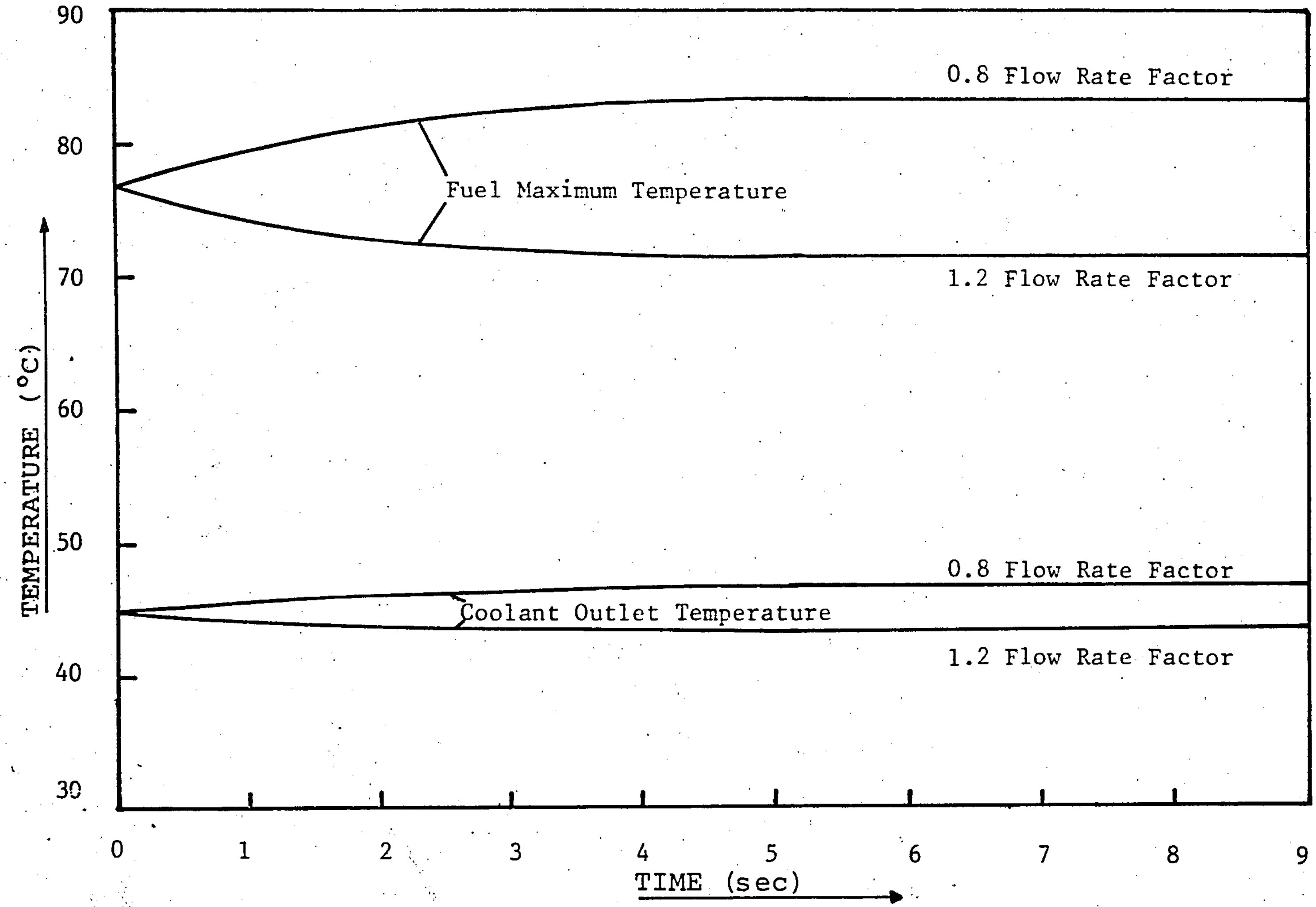

FIGURE 4-4 Temperature Change with Time due to the Coolant Flowrate Change

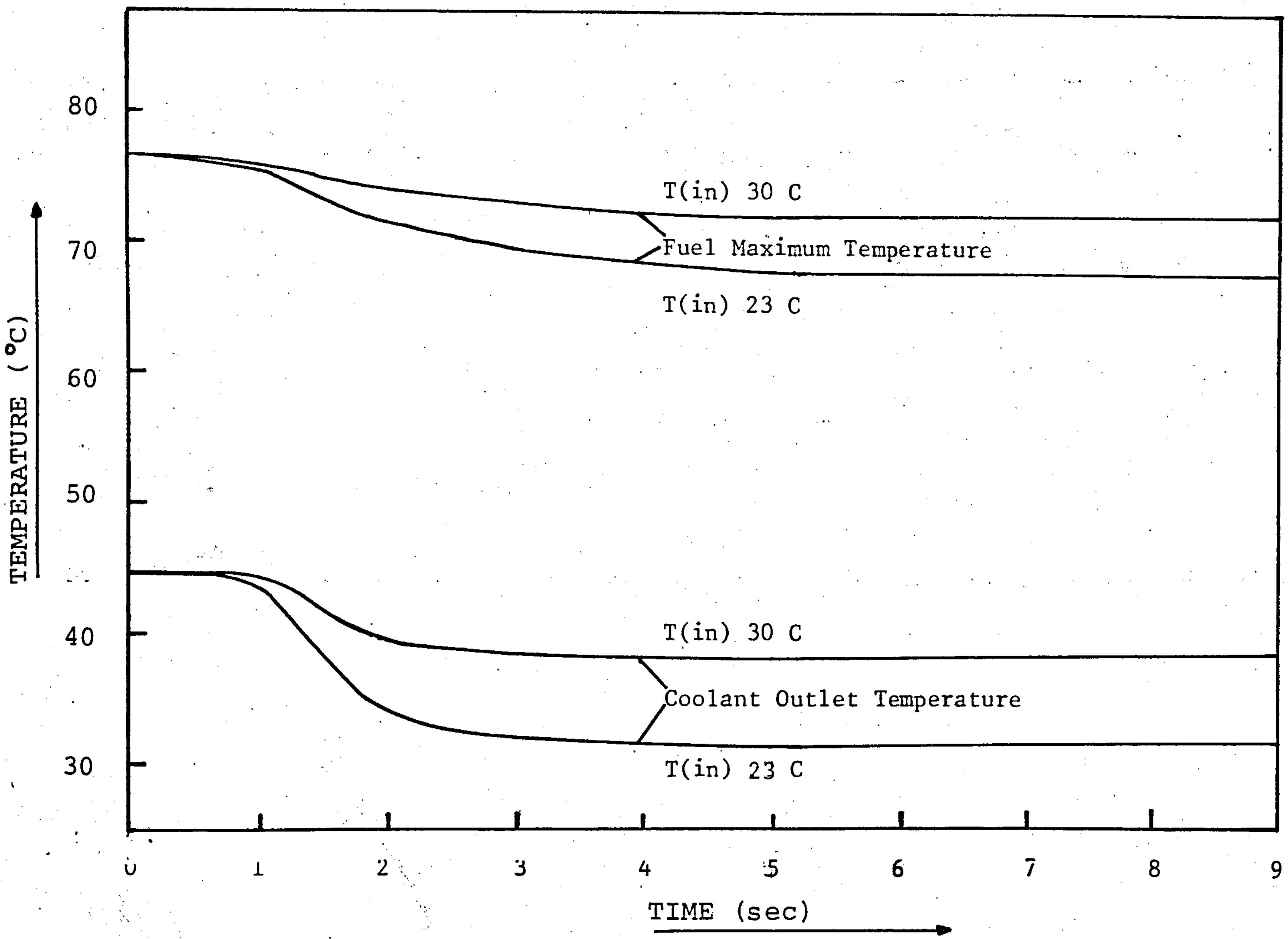

FIGURE 4-5 Temperature Change with Time due to the Inlet Coolant Temperature Change

power generation was examined. For this, factor of 0.8 and 3.0 corresponding to 7143.2 and 26787 w plate power were used. The change of temperature with time is given in figure (4-6). For the power factor of 0.8 , the maximum fuel temperature decreases from 76.7 °C to 69.3°C , the total change being 7.4 °C. The required time for the completion of 50 and 90 per cent of the total change is 1.1 and 3.7 seconds respectively. Coolant output temperature falls down to 43.4 °C from 44.9 °C and 50 and 90 per cent of this change occurs in 1.9 and 4.6 seconds while these are 1.9 and 4.0 seconds as calculated by TERHID

On the other hand the maximum fuel temperatures reaches 142.8 °C and coolant temperature reaches 60.8 °C when a power factor of 3.0 is used. 50 and 90 per cent of the total maximum fuel temperature change is completed at 1.0 and 3.1 seconds for coolant exit temperature these are obtained at 1.9 and 4.2 seconds. According to the solution of TERHID these time requirements are 0.9 , 2.8 seconds, and 1.9 , 4.0 seconds.

The unsteady state results of TERHID and NEKA are both given in tables (4-11) and (4-12) for the completion of the 50 and 90 per cent of the total changes in fuel maximum and coolant outlet temperatures respectively.

The results show an agreement between those of NEKA and TERHID in terms of time durating for 50 and 90 per cent change in temperatures. The maximum discrepeny is in the range of 0.3 second except the cases of 1.2 flowrate factor and 0.8 heat generation factor in which the discrepency is 0.8 and 0.6 seconds respectively.

Furthermore, if the fuel density of 3336 kg/m^3 which is the density of fuel composed of 20 per cent uranium-aluminium mixture is used, the time requirements for 50 and 90 per cent of total changes in fuel maximum and coolant outlet temperatures for all the step changes are given in

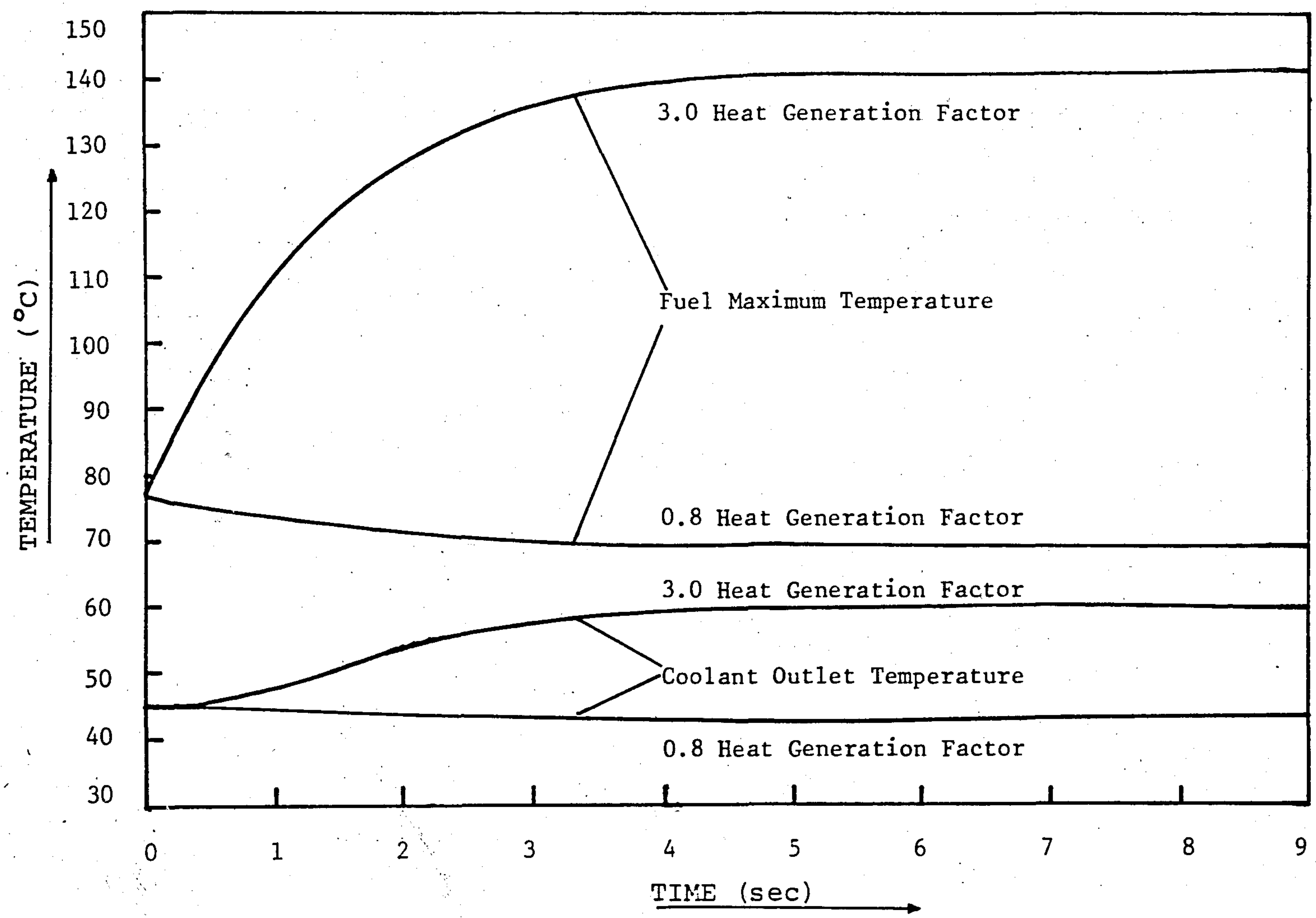

FIGURE 4-6 Temperature Change with Time due to the Heat Generation Change

TABLE 4-11 The Time Requirements for the Complation of 50 and 90 per cent of the Fuel Maximum temperature Change

Step Change	TERHID Time Required (In seconds)for 50 %	TERHID 90 %	NEKA Time Required (In seconds)For 50 %	NEKA 90 %
1.2 x Coolant Flowrate	1.0	2.4	1.0	3.2
0.8 x Coolant Flowrate	1.2	4.2	1.3	4.3
0.62 x Coolant Input Temperature	1.9	4.5	2.0	4.7
0.82 x Coolant Input Temperature	1.9	4.7	2.0	4.6
0.8 x Heat Generation	0.9	3.8	1.1	3.7
3.0 x Heat Generation	0.9	2.8	1.0	3.1

TABLE 4-12 The Time Requirements for the Completion of 50 and 90 per cent of the Coolant Outlet Temperature Change

Step Change	TERHID Time Required (In seconds)for 50 %	TERHID 90 %	NEKA Time Required (In seconds)for 50 %	NEKA 90 %
1.2 x Coolant Flowrate	1.3	3.3	1.4	3.7
0.8 x Coolant Flowrate	2.2	5.0	2.0	5.2
0.62 x Coolant Input Temperature	1.6	2.8	1.5	2.8
0.82 x Coolant Input Temperature	1.5	2.8	1.5	2.9
0.8 x Heat Generation	1.9	4.0	1.9	4.6
3.0 x Heat Generation	1.9	4.0	1.9	4.2

table (4-13) and (4-14) together with those of the density of 19000 kg/m^3.

As seen from the tables the time requirement for the completion of the total changes in temperatures become appreciably shorter, for the case of smaller fuel density.

C- SUBCOOLED BOILING CALCULATIONS

Needless to say that it is important to be able to predict the subcooled boiling occurance to be safe from burnout.

The application of the program NEKA to subcooled boiling calculations were examined for the Reactor II. The ratio between critical heat flux and the heat flux occuring must be greater then 2 [14] to be in the safe region (away from subcooled boiling). This ratio, under the normal working condition of Reactor II is calculated to be 8.6. If water flowrate is decreased to the value of 0.065 kg/s . (0.48 m/s) , from 0.31 kg/s subcooled boiling starts. In this case the cladding surface temperature reaches 151.3 ^{o}C and the coolant temperature at that point becomes 83.4 ^{o}C as coolant outlet temperature approaches 107.7 ^{o}C which is also below the boiling point of water under these conditions.

In placing the core power generation of 17.5 MW subcooled boiling occurance is encountered for the water flowrate of 0.31 kg/s (2.57 m/s) The cladding surface temperature and coolant temperature are 142.2 ^{o}C and 61.2 ^{o}C at nodel point of 318.9 mm at which subcooled boiling is first seen, while water outlet temperature reaches to 87.1 ^{o}C .

D- DISCUSSION

It is assumed that the rate of heat generation in a fuel plate changes in the axial directions and in the remaining directions average heat generation is assumed. This assumption leads the value of temperatures

TABLE 4-13 The Time Requirements for the Completion of 50 and 90 per cent of the Fuel Maximum Temperature Change

Step Change	Fuel Density = 19000 kg/m^3 Time required (in seconds) for 50 %	90 %	Fuel Density = 3336 kg/m^3 Time required (in seconds) for 50 %	90 %
1.2 x Coolant Flowrate	1.0	3.2	0.4	1.2
0.8 x Coolant Flowrate	1.3	4.3	0.5	1.6
0.62 x Coolant Input Temperature	2.0	4.7	1.3	2.2
0.82 x Coolant Input Temperature	2.0	4.6	1.2	2.2
0.8 x Heat Generation	1.1	3.7	0.4	1.4
3.0 x Heat Generation	1.0	3.1	0.4	1.1

TABLE 4-14 The Time Requirements for the Completion of 50 and 90 per cent of the Coolant Outlet Temperature Change

Step Change	Fuel Density = 19000 kg/m^3 Time required (in seconds) for 50 %	90 %	Fuel Density = 3336 kg/m^3 Time required (in seconds) for 50 %	90 %
1.2 x Coolant Flowrate	1.4	3.7	1.0	1.9
0.8 x Coolant Flowrate	2.0	5.2	1.3	2.6
0.62 x Coolant Input Temperature	1.5	2.8	1.5	2.2
0.82 x Coolant Input Temperature	1.5	2.9	1.5	2.2
0.8 x Heat Generation	1.9	4.6	1.2	2.3
3.0 x Heat Generation	1.9	4.2	1.2	2.2

to be smaller than the real ones.

Although, NEKA calculates fuel center, fuel-cladding interface and cladding surface temperature and, TERHID calculates the avarage temperature of the fuel and cladding, they can be comparable since the temperature difference within fuel and cladding is in the range of 0.1 ^{o}C. So the error can not be greater than 0.1 ^{o}C.

The calculations were based on the one half of fuel plate because of the symmetry. However, the channel was taken into consideration as a whole assuming that the heat transfered to the coolant from two adjacent fuel plate is the same. In fact, since a nuclear reactor core consists of many plates, the heat generation rate doesn't differ much between two adjacent plates.

The coolant channel area is assumed to be constant along coolant flow direction, but any change can be entered into the program requiring only a few changes.

The physical property changes of the coolant (water) with temperature are evaluated using functions (F(T)). The method and correlations is for single phase flow. In the case of power generation rate increase or coolant flowrate decrease, subcooled boiling may be encountered. After this point the calculations performed by NEKA are not valid.

V. CONCLUSIONS AND RECOMMENDATIONS

A- CONCLUSIONS

In this work, the conduction, convection and heat transport models and a computer program NEKA were developed to perform steady-state and transient thermo-hydraulic analysis of a plate type fueled water cooled nuclear reactor core.

The finite element method was used to determine the temperature distribution using the two dimensional heat conduction model. Galerkin's method was applied to obtain the element equations, and in order to approximate the time derivative finite difference approach was treated. The main difficulty and source of errors in the finite element method, the data prepation and entering the data into program, were overcome by using the grid generating subroutine.

Dittus-Boelter correlation was used to calculate the convective heat transfer coeffecient.

The mass, energy and momentum balance equation were applied to a control volume to determine coolant temperature and pressure change using finite difference method.

The computer program NEKA which enables a rapid means of performing many calculations involved in the models stated before, consists of one main, 17 subroutines and 7 function routines. The memory requirement of the program up to 400 element application is 171.5 KB. The execution time in DOC CYBER 170/815 system to perform steady state calculations is 8.269 seconds for Reactor II using 30 axial step. In the case of unsteady state calculations, 160 to 230cp seconds computer time is required depending on the type of step change while axial step (30), time step 0.0473 sec.) and the numbers of time step are constant. If the number of axial step is doubled time requirement is doubled.

The comparison of the results to those of TERHID showed an agreement. In the transient calculations temperatures reach steady state values asymptotically within 10 seconds in both works.

The analysis with an increased number of axial step showed that the number of current axial step is sufficient to give acceptable precision.

The 1 MW power geneting reactor in ÇNAEM, the Reactor I showed to have a maximum fuel temperature of 76.7 ^{o}C and 66.8 ^{o}C under normal operating conditions for 37°C and 23°C coolant input temperatures respectively In the transient calculations this system for 37°C coolant input temperature was taken as a referance system. In all transient calculations the time requirement to complete the 90 per cent of the total change were found to be in the range of 2.8 to 5.2 seconds.

In the other reactor in ÇNAEM, the Reactor II which produces 5MW, maximum fuel temperature reached to 69.2 ^{o}C under normal operating conditions for 30^{o}C coolant input temperature. A parametric study on the dimensions of the Reactor II core showed that two per cent increase in fuel length reduced the maximum fuel temperature to 68.7 ^{o}C from 69.2^{o}C, and five per cent increase in fuel width resulted in 1.9 per cent decrease in the maximum temperature also 12 per cent increase in channel thickness rose the maximum fuel temperature to 72.1 ^{o}C.

In the case of increasing the power level of Reactor II to 17.5 MW or the coolant flowrate decreased, to 0.065 kg/s for one channel the subcooled boiling starts and after this point the fuel temperature rises considerably.

The two reactors examined in this work were found to be safe under normal operating conditions from the view point of thermo-hydraulic analysis.

B- RECOMMENDATIONS

In view of the work carried out in this thesis, the following recomendations can be made

1- In a further work, the program can be arranged to be used together with a program which performs neutronic calculations.

2- The variation of physical properties of k, ρ, c with temperature can be entered to the program using functions or tabulated values.

3- Application of the program to other geometries rather than the plate type requires major changes.

4- The temperature distribution after subcooled boiling occurance is encountered can be determined adding the appropriate correlations to the program.

5- One could also try to use the Galerkin method or finite element approach instead of finite difference method of solution in time domain to see whether any advantages in the solution can be attained.

6- The thermal stresses can also be determined together with temperature distribution.

APPENDIX A

DERIVATION OF THE FINITE ELEMENT EQUATIONS

Finite element equation (2.9) written as follows;

$$\int_A k\left(\frac{\partial [N]^T}{\partial x} \cdot \frac{\partial [N]}{\partial x} + \frac{\partial [N]^T}{\partial y} \frac{\partial [N]}{\partial y}\right) dA \{T\} \tag{A-1}$$

$$+ \int_{\mathcal{L}} h \, [N]^T [N] \, d\mathcal{L} \, \{T\} \tag{A-2}$$

$$- \int_{\mathcal{L}} h \, [N]^T \, T_F \, d\mathcal{L} \tag{A-3}$$

$$- \int_A [N]^T \, Q \, dA \tag{A-4}$$

$$+ \int_A \rho \, c \, [N]^T [N] \, dA \, \frac{\partial \{T\}}{\partial t} = 0 \tag{A-5}$$

this equation can be analyzed by means of some necessary matrix applications

Shape function for two dimensional simplex element is

$$N_\beta = 1/2A \, (a_\beta + b_\beta \, x + c_\beta \, y) \quad \beta = i,j,k \tag{A-6}$$

where

$$a_i = X_j Y_k - X_k Y_j \qquad b_i = Y_j - Y_k \qquad C_i = X_k - X_j$$

$$a_j = X_k Y_i - X_i Y_k \qquad b_j = Y_k - Y_i \qquad C_j = X_i - X_k$$

$$a_k = X_i Y_j - X_j Y_i \qquad b_k = Y_i - Y_j \qquad C_k = X_j - X_i$$

Gradient matrix can be written as

$$\begin{bmatrix} \frac{\partial Ni}{\partial x} & \frac{\partial Nj}{\partial x} & \frac{\partial Nk}{\partial x} \\ \frac{\partial Ni}{\partial y} & \frac{\partial Nj}{\partial y} & \frac{\partial Nk}{\partial y} \end{bmatrix} \tag{A-7}$$

this can be rewritten substituting the shape function into

$$[B] = \frac{1}{2A} \begin{bmatrix} b_i & b_j & b_k \\ c_i & c_j & c_k \end{bmatrix}$$

integral (A-1) becomes

$$\int_A \frac{k}{4A^2} \begin{bmatrix} bi & bj & bk \\ ci & cj & ck \end{bmatrix} \begin{bmatrix} bi & ci \\ bj & cj \\ bk & ck \end{bmatrix} dA \ \{T\}$$

$$= \frac{k}{4A} \begin{bmatrix} bi\ bi & bj\ bi & bk\ bi \\ bi\ bj & bj\ bj & bk\ bj \\ bi\ bk & bj\ bk & bk\ bk \end{bmatrix} + \frac{k}{4A} \begin{bmatrix} ci\ ci & cj\ ci & ck\ ci \\ cj\ ci & cj\ cj & ck\ cj \\ ck\ ci & ck\ cj & ck\ ck \end{bmatrix} \{T\} \tag{A-8}$$

The second integral can be evaluated over a surface, performing matrix multiplication

$$\int_{\mathcal{L}} h [N]^T [N] d\mathcal{L} \{T\} = h \int_{\mathcal{L}} \begin{bmatrix} Ni\ Ni & Ni\ Nj & Ni\ Nk \\ Ni\ Ni & Ni\ Nj & Nj\ Nk \\ Nk\ Ni & Nk\ Nj & Nk\ Nk \end{bmatrix} d\mathcal{L} \{T\} \tag{A-9}$$

making use of area coordinate it is easier to evaluate the product terms.

$L_1 = N_i$, $L_2 = N_j$ and $L_3 = N_k$

L's are area coordinates if the side between node i and j is experiencing the convection phenomenon

$N_k = L_3 = 0$ and equation (A-9) becomes

$$h \int_{\mathcal{L}_{ij}} \begin{bmatrix} L_1 L_1 & L_1\ L_2 & 0 \\ L_2 L_1 & L_2\ L_2 & 0 \\ 0 & 0 & 0 \end{bmatrix} d\mathcal{L} \ \{T\} \tag{A-10}$$

integration of squared quantity and cross products is $\frac{\mathcal{L}_{ij}}{3}$ and $\frac{\mathcal{L}_{ij}}{6}$ respectively where $\mathcal{L}_{ij}$ is the length of the side between the nodes i and j

equation (A-10) becomes

$$\frac{h\,\mathcal{L}_{ij}}{6}\begin{bmatrix} 2 & 1 & 0 \\ 1 & 2 & 0 \\ 0 & 0 & 0 \end{bmatrix}\{T\} \qquad \text{(A-11)}$$

The third integral is also approximated as in the second integral

$$h\int_{\mathcal{L}} [N]^T \; T_f \; d\,\mathcal{L} = h\,T_f\,\frac{\mathcal{L}_{ij}}{2}\begin{bmatrix} 1 \\ 1 \\ 0 \end{bmatrix} \qquad \text{(A-12)}$$

The other term in equation (2.9) is

$$\int_A [N]^T \, Q \;\; dA \qquad \text{(A-13)}$$

assuming Q is constant in one element then the results of equation (A-13) is

$$\frac{Q\,A}{3}\begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \qquad \text{(A-14)}$$

The heat generated within the element is allotted to the three nodes

The last term is also rewritten in terms of area coordinate

$$\int_A \rho c \begin{bmatrix} L_1 \\ L_2 \\ L_3 \end{bmatrix}\begin{bmatrix} L_1 & L_2 & L_3 \end{bmatrix} dA\,\frac{\partial\{T\}}{\partial t} = \rho\, c \int_A \begin{bmatrix} L_1L_1 & L_1\,L_2 & L_1\,L_3 \\ L_2L_1 & L_2\,L_2 & L_2\,L_3 \\ L_3L_1 & L_3\,L_2 & L_3\,L_3 \end{bmatrix} dA\,\frac{\partial\{T\}}{\partial t} \qquad \text{(A-15)}$$

squared quantity and cross product is approximated as A/6 and A/12 respectively in area integral and rewritten as

$$\rho\,\frac{c\,A}{12}\begin{bmatrix} 2 & 1 & 1 \\ 1 & 2 & 1 \\ 1 & 1 & 2 \end{bmatrix}\frac{\partial\{T\}}{\partial t} \qquad \text{(A-16)}$$

Equation (A-8) and (A-11) contributes to element conduction matrix, (A-12) and (A-14) element force vector, and (A-16) element capacitance matrix.

APPENDIX B.

LISTING OF THE COMPUTER PROGRAM

```
      PROGRAM NEKA(INPUT,OUTPUT,NEKADAT,RELDATA,TAPE59=
     1RELDATA,TAPE60=NEKADAT,TAPE1=INPUT,TAPE61=OUTPUT)
      COMMON /MATR1/EF(3),ECM(3,3),EQ(3,3),EP(3,3)
      COMMON /MATR2/ESM(400,3,3),ESMOLD(400,3,3)
      COMMON /TEMP/TEMF(300),TEMFOLD(300),TEM(2500),TEMOLD(600)
      COMMON /COOR/X(400,3),Y(400,3),NS(400,3),B(3),C(3),NCOL
      COMMON /REL/DY(99),DREL(99),REL(3),NREL,HG
      COMMON /ELM/ISIDE(400),IHEATGE(400),NP,NELEM,NBW
      COMMON /FLUID/H(300),FLOW(300)
      COMMON /STORE/A(2500),PA(2500),P(2500)
      COMMON /TLE/TITLES(20),TITLEUS(20)
      COMMON /PHYF/KF,RHOF,HECAPF,DFL,DFW,DFHT
      COMMON /PHYC/DCW,DCT,KC,RHOC,HECAPC,DCLADT
      DIMENSION DELPR(300)
      CHARACTER* 6 STATE,SCOUL,CHOSE
      REAL KC,KF ,LG
      DATA IN/60/,IO/61/,NCL/1/,ID1/0/
C     DEFINITION OF THE CONTROL PARAMETERS
C                NP - NUMBER OF GLOBAL TEMPERATURES
C                NE - NUMBER OF ELEMENTS
C                NBW- BAND WIDTH
C                KC - CONDUCTIVITY IN CLEADING
C                KF - CONDUCTIVITY IN FUEL
C                H  - CONVECTION COEFFICIENT
C                TINF-FLUID INPUT TEMPERATURE
C
C
C     INPUT OF THE TITLE CARD, THE CONTROL PARAMETERS AND THE ELEMENT DATA
C
C
      PRINT*,'  ** DO YOU WANT INTERACTIVE USJAGE (YES OR NO) **'
      READ(*,10) CHOSE
      PRINT '("  ?  ",A4)',CHOSE
      IF(CHOSE.EQ.'YES') IN=1
C
      CALL GIVEN(IN,TINF,FLWRATE)
C
      CALL GRID(IN)
C
      CALL NORMLIS(TINF,FLWRATE)
C
C     CALCULATION OF POINTERS AND INITILIZATION OF THE COLUMN VECTOR A
C
      JGF=NP*NCL
      JGSM=JGF*2
      JEND=JGSM+NP*NBW
      DO 100 I=1,JEND
 100  A(I)=0.0
C   ***************************************
C   ASSEMLYING OF THE GLOBAL STIFFNESS, CAPACITANCE AND FORCE MATRIX
C   ***************************************
      IK=1
      IIK=1
      DELTIME=0.0473
      IF(ISS.EQ.0) GO TO 105
 275  ITT=(IT-1)/10
      IF(ITT.EQ.((IT-1.)/10.))THEN
      WRITE(IO,510)TITLEUS
      TIME=0.0473*(IT-1)
      WRITE(IO,500)  TIME
 500  FORMAT(/2X,'   TIME IN SECOND = ',F7.4)
      WRITE(IO,520)
      DO 101 I=1,NP,NCOL
      DO 102 II=1,NELEM
      DO 102 IJ=1,3
      IF(I.EQ.NS(II,IJ)) GO TO 106
```

```
102   CONTINUE
106   YY=(DFL-Y(II,IJ))*1000.
101   WRITE(10,530) YY,(TEMOLD(J),J=I,I+2),TEMFOLD(I+2),DELPR(I+2)
      PRINT 531
531   FORMAT(1H1)
      END IF
105   DO 110 I=1,NP
110   DELPR(I)=0.0
      DO 120 KK=1,NELEM
C
      CALL SHAPE(KK,AR4)
C
      IF(IHEATGE(KK).GE.1) GO TO 115
C
      CALL MAT(KK,AR4,ISS,DELTIME)
C
      IF(ISIDE(KK).LE.0) GO TO 125
C    **************************
C
C  CALCULATION OF THE CONVECTION RELATED QUANTITIES
C
      CALL CONVEC(KK,IK,IT,DELTIME,SUM,IO,ISS,IIK,DELPR)
C
C    **************************
      GO TO 125
C    **************************
C
C   CALCULATION OF  THE HEAT GENERATION RELATED QUANTITIES
C
115   CALL HEAT(KK,IK,AR4,DELTIME,SUM,ISS)
C
C    **************************
C   INSERTION OF ELEMENT PROPERTIES INTO THE GLOBAL STIFFNESS MATRIX
C
125   CALL STORAGE(KK,NCL,JGSM,ISS)
C
120   CONTINUE
      IF(ISS.EQ.0) GO TO 135
C
      CALL MULTBD(PA(1),TEMOLD(1),P(1),NP,NBW,NCL)
C
      INP=NP*NCL
      DO 130 I=1,INP
      KN=I+INP
130   P(I)=P(I)+(TEMOLD(KN)+A(KN))
C
135   CALL DCMPBD(A(JGSM+1),NP,NBW)
C
      IF(ISS.EQ.0) GO TO 145
      GO TO 155
145   NPP1=NP+1
      DO 140 I=NPP1,JGSM
140   TEMOLD(I)=A(I)
C
      CALL SLVBD(A(JGSM+1),A(JGF+1),A(1),NP,NBW,NCL,ID1,IT,ISS)
C
      GO TO 165
C
155   CALL SLVBD(A(JGSM+1),P(1),A(1),NP,NBW,NCL,ID1,IT,ISS)
C
165   IKK=0
      DO 150 KK=1,NP
      IF(ABS(A(KK)-TEM(KK)).LE.0.0005) IKK=IKK+1
150   CONTINUE
      IF(IKK.EQ.NP) GO TO 175
      DO 160 IK=1,JEND
```

```
      TEM(IK)=A(IK)
      A(IK)=0.0
      PA(IK)=0.0
 160  P(IK)=0.0
      GO TO 105
 175  IF(ISS.EQ.0) GO TO 185
      GO TO 195
 185  IIK=IIK+1
      IF(IIK.EQ.2)GO TO 205
      GO TO 215
 205  DO 170 I=1,JEND
      TEM(I)=A(I)
 170  A(I)=0.0
      GO TO 105
 215  WRITE(IO,510)TITLES
 510  FORMAT(1H1,14(/),20A4)
C
C   OUTPUT OF THE CALCULATED NODAL VALUES
C
      WRITE(IO,520)
 520  FORMAT( /,32X,'TEMPERATURES OF',//,'  DISTANCE       FUEL      FUEL
     1CLAD   CLADDING      COOLING     PRESSURE',//,'              CENTER
     2  INTERFACE    SURFACE        WATER     DIFFERENCE',//,4X,'(MM)',8X
     3,'(C)',10X,'(C)',3X,'(C)',10X,'(C)',6X,'(N/M**2)',/)
      DO 180 I=1,NP,NCOL
      DO 181 II=1,NELEM
      DO 181 IJ=1,3
      IF(I.EQ.NS(II,IJ)) GO TO 216
 181  CONTINUE
 216  YY=(DFL-Y(II,IJ))*1000
 180  WRITE(IO,530) YY,(A(J),J=I,I+2),TEMF(I+2),DELPR(I+2)
 530  FORMAT(5(F9.1,3X))
      WRITE(IO,540)
 540  FORMAT(1H1,4(/))
      PRINT*,'DO YOU WANT SUBCOOLED BOILING CALCULATION(YES OR NO)'
      READ(*,10)SCOOL
      PRINT '(" ? ",A4)',SCOOL
      IF(SCOOL.EQ.'NO') GO TO 225
C
      CALL SUBCOOL(DELPR,IO)
C
 225  PRINT*,'UNSTEADY STATE BEING ENCOUNTERED PRINT (YES OR NO)'
      READ(*,10)STATE
      PRINT '(" ? ",A4)',STATE
 10   FORMAT(A4)
      IF(STATE.EQ.'NO')GO TO 235
      PRINT*,'              WHAT IS THE STEP CHANGE'
      PRINT*,'                                              '
      PRINT*,' 1 STEP CHANGE IN FLOW RATE'
      PRINT*,' 2 STEP CHANGE IN INPUT FLUID TEMPERATURE'
      PRINT*,' 3 STEP CHANGE IN HEAT GENERATION'
      PRINT*,'                                                      '
      PRINT*,'ENTER THE NUMBER OF THE CASE ENCOUNTERED'
      READ(*,*)CASE
      ISS=1
      IT=0
      IF(CASE.EQ.1) GO TO 245
      IF(CASE.EQ.2) GO TO 255
      PRINT*,'ENTER THE STEP CHANGE IN HEAT GENERATION (LIKE 0.7 OR 1.5)
     1'
      READ(*,*)HGF
      PRINT*,' ? ',HGF
      HG=HG*HGF
      GO TO 195
 255  PRINT*,'ENTER THE STEP CHANGE IN INPUT FLUID TEMPERATURE (LIKE 0.5
     1 OR 1.7)'
```

```
      READ(*,*)TEF
      PRINT*,' ? ',TEF
      TINF=TINF*TEF
      GO TO 195
245   PRINT*,'ENTER STEP CHANGE IN FLOW RATE (LIKE 0.8 OR 1.2)'
      READ(*,*)FLWF
      PRINT*,' ? ',FLWF
      FLOW(NCOL)=FLOW(NCOL)*FLWF
195   IF(CASE.GT.0.) GO TO 265
      DO 190 I=1,JGSM
190   TEMOLD(I)=A(I)
265   CASE=0.
      DO 200 KK=1,NELEM
      DO 200  I=1,3
      DO 200  J=1,3
200   ESMOLD(KK,I,J)=ESM(KK,I,J)
      DO 210 I=1,NP
210   TEMOLD(I)=A(I)
      DO 220 IK=1,JEND
      A(IK)=0.0
      PA(IK)=0.0
220   P(IK)=0.0
      IK=1
      IT=IT+1
      DO 230 I=NCOL,NP,NCOL
230   TEMFOLD(I)=TEMF(I)
      TEMF(NCOL)=TINF
      IF(IT.LE.111) GO TO 275
235   STOP
      END
C     **********************************
C
      SUBROUTINE GIVEN(IN,TINF,FLWRATE)
C
C     **********************************
      COMMON /TEMP/TEMF(300),TEMFOLD(300),TEM(2500),TEMOLD(600)
      COMMON /COOR/X(400,3),Y(400,3),NS(400,3),B(3),C(3),NCOL
      COMMON /REL/DY(99),DREL(99),REL(3),NREL,HG
      COMMON /ELM/ISIDE(400),IHEATGE(400),NP,NELEM,NBW
      COMMON /FLUID/H(300),FLOW(300)
      COMMON /TLE/TITLES(20),TITLEUS(20)
      COMMON /PHYF/KF,RHOF,HECAPF,DFL,DFW,DFHT
      COMMON /PHYC/DCW,DCT,KC,RHOC,HECAPC,DCLADT
      REAL KC,KF
      CALL PF('GET','RELDATA')
      READ(59,1)TITLES
      READ(59,1)TITLEUS
1     FORMAT(20A4)
      PRINT*,'                              *********'
      PRINT*,'     ENTER THE THERMAL CONDUCTIVITY OF FUEL (W/M C)'
      READ(IN,*)KF
      PRINT*,' ? ',KF
      PRINT*,'     ENTER THE THERMAL CONDUCTIVITY OF CLADDING (W/M C)'
      READ(IN,*)KC
      PRINT*,' ? ',KC
      PRINT*,'     ENTER THE DENSITY OF FUEL (KG/M**3)'
      READ(IN,*)RHOF
      PRINT*,' ? ',RHOF
      PRINT*,'     ENTER THE DENSITY OF CLADDING (KG/M**3)'
      READ(IN,*)RHOC
      PRINT*,' ? ',RHOC
      PRINT*,'     ENTER THE HEAT CAPACITY OF FUEL (J/KG C)'
      READ(IN,*)HECAPF
      PRINT*,' ? ',HECAPF
      PRINT*,'     ENTER THE HEAT CAPACITY OF CLADDING (J/KG C)'
      READ(IN,*)HECAPC
```

```
      PRINT*,' ? ',HECAPC
      PRINT*,'    ENTER THE POWER FOR THE PLATE (W)'
      READ(IN,*)HG
      PRINT*,' ? ',HG
      PRINT*,'    ENTERING THE DIMENSIONAL PROPERTIES'
      PRINT*,'         FUEL LENGTH (MM)'
      READ(IN,*)DFL
      PRINT*,' ? ',DFL
      PRINT*,'         FUEL HALF THICKNESS (MM)'
      READ(IN,*)DFHT
      PRINT*,' ? ',DFHT
      PRINT*,'         FUEL WIDTH (MM)'
      READ(IN,*)DFW
      PRINT*,' ? ',DFW
      PRINT*,'         CLADDING THICKNESS (MM)'
      READ(IN,*)DCLADT
      PRINT*,' ? ',DCLADT
      PRINT*,'         CHANNEL WIDTH (MM)'
      READ(IN,*)DCW
      PRINT*,' ? ',DCW
      PRINT*,'         CHANNEL THICKNESS (MM)'
      READ(IN,*)DCT
      PRINT*,' ? ',DCT
      PRINT*,'    ENTER THE COOLANT INLET TEMPERATURE (C)'
      READ(IN,*)TINF
      PRINT*,' ? ',TINF
      PRINT*,'    ENTER THE COOLANT MASS FLOWRATE (KG/SEC)'
      READ(IN,*)FLWRATE
      PRINT*,' ? ',FLWRATE
      READ(59,*) NREL
      READ(59,2)(DY(I),DREL(I),I=1,NREL)
    2 FORMAT(2F10.5)
      RETURN
      END
C     ***************************************
C
      SUBROUTINE GRID(IN)
C
C     ***************************************
      DIMENSION XP(100),YP(100),XRG(9),YRG(9),N(8),NDN(8)
      DIMENSION NN(91,91),YC(91,91),XC(91,91),NNRB(20,4,91),JT(20,4)
      DIMENSION LB(3),NE(400),XE(400),YE(400),NR(4),ICOMP(4,4)
      COMMON /COOR/X(400,3),Y(400,3),NS(400,3),B(3),C(3),NCOL
      COMMON /ELM/ISIDE(400),IHEATGE(400),NP,NELEM,NBW
      COMMON /PHYF/KF,RHOF,HECAPF,DFL,DFW,DFHT
      COMMON /PHYC/DCW,DCT,KC,RHOC,HECAPC,DCLADT
      REAL N
      DATA ICOMP/-1,1,1,-1,1,-1,-1,1,1,-1,-1,1,-1,1,1,-1/
      DATA IO/61/,NBW/0/,NB/0/,NEL/0/
C
C    INPUT AND OUTPUT OF TITLE,CONTROL CARD, GLOBAL COORDINATES AND
C          CONNECTIVITY DATA
C
      PRINT*,' '
      PRINT*,'          ENTERING THE DATA FOR GRID GENERATION'
      PRINT*,' '
      PRINT*,'    ENTER THE NUMBER OF REGIONS'
      READ(IN,*)INRG
      PRINT*,' ? ',INRG
      PRINT*,'    ENTER THE NUMBER OF BOUNDARY POINTS'
      READ(IN,*)INBP
      PRINT*,' ? ',INBP
      PRINT*,'  ENTER THE ABSISSA VALUES OF THESE POINTS (MM)'
      READ(IN,*)(XP(I),I=1,INBP)
      PRINT*,' ? ',(XP(I),I=1,INBP)
      PRINT*,'  ENTER THE ORDINATE VALUES OF THESE POINTS (MM)'
```

```
      READ(IN,*)(YP(I),I=1,INBP)
      PRINT*,' ? ',(YP(I),I=1,INBP)
      IF(INRG.EQ.1) GO TO 36
      DO 2 I=1,INRG
      PRINT*,'  ENTER THE REGION CONNECTIVITY DATA OF THE REGION ',I
 2    READ(IN,*)(JT(I,J),J=1,4)
      PRINT*,' ? ',(JT(I,J),J=1,4)
C
C   LOOP ON THE REGIONS TO GENERATE THE ELEMENTS
C
 36   DO 16 KK=1,INRG
      NRG=KK
      PRINT*,'  ENTER THE NUMBER OF ROWS OF NODES IN REGION ',KK
      READ(IN,*)NROWS
      PRINT*,' ? ',NROWS
      PRINT*,'  ENTER THE NUMBER OF COLUMNS OF NODES IN REGION ',KK
      READ(IN,*)NCOL
      PRINT*,' ? ',NCOL
      PRINT*,'  ENTER THE GLOBAL NODE NUMBERS USED TO DEFINE THE'
      PRINT*,'  QUADRILATERAL OF REGION ',KK
      READ(IN,*)NDN
      PRINT*,' ? ',NDN
      WRITE(IO,18)NRG,NROWS,NCOL,(NDN(I),I=1,8)
 18   FORMAT(1H1///1X,12H***  REGION ,I2,6H  ****//10X,I2,5H ROWS,10X,I2
     1,8H COLUMNS//10X,21HBOUNDARY NODE NUMBERS,10X,8I5)
C
C  GENERATION OF THE ELEMENT NODAL COORDINATES
C
      DO 5 I=1,8
      II=NDN(I)
      XRG(I)=XP(II)
   5  YRG(I)=YP(II)
      XRG(9)=XRG(1)
      YRG(9)=YRG(1)
      TR=NROWS-1
      DETA=2./TR
      TR=NCOL-1
      DSI=2./TR
      DO 12 I=1,NROWS
      TR=I-1
      ETA=1.-TR*DETA
      DO 12 J=1,NCOL
      TR=J-1
      SI=-1.+TR*DSI
      N(1)=-0.25*(1.-SI)*(1.-ETA)*(SI+ETA+1.)
      N(2)=0.5*(1.-SI**2)*(1.-ETA)
      N(3)=0.25*(1.+SI)*(1.-ETA)*(SI-ETA-1.)
      N(4)=0.5*(1.+SI)*(1.-ETA**2)
      N(5)=0.25*(1.+SI)*(1.+ETA)*(SI+ETA-1.)
      N(6)=0.5*(1.-SI**2)*(1.+ETA)
      N(7)=0.25*(1.-SI)*(1.+ETA)*(ETA-SI-1.)
      N(8)=0.50*(1.-SI)*(1.-ETA**2)
      XC(I,J)=0.0
      YC(I,J)=0.0
      DO 12 K=1,8
      XC(I,J)=XC(I,J)+XRG(K)*N(K)
 12   YC(I,J)=YC(I,J)+YRG(K)*N(K)
C
C    GENERATION OF THE REGION NODE NUMBER
C
      KN1=1
      KS1=1
      KN2=NROWS
      KS2=NCOL
      DO 50 I=1,4
      NRT=JT(NRG,I)
```

```
      IF(NRT.EQ.0.OR.NRT.GT.NRG) GO TO 50
      DO 56 J=1,4
   56 IF(JT(NRT,J).EQ.NRG) NRTS=J
      K=NCOL
      IF(I.EQ.2.OR.I.EQ.4) K=NROWS
      JL=1
      JK=ICOMP(I,NRTS)
      IF(JK.EQ.-1) JL=K
      DO 44 J=1,K
      GO TO (45,46,47,43),I
   45 NN(NROWS,J)=NNRB(NRT,NRTS,JL)
      KN2=NROWS-1
      GO TO 44
   46 NN(J,NCOL)=NNRB(NRT,NRTS,JL)
      KS2=NCOL-1
      GO TO 44
   47 NN(1,J)=NNRB(NRT,NRTS,JL)
      KN1=2
      GO TO 44
   48 NN(J,1)=NNRB(NRT,NRTS,JL)
      KS1=2
   44 JL=JL+JK
   50 CONTINUE
      IF(KN1.GT.KN2) GO TO 105
      IF(KS1.GT.KS2) GO TO 105
      DO 10 I=KN1,KN2
      DO 10 J=KS1,KS2
      NB=NB+1
   10 NN(I,J)=NB
C
C   STORAGE OF THE BOUNDARY NODE NUMBERS
C
      DO 42 I=1,NCOL
      NNRB(NRG,1,I)=NN(NROWS,I)
   42 NNRB(NRG,3,I)=NN(1,I)
      DO 43 I=1,NROWS
      NNRB(NRG,2,I)=NN(I,NCOL)
   43 NNRB(NRG,4,I)=NN(I,1)
C
C  OUTPUT OF THE REGION NODE NUMBERS
C
      WRITE(IO,49)
   49 FORMAT(//1X,17HREGION NODE NUMBERS/)
      DO 52 I=1,NROWS
   52 WRITE(IO,53)(NN(I,J),J=1,NCOL)
   53 FORMAT(1X,20I5)
      NP=NN(NROWS,NCOL)
C
C   DIVISION INTO TRIANGULAR ELEMENTS
C
   55 FORMAT(//3X,17HNEL   NODE NUMBERS,9X,4HX(1),8X,4HY(1),8X,4HX(2),8X
     1,4HY(2),8X,4HX(3),8X,4HY(3)) .
  105 K=1.
      DO 54 I=1,NROWS
      DO 54 J=1,NCOL
      XE(K)=XC(I,J)
      YE(K)=YC(I,J)
      NE(K)=NN(I,J)
   54 K=K+1
      L=NROWS-1
      DO 15 I=1,L
      DO 15 J=2,NCOL
      DIAG1=SQRT((XC(I,J)-XC(I+1,J-1))**2+(YC(I,J)-YC(I+1,J-1))**2)
      DIAG2=SQRT((XC(I+1,J)-XC(I,J-1))**2+(YC(I+1,J)-YC(I,J-1))**2)
      NR(1)=NCOL*I+J-1
      NR(2)=NCOL*I+J
```

```
      NR(3)=NCOL*(I-1)+J
      NR(4)=NCOL*(I-1)+J-1
      DO 15 IJ=1,2
      NEL=NEL+1
      IF((DIAG1/DIAG2).GT.1.02) GO TO 41
      J1=NR(1)
      J2=NR(IJ+1)
      J3=NR(IJ+2)
      GO TO 40
 41   J1=NR(IJ)
      J2=NR(IJ+1)
      J3=NR(4)
 40   LB(1)=IABS(NE(J1)-NE(J2))+1
      LB(2)=IABS(NE(J2)-NE(J3))+1
      LB(3)=IABS(NE(J1)-NE(J3))+1
      DO 107 IK=1,3
      IF(LB(IK).LE.NBW) GO TO 107
      NBW=LB(IK)
      NELBW=NEL
 107  CONTINUE
      NS(NEL,1)=NE(J1)
      NS(NEL,2)=NE(J2)
      NS(NEL,3)=NE(J3)
      X(NEL,1)=XE(J1)
      X(NEL,2)=XE(J2)
      X(NEL,3)=XE(J3)
      Y(NEL,1)=YE(J1)
      Y(NEL,2)=YE(J2)
      Y(NEL,3)=YE(J3)
 15   CONTINUE
 16   CONTINUE
      NELEM=NEL
      WRITE(IO,55)
      DO 250 KK=1,NELEM
      KII=0
      KIJ=0
      DO 205 KI=1,3
      DLENG=DFHT+DCLADT
      IF(ABS(X(KK,KI)-DLENG).LE.1.E-3) KII=KII+1
      IF(X(KK,KI).LE.(DFHT+1.E-3)) KIJ=KIJ+1
 205  CONTINUE
      IF(KII.EQ.2) GO TO 106
      GO TO 108
 106  IF(ABS(X(KK,2)-X(KK,1)).LE.1.E-3)ISIDE(KK)=1
      IF(ABS(X(KK,3)-X(KK,2)).LE.1.E-5)ISIDE(KK)=2
 108  IF(KIJ.EQ.3) IHEATGE(KK)=1
C
C   OUTPUT OF ELEMENT DATA
C
      IF(IHEATGE(KK).GE.1) WRITE(IO,302) KK
      IF(ISIDE(KK).GE.1) WRITE(IO,303) ISIDE(KK),KK
 302  FORMAT('           HEAT GENERATION IN ELEMENT ',I3)
 303  FORMAT('           CONVECTION FROM SIDE ',I2,' OF ELEMENT ',I3)
      WRITE(IO,301) KK,NS(KK,1),NS(KK,2),NS(KK,3),X(KK,1),Y(KK,1),
     1X(KK,2),Y(KK,2),X(KK,3),Y(KK,3)
 301  FORMAT(1X,4I5,3X,6F12.4)
 250  CONTINUE
      RETURN
      END
C   ***********************************
C
      SUBROUTINE NORMLIS(TINF,FLWRATE)
C
C   ***********************************
      COMMON /TEMP/ TEMF(300),TEMFOLD(300),TEM(2500),TEMOLD(600)
      COMMON /COOR/ X(400,3),Y(400,3),NS(400,3),B(3),C(3),NCOL
```

```
      COMMON /REL/DY(99),DREL(99),REL(3),NREL,HG
      COMMON /ELM/ISIDE(400),IHEATGE(400),NP,NELEM,NBW
      COMMON /FLUID/H(300),FLOW(300)
      COMMON /PHYF/KF,RHOF,HECAPF,DFL,DFW,DFHT
      COMMON /PHYC/DCW,DCT,KC,RHOC,HECAPC,DCLADT
      DFL=DFL*1.E-3
      DFW=DFW*1.E-3
      DFHT=DFHT*1.E-3
      DCT=DCT*1.E-3
      DCW=DCW*1.E-3
      DO 1 KK=1,NELEM
      DO 1 KI=1,3
      X(KK,KI)=X(KK,KI)/1000.
    1 Y(KK,KI)=Y(KK,KI)/1000.
      DO 2 I=NCOL,NP,NCOL
    2 FLOW(I)=FLWRATE
      TEMF(NCOL)=TINF
      DO 3 I=1,NREL
    3 DY(I)=DFL*DY(I)
      RETURN
      END
C    ***********************************
C
      SUBROUTINE SHAPE(KK,AR4)
C
C    ***********************************
      COMMON /COOR/X(400,3),Y(400,3),NS(400,3),B(3),C(3),NCOL
      B(1)=Y(KK,2)-Y(KK,3)
      B(2)=Y(KK,3)-Y(KK,1)
      B(3)=Y(KK,1)-Y(KK,2)
      C(1)=X(KK,3)-X(KK,2)
      C(2)=X(KK,1)-X(KK,3)
      C(3)=X(KK,2)-X(KK,1)
      AR4=(X(KK,2)*Y(KK,3)+X(KK,3)*Y(KK,1)+X(KK,1)*Y(KK,2)-X(KK,2)
     1*Y(KK,1)-X(KK,3)*Y(KK,2)-X(KK,1)*Y(KK,3))*2.
      RETURN
      END
C    ****************************************
C
      SUBROUTINE MAT(KK,AR4,ISS,DELTIME)
C
C    *****************************************
      COMMON /MATR1/EF(3),ECM(3,3),EQ(3,3),EP(3,3)
      COMMON /MATR2/ESM(400,3,3),ESMOLD(400,3,3)
      COMMON /COOR/X(400,3),Y(400,3),NS(400,3),B(3),C(3),NCOL
      COMMON /PHYF/KF,RHOF,HECAPF,DFL,DFW,DFHT
      COMMON /PHYC/DCW,DCT,KC,RHOC,HECAPC,DCLADT
      REAL KC
      DO 5 I=1,3
      EF(I)=0.0
      DO 5 J=1,3
      ESM(KK,I,J)=(KC*B(I)*B(J)+KC*C(I)*C(J))/AR4
      IF(ISS.EQ.0) GO TO 5
      ECM(I,J)=RHOC*HECAPC*AR4/4./6.
      IF(I.EQ.J) GO TO 515
      ECM(I,J)=ECM(I,J)/2.
  515 EQ(I,J)=0.5*(ESM(KK,I,J)+ESMOLD(KK,I,J))+2./DELTIME*ECM(I,J)
      EP(I,J)=2./DELTIME*ECM(I,J)-0.5*(ESM(KK,I,J)+ESMOLD(KK,I,J))
    5 CONTINUE
      RETURN
      END
C    ************************************************************
C
      SUBROUTINE  CONVEC(KK,IK,IT,DELTIME,SUM,IO,ISS,IIK,DELPR)
C
C    ************************************************************
```

```
      COMMON /MATR1/EF(3),ECM(3,3),EQ(3,3),EP(3,3)
      COMMON /MATR2/ESM(400,3,3),ESMOLD(400,3,3)
      COMMON /TEMP/TEMF(300),TEMFOLD(300),TEM(2500),TEMOLD(600)
      COMMON /COOR/X(400,3),Y(400,3),NS(400,3),B(3),C(3),NCOL
      COMMON/ELM/ISIDE(400),IHEATGE(400),NP,NELEM,NBW
      COMMON/FLUID/H(300),FLOW(300)
      COMMON/PHYF/KF,RHOF,HECAPF,DFL,DFW,DFHT
      COMMON/PHYC/DCW,DCT,KC,RHOC,HECAPC,DCLADT
      DIMENSION DELPR(300)
      REAL LG
      J=ISIDE(KK)
      K=J+1
      IF(J.EQ.3) K=1
      LG=SQRT((X(KK,K)-X(KK,J))**2+(Y(KK,K)-Y(KK,J))**2)
C
      CALL TFLUID(J,KK,IK,LG,SUM,IT,DELTIME,ISS,IIK,DELPR)
C
      SUM=0.0
C
      CALL HCAL(J,IK,KK,ISS)
C
      EF(J)=H(NS(KK,J))*LG*TEMF(NS(KK,J))/2.
      EF(K)=H(NS(KK,K))*LG*TEMF(NS(KK,K))/2.
      ESM(KK,J,J)=ESM(KK,J,J)+H(NS(KK,J))*LG/3.
      ESM(KK,J,K)=ESM(KK,J,K)+(H(NS(KK,J))+H(NS(KK,K)))*LG/2./6.
      ESM(KK,K,J)=ESM(KK,J,K)
      ESM(KK,K,K)=ESM(KK,K,K)+H(NS(KK,K))*LG/3.
      IF(ISS.EQ.0) GO TO 11
      DO 10 JN=1,3
      DO 10 JM=1,3
      EQ(JN,JM)=0.5*(ESM(KK,JN,JM)+ESMOLD(KK,JN,JM))+2./DELTIME*
     1ECM(JN,JM)
      EP(JN,JM)=2./DELTIME*ECM(JN,JM)-0.5*(ESM(KK,JN,JM)+ESMOLD(
     1KK,JN,JM))
   10 CONTINUE
   11 RETURN
      END
C     ***************************************************************
C
      SUBROUTINE  TFLUID(J,KK,IK,LG,SUM,IT,DELTIME,ISS,IIK,DELPR)
C
C     ***************************************************************
      DIMENSION V(300),ROW(300),ROWOLD(300),ENT(300),ENTOLD(300)
      COMMON /TEMP/TEMF(300),TEMFOLD(300),TEM(2500),TEMOLD(600)
      COMMON /COOR/X(400,3),Y(400,3),NS(400,3),B(3),C(3),NCOL
      COMMON /FLUID/H(300),FLOW(300)
      COMMON /PHYF/KF,RHOF,HECAPF,DFL,DFW,DFHT
      COMMON /PHYC/DCW,DCT,KC,RHOC,HECAPC,DCLADT
      COMMON /ELM/ISIDE(400),IHEATGE(400),NP,NELEM,NBW
      DIMENSION DELPR(300),FLOWOLD(300)
      REAL LG
      CHAAREA=DCW*DCT
      IF(ISS.EQ.0) GO TO 11
      IF(IK.GT.1) GO TO 11
      IF(KK.GT.4) GO TO 11
      DO 10 I=NCOL,NP,NCOL
      ROWOLD(I)=ROW(I)
   10 ENTOLD(I)=ENT(I)
   11 I=NCOL
      ROW(I)=RHOWA(TEMF(I))
      V(I)=FLOW(I)/(ROW(I)*CHAAREA)
      ENT(I)=ENTWA(TEMF(I))
      I=NS(KK,J)
      IF(ISS.EQ.0) GO TO 12
      GO TO 13
   12 ROW(I)=RHOWA(TEMF(I))
```

```
      V(I)=FLOW(I)/(ROW(I)*CHAAREA)
      IF(IIK.EQ.1) GO TO 15
      GO TO 17
   15 ENT(I)=SUM/FLOW(I)+ENT(I-3)
      GO TO 16
   17 CALL HEFLUX(TEM(I-3),TEM(I),TEMF(I-3),TEMF(I),FLOW(I-3),
     1FLOW(I),QZ)
      ENT(I)=LG*QZ/FLOW(I)+ENT(I-3)
   16 TEMF(I)=TWA(ENT(I))
      GO TO 101
   13 IF(IK.EQ.1) GO TO 102
      GO TO 104
  102 CALL HEFLUX(TEMOLD(I-3),TEMOLD(I),TEMFOLD(I-3),TEMFOLD(I),
     1FLOW(I-3),FLOW(I-3),QZ)
      GO TO 103
  104 CALL HEFLUX(TEM(I-3),TEM(I),TEMF(I-3),TEMF(I),FLOW(I-3),
     1FLOW(I-3),QZ)
  103 ENT(I)=(LG*QZ/FLOW(I-3)+(LG*ENTOLD(I))/(V(I-3)*DELTIME)+ENT(I-3))/
     1(LG/(V(I-3)*DELTIME)+1.0)
      TEMF(I)=TWA(ENT(I))
  100 ROW(I)=RHOWA(TEMF(I))
      TEMF1=TEMF(I)
      IF(IT.EQ.1) GO TO 150
      FLOW(I)=FLOW(I-3)-CHAAREA*(ROW(I)-ROWOLD(I))*LG/DELTIME
      GO TO 151
  150 FLOW(I)=FLOW(I-3)
  151 V(I)=FLOW(I)/(ROW(I)*CHAAREA)
      IF(IK.EQ.1) GO TO 202
      GO TO 204
  202 CALL HEFLUX(TEMOLD(I-3),TEMOLD(I),TEMF(I-3),TEMF(I),FLOW(I-3),
     1FLOW(I),QZ)
      GO TO 203
  204 CALL HEFLUX(TEM(I-3),TEM(I),TEMF(I-3),TEMF(I),FLOW(I-3),
     1FLOW(I),QZ)
  203 ENT(I)=(LG*QZ/FLOW(I)+(LG*ENTOLD(I))/(V(I)*DELTIME)+ENT(I-3))/
     1(LG/(V(I)*DELTIME)+1.0)
      TEMF(I)=TWA(ENT(I))
      ROW(I)=RHOWA(TEMF(I))
      IF(IT.EQ.1) GO TO 250
      FLOW(I)=FLOW(I-3)-CHAAREA*(ROW(I)-ROWOLD(I))*LG/DELTIME
      GO TO 251
  250 FLOW(I)=FLOW(I-3)
  251 V(I)=FLOW(I)/(ROW(I)*CHAAREA)
      IF(ABS(TEMF1-TEMF(I)).LE.0.0005) GO TO 101
      GO TO 100
C
  101 CALL FRICTN(I,ROW(I),CHAAREA,FRIC)
C
      IF(ISS.GT.0) GO TO 301
      FLOWOLD(I)=FLOW(I)
      ROWOLD(I)=ROW(I)
  301 DELP=9.81*ROW(I)*LG+2.*V(I)*LG*(ROW(I)-ROWOLD(I))/DELTIME
     1-FLOW(I)**2.*(1./ROW(I)-1./ROW(I-3))/CHAAREA**2.-FRIC
     2*LG/CHAAREA-(FLOW(I)-FLOWOLD(I))*LG/(CHAAREA*DELTIME)
      DELPR(I)=DELPR(I-3)+DELP
      RETURN
      END
C     ***********************************************************
C
      SUBROUTINE HEFLUX(T1,T2,TF1,TF2,FR1,FR2,QH)
C
C     ***********************************************************
      DIMENSION T(2),TF(2),FR(2)
      COMMON /PHYC/DCW,DCT,KC,RHOC,HECAPC,DCLADT
      COMMON /PHYF/KF,RHOF,HECAPF,DFL,DFW,DFHT
      DE=(2.0*DCW*DCT/(DCW+DCT))
```

```
      QH=0.0
      T(1)=T1
      T(2)=T2
      TF(1)=TF1
      TF(2)=TF2
      FR(1)=FR1
      FR(2)=FR2
      DO 1 I=1,2
      FLRATE=FR(I)/(DCW*DCT)
      RE=DE*FLRATE/VISCWA(TF(I))
      PR=VISCWA(TF(I))*SPEHEAT(TF(I))/CONDWA(TF(I))
      H=0.023*CONDWA(TF(I))*RE**0.8*PR**0.4/DE
      IF(T(I).GT.125) GO TO 2
      VISCR=(VISCWA(TF(I))/VISCWA(T(I)))**0.14
      GO TO 3
  2   VISCR=(VISCWA(TF(I))/VISCWA1(T(I)))**0.14
  3   H=H*VISCR
      Q=DFW*H*(T(I)-TF(I))
  1   QH=QH+Q
      RETURN
      END
C    ***********************************************************
C
      SUBROUTINE FRICTN(I,RHO,CHAAREA,FRIC)
C
C    ***********************************************************
      COMMON /TEMP/ TEMF(300),TEMFOLD(300),TEM(2500),TEMOLD(600)
      COMMON /FLUID/H(300),FLOW(300)
      COMMON /PHYC/ DCW,DCT,KC,RHOC,HECAPC,DCLADT
      DE=2.0*DCW*DCT/(DCW+DCT)
      FLRATE=FLOW(I)/(DCW*DCT)
      RE=DE*FLRATE/VISCWA(TEMF(I))
      FF=0.047*RE**(-0.2)
      FRIC=2.0*FF*FLOW(I)**2./(DE*RHO*CHAAREA)
      RETURN
      END
C    ******************************************
C
      SUBROUTINE HCAL(J,IK,KK,ISS)
C
C    ******************************************
      COMMON /TEMP/ TEMF(300),TEMFOLD(300),TEM(2500),TEMOLD(600)
      COMMON /COOR/ X(400,3),Y(400,3),NS(400,3),B(3),C(3),NCOL
      COMMON /FLUID/H(300),FLOW(300)
      COMMON /PHYC/ DCW,DCT,KC,RHOC,HECAPC,DCLADT
      DE=(2.0*DCW*DCT/(DCW+DCT))
      IF(KK.GT.4) GO TO 184
      I=NCOL
      GO TO 185
 184  I=NS(KK,J)
 185  TFX=TEMF(I)
      FLRATE=FLOW(I)/(DCW*DCT)
      RE=DE*FLRATE/VISCWA(TFX)
      PR=VISCWA(TFX)*SPEHEAT(TFX)/CONDWA(TFX)
      H(I)=0.023*CONDWA(TFX)*RE**0.8*PR**0.4/DE
      IF(ISS.EQ.0) GO TO 190
      GO TO 191
 190  IF(IK.EQ.1) GO TO 195
      GO TO 192
 191  IF(IK.EQ.1) GO TO 187
 192  TFW=TEM(I)
      GO TO 188
 187  TFW=TEMOLD(I)
 188  IF(TFW.GT.125) GO TO 201
      VISCR=(VISCWA(TFX)/VISCWA(TFW))**0.14
      GO TO 202
```

```
 201  VISCR=(VISCWA(TFX)/VISCWA1(TFW))**0.14
 202  H(I)=H(I)*VISCR
 195  IF(I.EQ.NCOL) GO TO 184
      RETURN
      END
C    ************************************************
C
      SUBROUTINE HEAT(KK,IK,AR4,DELTIME,SUM,ISS)
C
C    ************************************************
      COMMON /MATR1/EF(3),ECM(3,3),EQ(3,3),EP(3,3)
      COMMON /MATR2/ESM(400,3,3),ESMOLD(400,3,3)
      COMMON /COOR/X(400,3),Y(400,3),NS(400,3),B(3),C(3),NCOL
      COMMON /REL/DY(99),DREL(99),REL(3),NREL,HG
      COMMON /PHYF/KF,RHOF,HECAPF,DFL,DFW,DFHT
      COMMON /PHYC/DCW,DCT,KC,RHOC,HECAPC,DCLADT
      REAL KC,KF
      DO 155 I=1,3
C
      CALL INTERP(REL(I),Y(KK,I),DREL,DY,NREL)
C
      QV=HG/(DFL*DFW*DFHT*2)
      Q=QV*REL(I)
      EF(I)=Q*AR4/4./3.
      SUM=SUM+EF(I)*DFW*2.
      DO 155 J=1,3
      ESM(KK,I,J)=(KF *B(I)*B(J)+KF *C(I)*C(J))/AR4
      IF(ISS.EQ.0) GO TO 155
      ECM(I,J)=RHOF*HECAPF*AR4/4./6.
      IF(I.EQ.J) GO TO 1555
      ECM(I,J)=ECM(I,J)/2.
 1555 EQ(I,J)=0.5*(ESM(KK,I,J)+ESMOLD(KK,I,J))+2./DELTIME*ECM(I,J)
      EP(I,J)=2./DELTIME*ECM(I,J)-0.5*(ESM(KK,I,J)+ESMOLD(KK,I,J))
 155  CONTINUE
      RETURN
      END
C    ***************************************
C
      SUBROUTINE INTERP(FX,X,F,Y,N)
C
C    ***************************************
      DIMENSION F(N),Y(N)
      IO=61
C FX: ORDINATE VALUE TO BE CALCULATED
C  X: ABSISSA VALUE TO BE GIVEN
C  F: INPUT ORDINATE VALUE
C  Y: INPUT ABSISSA VALUE
C  N: NUMBER OF F(I) AND Y(I)
      DO 30 M=1,N
      IF(X-Y(M))40,25,30
  25  IF(M.EQ.N) GO TO 50
  30  CONTINUE
      GO TO 70
  40  IF(M.EQ.1) GO TO 70
  50  B=(X-Y(M-1))/(Y(M)-Y(M-1))
      FX=F(M-1)+B*(F(M)-F(M-1))
      RETURN
  70  WRITE(IO,11)FX,X
  11  FORMAT('NO VALUE, FX=',E12.6,'X=',E12.6)
      RETURN
      END
C    *************************************
C
      SUBROUTINE SUBCOOL(DELPR,IO)
C
C    *************************************
```

```
      COMMON /TEMP/TEMF(300),TEMFOLD(300),TEM(2500),TEMOLD(600)
      COMMON /FLUID/H(300),FLOW(300)
      COMMON /PHYC/DCW,DCT,KC,RHOC,HECAPC,DCLADT
      COMMON /COOR/X(400,3),Y(400,3),NS(400,3),B(3),C(3),NCOL
      COMMON /ELM/ISIDE(400),IHEATGE(400),NP,NELEM,NBW
      DIMENSION ROW(300),V(300),DELPR(300),DNBR(300)
      CHAAREA=DCW*DCT
      DE=2.0*DCW*DCT/(DCW+DCT)
      DI=2.*DCW/3.14
      DO 1 I=NCOL,NP,NCOL
      ROW(I)=RHOWA(TEMF(I))
      V(I)=FLOW(I)/(ROW(I)*CHAAREA)
      ALFA=61840*DE/(DE+DI)+433.4*V(I)/DE**0.6
      PRESS=1.737+DELPR(I)*1.E-5
      TWALL=57*ALOG(14.503*PRESS)-54*PRESS/(PRESS+1.034)
     1-0.32*V(I)
      CRIFLUX=ALFA*(TWALL-TEMF(I))
      FLUX=H(I)*(TEM(I)-TEMF(I))
      DNBR(I)=CRIFLUX/FLUX
      WRITE(IO,*)'  DNBR=',DNBR(I)
      IF(DNBR(I).LE.2.0) GO TO 6
    1 CONTINUE
      WRITE(IO,4)
      GO TO 7
    6 WRITE(IO,5)
      WRITE(IO,*)' TWAL=',TEM(I),'    VELOCITY =',V(I)
    4 FORMAT(//,10X,'NO  SUBCOOLED BOILING     ')
    5 FORMAT(//,10X,'SUBCOOLED BOILING OCCURS ')
    7 RETURN
      END
C    ******************************************
C
      SUBROUTINE STORAGE(KK,NCL,JGSM,ISS)
C
C    ******************************************
      COMMON /MATR1/EF(3),ECM(3,3),EG(3,3),EP(3,3)
      COMMON /MATR2/ESM(400,3,3),ESMOLD(400,3,3)
      COMMON /COOR/X(400,3),Y(400,3),NS(400,3),B(3),C(3),NCOL
      COMMON /ELM/ISIDE(400),IHEATGE(400),NP,NELEM,NBW
      COMMON /STORE/A(2500),PA(2500),P(2500)
      DO 77 I=1,3
      II=NS(KK,I)
      DO 15 J=1,NCL
      J5=(NCL+J-1)*NP+II
   15 A(J5)=A(J5)+EF(I)
      DO 17 J=1,3
      JJ=NS(KK,J)
      JJ=JJ-II+1
      IF(JJ)17,17,16
   16 J4=(JJ-1)*NP+II
      J5=JGSM+J4
      IF(ISS.EQ.0) GO TO 10
      PA(J4)=PA(J4)+EP(I,J)
      A(J5)=A(J5)+EG(I,J)
      GO TO 17
   10 A(J5)=A(J5)+ESM(KK,I,J)
   17 CONTINUE
   77 CONTINUE
      RETURN
      END
C    **********************************************
C
      SUBROUTINE MULT3D(GSM,GF,RF,NP,NBW,NCL)
C
C    **********************************************
      DIMENSION GSM(NP,NBW),GF(NP,NCL),RF(NP,NCL)
```

```
      DO 278 KK=1,NCL
      DO 277 I=1,NP
      SUM=0.0
      K=I-1
      DO 276 J=2,NBW
      M=J+I-1
      IF(M.GT.NP) GO TO 275
      SUM=SUM+GSM(I,J)*GF(M,KK)
  275 IF(K.LE.0) GO TO 276
      SUM=SUM+GSM(K,J)*GF(K,KK)
      K=K-1
  276 CONTINUE
  277 RF(I,KK)=SUM+GSM(I,1)*GF(I,KK)
  278 CONTINUE
      RETURN
      END
C     ****************************************
C
      SUBROUTINE DCMPBD(GSM,NP,NBW)
C
C     ****************************************
      DIMENSION GSM(NP,NBW)
      IO=61
      NP1=NP-1
      DO 226 I=1,NP1
      MJ=I+NBW-1
      IF(MJ.GT.NP)MJ=NP
      NJ=I+1
      MK=NBW
      IF((NP-I+1).LT.NBW) MK=NP-I+1
      ND=0
      DO 225 J=NJ,MJ
      MK=MK-1
      ND=ND+1
      NL=ND+1
      DO 225 K=1,MK
      NK=ND+K
  225 GSM(J,K)=GSM(J,K)-GSM(I,NL)*GSM(I,NK)/GSM(I,1)
  226 CONTINUE
      RETURN
      END
C     *******************************************************
C
      SUBROUTINE  SLVBD(GSM,GF,XX,NP,NBW,NCL,ID,IT,ISS)
C
C     *******************************************************
      DIMENSION GSM(NP,NBW),GF(NP,NCL),XX(NP,NCL)
      COMMON /TEMP/TEMF(300),TEMFOLD(300),TEM(2500),TEMOLD(600)
      COMMON /TLE/TITLES(20),TITLEUS(20)
      COMMON /COOR/X(400,3),Y(400,3),NS(400,3),B(3),C(3),NCOL
      IF(IJ.LE.0)IJ=1
      IO=61
      NP1=NP-1
      DO 265 KK=1,NCL
      JM=KK
C
C DECOMPOSITION OF THE COLUMN VECTOR GF( )
C
      DO 250 I=1,NP1
      MJ=I+NBW-1
      IF(MJ.GT.NP) MJ=NP
      NJ=I+1
      L=1
      DO 250 J=NJ,MJ
      L=L+1
  250 GF(J,KK)=GF(J,KK)-GSM(I,L)*GF(I,KK)/GSM(I,1)
```

```
C
C BACKWARD SUBSTITUTION FOR THE DETERMINATION OF X( )
C
      XX(NP,KK)=GF(NP,KK)/GSM(NP,1)
      DO 252 K=1,NP1
      I=NP-K
      MJ=NBW
      IF((I+NBW-1).GT.NP) MJ=NP-I+1
      SUM=0.0
      DO 251 J=2,MJ
      N=I+J-1
  251 SUM=SUM+GSM(I,J)*XX(N,KK)
  252 XX(I,KK)=(GF(I,KK)-SUM)/GSM(I,1)
C
C  OUTPUT OF THE CALCULATED NODAL VALUES
C
      IF(ISS.EQ.0) GO TO 10
      WRITE(IO,261)   IJ
      PRINT*,'IT=',IT*0.0475
  261 FORMAT(1X,'        ITERATION          ',I3)
      GO TO 11
   10 WRITE(IO,261) IJ
   11 NML=NP/2+3
      WRITE(IO,264) XX(NML,1) ,TEMF(NCOL),TEMF(NP)
  264 FORMAT(1X,3(F25.3))
  265 CONTINUE
      IJ=IJ+1
      RETURN
      END
C
      FUNCTION VISCWA(T)
      VISCWA=0.143237E-2-0.295743E-4*T+0.253156E-6*T**2.
     1-0.322939E-9*T**3.
      RETURN
      END
C
      FUNCTION VISCWA1(T)
      VISCWA1=-6.896276E-9+6.853976E-6*T-5.680827E-8*T**2.
     1+1.299773E-10*T**3.
      RETURN
      END
C
      FUNCTION CONDWA(T)
      CONDWA=0.570671+0.17869E-2*T-0.684359E-5*T**2.
      RETURN
      END
C
      FUNCTION SPEHEAT(T)
      SPEHEAT=0.419313E4-0.744678*T+0.100875E-1*T**2.
      RETURN
      END
C
      FUNCTION TWA(ENT)
      TWA=-0.121704+0.240234E-3*ENT-0.682278E-11*ENT**2.+0.230918E-16
     1*ENT**3.-0.344210E-22*ENT**4
      RETURN
      END
C
      FUNCTION ENTWA(T)
      ENTWA=0.166564E3+0.419253E4*T-0.386479*T**2.+0.352709E-2*T**3.
      RETURN
      END
C
      FUNCTION RHOWA(T)
      RHOWA=1./(0.997426E-3+0.135302E-6*T+0.325184E-8*T**2.)
      RETURN
      END
19.14.23.UCLP, BU, P04     ,        1.094KLNS.
```

APPENDIX C.

TABLES

TABLE C-1 Thermo-Hydraulic Calculation(60 axial steps)

DISTANCE (MM)	FUEL CENTER (C)	TEMPERATURES OF FUEL CLAD INTERFACE (C)	CLADDING SURFACE (C)	COOLING WATER (C)	PRESSURE DIFFERENCE (N/M**2)
.0	44.1	44.1	44.1	37.0	.0
9.9	45.4	45.4	45.3	37.0	94.4
19.9	47.1	47.1	47.0	37.1	188.9
29.8	48.8	48.8	48.7	37.1	283.3
39.7	50.5	50.5	50.4	37.2	377.8
49.7	52.2	52.2	52.1	37.3	472.2
59.6	53.8	53.8	53.7	37.3	566.7
69.5	55.4	55.4	55.3	37.4	661.1
79.5	57.0	57.0	56.9	37.5	755.5
89.4	58.5	58.5	58.3	37.6	850.0
99.4	60.0	59.9	59.8	37.7	944.4
109.3	61.4	61.3	61.2	37.8	1038.8
119.2	62.7	62.7	62.6	38.0	1133.2
129.2	64.0	64.0	63.9	38.1	1227.6
139.1	65.3	65.2	65.1	38.2	1322.1
149.0	66.5	66.4	66.3	38.4	1416.5
159.0	67.6	67.6	67.4	38.5	1510.9
168.9	68.7	68.6	68.5	38.7	1605.3
178.8	69.7	69.7	69.5	38.8	1699.6
188.8	70.7	70.6	70.4	39.0	1794.0
198.7	71.6	71.5	71.3	39.2	1688.4
208.6	72.4	72.3	72.1	39.3	1982.8
218.6	73.1	73.1	72.9	39.5	2077.2
228.5	73.8	73.7	73.6	39.7	2171.5
238.5	74.4	74.3	74.2	39.9	2265.9
248.4	75.0	74.9	74.7	40.0	2360.2
258.3	75.4	75.3	75.1	40.2	2454.6
266.3	75.8	75.7	75.5	40.4	2548.9
278.2	76.1	76.0	75.9	40.6	2643.3
288.1	76.4	76.3	76.1	40.8	2737.6
298.1	76.6	76.5	76.3	41.0	2831.9
308.0	76.6	76.6	76.4	41.2	2926.2
317.9	76.7	76.6	76.4	41.3	3020.6
327.9	76.6	76.6	76.4	41.5	3114.9
337.6	76.5	76.4	76.3	41.7	3209.2
347.7	76.3	76.3	76.1	41.9	3303.5
357.7	76.1	76.0	75.8	42.1	3397.7
367.6	75.7	75.7	75.5	42.3	3492.0
377.6	75.3	75.3	75.1	42.4	3586.3
387.5	74.9	74.8	74.6	42.6	3680.6
397.4	74.3	74.2	74.1	42.8	3774.9
407.4	73.7	73.6	73.5	43.0	3869.1
417.3	73.0	73.0	72.8	43.1	3963.4
427.2	72.3	72.2	72.0	43.3	4057.6
437.2	71.5	71.4	71.2	43.4	4151.9
447.1	70.6	70.5	70.4	43.6	4246.1
457.0	69.7	69.6	69.5	43.7	4340.4
467.0	68.7	68.6	68.5	43.8	4434.6
476.9	67.6	67.5	67.4	44.0	4528.8
486.8	66.5	66.4	66.3	44.1	4623.1
496.8	65.3	65.3	65.2	44.2	4717.3
506.7	64.1	64.1	63.9	44.3	4811.5
516.7	62.8	62.8	62.7	44.4	4905.7
526.6	61.5	61.5	61.4	44.5	5000.0
536.5	60.1	60.1	60.0	44.6	5094.2
546.5	58.7	58.7	58.6	44.7	5188.4
556.4	57.2	57.2	57.2	44.7	5282.6
566.3	55.7	55.7	55.7	44.8	5376.8
576.3	54.2	54.2	54.1	44.9	5471.0
586.2	52.7	52.7	52.6	44.9	5565.2
596.1	51.6	51.5	51.5	44.9	5659.4

TABLE C-2 Thermo-Hydraulic Calculation (90 axial step)

DISTANCE (MM)	FUEL CENTER (C)	TEMPERATURES OF FUEL CLAD INTERFACE (C)	CLADDING SURFACE (C)	COOLING WATER (C)	PRESSURE DIFFERENCE (N/M**2)
.0	44.4	44.4	44.4	37.0	.0
6.6	45.0	45.0	45.0	37.0	63.0
13.2	46.0	46.0	45.9	37.1	125.9
19.9	47.1	47.1	47.0	37.1	188.9
26.5	48.2	48.2	48.2	37.1	251.9
33.1	49.4	49.4	49.3	37.2	314.8
39.7	50.5	50.5	50.4	37.2	377.8
46.4	51.6	51.6	51.5	37.2	440.8
53.0	52.7	52.7	52.6	37.3	503.7
59.6	53.8	53.8	53.7	37.3	566.7
66.2	54.9	54.9	54.8	37.4	629.6
72.9	56.0	55.9	55.8	37.5	692.6
79.5	57.0	56.9	56.8	37.5	755.5
86.1	58.0	58.0	57.9	37.6	818.5
92.7	59.0	58.9	56.8	37.7	881.4
99.4	60.0	59.9	59.8	37.7	944.4
106.0	60.9	60.9	60.7	37.8	1007.3
112.6	61.8	61.8	61.7	37.9	1070.3
119.2	62.7	62.7	62.6	38.0	1133.2
125.9	63.6	63.6	63.4	38.1	1196.2
132.5	64.5	64.4	64.3	38.1	1259.1
139.1	65.3	65.2	65.1	38.2	1322.1
145.7	66.1	66.0	65.9	38.3	1385.0
152.3	66.9	66.8	66.7	38.4	1447.9
159.0	67.6	67.6	67.4	38.5	1510.9
165.6	68.4	68.3	68.1	38.6	1573.8
172.2	69.1	69.0	68.8	38.7	1636.7
178.8	69.7	69.7	69.5	38.8	1699.7
185.5	70.4	70.3	70.1	38.9	1762.6
192.1	71.0	70.9	70.7	39.0	1825.5
198.7	71.6	71.5	71.3	39.2	1888.4
205.3	72.1	72.0	71.9	39.3	1951.3
212.0	72.6	72.6	72.4	39.4	2014.3
218.6	73.1	73.1	72.9	39.5	2077.2
225.2	73.6	73.5	73.3	39.6	2140.1
231.8	74.0	73.9	73.8	39.7	2203.0
238.5	74.4	74.3	74.2	39.9	2265.9
245.1	74.8	74.7	74.5	40.0	2328.8
251.7	75.1	75.0	74.8	40.1	2391.7
258.3	75.4	75.3	75.1	40.2	2454.6
265.0	75.7	75.6	75.4	40.3	2517.5
271.6	75.9	75.8	75.6	40.5	2580.4
278.2	76.1	76.0	75.8	40.6	2643.3
284.8	76.3	76.2	76.0	40.7	2706.2
291.4	76.4	76.4	76.2	40.8	2769.1
298.1	76.5	76.5	76.3	41.0	2831.9
304.7	76.6	76.5	76.3	41.1	2894.8
311.3	76.7	76.6	76.4	41.2	2957.7
317.9	76.7	76.6	76.4	41.3	3020.6
324.6	76.7	76.6	76.4	41.5	3083.4
331.2	76.6	76.5	76.3	41.6	3146.3
337.8	76.5	76.4	76.2	41.7	3209.2
344.4	76.4	76.3	76.1	41.8	3272.0
351.1	76.3	76.2	76.0	42.0	3334.9
357.7	76.1	76.0	75.8	42.1	3397.8
364.3	75.9	75.8	75.6	42.2	3460.6
370.9	75.6	75.5	75.4	42.3	3523.5
377.5	75.3	75.3	75.1	42.4	3586.3
384.2	75.0	75.0	74.8	42.6	3649.2
390.8	74.7	74.6	74.4	42.7	3712.0
397.4	74.3	74.2	74.1	42.8	3774.9
404.0	73.9	73.8	73.7	42.9	3837.7
410.7	73.5	73.4	73.2	43.0	3900.6
417.3	73.0	72.9	72.8	43.1	3963.4
423.9	72.5	72.5	72.3	43.2	4026.2
430.5	72.0	71.9	71.8	43.3	4089.1
437.2	71.5	71.4	71.2	43.4	4151.9
443.8	70.9	70.8	70.7	43.5	4214.7
450.4	70.3	70.2	70.1	43.6	4277.6
457.0	69.6	69.6	69.4	43.7	4340.4
463.7	69.0	68.9	68.8	43.8	4403.2
470.3	68.3	68.2	68.1	43.9	4466.1
476.9	67.6	67.5	67.4	44.0	4528.9

TABLE C-2 Thermo-Hydraulic Calculation (90 axial step)(continued)

483.5	66.9	66.8	66.7	44.1	4591.7
490.2	66.1	66.0	65.9	44.1	4654.5
496.8	65.3	65.3	65.1	44.2	4717.3
503.4	64.5	64.5	64.4	44.3	4780.2
510.0	63.7	63.6	63.5	44.4	4843.0
516.7	62.8	62.8	62.7	44.4	4905.8
523.3	61.9	61.9	61.8	44.5	4968.6
529.9	61.0	61.0	60.9	44.5	5031.4
536.5	60.1	60.1	60.0	44.6	5094.2
543.1	59.2	59.2	59.1	44.6	5157.0
549.6	58.2	58.2	58.1	44.7	5219.8
556.4	57.2	57.2	57.1	44.7	5282.6
563.0	56.2	56.2	56.2	44.8	5345.5
569.6	55.2	55.2	55.2	44.8	5408.3
576.3	54.2	54.2	54.2	44.9	5471.1
582.9	53.2	53.2	53.2	44.9	5533.9
589.5	52.3	52.3	52.3	44.9	5596.7
596.1	51.8	51.8	51.8	44.9	5659.5

TABLE C-3 Transient Thermo-Hydraulic Calculations-t=0.473 sec

DISTANCE (MM)	TEMPERATURES OF FUEL CENTER (C)	FUEL CLAD INTERFACE (C)	CLADDING SURFACE (C)	COOLING WATER (C)	PRESSURE DIFFERENCE (N/M**2)
.0	43.2	43.2	43.2	37.0	.0
19.9	47.5	47.5	47.4	37.1	225.5
39.7	51.1	51.0	51.0	37.2	451.0
59.6	54.5	54.5	54.4	37.4	676.5
79.5	57.8	57.8	57.7	37.6	902.0
99.4	60.9	60.8	60.7	37.8	1127.5
119.2	63.8	63.7	63.6	38.0	1352.9
139.1	66.5	66.4	66.3	38.3	1578.3
159.0	68.9	68.8	68.7	38.6	1803.7
178.8	71.1	71.0	70.9	38.9	2029.1
198.7	73.0	72.9	72.8	39.3	2254.5
218.6	74.6	74.5	74.4	39.6	2479.8
238.5	75.9	75.9	75.7	40.0	2705.1
258.3	77.0	76.9	76.7	40.4	2930.4
278.2	77.7	77.6	77.5	40.8	3155.7
298.1	78.1	78.1	77.9	41.2	3380.9
317.9	78.3	78.2	78.0	41.5	3606.1
337.8	78.1	78.0	77.8	41.9	3831.3
357.7	77.6	77.5	77.4	42.3	4056.4
377.6	76.8	76.7	76.6	42.6	4281.5
397.4	75.7	75.7	75.5	43.0	4506.6
417.3	74.4	74.3	74.2	43.3	4731.7
437.2	72.7	72.7	72.5	43.6	4956.7
457.0	70.8	70.8	70.6	43.9	5181.8
476.9	68.7	68.6	68.5	44.2	5406.8
496.8	66.3	66.2	66.1	44.4	5631.8
516.7	63.7	63.6	63.5	44.6	5856.7
536.5	60.8	60.8	60.7	44.7	6081.7
556.4	57.8	57.8	57.7	44.9	6306.7
576.3	54.7	54.6	54.6	45.0	6531.6
596.1	50.7	50.7	50.7	45.0	6756.6

TABLE C-4 Transient Thermo-Hydraulic Calculations-t=0.946 sec

DISTANCE (MM)	TEMPERATURES OF FUEL CENTER (C)	FUEL CLAD INTERFACE (C)	CLADDING SURFACE (C)	COOLING WATER (C)	PRESSURE DIFFERENCE (N/M**2)
.0	43.4	43.4	43.4	37.0	.0
19.9	47.8	47.8	47.8	37.1	225.5
39.7	51.5	51.5	51.4	37.2	451.0
59.6	55.1	55.0	55.0	37.4	676.5
79.5	58.5	58.4	58.3	37.6	902.0
99.4	61.6	61.6	61.5	37.8	1127.4
119.2	64.6	64.6	64.5	38.1	1352.9
139.1	67.4	67.3	67.2	38.4	1578.3
159.0	69.9	69.8	69.7	38.7	1803.7
178.8	72.1	72.1	71.9	39.0	2029.1
198.7	74.1	74.0	73.9	39.4	2254.4
218.6	75.8	75.7	75.5	39.8	2479.8
238.5	77.2	77.1	76.9	40.1	2705.1
258.3	78.2	78.1	78.0	40.5	2930.4
278.2	79.0	78.9	78.7	40.9	3155.6
298.1	79.4	79.3	79.2	41.3	3380.8
317.9	79.5	79.4	79.3	41.7	3606.0
337.8	79.3	79.3	79.1	42.1	3831.2
357.7	78.8	78.8	78.6	42.5	4056.3
377.6	78.0	77.9	77.8	42.9	4281.4
397.4	76.9	76.8	76.7	43.2	4506.5
417.3	75.5	75.4	75.2	43.6	4731.5
437.2	73.7	73.7	73.5	43.9	4956.6
457.0	71.8	71.7	71.6	44.2	5181.6
476.9	69.5	69.5	69.4	44.4	5406.6
496.8	67.0	67.0	66.9	44.7	5631.5
516.7	64.4	64.3	64.2	44.9	5856.5
536.5	61.4	61.4	61.3	45.0	6081.5
556.4	58.3	58.3	58.2	45.1	6306.4
576.3	55.0	55.0	55.0	45.2	6531.3
596.1	51.0	50.9	50.9	45.3	6756.2

TABLE C-5 Transient Thermo-Hydraulic Calculations-t=1.419 sec

DISTANCE (MM)	TEMPERATURES OF FUEL CENTER (C)	FUEL CLAD INTERFACE (C)	CLADDING SURFACE (C)	COOLING WATER (C)	PRESSURE DIFFERENCE (N/M**2)
.0	43.6	43.6	43.6	37.0	.0
19.9	48.1	48.1	48.0	37.1	225.5
39.7	51.8	51.8	51.8	37.2	451.0
59.6	55.5	55.5	55.4	37.4	676.5
79.5	59.0	58.9	58.8	37.6	902.0
99.4	62.2	62.2	62.1	37.8	1127.4
119.2	65.3	65.2	65.1	38.1	1352.9
139.1	68.1	68.1	67.9	38.4	1578.3
159.0	70.7	70.6	70.5	38.7	1803.7
178.8	73.0	72.9	72.7	39.1	2029.1
198.7	75.0	74.9	74.7	39.5	2254.4
218.6	76.7	76.6	76.4	39.8	2479.8
238.5	78.1	78.0	77.9	40.2	2705.0
258.3	79.2	79.1	78.9	40.7	2930.3
278.2	79.9	79.9	79.7	41.1	3155.6
298.1	80.4	80.3	80.1	41.5	3380.8
317.9	80.5	80.4	80.3	41.9	3605.9
337.8	80.3	80.2	80.1	42.3	3831.1
357.7	79.8	79.7	79.6	42.7	4056.2
377.6	78.9	78.9	78.7	43.1	4281.3
397.4	77.8	77.7	77.6	43.5	4506.4
417.3	76.3	76.3	76.1	43.8	4731.4
437.2	74.6	74.5	74.4	44.2	4956.4
457.0	72.6	72.5	72.4	44.4	5181.4
476.9	70.3	70.2	70.1	44.7	5406.4
496.8	67.7	67.7	67.6	45.0	5631.4
516.7	65.0	64.9	64.8	45.2	5856.3
536.5	61.9	61.9	61.8	45.3	6081.2
556.4	58.7	58.7	58.6	45.5	6306.2
576.3	55.4	55.4	55.3	45.5	6531.1
596.1	51.2	51.2	51.2	45.6	6756.0

TABLE C-6 Transient Thermo-Hydraulic Calculations-t=1.892

DISTANCE (MM)	FUEL CENTER (C)	TEMPERATURES OF FUEL CLAD INTERFACE (C)	CLADDING SURFACE (C)	COOLING WATER (C)	PRESSURE DIFFERENCE (N/M**2)
.0	43.8	43.7	43.7	37.0	.0
19.9	48.3	48.3	48.2	37.1	225.5
39.7	52.1	52.1	52.0	37.2	451.0
59.6	55.8	55.8	55.7	37.4	676.5
79.5	59.4	59.3	59.2	37.6	902.0
99.4	62.7	62.6	62.5	37.8	1127.4
119.2	65.8	65.7	65.6	38.1	1352.9
139.1	68.7	68.6	68.5	38.4	1578.3
159.0	71.3	71.2	71.1	38.8	1803.7
178.8	73.6	73.5	73.4	39.1	2029.1
198.7	75.6	75.6	75.4	39.5	2254.4
218.6	77.4	77.3	77.1	39.9	2479.7
238.5	78.8	78.8	78.6	40.3	2705.0
258.3	79.9	79.8	79.7	40.7	2930.3
278.2	80.7	80.6	80.4	41.2	3155.5
298.1	81.2	81.1	80.9	41.6	3380.7
317.9	81.3	81.2	81.0	42.0	3605.9
337.8	81.1	81.0	80.8	42.4	3831.0
357.7	80.6	80.5	80.3	42.9	4056.2
377.6	79.7	79.6	79.4	43.3	4281.2
397.4	78.5	78.4	78.3	43.6	4506.3
417.3	77.0	77.0	76.8	44.0	4731.3
437.2	75.2	75.2	75.0	44.3	4956.3
457.0	73.2	73.1	73.0	44.7	5181.3
476.9	70.9	70.8	70.7	44.9	5406.3
496.8	68.3	68.2	68.1	45.2	5631.2
516.7	65.5	65.4	65.3	45.4	5856.2
536.5	62.4	62.4	62.3	45.6	6081.1
556.4	59.1	59.1	59.0	45.7	6306.0
576.3	55.7	55.7	55.6	45.8	6530.9
596.1	51.5	51.5	51.5	45.9	6755.8

TABLE C-7 Transient Thermo-Hydraulic Calculations-t=3.311

DISTANCE (MM)	FUEL CENTER (C)	TEMPERATURES OF FUEL CLAD INTERFACE (C)	CLADDING SURFACE (C)	COOLING WATER (C)	PRESSURE DIFFERENCE (N/M**2)
.0	44.0	44.0	44.0	37.0	.0
19.9	48.6	48.6	48.6	37.1	225.5
39.7	52.6	52.6	52.5	37.2	451.0
59.6	56.4	56.4	56.3	37.4	676.5
79.5	60.1	60.1	60.0	37.6	902.0
99.4	63.5	63.4	63.3	37.9	1127.4
119.2	66.7	66.7	66.5	38.2	1352.9
139.1	69.7	69.6	69.5	38.5	1578.3
159.0	72.3	72.3	72.1	38.8	1803.7
178.8	74.7	74.7	74.5	39.2	2029.0
198.7	76.9	76.8	76.6	39.6	2254.4
218.6	78.7	78.6	78.4	40.0	2479.7
238.5	80.1	80.1	79.9	40.5	2705.0
258.3	81.3	81.2	81.0	40.9	2930.2
278.2	82.1	82.0	81.8	41.3	3155.5
298.1	82.6	82.5	82.3	41.8	3380.6
317.9	82.7	82.6	82.4	42.2	3605.8
337.8	82.5	82.4	82.2	42.7	3830.9
357.7	82.0	81.9	81.7	43.1	4056.0
377.6	81.1	81.0	80.8	43.6	4281.1
397.4	79.9	79.8	79.6	44.0	4506.1
417.3	78.4	78.3	78.1	44.3	4731.2
437.2	76.5	76.5	76.3	44.7	4956.1
457.0	74.4	74.4	74.3	45.0	5181.1
476.9	72.1	72.0	71.9	45.4	5406.1
496.8	69.4	69.3	69.2	45.6	5631.0
516.7	66.5	66.5	66.4	45.9	5855.9
536.5	63.4	63.3	63.3	46.1	6080.8
556.4	60.0	60.0	59.9	46.2	6305.7
576.3	56.5	56.5	56.5	46.3	6530.5
596.1	52.3	52.2	52.2	46.4	6755.4

TABLE C-8 Transient Thermo-Hydraulic Calculations-t=5.203 sec

DISTANCE (MM)	FUEL CENTER (C)	TEMPERATURES OF FUEL CLAD INTERFACE (C)	CLADDING SURFACE (C)	COOLING WATER (C)	PRESSURE DIFFERENCE (N/M**2)
.0	44.2	44.2	44.2	37.0	.0
19.9	48.9	48.8	48.8	37.1	225.5
39.7	52.9	52.9	52.8	37.2	451.0
59.6	56.8	56.7	56.7	37.4	676.5
79.5	60.5	60.4	60.3	37.6	902.0
99.4	63.9	63.9	63.8	37.9	1127.4
119.2	67.2	67.2	67.0	38.2	1352.9
139.1	70.2	70.1	70.0	38.5	1578.3
159.0	72.9	72.9	72.7	38.9	1803.7
178.8	75.4	75.3	75.1	39.3	2029.0
198.7	77.5	77.4	77.3	39.7	2254.4
218.6	79.3	79.3	79.1	40.1	2479.7
238.5	80.8	80.8	80.6	40.5	2705.0
258.3	82.0	81.9	81.7	41.0	2930.2
278.2	82.8	82.7	82.6	41.4	3155.4
298.1	83.3	83.2	83.1	41.9	3380.6
317.9	83.5	83.4	83.2	42.4	3605.8
337.8	83.3	83.2	83.0	42.8	3830.9
357.7	82.7	82.7	82.5	43.3	4056.0
377.6	81.9	81.8	81.6	43.7	4281.0
397.4	80.7	80.6	80.4	44.1	4506.1
417.3	79.2	79.1	78.9	44.5	4731.1
437.2	77.3	77.3	77.1	44.9	4956.0
457.0	75.2	75.2	75.0	45.3	5181.0
476.9	72.8	72.8	72.6	45.6	5405.9
496.8	70.2	70.1	70.0	45.9	5630.8
516.7	67.3	67.2	67.1	46.1	5855.7
536.5	64.1	64.1	64.0	46.3	6080.6
556.4	60.7	60.7	60.6	46.5	6305.5
576.3	57.2	57.2	57.1	46.6	6530.3
596.1	52.9	52.9	52.9	46.7	6755.2

TABLE C-9 Data Input for Reactor-I

```
167.           /THERMAL CONDUCTIVITY OF FUEL
210.           /THERMAL CONDUCTIVITY OF CLADDING
19000.         /DENSITY OF FUEL
2707.          /DENSITY OF CLADDING
740.           /HEAT CAPACITY OF FUEL
396.           /HEAT CAPACITY OFCLADDING
3929.          /GENERATION OF HEAT
596.138        /FUEL LENGTH
.254           /FUEL THICKNESS
59.693         /FUEL WIDTHNESS
.381           /CLADDING THICKNESS
59.9           /CHANNEL WIDTHNESS
5.476          /CHANNAL THICKNESS
37             /WATER INPUT TEMPERATURE
.1839          /WATER FLOWRATE
1              /NUMBER OF REGION
8              /NUMBER OF BOUNDARY POINTS
.0,  .254,  .635,  .635,  .635,  .254,  .0,  .0
.0,  .0,  .0,  298.069,  596.138,  596.138,  596.138,  298.069
31             /NUMBER OF ROWS
  3            /NUMBER OF COLUMNS
          1,2,3,4,5,6,7,3
```

TABLE C-10 Interactive Sample Data Input

```
** DO YOU WANT INTERACTIVE USUAGE (YES OR NO) **
?  YES
                    ********
  ENTER THE THERMAL CONDUCTIVITY OF FUEL (W/M C)
? 167.
  ENTER THE THERMAL CONDUCTIVITY OF CLADDING (W/M C)
? 210.
  ENTER THE DENSITY OF FUEL (KG/M**3)
? 3336.
  ENTER THE DENSITY OF CLADDING (KG/M**3)
? 2707.
  ENTER THE HEAT CAPACITY OF FUEL (J/KG C)
? 740.
  ENTER THE HEAT CAPACITY OF CLADDING (J/KG C)
? 896.
  ENTER THE POWER FOR THE PLATE (W)
? 30201.
  ENTERING THE DIMENSIONAL PROPERTIES
     FUEL LENGTH (MM)
? 598.
     FUEL HALF THICKNESS (MM)
? .255
     FUEL WIDTH (MM)
? 62.3
     CLADDING THICKNESS (MM)
? .38
     CHANNEL WIDTH (MM)
? 66.6
     CHANNEL THICKNESS (MM)
? 2.1
  ENTER THE COOLANT INLET TEMPERATURE (C)
? 30.
  ENTER THE COOLANT MASS FLOWRATE (KG/SEC)
? .31

    ENTERING THE DATA FOR GRID GENERATION

  ENTER THE NUMBER OF REGIONS
? 1
  ENTER THE NUMBER OF BOUNDARY POINTS
? 8
ENTER THE ABSISSA VALUES OF THESE POINTS (MM)
? 0. .255 .635 .635 .635 .255 0. 0.
ENTER THE ORDINATE VALUES OF THESE POINTS (MM)
? 0. 0. 0. 299. 598. 598. 598. 299.
ENTER THE NUMBER OF ROWS OF NODES IN REGION 1
? 31
ENTER THE NUMBER OF COLUMNS OF NODES IN REGION 1
? 3
ENTER THE GLOBAL NODE NUMBERS USED TO DEFINE THE
QUADRILATERAL OF REGION 1
? 1 2 3 4 5 6 7 8
```

TABLE C-11 Data Input for Reactor-II

```
167.          /THERMAL CONDUCTIVITY OF FUEL
210.          /THERMAL CONDUCTIVITY OF CLADDING
5336.         /DENSITY OF FUEL
2707.         /DENSITY OF CLADDING
740.          /HEAT CAPACITY OF FUEL
896.          /HEAT CAPACITY OFCLADDING
50201.        /GENERATION OF HEAT
596.          /FUEL LENGTH
.255          /FUEL THICKNESS
62.3          /FUEL WIDTH
.38           /CLADDING THICKNESS
56.6          /CHANNEL WIDTH
2.1           /CHANNAL THICKNESS
50            /WATER INPUT TEMPERATURE
.31           /WATER FLOWRATE
1             /NUMBER OF REGION
8             /NUMBER OF BOUNDARY POINTS
.0,  .255,  .635,  .635,  .635,  .255,  .0,  .0
.0,  .0,  .0,  299.,  598.,  598.,  598.,  299.
51            /NUMBER OF ROWS
  3           /NUMBER OF COLUMNS
           1,2,3,4,5,6,7,8
```

TABLE C-12 Input Data (Heat Flux Distribution)

```
FINITE ELEMENT ANALYSIS OF   STEADY STATE HEAT CONDUCTION IN TWO DIMENSION
FINITE ELEMENT ANALYSIS OF UNSTEADY STATE HEAT CONDUCTION IN TWO DIMENSION
51
     0.00     .165
     0.02     .220
     0.04     .275
     0.06     .328
     0.08     .381
     0.10     .432
     0.12     .482
     0.14     .531
     0.16     .577
     0.18     .622
     0.20     .665
     0.22     .706
     0.24     .745
     0.26     .781
     0.28     .815
     0.30     .846
     0.32     .875
     0.34     .901
     0.36     .924
     0.38     .944
     0.40     .961
     0.42     .975
     0.44     .986
     0.46     .994
     0.48     .998
     0.50    1.000
     0.52     .998
     0.54     .994
     0.56     .986
     0.58     .975
     0.60     .961
     0.62     .944
     0.64     .924
     0.66     .901
     0.68     .875
     0.70     .846
     0.72     .815
     0.74     .781
     0.76     .745
     0.78     .706
     0.80     .665
     0.82     .622
     0.84     .577
     0.86     .531
     0.88     .482
     0.90     .432
     0.92     .381
     0.94     .328
     0.96     .275
     0.98     .220
     1.00     .165
```

BIBLIOGRAPHY

1. Lamarsh , S.R. , Introduction to Nuclear Engineering, Addison-Wesley, Reading , Mass. , 1975.

2. Sesonske, A. , Nuclear Power Plant Analysis , E.C. Report TID -26241 , 1973.

3. Segerlind, L.S. , Applied Finite Element Analysis, John Wiley and Sons Inc. , New York , 1976

4. Borak , F., 'Plaka Yakıt Elemanlı Nükleer Reaktör Geçici ve Sürekli Rejim Termohidrolik Analizi', Doçentlik Tezi, Boğaziçi Üniversitesi İstanbul, 1979

5. Vigassy, J. , L.M. , Kovacs, 'COBRA- 3c / KFKI : A digital Computer Program for Steady and Transient Thermal Hydraulic Analysis of Rod Bundle Nuclear Fuel Elements', Kozponti Fizikai Kutoto Intezet, Budapest (Hungary) , Nov. 1977

6. Conklin, J.C. , 'Development and Adaption of Conduction and Radiation Heat Transfer Computer Codes for the CFTL', Oak Rıdge National Lab., TN (USA). ORNL/TM-7854. Aug. 1981

7. Kenedy, T.D.A , 'Two-and-Three. Dimensional Transient and Two-Dimensional Steady State Heat Transfer Finite Difference Computer Programs', UKAEA, Harwell. Atomic Energy Research Establishment. AERE-R-9210, Aug 1978

8. Turner, W.D. , 'A Three Dimensional, Transient Heat Analysis Code Using the Strongly Implicit Procedure', Oak Ridge Gaseous Diffusion Plant, TN(USA). K/CSD/TM-24, Sep 1978

9. Toth, I. , 'Three Dimensional, Steady State and Transient Heat Conduction Code', DUS- M. Koezponti Fizikai Kutato Intezet, Budapest

(Hungary) , Nov 1979

10. Haner , A. ; R. Fremd, ; F.Schmidt. ; 'Solution of the Two-Dimensional Transient Heat Conduction Equation Using the Finite Element Method', Stuttgart Univ. (TH) (Germany, F.R.) IKE-4-92. Dec 1979 78 p.
11. Estes, P.H. , 'A Linear Thermal Conduction Analysis for Two Dimensional Problems Using the Finite Element Method', UNC Nuclear Industries,Inc, Richland, WA(USA) UNI-1932, Sep 1979
12. Enderby , J.A., 'The UNCLE Finite Element System', UKAEA Risley Nuclear Power Development Establishment, Sep 1979.
13. Nuclear Program Abstracts, Nuclear Energy Agency, Organization for Economic Co-operation and Development, 1980-1985
14. Kakaç, S., Nükleer Reaktör Isı Transferi, ODTÜ, Müh.Fak.Yayın No.58, Ankara, 1978
15. El-Wakil, M.M. , Nuclear Heat Transport, International Scranton ,Pa.,1971

REFERENCES NOT CITED

Desai , C.S. and J.F. Abel, Introduction to the Finite Element Method, Von Nostrand Reinhold Company, New York, 1972

El-Wakil, M.M. , Nuclear Power Engineering, Mc.Graw-Hill, New York, 1962

Mickley, H.S. , T.K. , Sherwood and C.E., Reed , Applied Mathematics in Chemical Engineering,Mc. Graw-Hill, New York, 1957.