A Computer Package for Calculating Temperature Distributions in Machining from Force, Shear Angle and Contact Length Measurements

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Abstract

A means of accurately calculating temperature distributions in cutting tools is an important part of a system of on-line temperature monitoring and hence, process control. The computer programs described use the finite clement method to calculate steady-state temperature distributions in both workpiccc and tool in orthogonal cutting. Realistic heat generation zones are used, consisting of primary deformation, tool-chip interface friction and secondary deformation.

The input required consists of the stress-strain and thermal properties of the work material, the thermal properties of the tool, the set cutting conditions and the measured values of cutting force, shear angle and contact length. An initial finite clement mesh is automatically adjusted for different cutting conditions.

The method is illustrated by comparing temperature distributions for flat rake face tools with distributions for controlled contact tools under the same conditions.

1 Introduction

The use of a finite element method for calculating temperature distributions in the workpiece, chip and tool in orthogonal machining (Figure 1) was first described in 1974 by Tay, Stevenson and de Vahl Davis [1]. That program required as input not only the measured force components F_c and F_T, shear angle ϕ and contact length h, but also the strain, strain rate and velocity fields for the primary deformation zone (Figure 1). These fields were obtained experimentally, using quick-stop tests, with fine grids printed on the workpiece. The finite element mesh was based on the deformed grid for each case and adjusted manually as required. To calculate the heat generation rates at mesh points throughout the primary zone, the flow stress at these points was estimated as a function of strain, strain rate and temperature. In the absence of suitable data from conventional tests, machining test results were used as the source of the stress functions.

The original program has gradually been developed to increase its versatility, in particular its ability to handle a wide range of cutting conditions with little or no need for manual adjustment of the mesh. Another development trend has been in the use of flow stress data from high-speed torsion tests [2]. In this data, stress is a function of strain rate alone, and this is applied to machining on the assumption that the temperature rise in the material passing through the primary zone in machining will be equivalent to that in a torsion specimen subjected to the same strain rate. In fact, this is a simplification because the strain rate histories are different [3], but it is considered to be justified, considering the probable errors in torsion results and the machining strain rate field. Also, the torsion tests [2] show negligible strain hardening at the high strains pertaining to machining, suggesting the additional simplification of allowing the stress to be independent of strain.

Some of these developments were described by Stevenson, Wright and Chow [4] who also compared their calculated temperature distributions in the tool with the distributions obtained experimentally by etching the tool after the test. The agreement between these two methods was very good. Further developments made recently include the automatic generation of the finite element mesh in the primary zone and chip for different feed rates, rake angles and contact lengths, and the simplification of program modules and data file requirements. The program may now be more easily applied to a wide range of practical machining applications. It is still confined to the orthogonal case, but oblique machining conditions can usually be approximated by an orthogonal equivalent This report describes the resulting system, and provides a guide to its use. An example of its application is given in which temperature distributions are compared for cutting with controlled contact and natural contact length cutting tools, both with a negative rake angle.

2 The Heat Transfer Model

The equation governing the heat transfer processes occurring during orthogonal machining is the steady, two-dimensional energy equation

$$\rho S\left[u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right] - K\left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right] = Q$$

where ρ, S, K and T are respectively the density, specific heat, thermal conductivity and temperature of the material concerned, Q is the heat generation rate per unit volume, x and y are cartesian co-ordinates, while u and v are the velocity components in the x and y directions, respectively. This equation is to be solved for the region illustrated in Figure 2, subject to the boundary conditions shown there and further discussed below. The use of the finite element method for the numerical solution is described in Tay, Stevenson and Davis [1].

The external surfaces in contact with air are assumed to be adiabatic, i.e., heat losses to the surroundings by convection and radiation are assumed to be zero. Boundaries for the "downstream" end of the chip, and the exit of the work material from the solution region, were assumed to have zero temperature gradients. Positions for these boundaries were selected to ensure that this assumption was realistic.

Along the lower boundary between the primary zone and the workpiece, a temperature of "TROOM," usually the ambient temperature, is imposed. The value of TROOM could be increased above ambient if there tends to be a build-up in workpiece temperature from previous cuts. If the workpiece is deliberately pre-heated, TROOM would be made equal to the pre-heat temperature. A stress function applying to that starting temperature would then need to be applied.

An important feature of the present system is that the solution region in the tool is confined to the tool tip. In the original system, the mesh also extended throughout the cross-section of the toolholder, making mesh adjustment more complex. The present system requires that the conductance of heat from the tool tip to the tool shim (if any) and then to the toolholder be estimated. Most machining is done with disposable inserts which are clamped in place rather than brazed, so this modification allows the mesh to be more readily adapted to a practical set-up.

It is assumed that conductance takes place across the entire base of the tool tip, the rate of heat flow at a point on the base where the temperature is T being given by

$$Q = h_f(T - TSHANK)$$

where h_f is the contact conductance for the interface between the tool tip and its seating and TSHANK is the temperature of the supporting material immediately below the tool tip. TSHANK is assumed constant over the length of the tool base; it may be measured by a thermocouple during a test. Otherwise, a reasonable value to assume for conditions similar to the examples given here is 80^oC. While these may seem to be rough approximations, the temperature distribution along the tool-chip interface is not greatly affected by them. For the present results, a value of conductance was obtained from the experimental results of Brunot and Buckland [5]. The conductance values for difference conditions vary with the finish of the surfaces and the clamping pressure. The value for a particular type of surface tends to a constant value as pressure is increased. It is this constant value for clean milled surfaces, viz. 0.00171 C.H.U./s.in$^{2\,o}$ C, which was used for the present results.

3 Mesh Generation

The finite element mesh used for the solution consists of quadrilaterals graded in size to suit the expected temperature gradients; a fine mesh being used in areas such as the tool tip where gradients will be high. The boundaries of the tool tip are established from the cross section of the actual tip to be used in the experiments. The basic mesh for the tip is established with a rake angle α of zero. As in previous programs, the 22 nodes making up the tool-chip contact length are shared by adjacent elements in the tool and chip. The total length taken up by these nodes, and their spacing, is adjusted later to match the measured tool-chip contact length. The basic tool tip mesh used for the results described in this paper is shown in Appendix I.

The resulting co-ordinates of the nodes in the tool tip, the nodes in the workpiece below the primary zone (these need not be changed for different cutting conditions), and a set of base nodes on which the primary zone and chip will be built, are kept in a file which becomes an input to the Fortran program PRIMRY. PRIMRY, which is listed in Appendix II, adjusts the tool tip nodes, generates the nodes in the primary zone and chip and then calculates the distributions of strain, strain rate and velocity in the primary zone. The procedure is briefly described as follows:

a. **Adjustment of the tool-chip contact length.** Mesh point 538 on the rake face is moved to a distance from the tool edge equal to the total contact length. Points further away from the tool edge are moved a distance equal to that moved by 538, except for points making up the end face of the tool tip which are kept fixed. Points closer to the tool edge are moved by progressively smaller amounts to maintain the relative gradation of elements, except for points on the clearance face which are kept fixed.

   The chip base nodes, which become separate from the tool beyond point 538, are gradually increased in spacing to a maximum of 0.01 inch.

b. **Rotation of the tool-tip.** The tool tip and chip base nodes are now rotated about the tool edge to give the required rake angle (Figure 3a). The basic tool mesh read in to PRIMRY has its origin at the tool edge. After rotation, the origin is shifted 0.05 inch to the left so that x-co-ordinates in the mesh will be positive.

c. **Generation of mesh in primary zone and chip.** This part of the mesh is based on a set of 5 equally spaced streamlines. The streamlines in machining have been found [6] to be well approximated by hyperbolae. Tay *et al.* [7] showed that an hyperbola of the form

$$y^2 \tan\alpha - xy = a \quad , \tag{1}$$

   where the origin is at the intersection of the asymptotes with shear plane AB, gives a peak strain rate value on AB, as was found in the experiments. The constant "a" in equation (1) is given by

$$a = \frac{t_1^2}{16C^2 \sin^2\varphi\,(\tan\alpha + \cot\varphi)} \tag{2}$$

   where t_1 is the uncut chip thickness, φ the shear angle, α the rake angle (Figure 1) and C the constant in the empirical equation

$$\dot{\gamma}_{AB} = \frac{CV_S}{t_1} \quad , \tag{3}$$

   where $\dot{\gamma}_{AB}$ is the shear strain rate on AB, i.e., the peak value along the streamline, and V_S is the shear velocity, given by

$$V_S = \frac{U\cos\alpha}{\cos(\varphi\text{-}\alpha)} \quad , \tag{4}$$

   where U is the cutting speed.

The uncut chip thickness is divided into 5 layers of equal thickness by the streamlines. The first streamline forms the free surface, and it is positioned at a height t_1 above the cut surface. The equivalent hyperbolae to equation (1), using x_0, y_0 as origin (the actual origin of the mesh co-ordinates) are given by

$$Ay^2 + Bx^2 + Cxy + Dy + Ex = 1 \qquad (5)$$

where

$$A = \frac{\tan\alpha}{Z} \ ,$$

$$B = 0 \ ,$$

$$C = -\frac{1}{Z} \ ,$$

$$D = \frac{x_{AB} - 2\tan\alpha y_{AB}}{Z} \ ,$$

and

$$E = \frac{Y_{AB}}{Z} \ ,$$

where

$$Z = a - \tan\alpha y^2_{AB} + x_{AB} y_{AB} \ ,$$

and (x_{AB}, y_{AB}) are the co-ordinates of the intersection of the asymptotes with AB (different for each streamline) as shown in Figure 1. With this procedure, each of the 5 streamlines will be identical in shape and have the same strain and strain rate distributions along them. If it were considered that the strain rates should be greater on streamlines closer to the tool edge, it would not be difficult to progressively increase the constant C for each streamline. However, there seems at present to be insufficient evidence to justify this.

Having established the coefficients of the equation of a streamline, mesh points along it are found from the intersection of the streamline with lines emanating from the base points, parallel to AB (Figure 3b). Each such point is found from the solution of a quadratic equation. This procedure gives 55 points along each streamline, 27 in the primary zone and 28 in the chip. The final boundary of the primary zone is rather arbitrarily positioned by the limit of 27 points, and the program could be slightly improved, at the cost of more complication, by terminating the primary zone only when the shear strain rate had dropped to some given low level. However, such a refinement would have little effect on the variable of greatest concern, the maximum temperature at the tool-chip interface. A typical primary zone mesh, generated as described above, is shown in Appendix III.

4 Primary Zone Heat Generation

The heat generation rate at points throughout the primary deformation zone is given by

$$Q = \tau \dot{\gamma}$$

where τ is the plastic shear flow stress at the point and $\dot{\gamma}$ the shear strain rate at the point. τ may be determined as a function of the shear strain, shear strain rate and temperature at the point, but in the present application, as explained below, it is assumed to be a function of strain rate only.

Shear strain rate, shear strain and velocity distributions are found at each primary zone mesh point along the streamlines, using the following equations. These equations are based on the assumption that the maximum shear strain rate directions throughout the zone are parallel to AB.

$$\beta = \tan^{-1} \frac{dy}{dx}$$

$$\dot{\gamma} = \frac{d^2y}{dx^2} \cdot \frac{V_C \cos(\varphi - \alpha)}{(\sin\varphi + \cos\varphi(\frac{dy}{dx}))^3}$$

$$\gamma = \cot\varphi - \cot(\varphi + \beta)$$

$$V = V_C \frac{\cos(\varphi - \alpha)}{\sin(\varphi + \beta)} \qquad (6)$$

where V_C is the chip velocity, and $\frac{dy}{dx}$ and $\frac{d^2y}{dx^2}$ are found from the equations of the streamline (equation (5)).

Strain rates, etc., cannot be determined in this way for the straight streamline which intersects the tool edge, yet the deformed grids in the quick-stop tests indicated substantial strain along this line. This is consistent with the plastic deformation remaining in the cut surface. In the present procedure, the tool-edge streamline is given the same distributions for strain rate, etc., as the one just above it, up to the tool edge. Beyond the tool edge, i.e., along the tool rake face, the primary strain rates on this streamline are made equal to zero, since it is in this region that secondary deformation takes over.

The flow stress τ is now found from a function of strain rate alone, where this function is derived from high speed torsion test results [2]. This is appropriate for a workpiece starting at room temperature, as the torsion tests also did. The temperature history of material in the torsion and machining tests would be similar, so there is no need to include temperature in the stress function. This avoids the need for iteration to find the heat generation rates in the primary zone. The torsion tests on two low-carbon steels showed negligible strain hardening at the high strains applicable to machining, so the strain effect is considered negligible here. It may not be so for other materials, and the program has provision for inserting an appropriate value for the strain hardening exponent, n, in the power law equation:

$$\tau = \tau_1 \gamma^n \quad .$$

The torsion test data is limited at present, and any bar of low-carbon steel will inevitably differ in strength from the steels so far tested, due to differences in composition and cold working. For this reason, the torsion data is used to give the strain rate sensitivity of the stress, while the stress magnitude is adjusted on the basis of the shear stress on the shear plane, calculated from the machining test itself [8].

5 Secondary Zone Heat Generation

The secondary zone heat generation rates are divided into two parts: Q_1 is the generation rate due to secondary plastic deformation, while Q_2 is the generation rate due to sliding friction along the tool-chip interface.

Secondary plastic deformation is confined to a relatively narrow zone of material adjacent to the tool-chip interface. This zone has been found to be approximately triangular in shape (Figure 1). Its length is usually readily measurable from the wear on the tool rake face after a test, being that part of the scar where abrasion is not evident. This "plastic contact length," shown as p in Figure 1, is usually close to half of the total contact length h, if the rake face length is sufficient to allow natural contact. In controlled contact tools, the total contact length may be so reduced that secondary plastic deformation takes place throughout its length, i.e.,

$$p = h \quad .$$

The heat generation rate due to plastic deformation adjacent to the interface is given by

$$Q_1 = \tau_{INT} \; \dot{\gamma}_{INT} \quad , \tag{7}$$

where

$$\tau_{INT} = \frac{2F}{w(p+h)} \tag{8}$$

and

$$\dot{\gamma}_{INT} = \frac{V_c}{\delta t_2} \quad , \tag{9}$$

where F is the friction force, calculated from the measured force components F_C and F_T, using

$$F = F_C \sin\alpha + F_T \cos\alpha$$

and δt_2 is the maximum thickness of the secondary zone. δ, the proportion of chip width t_2 over which secondary deformation takes place, has been measured for a wide range of conditions when machining two low-carbon steels [9]. If that data is inadequate, a chip sample will need to be mounted, polished and etched for estimation of δ.

τ_{INT} in equation (7) is assumed to be constant throughout the secondary deformation zone. $\dot{\gamma}$ at the tool-chip interface is assumed to be constant along the plastic contact length and zero beyond it. $\dot{\gamma}$ is further assumed to decrease linearly from its interface value to zero along the secondary zone boundary within the chip.

Equation (8) is obtained from the assumption that the interface shear stress is equal to τ_{INT} over the plastic contact length and then drops linearly to zero at the end of the total contact length. Equation (9) is based on examination of a limited number of quick-stop results in which the further deformation of the grids in the secondary zone could be measured.

The heat generation rate along the tool-chip interface due to friction is given by

$$Q_2 = \tau_{INT} V_x$$

where V_x is the velocity parallel to the rake face of chip material at a distance x from the tool edge. Again on the basis of quick-stop results, it is assumed that V_x starts at $V_C/3$ at the tool edge and accelerates uniformly to the chip velocity V_C at the end of the plastic contact length, beyond which it remains constant at V_C.

It will be evident from the above description of heat sources that contact length measurement is an important part of the procedure. However, in the absence of such measurement, an approximation to the total contact length may be calculated [7].

6 Arrangement of Program and Data Files

The system used for the present results is illustrated in Figure 4. Individual users are likely to modify this arrangement to suit their application and computer system.

The Fortran program, PRIMRY, is run first, using a basic mesh from a file such as XYBASE and data in the file PRIMD as input. Output from PRIMRY consists of the file RESULT, which contains a listing of the calculated strain and strain rate distributions for printing if required, the file UVEDOT which contains the strain, strain rate and velocity distributions for reading in to the next program, FINELT, and the file XYTSTN which contains the generated mesh for Test N, also to be read in to FINELT.

FINELT, the main finite element program, is listed in Appendix IV. Apart from UVEDOT and XYTSTN, it also requires as input the data file FINREV. FINELT is an iterative procedure which usually converges to a sufficiently accurate solution (2% maximum relative error) within 5 iterations. If it does converge (and there is something wrong if it does not), it will produce a final listing of temperatures at all nodes, TRESUL. It will also produce a file, CALC26, for the Calcomp plotter for plotting the isothermals.

The finite element mesh may also be plotted using the Fortran program MESHPL, shown in Figure 4. Since mesh plotting takes around 7 minutes of plotter time, it should not be done as a matter of course, but only when there is some need to check the mesh. MESHPL is listed in Appendix V. Data files for the example experiments are given in Appendix VI.

7 Input Data Requirements

Variables Involved in Mesh Adjustment

In adjusting the tool tip mesh to suit its size and shape, only a few nodes may need to be changed in position. More extensive changes will require changes in the number of nodes and elements. The following variables specify the mesh and may require to be changed:

NPOIN: the total number of nodes.

x(i,j): the co-ordinates of the nodes; J-1 for the x-co-ordinate and 2 for the y-co-ordinate. The number i of each node is obtained from its order in the list.

NELEM: the total number of elements.

NOD(i,J): the numbers of the 4 nodes (J = 1 to 4) which make up each of the elements i.

MPRI: the number of nodes in the primary zone.

WENDR1: the number of the last element in the primary zone.

NENDR2: the number of the last element in the chip,

NEMDR3: the number of the last element in the chip. (The element numbering starts in tie primary zone* then continues in the chip, then in the workpiece and finally the tool tip.)

NBOUN: the number of nodes fonraicif fie boundary between ttte primary zone and the work.

NKNOW(i): f^e node numbers a§ora§ the towicfary of the primary zone witft fie work.

NHCWT^; tie pairs of ncMfe numbers wtfch gte 'the etement petes forming fie boundaries of *§ system wtt) the air. The falwwig *mriakties mm* used to bredk fliese *bmMwSmm^* Into parts as iBcpireci, § » parte being in the *Mkmlmg* ©rd#r in NHCWT.

fie nuMbcr erf baitxteri^ ii. *ftm* «*%^

Mr: the number erf tanitfsrfes A » g *limtMwmkmxrimm-**

Mftr9amD: **identify the nodes tip and its seating.** ta *mmm* wWch begin aid end fie cxmtacttengttil«t«^»i i« ^

NFLUX(i,J): **the pairs** of node numbers giving the element sides which form the tool-chip intact. **These si** S? Z\ sh YS by ohip "^ t00, elements in eith*r side of the iaterfiti. **NFLUX(1,** ·) is thetoof edge node (point 156).

NFE: the number of element sides forming the tool-chip interface, i.e., the maximum value of i in NFLUX(i,j).

LH: the number of elements in the vector H. The value of H is calculated in the subroutine BANWTH, but a maximum expected value of LH is given as MAXH in the parameter statement of FINELT for dimensioning H.

IQTL: the number of primary zone nodes at which the heat generation due to primary deformation is calculated.

NXI: the number of points on a streamline.

NYI: the number of streamlines.

NITL1 and NITL2:
the numbers of the two primary zone elements sharing the tool point node, the former just ahead of the shear place and the latter just past it.

NXBTI: the number of points on streamline 6 up to the tool edge.

NELSLI (i): the numbers of the 27 elements along the free surface of the primary zone.

NUVQ(i,j): the node numbers for elements in the primary zone, using the system where points are numbered consecutively along streamlines, starting with the one at the free surface.

Variables Possibly Needing to be Changed for Each Test

CHIP: the identifying name for the test being analysed.

NSTEEL: the code name for the work material being machined, e.g., 1080.

ITST: the number of the starting iteration, normally 1, but if previous iterations are to be resumed, a value greater than 1 should be given.

ITMAX: the maximum iteration number. If ITST is 1, putting ITMAX at 7 should suffice to prevent the use of excessive computer time if the program happens not to converge.

RERROR: the criterion for stopping the iterations; if set to 2%, then the program stops when the greatest relative change in temperature among all points from one iteration to the next is 2% or less.

U, T1, T2, ALPHA, FT, FC»CL, W, TROOM, TSHANK, DT2 and PCL:

the machining test data* all defined in the source program, including their units.

DCN: the density of the work material at 50°C, in lb/cu. in,

€P: the specific heat of the work material at 5Q°C, in C.H.U. (centigrade heat units)/lb.

WCOND: the conductivity of the work material at 50°C, in C.H.U./s.in. °C.

TCOND: the tool tip conductivity at 22°C in C.H.U./s.in. °C.

NDATA: the number of values in the arrays giving the variation of the thermal properties with temperature, starting at 0°C, in 50° steps.

DENCPS(i): the array giving the products of work material density and specific heat for NDATA temperature steps.

CONDS(i): the array giving the conductivity of the work material for NDATA temperature steps.

HINTF: the conductance between the tool tip and tool base in C.H.IL/s.in.^{2} °C.

8 Some Results

To demonstrate its applicability to practical machining conditions, the package was applied to some experimental results in which commercial disposable insert tools, supplied by the Kennametal Company, were used. Two types of coated-insert were used: Kenloc SNMA-432, which has a flat rake surface, and Kentrol SNMM-432, which has a land around its edge giving a controlled tool-chip contact length of 0.01 inch. Both inserts were 0.5 inch square and 3/16 inch thick, and were of KC850 grade. A low-carbon free-cutting steel bar was turned, with the tool set to cut orthogonally (side cutting-edge angle = 0). Force components F_T and F_c were measured with a Kistler dynamometer, chip thickness with a micrometer and contact lengths from the wear scar on the tool, using a Nikon Shadowgraph projector. The,other cutting conditions and the test results are given in Table 8-1.

Isothermal plots obtained with the package for the above tests are given in Figure 5 a~f. The plots in Figure 5 show the areas of most interest, viz., the primary and secondary zones and the hottest segment of the tool tip. A typical plot for the remainder of the tool tip is given in Figure 6. The maximum interface temperatures for each of the tests are listed in Table 8-2.

As might be expected, where the controlled contact was much less than the natural contact at a particular feed, the shear angle was increased and the force components decreased. It turned out that the reduction of contact length also decreased the interface temperature in these cases, substantially so in the case of the 0.008 inch feed. With the smallest feed, there was little change in shear angle and force and the temperature turned out to be higher for the controlled contact case. Apparently* the contact length was not sufficiently reduced in this case to have a significant effect

Experimental results for comparison are sparse. Spur and Beyer [10] used a radiation detection technique to measure tool temperature distributions and gave an example for controlled contact tools. A higher carbon steel was machlned$_s$ and the cutting speed was higher (80 in./s). With a fea^ rate of 0.01 inch, the natural contact length was 0.041 inch, and the maximum temperature was foufld to be 790°C. When the contact length was reduced to 0.017 inch using a controlled contact tool, the maximum temperature decreased to 72G°C$_?$ a similar reduction to that found in the present results.

Table 1: Summary of Experimental Results

In all cases: α = -5
U = 60 in./s
W = 0.200 in.
TROOM = 25.0°C

Test No.	Tip	t_1 inch	t_2 inch	ϕ deg.	Total C.L. h, inch	Plastic C.L. p, inch	F_T lb.	F_C lb.
T1	Kenloc	0.0104	0.029	19.11	0.035	0.019	331.6	522.7
T2	Kentrol	0.0104	0.022	24.34	0.010	0.010	196.7	420.4
T3	Kenloc	0.0080	0.021	20.17	0.027	0.016	219.2	382.2
T4	Kentrol	0.0080	0.015	26.92	0.010	0.010	114.7	305.7
T5	Kenloc	0.0052	0.013	21.06	0.018	0.011	140.5	250.7
T6	Kentrol	0.0052	0.013	21.06	0.010	0.010	134.9	243.9

Table 2: Maximum Interface Temperatures

Test No.	Feed t_1, inch	Contact Length, h, inch	Maximum Interface Temp., °C
T1	0.0104	0.035	721
T2	0.0104	0.010	676
T3	0.0080	0.027	594
T4	0.0080	0.010	496
T5	0.0052	0.018	517
T6	0.0052	0.010	557

9 Concluding Remarks

The package can now handle the full range of rake angles, feeds, shear angles and contact lengths likely to be encountered in practice. Some development of automatic mesh generation in the tool tip, for the full range of tool tip sizes, would be a desirable further development. A study of the sensitivity of the results to mesh size would also be desirable. Probably the mesh could be made substantially coarser with little loss in accuracy. This would speed up execution of the program and possibly even allow its use on a microcomputer.

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10 References

1. Tay, A. O., Stevenson, M. G., and de Vahl Davis, G. "Using the Finite Element Method to Determine Temperature Distributions in Orthogonal Machining." *Proc. Instn. of Mech. Engrs.* 188(1974): 627-638.

2. Stevenson, M. G. "Further Development and Use of a Torsional Hopkinson-bar System for Stress-Strain Measurements to Large Strains." In *Proc. of 3rd Oxford Conf. on the Mechanical Properties of Materials at High Rates of Strain, The Inst. of Physics* (April 1984).

3. Stevenson, M. G. "Stress-strain Data for Predictions in Machining." In *Proc. of Conf. on Mechanical Properties of Materials at High Rates of Strain, The Inst. of Physics Conf.* Series No. 21 (April 1974): 393-403.

4. Stevenson, M. G., Wright, P. K., and Chow, J. G. "Further Developments in Applying the Finite Element Method to the Calculation of Temperature Distributions in Machining and Comparisons with Experiment" *ASME Journal of Engineering for Industry* 105 (1983): 149-154.

5. Brunot, A. W. and Buckland, F. F. "Thermal Contact Resistance of Laminated and Machined Joints," *Trans. ASME* 71 (1949): 253-257.

6. Stevenson, M. G. "Measurement of the Strain Rate in the Primary Deformation Zone in the Machining of Three Metals." In *Proc. 7th North American Metalworking Research Conf.* (May 1979): 234-240.

7. Tay, A. O., Stevenson, M. G., de Vahl Davis, G., and Oxley, P. L. B. "A Numerical Method for Calculating Temperature Distributions in Machining, from Force and Shear Angle Measurements." *International Journal of Machine Tool Design and Research* 16 (1976): 335-349.

8. Stevenson, M. G. "Torsional Hopkinson-Bar Tests to Measure Stress-Strain Properties Relevant to Machining and High Speed Forming." In *Proc. of 3rd North American Metalworking Research Conf.* (May 1975): 291-304.

9. Stevenson, M. G., and Duncan, K. R- "Effect of Manganese Sulphide Inclusions on the Tool/Chip Interface Shear Stress in Machining of Low-Carbon SteeL" *Journal of the Iron and Steel Inst* 211 (1973): 710-717.

10. Spur, G., and Beyer, H. "Erfassung der Temperaturverteilung am Drehmeissel mit Hilfe derFernsehthermographie." *Annals CIRP 22,* no. 1 (1973): 3-4.

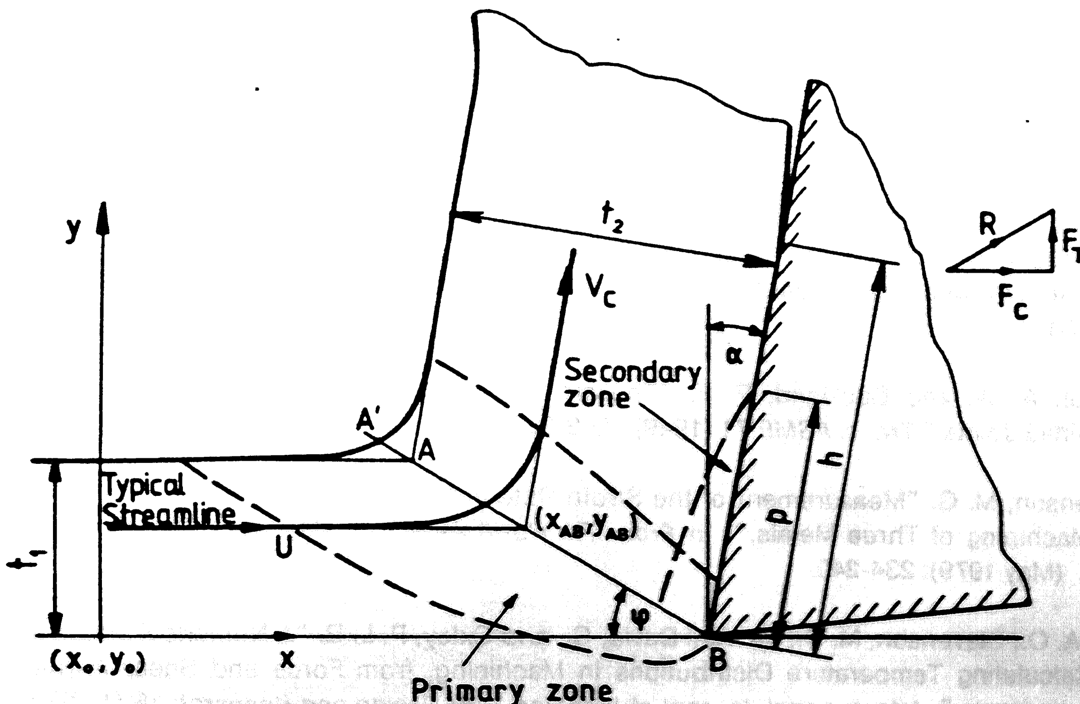


Figure 1: Typical cross-section of deformation zones in steady-state orthogonal machining

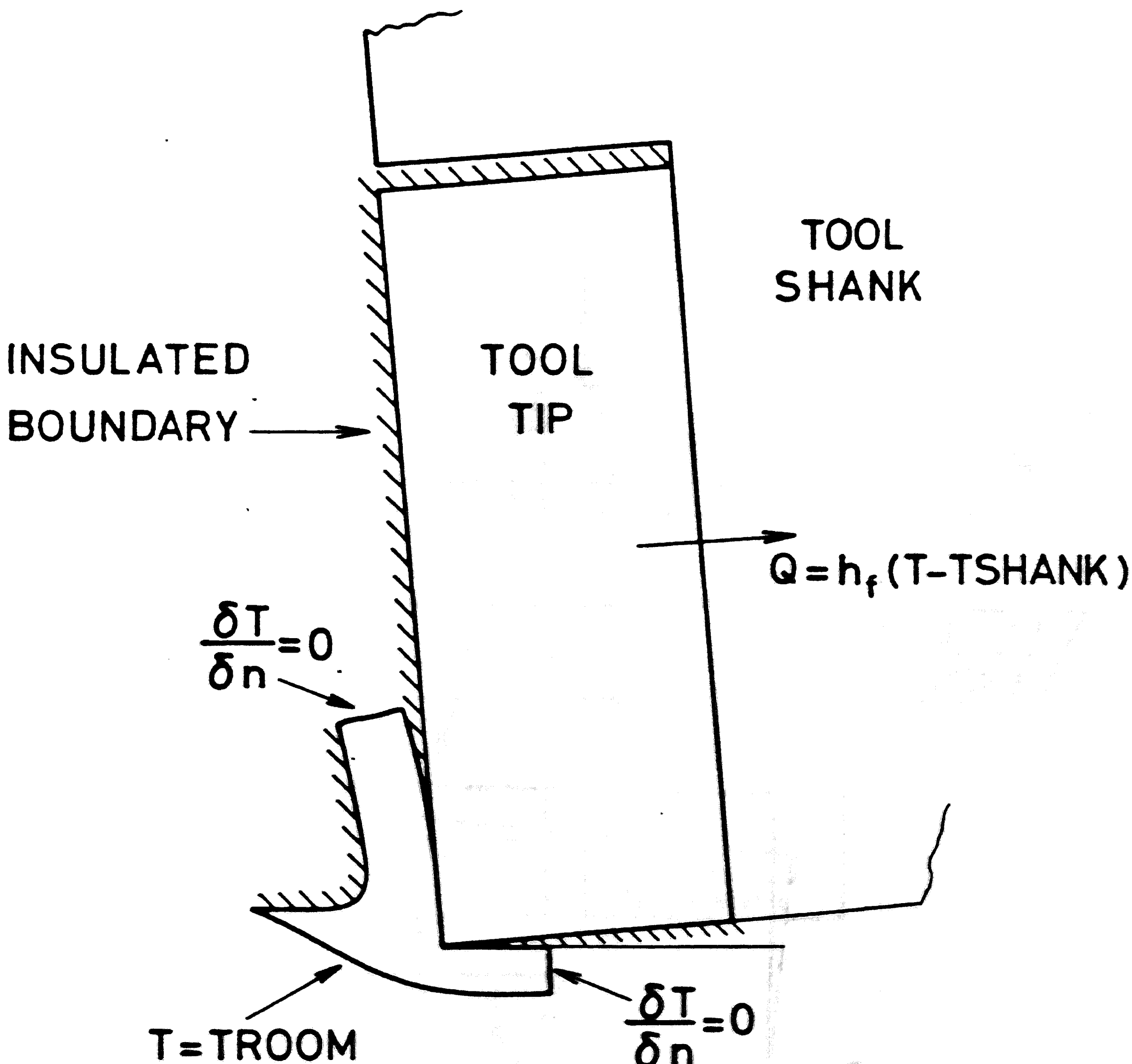


Figure 2: Boundary conditions for the finite element model

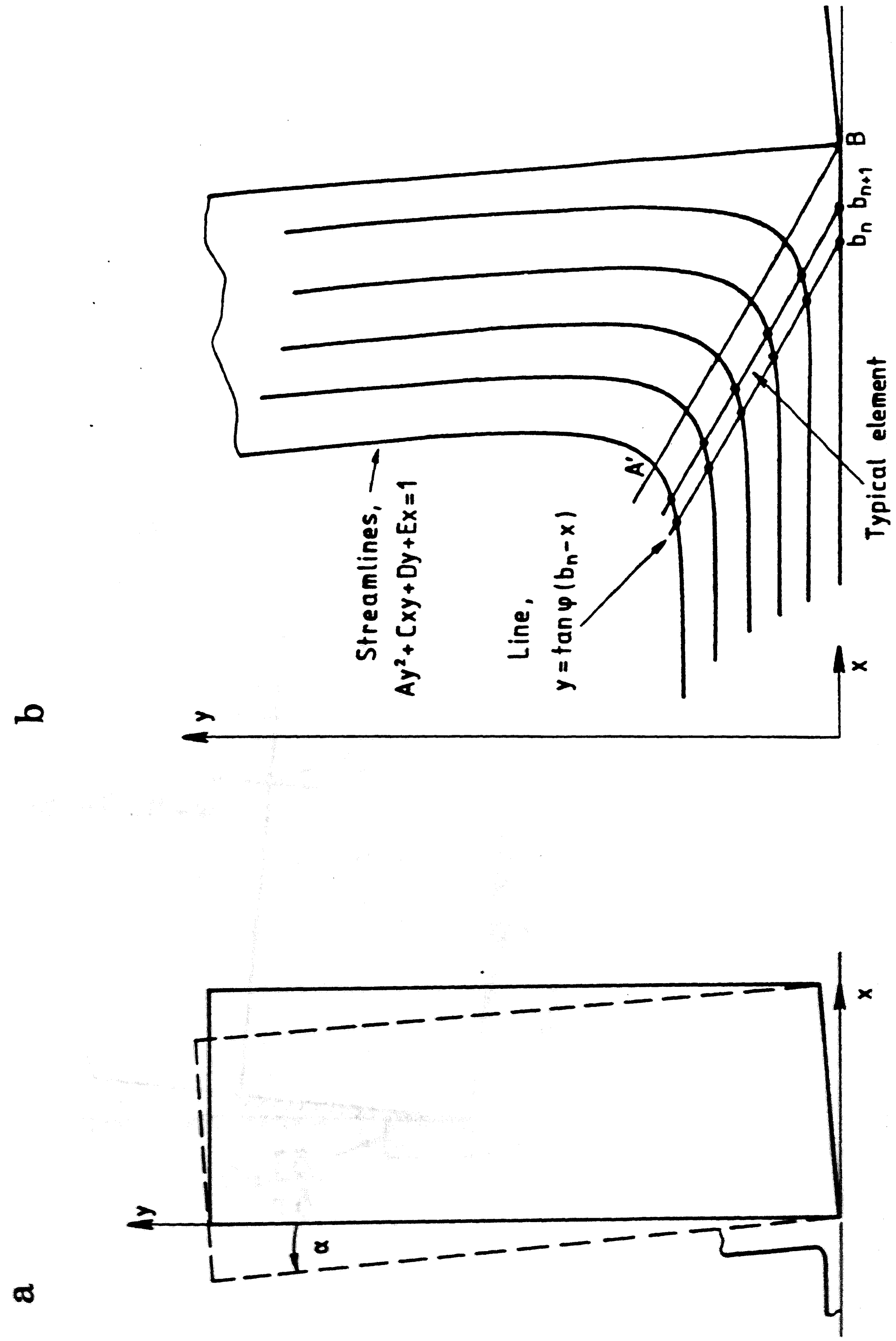


Figure 3: Steps in the mesh generation; (a) rotation of tool tip about its edge to form α, and (b) formation of mesh points in primary zone and chip.

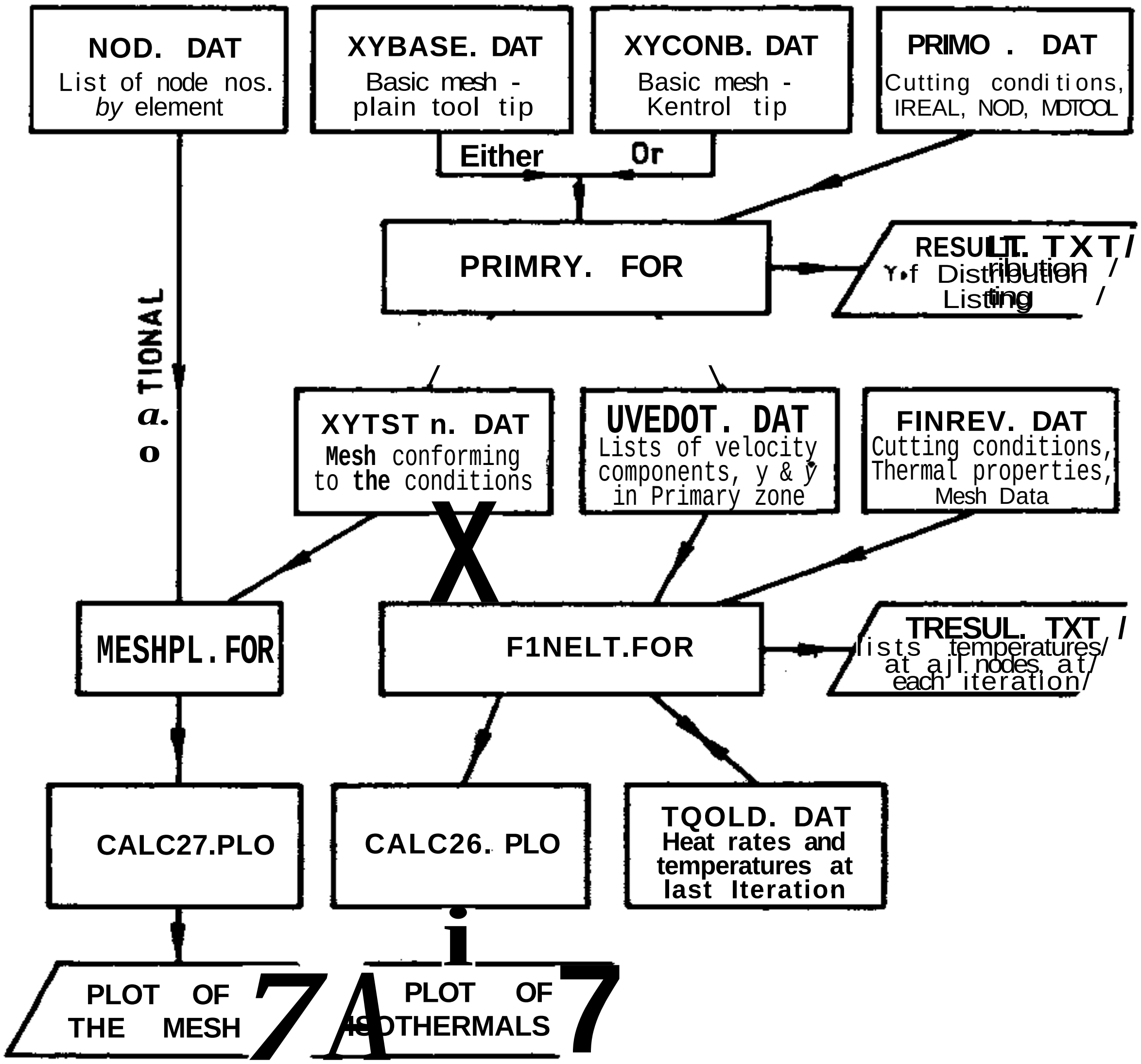


Figure 4: Arrangement of the program modules

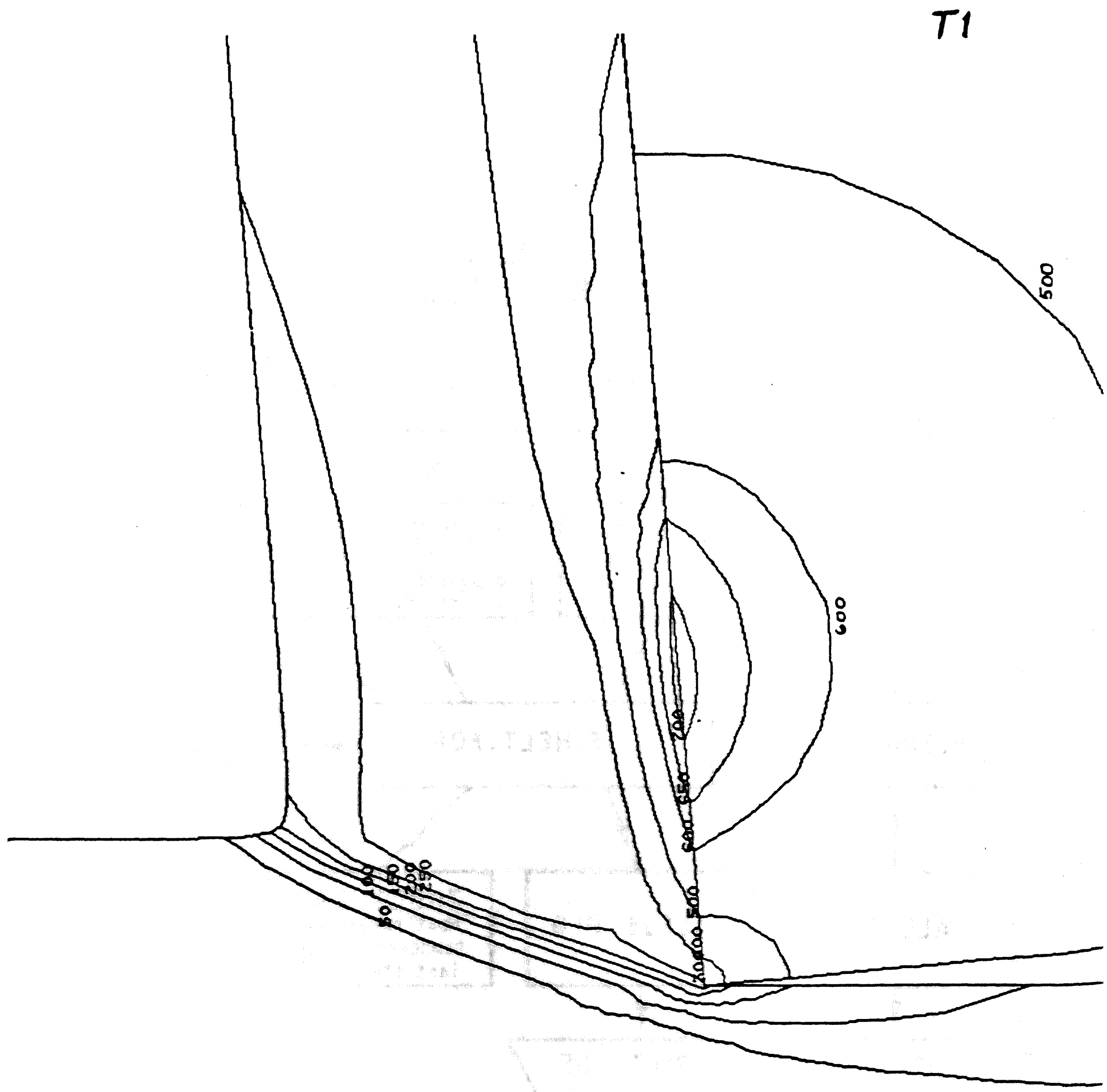
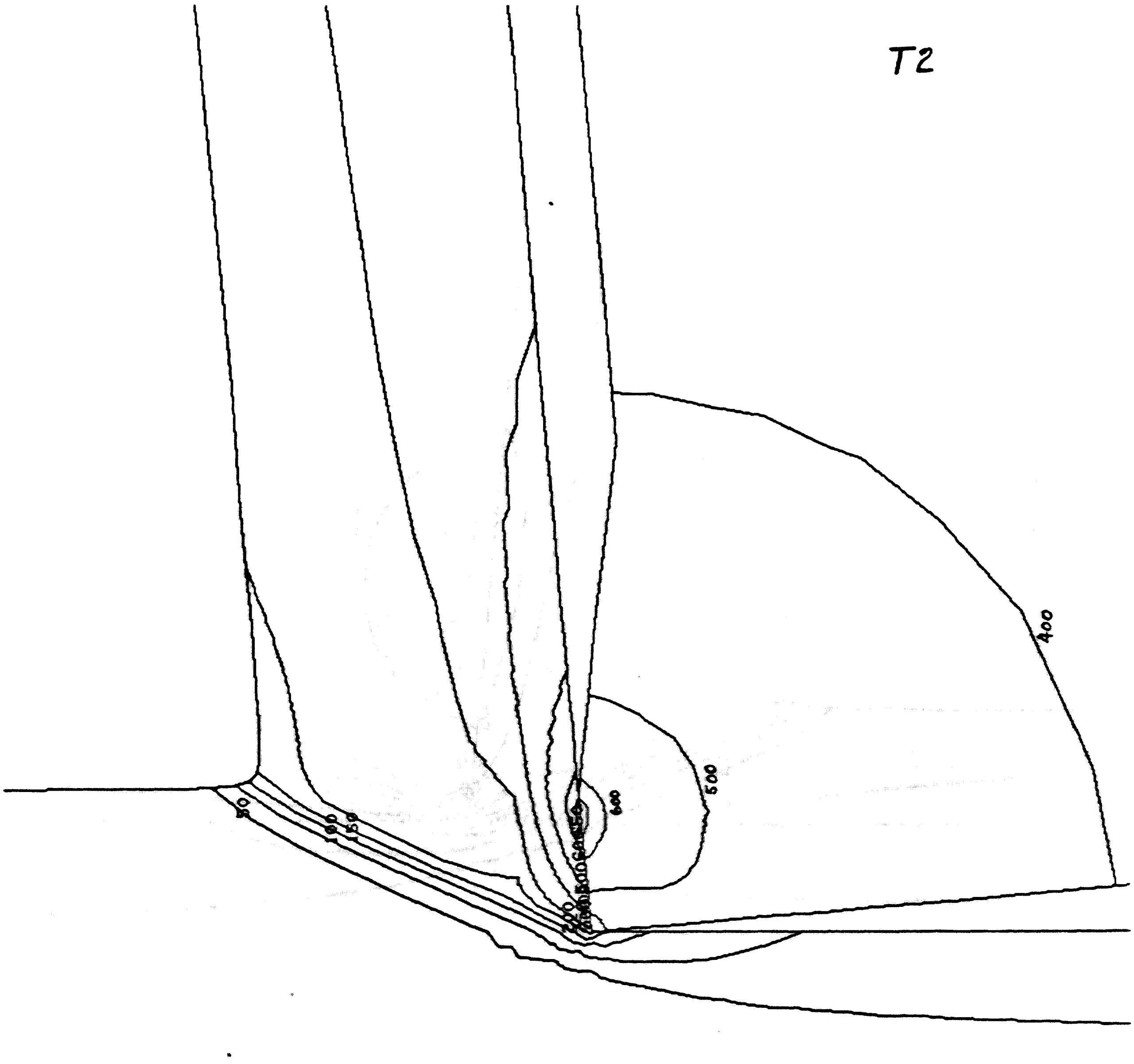


Figure 5: Isothermal plots for the experiments. Isothermal values are 50, 100, 150, 200, 250, 300, 400, 500, 600, 650, 700, 750.


T2
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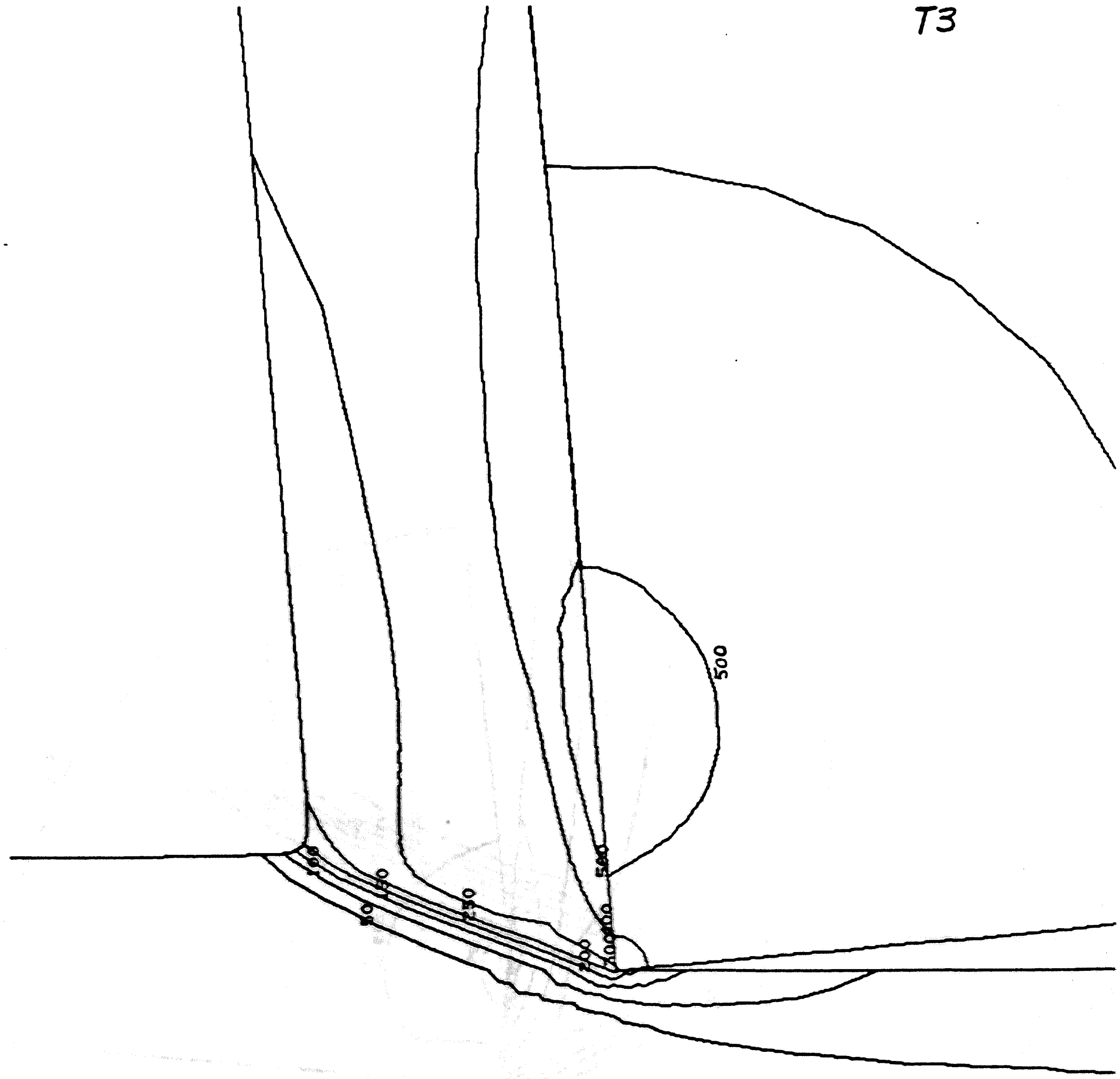
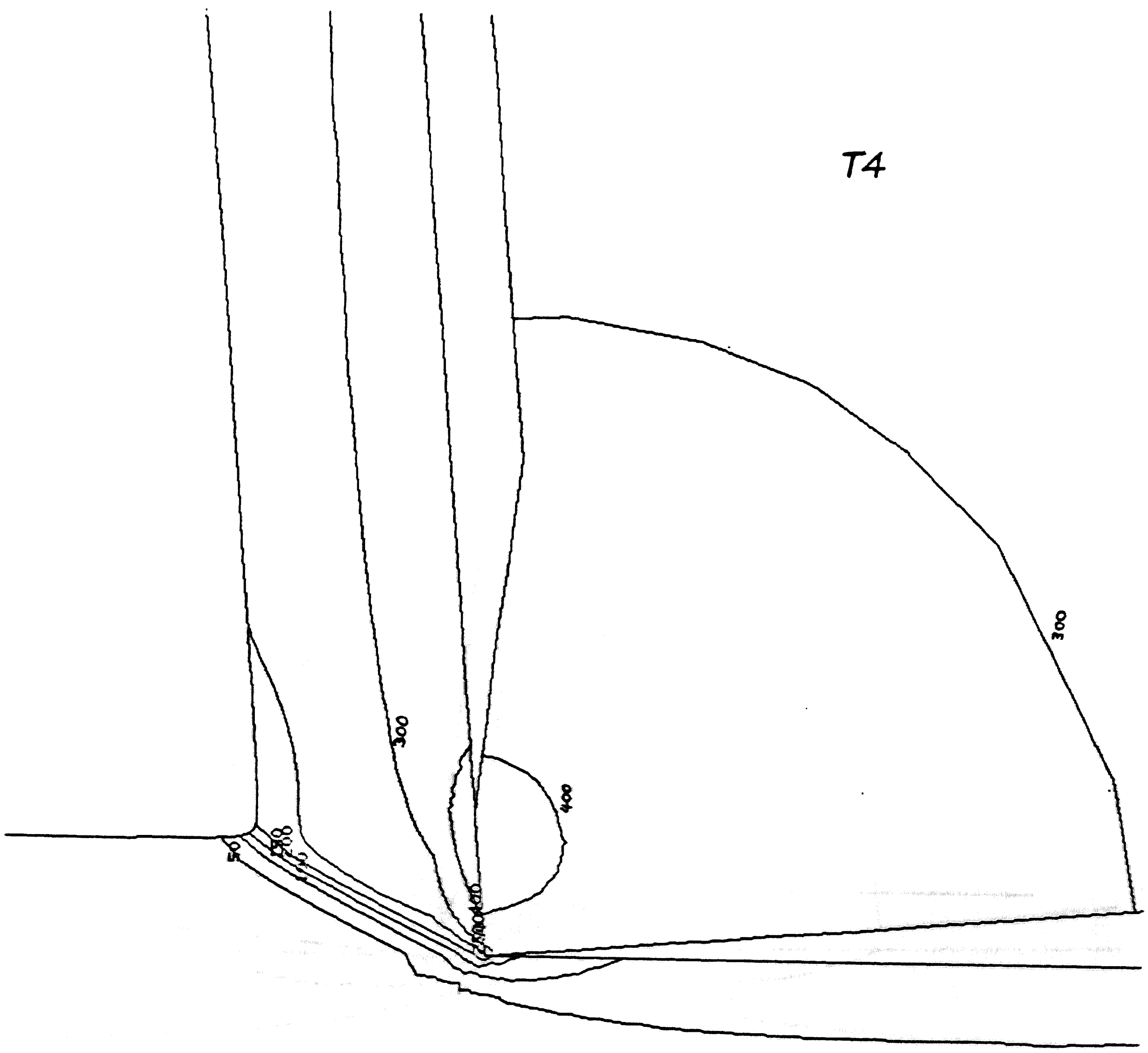
100
150

T3




T4
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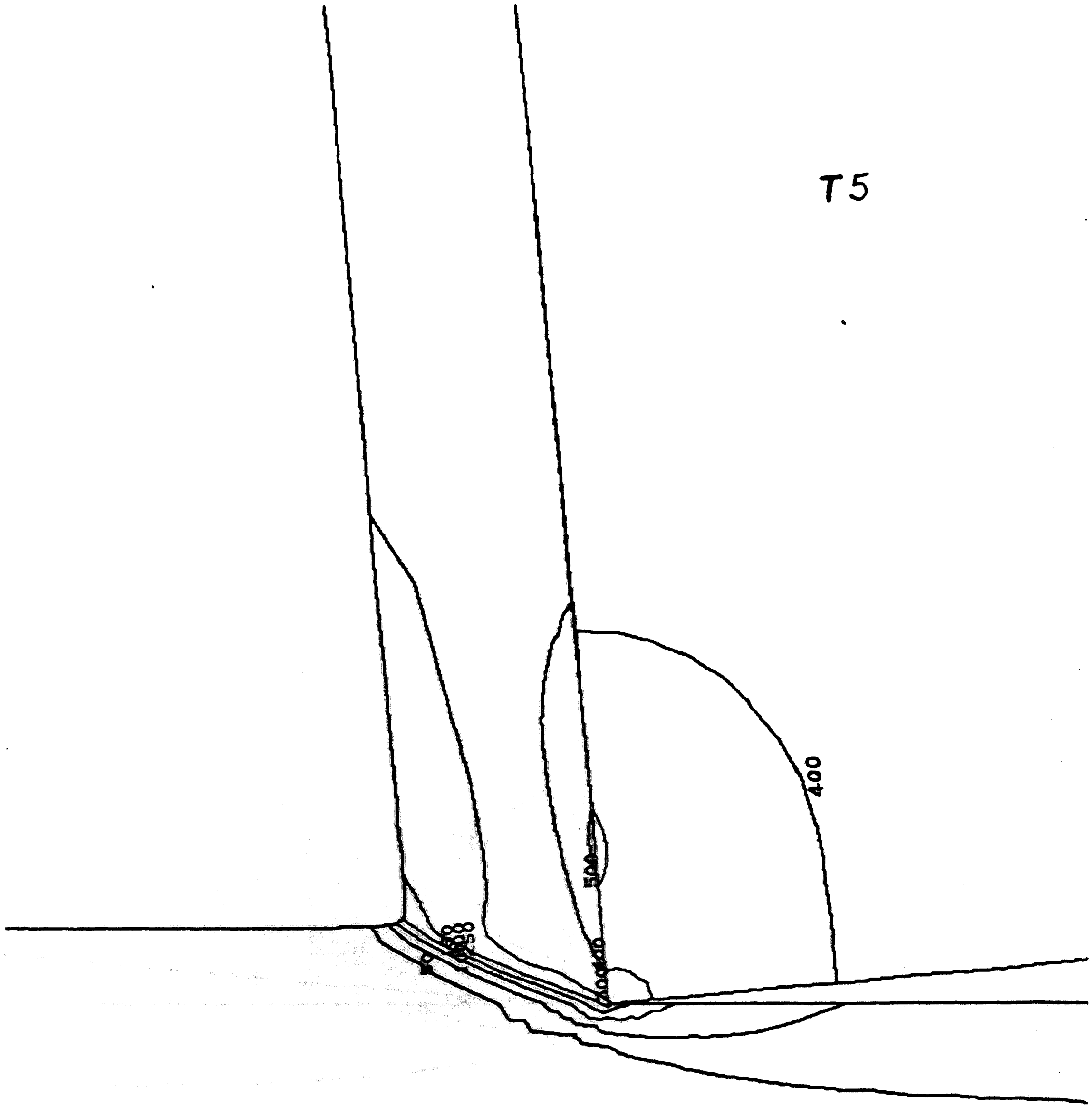
T5
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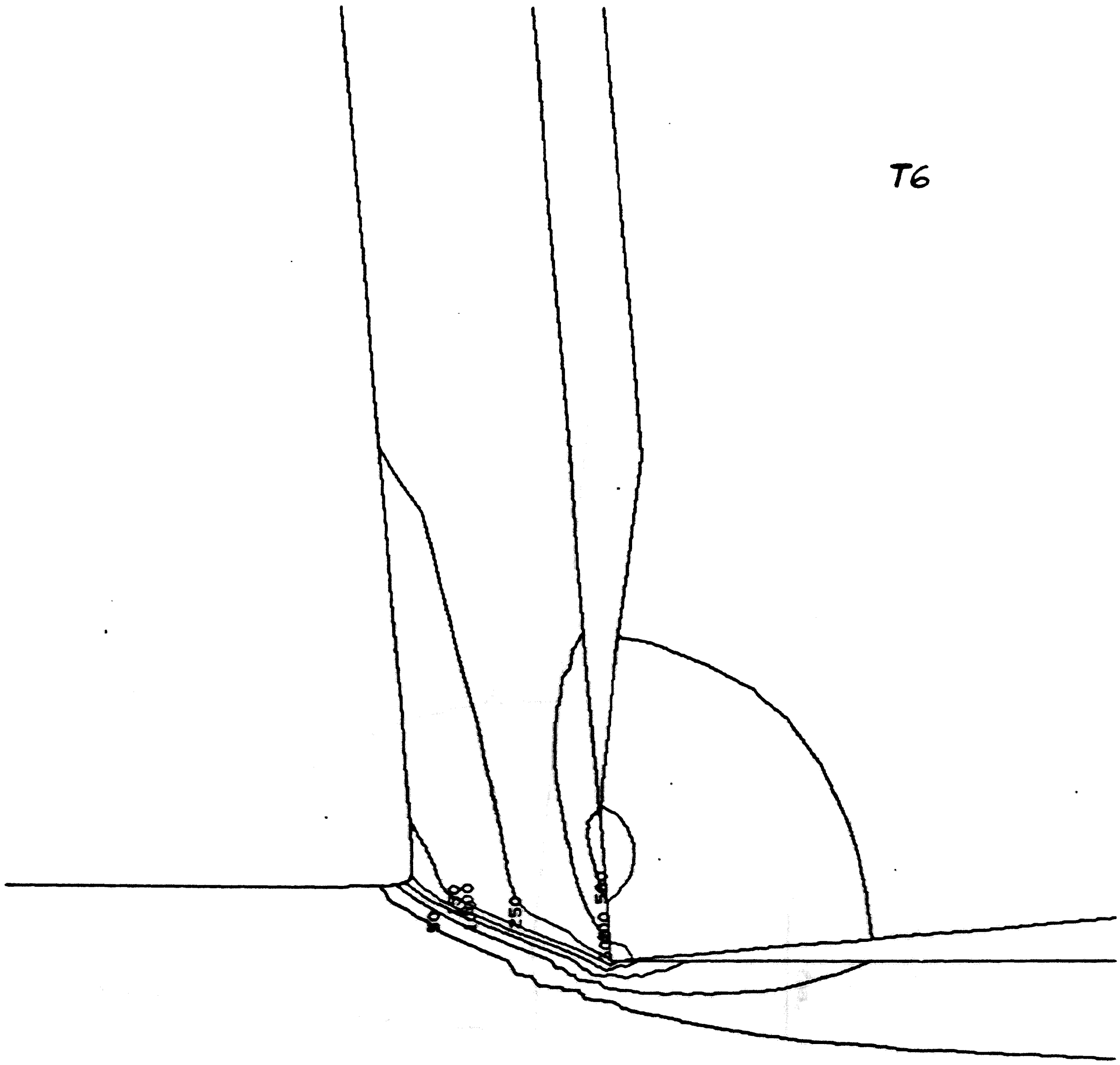
500

T6



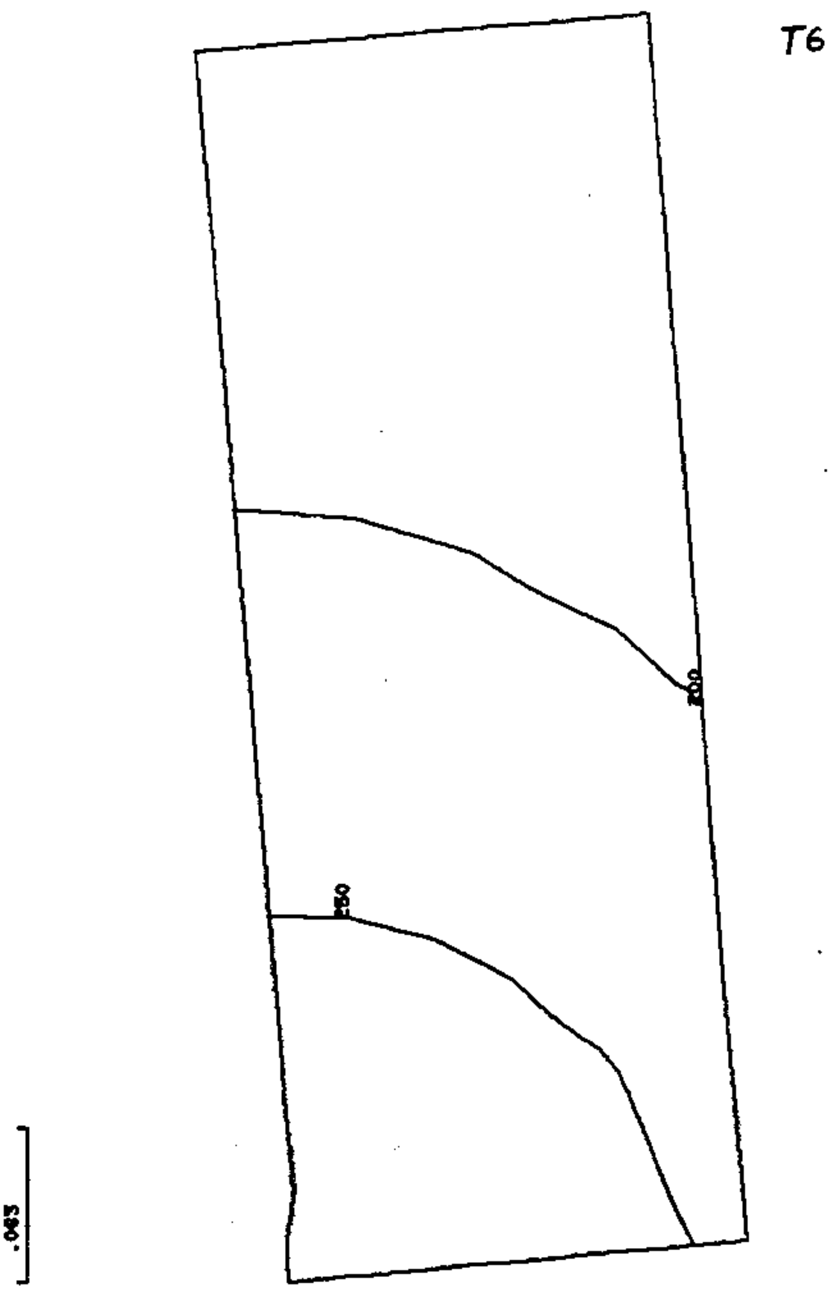
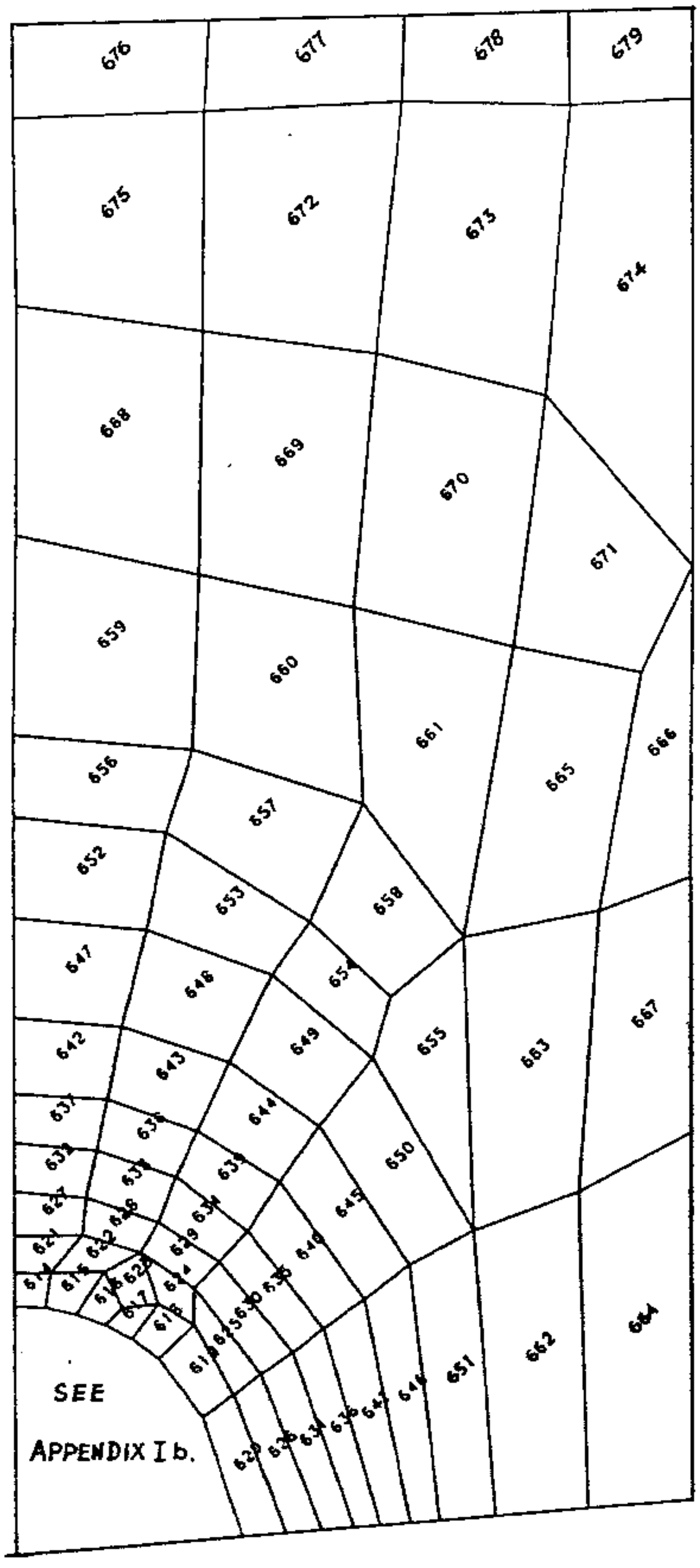


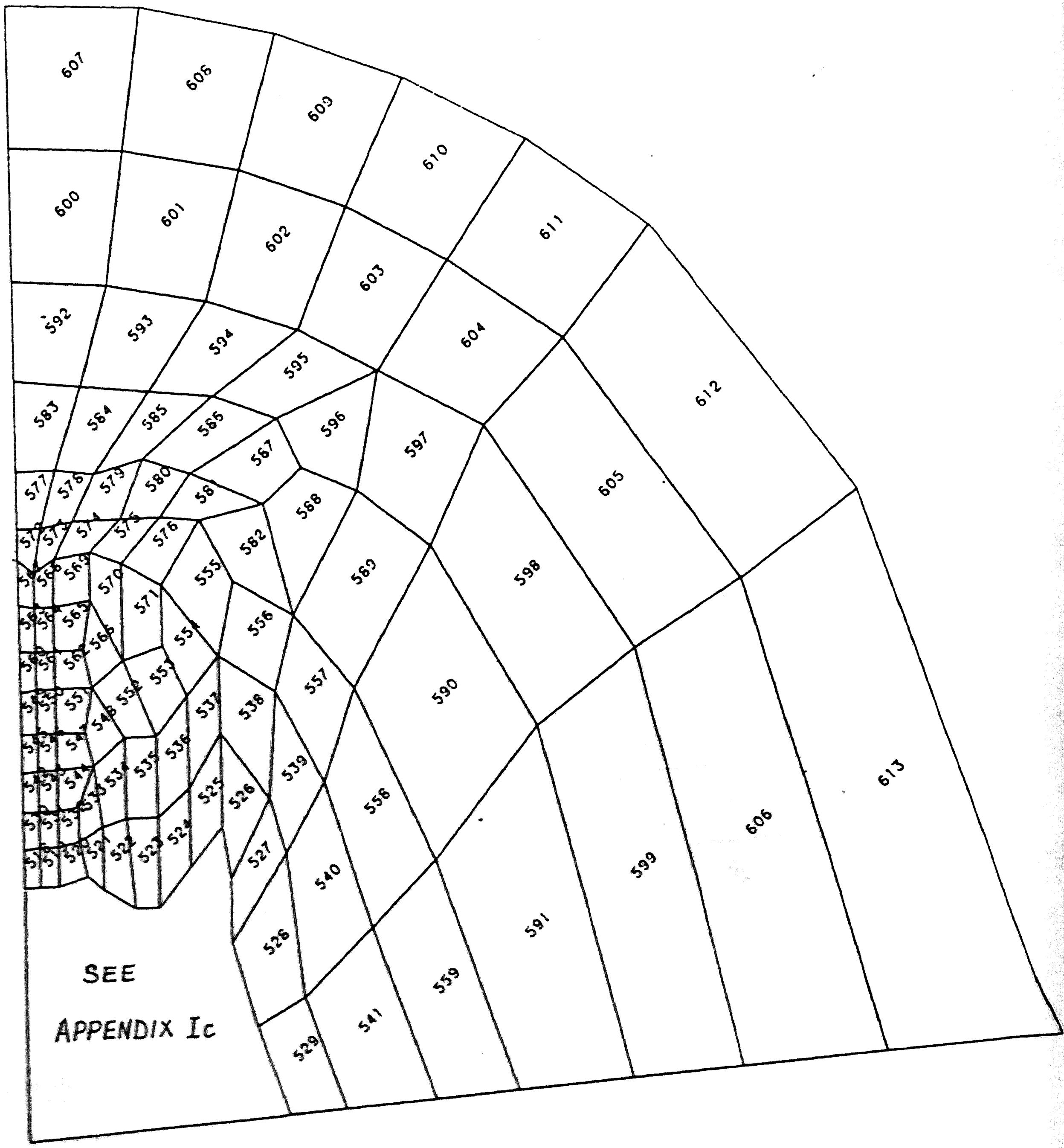
Figure 6: Typical isothermal plot for the remainder of the tool tip (Isothermals already shown in the finer detail plot are omitted)

APPENDICES



APPENDIX Ia

TOOL TIP MESH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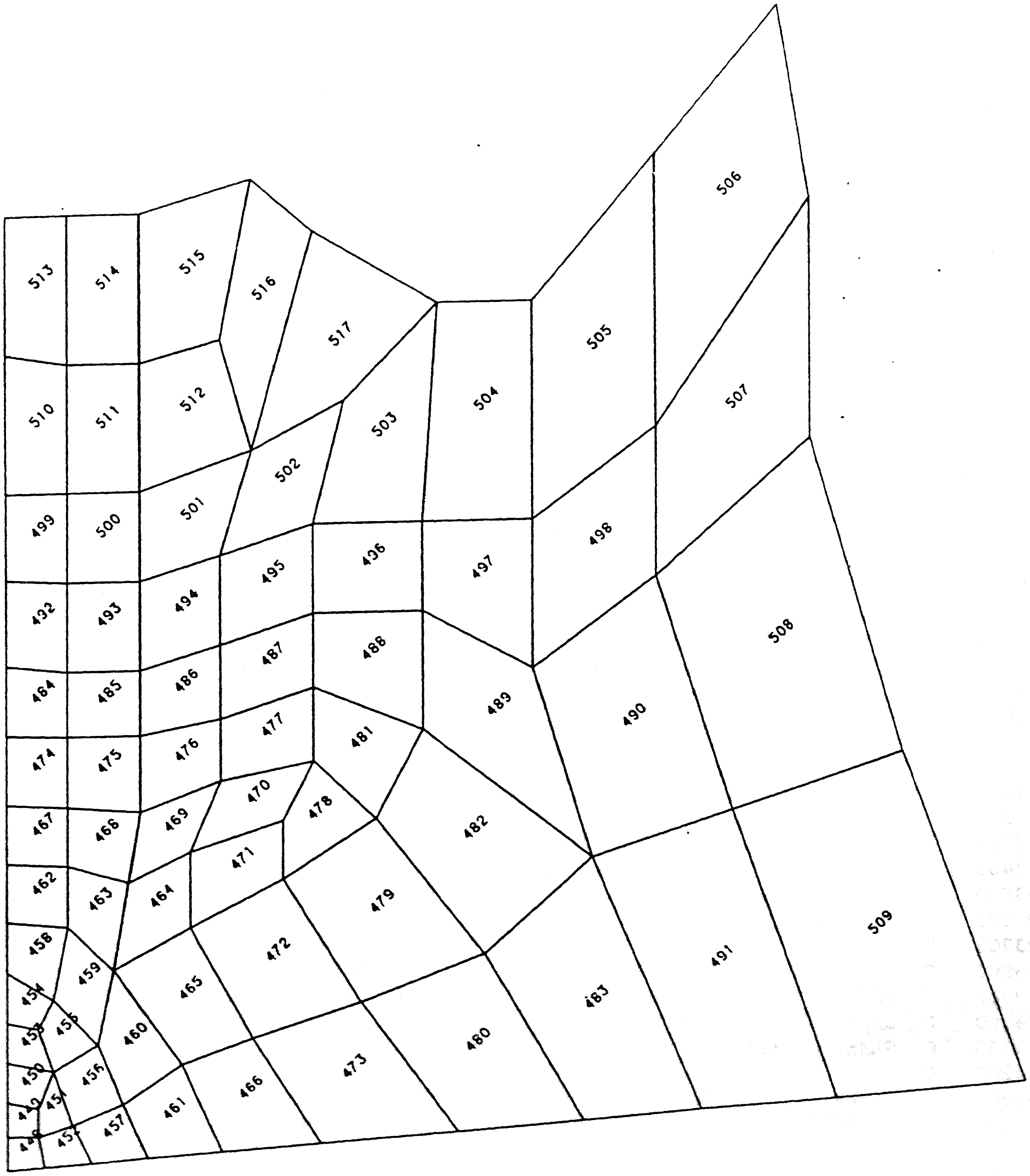
SEE
APPENDIX Ic

APPENDIX Ib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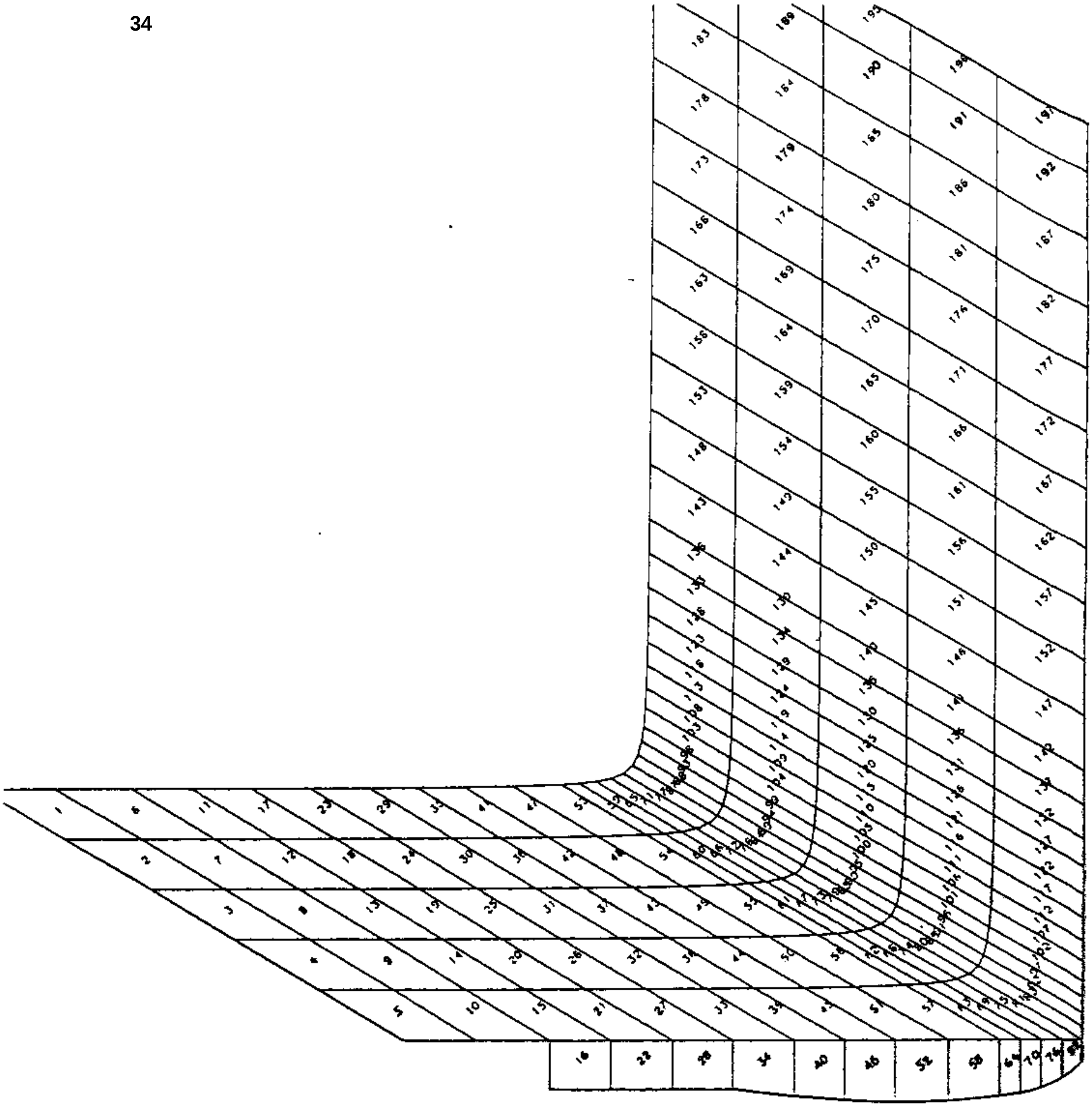
APPENDIX Ic

```
      PROGRAM PRIMRY
C
C   PRIMRY TAKES AS INPUT A BASIC MESH FOR ALPHA=0, AND THE MEASURED
C   CONDITIONS. IT PUTS OUT FOR FURTHER PROCESSING BY PROGRAM FINELT
C   A MESH GENERATED FOR THE GIVEN ALPHA, PHI, TI AND CONTACT LENGTH.
C   IT ALSO PRODUCES FILES OF SHEAR STRAIN, SHEAR STRAIN RATE AND
C   VELOCITY FOR POINTS THROUGHOUT THE PRIMARY ZONE.
C
      DIMENSION X(769,2),NOD(679,4),IREAL(343),NFIXD(31),NDTOOL(271)
      DIMENSION UV(175,2),GAMMA(175),GAMMAD(175)
      DOUBLE PRECISION ACONST,ZED,CAPPA,ABLE,BAKER,CHARLY,
     & ALPHA,PHI,SPHI,CPHI,TPHI,SALPHA,CALPHA,TALPHA,SQARG,
     & XAB,YAB,XB,YB,SSPACE,T1,ALF,COL,DAN,ERN
      DATA NFIXD/187,220,252,282,307,332,356,380,402;420,440,460,482,
     & 506,528,550,573,594,611,626,639,651,663,675,689,705,723,724,
     & 725,726,727/
C  THE FIRST 26 POINTS OF NFIXD ARE THE CLEARANCE FACE NODES OF THE
C  TOOL(NOT TO BE ROTATED). THE LAST 5 ARE THE END FACE NODES.
      OPEN(UNIT=7,DEVICE='DSK',FILE='XYINPT.DAT')
      OPEN(UNIT=5,DEVICE='DSK',FILE='PRIMD.DAT')
      OPEN(UNIT=3,DEVICE='DSK',FILE='RESULT.TXT')
      OPEN(UNIT=20,DEVICE='DSK',FILE='UVEDOT.DAT')
      OPEN(UNIT=8,DEVICE='DSK',FILE='XYTEST.DAT')
C   XYTEST.DAT WILL BE THE NEW MESH PRODUCED BY THIS PROGRAM FOR USE
C   BY FINELT. XYINPT.DAT IS A BASIC MESH WITH ALPHA=0.0 AND THE ORIGIN
C   AT THE TOOL EDGE. THE APPROPRIATE FILE IS COPIED TO XYINPT.DAT
C   BEFORE RUNNING THIS PROGRAM. NOTE THAT THIS PROGRAM SHIFTS THE
C   ORIGIN 0.05 IN. TO THE LEFT, MAKING NEARLY ALL X POSITIVE.
      READ(7,16)  ((X(I,J),J=1,2),I=1,769)

   16 FORMAT(8F10.6)
      READ(5,5)ALPHA,T1,U,T2,CL,CCONST
    5 FORMAT(8F10.6)
      ALPHR=ALPHA*0.017453293
      TPHI=T1/T2*COS(ALPHR)/(1.-T1/T2*SIN(ALPHR))
      PHIR=ATAN(TPHI)
      PHI=PHIR/0.0174533
C
C  ALPHA IS THE RAKE ANGLE(DEG.), T1 THE FEED(INCH), U THE CUTTING
C  SPEED(IN./SEC.), T2 IS THE CHIP THICKNESS(INCH), CL THE TOOL-CHIP
C  CONTACT LENGTH(INCH) AND CCONST IS THE CONSTANT IN THE EQUATION:
C  GAMMADOT(MAX)=C*VS/T1.
C
      WRITE(3,5)ALPHA,T1,U,PHI,CL,CCONST
      READ(5,10)  (IREAL(I),I=1,343)

      WRITE(3,10)(IREAL(I),I=1,343)
   10 FORMAT(20I4)
C   IREAL IS A LIST OF NODE NUMBERS ALONG STREAMLINES, TO THE END
C   OF THE CHIP. THE FIRST STREAMLINE IS AT THE FREE SURFACE.
C   THERE ARE 55 POINTS ON EACH STREAMLINE. THE LAST 13 POINTS IN
C   THIS LIST ARE JUST BELOW THE TOOL EDGE STREAMLINE.
      READ(5,12)((NOD(I,J),J=1,4),I=1,679)
      READ(5,12)(NDTOOL(I),I=1,271)
   12 FORMAT(16I5)
C  NDTOOL IS A LIST OF ALL NODES IN THE TOOL.
      SPHI=SIN(PHIR)
      CPHI=COS(PHIR)
      COTPHI=CPHI/SPHI
      SALPHA=SIN(ALPHR)
```

```
      CALPHA=COS(ALPHR)
      TALPHA=SALPHA/CALPHA
      CONST=U*TPHI*(l.+TPHI*TPHI)

C   •CONST' IS USED IN THE EQUATION FOR SHEAR STRAIN RATE LATER.
      PMA=PHIR-ALPHR
      VC=U*SPHI/COS(PMA)
      ACONST=T1*T1/(16.*CC0NST**2*SPHI**2*(TALPHA + COTPHI))
C   •ACONST' IS USED LATER IN THE CALCULATION OF STREAMLINE COEFFICIENTS.
C*
C  THE FOLLOWING SEGMENT ADJUSTS THE CONTACT LENGTH IN THE MESH, I.E.
C  THE DISTANCE FROM THE TOOL EDGE TO POINT 538 ON THE TOOL FACE.
C  OTHER POINTS THROUGHOUT THE TOOL ARE ADJUSTED TO RETAIN A SIMILAR
C  MESH GRADATION. CLEARANCE & END FACE NODES ARE NOT DISTURBED.
      CLOLD=X(538,2)
      CLDIFF=CL-CLOLD
      DO 25 L=2,271
      M=NDTOOL(L)
      DO 22 N=l,31
      IF(NFIXD(N).EQ.M) GO TO 25
   22 CONTINUE
      IF(X(M,2) .GT.CLOLD) GO TO 24
      X(M,2)=X(M,2) + (X(M,2)/CLOLD)**1.1 * CLDIFF
      GO TO 25
   24 X(M,2)=X(M,2) + CLDIFF
   25 CONTINUE
C  ALSO SHIFT THE CHIP BASE NODES BEYOND POINT 538. THE GAP BETWEEN
C  NODES IS INCREASED 30% AT A TIME UNTIL IT REACHES 0.01, WHERE
C  IT STAYS.
      GAP=X(538,2)-X{537,2)
      GSUM=0.0
      DO 26 K=313,330
      GAP=GAP*1.3
      IF(GAP.GT.0.01) GAP=0.01
      GSUM=GSUM + GAP
      J=IREAL(K)
      X(J,2)=CL + GSUM
   26 CONTINUE
C************************************************************************
C  THE FOLLOWING SEGMENT ROTATES THE TOOL AND CHIP BASE NODES TO SUIT
C  THE GIVEN RAKE ANGLE, KEEPING THE CLEARANCE FACE FIXED.
      DO 35 K=2,271
      J=NDTOOL(K)
      DO 30 L=l,26
      IF(NFIXD(L).EQ.J) GO TO 35
   30 CONTINIip
      X?J,1)=XOLD  *CALPHA+X(J,2)*SALPHA
      X(J,2)=X(J,2)*CAXJ»HA-XOLl>  *SALPHA
   35 CONTINUE
C  ROTATION OF CHIP BASE MODES BEYOMD THE CONTACT LENGTH:
      DO 50 K=313,33Q
      J=IREAL(K)
      X(J,l)=X(J,l)*CALPHA+X(J,2)*SALPHA
      X(J,2)*X(J,2)*CALPHA-X(J,l)*SALPHA
   50 C30HTIMDE
   60 CONTINUE
C  1OW SHIFT THE ORIGIN TO MAKE X VALUES POSITIVE:
      DO 70 1*1,769
      X(I,1)*X(I,1) + 0.0500000
   70 CONTINUE
```

```
C***********************************************************************
C  THIS SEGMENT BUILDS UP THE PRIMARY ZONE AND CHIP MESH FROM THE BASE
C  COORDINATES, VIZ. IREAL(276 TO 330). FIRST THE STREAMLINE EQUATION
C  IS FOUND AND THEN ITS INTERSECTIONS WITH LINES EMANATING FROM THE
C  BASE NODES, PARALLEL TO THE SHEAR PLANE. WE START WITH THE STREAMLINE
C  AT THE FREE SURFACE, WHICH IS PLACED AT A DISTANCE ABOVE THE CUT
C  SURFACE EQUAL TO THE FEED, T1. THE SPACING BETWEEN THE STREAMLINES
C  IS MADE EQUAL TO T1/5. 55 POINTS ARE DETERMINED ON EACH STREAMLINE.
C
      SSPACE=T1/5.
      INDEX=0
      J=0
      DO 100 NSLINE=1,5
      NPRIM=0
      YAB=SSPACE*(6-NSLINE)
      XAB=X(156,1)-YAB/TPHI
C  XAB AND YAB ARE THE POINTS ON THE SHEAR PLANE WHERE THE ASYMTOTES
C  OF THE HYPERBOLIC STREAMLINE INTERSECT.
C  THE COEFFICIENTS OF THE HYPERBOLA, A*Y*Y+B*X*X+C*X*Y+D*Y+E*X=1,
C  ARE FOUND AS FOLLOWS:
      ZED=ACONST-TALPHA*YAB**2+XAB*YAB
      ALF=TALPHA/ZED
      BOB=0.
      COL=-1./ZED
      DAN=(XAB-2.*TALPHA*YAB)/ZED
      ERN=YAB/ZED
      WRITE(3,250)NSLINE
  250 FORMAT(/'  THE COEFFICIENTS FOR STREAMLINE',I3,' ARE:')
      WRITE(3,260)ALF,BOB,COL,DAN,ERN
  260 FORMAT(/'    A =',E15.5,'   B =',E15.5,'   C =',E15.5,'   D ='
     & ,E15.5,'   E =',E15.5)
      WRITE(3,280)
  280 FORMAT(//'  INDEX  NPOINT',7X,'X',11X,'Y',9X,'BETA',7X,'GAMMA',
     & 5X,'GAMMADOT')
C  FINDING THE MESH POINTS ALONG THE STREAMLINE:
      DO 150 I=1,55
      INDEX=INDEX+1
      NPRIM=NPRIM+1
      NBASE=IREAL(275+I)
      XB=X(NBASE,1)
      YB=X(NBASE,2)
      CAPPA=TPHI*XB+YB
C  THE COEFFICIENTS OF THE QUADRATIC WHOSE SOLN. GIVES THE MESH POINT:
      ABLE=ALF-COL/TPHI
      BAKER=COL*CAPPA/TPHI +DAN - ERN/TPHI
      CHARLY=ERN*CAPPA/TPHI-1
C  GIVING THE SOLUTION:
      SQARG=BAKER**2-4.*ABLE*CHARLY
      IF(SQARG.LT.0.0) GO TO 99
      YY=(-BAKER+SQRT(SQARG))/(2.*ABLE)
      XX=(CAPPA-YY)/TPHI
C  MAKING THE SOLUTION A MESH POINT:
      NPOINT=IREAL(INDEX)
      X(NPOINT,1)=XX
      X(NPOINT,2)=YY
C***********************************************************************
C  THE FOLLOWING CALCULATIONS FOR SHEAR STRAIN, SHEAR STRAIN RATE AND
C  VELOCITY ARE ONLY DONE FOR THE PRIMARY ZONE, VIZ. THE FIRST 27 POINTS
C  OF EACH STREAMLINE.
      IF(NPRIM.GT.27) GO TO 150
      J=J+1.
```

```
      DD=2.*ALF*YY + COL*XX + DAN
      SLP=-(2.*BOB*XX + COL*YY + ERN)/DD
      YDD=-2.*(ALF*SLP*SLP + COL*SLP + BOB)/DD
      BETA=ATAN(SLP)
      PPA=PHIR+BETA
      COTPPA=COS(PPA)/SIN(PPA)
      GAMMA(J)=COTPHI-COTPPA
      GAMMAD(J)=YDD*CONST/(TPHI+SLP)**3
      BETAD=BETA/0.01745329
      WRITE(3,450)INDEX,NPOINT,XX,YY,BETAD,GAMMA(J),GAMMAD(J)
  450 FORMAT(I7,I8,2X,F10.6,3X,F10.6,3X,F7.3,3X,F8.3,3X,F9.1)
      UV(J,1)=VC*COS(PMA)*COS(BETA)/SIN(PPA)
      UV(J,2)=VC*COS(PMA)*SIN(BETA)/SIN(PPA)
  150 CONTINUE
  100 CONTINUE
C  THE TOOL EDGE STREAMLINE, UP TO THE TOOL EDGE, IS NOW GIVEN STRAIN,
C  STRAIN RATE & VELOCITY DISTRIBUTIONS OF THE STREAMLINE ABOVE IT.
      DO 600 J=136,150
      K=(J-27)
      GAMMA(J)=GAMMA(K)
      GAMMAD(J)=GAMMAD(K)
      UV(J,1)=UV(K,1)
      UV(J,2)=UV(K,2)
  600 CONTINUE
      DO 650 J=151,162
      UV(J,1)=VC*SALPHA
      UV(J,2)=VC*CALPHA
      GAMMAD(J)=0.0
      GAMMA(J)=SIN(PMA)/COS(PMA) + COTPHI
  650 CONTINUE
      DO 700 J=163,175
      UV(J,1)=U
      UV(J,2)=0.0
      GAMMA(J)=0.0
      GAMMAD(J)=0.0
  700 CONTINUE
C***********************************************************************
      WRITE(20,900)((UV(I,J),J=1,2),I=1,175)
      WRITE(20,900)(GAMMA(I),GAMMAD(I),I=1,175)
      WRITE(8,16)((X(I,J),J=1,2),I=1,769)
  900 FORMAT(2E20.7)
      GO TO 999
   99 WRITE(3,400)
  400 FORMAT(/' NEGATIVE ARGUMENT IN SQUARE ROOT!')
  999 CONTINUE
      STOP
      END
```



APPENDIX IE

GENERATED PRIMAL XON£

MESH .

PS;<MS7Y>FINELT,F0R

APPENDIX m

```
      PROGRAM FINELT
C
C       CALCULATION OF TEMPERATURE DISTRIBUTIONS IN ORTHOGONAL
C       MACHINING,USING THE FINITE ELEMENT METHOD.
C       THIS PROGRAM IS RUN AFTER PRIMRY & MUST USE CORRESPONDING DATA.
C       MAIN PROGRAM:
C
      PARAMETERMAXH=34000,MAXP=769,MAXEL=679,MAXDAT=24,MFB*22*MFE1«23,
     & NTYPE=3,PI=3.141593
      LOGICAL TEST

      DIMENSION H(MAXH),X(MAXP,2),NOD(MAXEL,4),NBANR(MAXP),NBANL(HAXP),
     & ND(MAXP)fT(MAXP),TOLD(MAXP),DENCPS(MAXDAT),CONDS(MAXDAT)
      DIMENSION GAMMA(175)rGAMMAD(175),UV(175,2),Q(175),NFLUX(NFE,2)•„
     & QSEC(NFE,4),VSEC(NFE1)fXSEC(NFElf2)
      DIMENSION NELSLK27)#NUVQ(142f4),NKNOW(22)#NHCWT(148r2),
     & HCWT(148)fHPE(8),PELQS(3,4)fXGAU(3),WTC(3)fWTG(3#3)fXEG(3#3r2)
      OPEN (UNIT=1,DEVICE=•DSK'r FILE='FINREV.DAT' )
      OPEN (UNIT=3,DEVICE='DSK'fFILE='TRESUL.TXT1)
      OPEN(UNIT=7,DEVICE=1DSKt fFILE='XYTEST.DAT1)
C       XYTEST.DAT CONTAINS THE MESH CO-ORDINATES, APPROPRIATE TO THE
C       CONDITIONS, PRODUCED BY THE PROGRAM PRIMRY.
      OPEN(UNIT=20rDEVICE='DSKt, FILE='UVEDOT.DAT1)
      OPEN (UNIT=22f DEVICE^'DSK1,FILE='TQOLD.DAT1)
      OPEN(UNIT=24,DEVICE='DSK1 ,FILE='TEMPS.DAT1)
      READ(1,2) EXPT,NSTEEL

    2 FORMAT(A5,110)
C       •EXPT1 IS AN IDENTIFICATION OF THE MACHINING EXPERIMENT,
C      & •NSTEEL1 IS THE SAE NUMBER FOR THE STEEL, EG. 1020.
      WRITE(3,5) EXPT,NSTEEL

    5-FORMAT(***********************************************!/*..*EXPT*',A10#

      READ(1,1 ) ITSTfITMAX

      WRITE(3,1) ITST,ITMAX

    1 FORMAT(8110)
C      MAKE ITST=1 IF ALL TEMPERATURES TO START AT TROOK; 2 IF PRE¥I0U8
C       ITERATIONS TO BE RESUMED.
      READ(1,8)  RERROR
      WRITE (3,33 RERROR

    3 FORMAT(/' ITERATIONS STOP WHEN MAX. EEL. ERROR < *fF6»3)
C
C       READING CUTTING CONDITIONS, MATERIAL PROPERTIES* ETC.
C
      READ(1,6) l!wlllwT2,ALPHA,PT,FC,CL,W,TROON,TSHAMK,DT2,PCL

    6 FORMAT(8F10.4>
C       THE DATA VALUE FOR PCL SHOULD BE 0.0 IF TBE PLASTIC CQ1TACT
C       LENGTH WAS NOT MEASURED.  GIVE A VALUE OF 80 DE8.C TO TSRAMK
C       IF THE TCX)L SHMK TEMPERATURE WAS MOT MEASURED.  GIVE I
C       VALUE OF 0.0' TO DT2 IF SBC.ZQMB TH1CK1ESS HOT MEASURED.
      ALPHR=ALPHA*O.0174533
      TPHI«T1/T2*COS(ALPHR)/(1.-Tl/T2*SII(ALPHR))
      PHIR=ATAH(TPHI)
      PHI*PHIR/0.0174533
      VC « U*SIH(PHIR)/(COS(PHIR-ALPHR))
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```
      IF(DT2.EQ.0.0) DT2=0.05*T2
      IF(PCL.EQ.0.0) PCL=CL/2.
      WRITE(3,14)U,T1,PHI,ALPHA,FT,FC,CL,W,TROOM,TSHANK,VC,DT2,PCL
   14 FORMAT(///' ******************'/' CUTTING CONDITIONS:'/' *********

     &**********'//T26' WORK VELOCITY,  U =',F10.4,'  IN/SEC'
     & //T26,' FEED RATE, T1 =',F10.4,' INCH/REV.'
     & //T26,' SHEAR ANGLE, PHI =',F10.4,' DEGREES'
     & //T26,' RAKE ANGLE, ALPHA =',F10.4,' DEGREES'
     & //T26,' FEED FORCE, FT =',F10.4,' LBS.'
     & //T26,' CUTTING FORCE, FC =',F10.4,' LBS.'
     & //T26,' CONTACT LENGTH, CL =',F10.4,' INCH'
     & //T26,' WIDTH OF CHIP, W =',F10.4,' INCH'
     & //T26,' ROOM TEMP., TROOM =',F10.4,' DEGREES'
     & //T26,' TOOL SHANK TEMP.,TSHANK ='F8.2,' DEG.C'
     & //T26,' CHIP VELOCITY, VC =',F10.4,' INCH/SEC.'
     & //T26,' SEC.ZONE THICKN., DT2 =',F10.4,' INCH'
     & //T26,' PLASTIC CONTACT, PCL =',F10.4,' INCH')
      READ(1,8) DEN,CP,WCOND,TCOND
      WRITE(3,13) DEN,CP,WCOND,TCOND
      READ(1,1) NDATA

      READ(1,8) (DENCPS(I),I=1,NDATA)

      WRITE(3,8)(DENCPS(I),I=1,NDATA)

      READ(1,8)   (CONDS(I),I=1,NDATA)

      WRITE(3,8)  (CONDS(I),I=1,NDATA)

    8 FORMAT(4E20.7)
   13 FORMAT(/////' ****************************'/' MATERIAL THERMAL PROP
     &ERTIES:'/' ****************************'
     & //T26,' WORK DENSITY AT 50C =',E20.7,' LB/CU.IN.'
     & //T26,' WORK SPECIFIC HEAT AT 50C =',E20.7,' CHU/LB'
     & //T26,' WORK CONDUCTIVITY AT 50C =',E20.7,' CHU/SEC.IN.DEG.C'
     & //T26,' TOOL TIP CONDUCTIVITY AT 22C =',E20.7,' CHU/SEC.IN.DEG.C'
     & //' WORK PROPERTY VARIATION WITH TEMPERATURE, 50 DEG.C STEPS:'/
     &' FIRST SET:PRODUCT OF DENSITY & SPEC.HT.;SECOND:CONDUCTIVITY'/)
C
C       READING MESH PARAMETERS
C
      READ  (1,1) NPOIN,NELEM,NPR1,NENDR1,NENDR2,NENDR3,NENDR4,NBOUN,

     &IHC,IHW,IHT
      WRITE(3,15) NPOIN,NELEM,NPR1,NENDR1,NENDR2,NENDR3,NENDR4,NBOUN,

     &IHC,IHW,IHT
      READ (1,1) IQTL,NX1,NY1,NITL1,NITL2,NXBT1

      WRITE(3,1) IQTL,NX1,NY1,NITL1,NITL2,NXBT1

      READ(1,1)   IHST,IHEND

      WRITE(3,1)  IHST,IHEND

C      IHST & IHEND IDENTIFY THE FIRST & LAST NODES OF TOOL-TO-SHANK
C      CONTACT IN THE MATRIX (NHCWT).
      READ (1,8)  HINTF
```

```
      WRITE(3,8)  HINTF
C      HINTF IS THE TOOL TO SHANK CONDUCTANCE IN CHU/S. SQ.IN. DEG.C
   15 FORMAT(///f ****************•/• MESH PARAMETERS:1/1 ************
     £****«//T26,• NPOIN =ffI10//T26,1 NELEM =•,I10//T26,f NPR1  =',110
     &//T26,1 NENDRl=r,I10//T26,f NENDR2=',I10//T26,• NENDR3=f,I10//T26,
     &' NENDR4=',I10//T26r' NBOUN =f,I10//T26,f IHC   =f,I10//T26,f IHW
     &  =lfI10//T26rf IHT   «f,I10/)
      IHCWT=IHC+IHW+IHT
      IHCW=IHC+IHW
C     IHCW2=IHCW+1
C       CALCULATION OF SHEAR STRESS ON AB & ANY RESULTING CORRECTION
C       REQUIRED FOR THE STRESS FUNCTION.
C
      GAMDOT=4.67*U*COS(ALPHR)/(T1*COS(PHIR-ALPHR))
      ALMINA=ATAN(FT/FC)
      THETA=PHIR+ALMINA
      RESUL=SQRT(FC*FC +FT*FT)
      ZEE=1. + 1./(4-*4.67*SIN(PHIR)*(TAN(ALPHR)+1./TAN(PHIR)))
      TAUAB=RESUL*COS(THETA)*SIN(PHIR)/(T1*V*2EE)
      CALL     STRESS(GAMTOT,NSTEEL9TAU)
      DELTAU=TAUAB-TAU
      WRITE(3,10)TAU,TAUAB
   10 FORMAT(//f  CALCULATED SHEAR STRESS «ffF10.2ff    SHEAR STRESS ON
     &AB =ffF10.2,•    (PSI)•//)
C
C     CALCULATING GAUSSIAN CO-ORDINATES
C
      READ(lfl)  (HPE(I)fI=lf3 )
      READ(lrl) NGP
      READ(lf8)  (XGAU(I)fI=1,NGP),(WTC(I)#J=lfNGP)
      DO 30 I=1-,NGP
      XDUM=XGAU(I)
      DO 30 J=1,NGP
      WTG(I,J)= WTC(I)*WTC(J)
      XEG(I,J,2)= XfiUH
      XEG(J,I,1) * XDUM
   30 CX>NTINUE
      WRITE(3,22)  (((XEG(I,J,K),J»1,KGP),I=1,NGP),K=1,2)
   22 FORMAT(3E20.7 )
      WRITE (3r23) NGP,(XGAU(I),I=1,MGP),(WTC(I),1=1,NGP )
```

```
   23 FORMAT(///' NGP   =',I10//' XGAU(I)=',3E20.7//' WTC(I) =',3E20.7/)

C

C      READING NODE NUMBERS, BOUNDARY NODES, PRIMARY ZONE STRAINS,
C      STRAIN RATES & VELOCITIES AND NODE COORDINATES.
C

      READ(1,920) (NELSL1(I),I=1,NX1)

      READ(1,920)((NOD(I,J),J=1,4),I=1,NELEM )
      READ(1,920) (NKNOW(I),I=1,NBOUN)

      READ(1,920) ((NHCWT(I,J),J=1,2),I=1,IHCWT )

      READ(1,920) ((NFLUX(I,J),J=1,2),I=1,NFE )

      READ(1,920) ((NUVQ(I,J),J=1,4),I=1,NENDR1 )

      READ(20,970) ((UV(I,J),J=1,2),I=1,NPR1)
      READ(20,970) (GAMMA(I),GAMMAD(I),I=1,NPR1)
      READ(7,950) ((X(I,J),J=1,2),I=1,NPOIN )

  900 FORMAT(10I8)
  920 FORMAT(16I5)
  950 FORMAT(8F10.6)
  970 FORMAT(2E20.7)
C

      CALL BANWTH(NELEM,NPOIN,NTYPE,NPE,NOD,ND,NBANR,LH,NBANL)
C
      IF(LH.LE.MAXH) GO TO 40

      WRITE (3,610) LH

  610 FORMAT(//' CHECK LH=',I10)
      STOP

   40 CONTINUE

      WRITE (3,611) LH

  611 FORMAT(//' LENGTH OF ARRAY H, LH = ',I10)
      F=FT*COS(ALPHR)+FC*SIN(ALPHR)
      QC= F*VC/16800./CL/W
      QCL= QC*CL

      QTOT= FC*U/W/16800. - QCL
      WRITE (3,614)QCL,QC,QTOT

  614 FORMAT(//' QCL=',E20.8,5X,' QC=',E20.8,5X,' QTOT=',E20.8)

C

C     CALCULATING COORDINATES OF THE SECONDARY ZONE (ASSUMED TRIANGULAR)
C

      NY=NY1-1
```

```
C    BY-PASS THIS SEGMENT IF SECONDARY DEFORMATION IS NEGLIGIBLE.
       IF(DT2.LT.0.0001) GO TO 840

C        CALCULATE NFHALF, THE NUMBER OF NODES FROM THE TOOL EDGE
C        WHERE PLASTIC CONTACT FINISHES.
       YPCL=PCL*COS(ALPHR)
C        IF THE PLASTIC CONTACT LENGTH HAS NOT BEEN MEASURED, A VALUE
C        OF 0.0 SHOULD BE GIVEN FOR IT IN THE DATA. THE PROGRAM WILL
C        THEN ASSIGN IT A VALUE OF HALF THE TOTAL CONTACT LENGTH.
       IF(PCL.EQ.CL)GO TO 715
       DO 714 I=1,NFE
       K=NFLUX(I,2)
       YK=X(K,2)
       IF(YK.LT.YPCL)GO TO 714
       NFHALF=I
       YPCL=YK
       PCL=YPCL/COS(ALPHR)
       GO TO 716
   714 CONTINUE
   715 NFHALF=NFE
   716 NFH1=NFHALF+1
       J3=NOD(NITL1+1+NFHALF*NY,2)

       WRITE(3,618)NFHALF,PCL,J3
   618 FORMAT(/'  NFHALF=',I4,'    PCL=',F8.4,'     J3=',I6//)
       NFEF=NFHALF

       DO 751 I=1,NFEF

       N=NITL1+1+I*NY

       IF(I.EQ.1) N=NITL2

       J1=NOD(N,1)

       J2=NOD(N,4)

       DIST= SQRT((X(J1,1)-X(J2,1))**2 + (X(J1,2)-X(J2,2))**2)

       ANG=ATAN((X(J2,2)-X(J1,2))/(X(J1,1)-X(J2,1))) - ALPHR

       IF(I.NE.1) GO TO 752
       BIT=DT2/COS(ANG)/DIST

       HEFF=PCL-DT2*TAN(ANG)
       PSY=ATAN(HEFF/DT2)

       XSEC(NFH1,1)=X(J3,1)

       XSEC(NFH1,2)=X(J3,2)

       GO TO 753

   752 CONTINUE

       ANG1=PI-ANG-PSY
       DIS = SQRT((X(J1,1)-X(J3,1))**2 + (X(J1,2)-X(J3,2))**2)

       DSEC=DIS/HEFF*DT2
```

```
      BIT=DSEC*SIN(PSY)/SIN(ANG1)/DIST
  753 CONTINUE
      DO 751 J=1,2
      XSEC(I,J)=X(J1,J)+BIT*(X(J2,J)-X(J1,J))
  751 CONTINUE
      WRITE (3,8) ((XSEC(I,J),J=1,2),I=1,NFH1)
C
C     CALCULATING Q DISTRIBUTION IN SECONDARY ZONE
C
      TAUINT=F*2./(PCL+CL)/W
      GMDMAX=VC/DT2
      QSITL=TAUINT*GMDMAX/16800.
      DO 456 K=1,NFHALF
      DO 456 L=1,2
      QSEC(K,L)=QSITL
  456 CONTINUE
      DO 810 I=1,NFHALF
      QSEC(I,3)= 0.
      QSEC(I,4)= 0.
  810 CONTINUE
      WRITE (3,8) ((QSEC(I,J),J=1,4),I=1,NFHALF)
  840 CONTINUE
C
C     ITERATING FOR TEMPERATURE DISTRIBUTION
C
      DO 100 ITER=ITST,ITMAX
      IF(ITER.NE.ITST) GO TO 133
      IF(ITER.NE.1) GO TO 131
      DO 135 I=1,NPOIN
      TOLD(I)= TROOM
  135 CONTINUE
      DO 136 I=1,NPR1
      Q(I)= 0.1000000E+05
  136 CONTINUE
      GO TO 134
  131 READ (22,980) (TOLD(I),I=1,NPOIN)
      READ (22,980) (Q(I),I=1,NPR1)
  980 FORMAT(5F10.2)
      GO TO 134
```

```
  133 DO 130 1=1,NPOIN
  130 TOLD(I)=T(I)
  134 CONTINUE
C
C     CALCULATING DISTRIBUTION OF HEAT SOURCES IN PRIMARY ZONE.
C     SINCE STRESS IS A FUNCTION OF STRAIN RATE ONLY, THIS ONLY
C     NEEDS TO BE DONE ON THE FIRST ITERATION.
C
      IF(ITER-GT.l) GO TO 140
      CALL QRATE(Q,GAMMA,GAMMAD,NPR1,TOLD,NPOIN,NELSL1,NX1,NY1,QITL,
     SIQTL,IHCWT,ITER,ITST,NXBT1,NITL2,NOD,NELEM,NSTEEL,DELTAU)
  140 CONTINUE
C
C     ASSEMBLYING PROBLEM MATRICES (H) AND (P)
C
      CALL   HMATEL(NOD,X,NELEM,NPOIN,NTYPErNPE,DENCPS,CONDS,
     &QCrWTG,VC,U,ALPHR,NENDR1,NENDR2,NENDR3,NENDR4,NFE,NGP,T,UV,Q,NPR1,
     &XEGfH,LH,ND,TOLD,QTOTrNITLl#NITL2,NFLUXfNUVQ/IQTL#NDATAlITER,NBANR
     &fPELQS,SUMA)
C
C     lODIFYING (H) AMD (P) ACX^RDIIG TO INTERFACIAL VEDXITY DISTRIBUTION
C     AND SECONDARY ZONE HEAT SOURCES
C
      CALL    HSECP(NODrX,NELEUfNPOINrNTYPE,NPEfDENCPS,O)NDS,
     &QC,WTG,VC,U,ALPHR,NENDR1,NENDR2,NENDR3fNENDR4,HFE,NGP/T',UVfQ>HPRlf
     &XEG,H,LH,ND,TOLD,QTOT,NITL1,NITL2,NFLUX,NUVQ,IQTL,NDATA,ITER,NBANR
     &,QSEC,XSEC,NFE1,NX1NBT,CL,NY,VSEC,DT2,PELQS,SUMA,ISHAPE,QSITL,
     & NFHALFrPCLfTAUINT)
C
      SHK«O.
      W3 702 I=lfNP01N
      SUM=SUM+T(I)
  702 CONTINUE
      WRITE (3f9) SUM
```

```
    9 FORMAT(/' TEMP.SUM =',E20.7/)
C
C     IMPOSING BOUNDARY CONDITIONS
C
      CALL   BC(H,LH,NKNOW,NBOUN,ND,NBANR,T,NPOIN,X,NHCWT,IHCWT,HCWT,
     &TROOM,IHST,IHEND,HINTF,TSHANK)
C
C     SOLVING FOR TEMPERATURE DISTRIBUTION
C
      CALL  GBAND(NPOIN,H,LH,ND,T,NBANR )
C
      WRITE (3,622) ITER
  622 FORMAT(/' NUMBER OF ITERATIONS  =',I5)
      WRITE (3,11)
   11 FORMAT(//' TEMPERATURES:  (DEG C)'/)
      WRITE (3,4) (I,T(I),I=1,NPOIN)
    4 FORMAT(I10,F10.2,I10,F10.2,I10,F10.2,I10,F10.2,I10,F10.2)
C
C     TESTING CONVERGENCE OF TEMPERATURE DISTRIBUTION
C
      DIFMAX=0.
      RERMAX=0.
      TEST=.FALSE.
      DO 110 I=1,NPOIN
      TNEW=T(I)
      TOLE=TOLD(I)
      IF(TOLE.LT.0.1) GO TO 110
      DIFF=TNEW-TOLE
      RDIFF=DIFF/TOLE
      DIFF=ABS(DIFF)
      RDIFF=ABS(RDIFF)
```

```
      IF(DIFF.GT.DIFMAX) DIFMAX=DIFF
      IF(RDIFF.GT.RERMAX) RERMAX=RDIFF
      IF(RDIFF.GT.RERROR) TEST=.TRUE.
  110 CONTINUE
      WRITE (3,634) DIFMAX,RERMAX
  634 FORMAT(/' MAX ERROR=',E20.6,8X,'MAX RELATIVE ERROR=',E20.6)
      IF(TEST) GO TO 100
      WRITE (3,400)
  400 FORMAT(//' CONVERGENCE HAS BEEN REACHED')
C
      CALL TEMPLT(NPOIN,NELEM,NHCWT,NKNOW,NOD,X,T,IHC,IHW,IHT,NBOUN,
     & NENDR3,IHCWT)
C
      GO TO 120
  100 CONTINUE
      WRITE (3,401)
  401 FORMAT(//' CONVERGENCE HAS NOT BEEN REACHED')
  120 CONTINUE
      WRITE (22,980) (T(I),I=1,NPOIN)
      WRITE (22,980) (Q(I),I=1,NPR1)
      WRITE (24,980) (T(I),I=1,NPOIN)
      STOP
      END
C***********************************************************************
      SUBROUTINE HMATEL(NOD,X,NELEM,NPOIN,NTYPE,NPE,DENCPS,CONDS,
     &QC,WTG,VC,U,ALPHR,NENDR1,NENDR2,NENDR3,NENDR4,NFE,NGP,T,UV,Q,NPR1,
     &XEG,H,LH,ND,TOLD,QTOT,NITL1,NITL2,NFLUX,NUVQ,IQTL,NDATA,ITER,NBANR
     &,PELQS,SUMA)
C
C     ASSEMBLYING PROBLEM MATRICES  (H)  AND  (P)
C     CONSIDERING ONLY THE PLANE UNIFORM HEAT SOURCE ALONG THE
C     INTERFACE DUE TO SLIDING FRICTION.
C
      DIMENSION DENCPS(NDATA),CONDS(NDATA)
      DIMENSION NOD(NELEM,4),X(NPOIN,2),WTG(NGP,NGP),
     &XEG(NGP,NGP,2),H(LH),ND(NPOIN),UV(NPR1,2),Q(NPR1),TOLD(NPOIN),TE(4
     &),PELQS(3,4),T(NPOIN),NUVQ(NENDR1,4),NFLUX(NFE,2),NBANR(NPOIN)
```

```
      DIMENSION XE(4,2),NPE(3),ZETA(4,2),HEL(4,4),PEL(4)
      VCX=VC*SIN(ALPHR)
      VCY=VC*COS(ALPHR)
      KNTL=0
      ZETA(1,1)=-1.
      ZETA(1,2)=-1.
      ZETA(2,1)= 1.
      ZETA(2,2)=-1.
      ZETA(3,1)= 1.
      ZETA(3,2)= 1.
      ZETA(4,1)=-1.
      ZETA(4,2)= 1.
      DO 80 I=1,LH
   80 H(I)= 0.
      DO 81 I=1,NPOIN
   81 T(I)= 0.
C
C     ASSEMBLYING PROBLEM MATRICES  (H)  AND  (P)
C
      DO 20 N=1,NELEM
      LL=NPE(NTYPE)
      DO 51 I=1,LL
      PEL(I)= 0.
      DO 51 J=1,LL
   51 HEL(I,J)= 0.
      DO 30 I=1,LL
      JJ=NOD(N,I)
      TE(I)=TOLD(JJ)
      XE(I,1)=X(JJ,1)
   30 XE(I,2)=X(JJ,2)
```

```
      CALL      ESTQ4L(XE,XEG,LL,UV,Q,NPR1,NGP,HEL,PEL,DENCPS,CONDS,
     &NDATA,WTG,NENDR1,NENDR2,NENDR3,NENDR4,VCX,VCY,U,ZETA,N,TOLD,TE
     &,NITL1,NITL2,PELQS,KNTL,IQTL,NPOIN,NUVQ)
   40 CONTINUE
      CALL      ASMBLY(H,LH,NOD,ND,NELEM,NPOIN,HEL,PEL,LL,N,T,NENDR1)
   20 CONTINUE
C
C     ADJUSTING QITL FOR ENERGY BALANCE
C
      SUMQ=0.
      DO 100 I=1,NPOIN
  100 SUMQ=SUMQ+T(I)
      WRITE (3,3) SUMQ
    3 FORMAT(//' SUMQ  =',E20.7)
      SUMA=0.
      DO 110 I=1,KNTL
      DO 110 J=1,4
  110 SUMA=SUMA+PELQS(I,J)
      WRITE(3,4)
    4 FORMAT(/'  PELQS VALUES, FOLLOWED BY SUMA:')
      WRITE (3,5) ((PELQS(I,J),J=1,4),I=1,KNTL),SUMA
    5 FORMAT(/4E20.7)
      QDIFF=(QTOT-SUMQ)/SUMA
      Q(IQTL)=Q(IQTL) +QDIFF
      WRITE (3,5) Q(IQTL)
      DO 120 I=1,KNTL
      N=NITL1+I-1
      DO 120 J=1,4
      II=NOD(N,J)
  120 T(II)=T(II)+PELQS(I,J)*QDIFF
C
C     ADDITIONAL CONTRIBUTIONS FROM HEAT FLUX ALONG INTERFACE
C
```

```
      DO 60 K=1,NFE
      J1= NFLUX(K,1)
      J2=NFLUX(K,2)
      DIST= SQRT((X(J1,1)-X(J2,1))**2+(X(J1,2)-X(J2,2))**2)
      WRITE (3,74) J1,J2,DIST
      T(J1)= T(J1) + QC*DIST/2.
   74 FORMAT(/' J1 =',I10,'    J2 =',I10,'    DIST =',F12.6)
  60  T(J2)= T(J2) + QC*DIST/2.
      RETURN
      END
C**********************************************************************
      SUBROUTINE MULT(A,B,C,L,M,N)
C
C     MATRIX MULTIPLICATION  A * B = C
C
      DIMENSION A(L,M),B(M,N),C(L,N)
      DO 10 I=1,L
      DO 10 J=1,N
      SUM=0.
      DO 20 K=1,M
   20 SUM=SUM+A(I,K)*B(K,J)
   10 C(I,J)=SUM
      RETURN
      END
C**********************************************************************
      SUBROUTINE ESTQ4L(XE,XEG,LL,UV,Q,NPR1,NGP,HEL,PEL,DENCPS,CONDS,
     &NDATA,WTG,NENDR1,NENDR2,NENDR3,NENDR4,VCX,VCY,U,ZETA,N,TOLD,TE
     $,NITL1,NITL2,PELQS,KNTL,IQTL,NPOIN,NUVQ)
C
C     CALCULATION OF ELEMENT MATRICES:-
C     LOCAL VALUES OF MATERIAL PROPERTIES ARE USED.
C
      DIMENSION XE( 4,2),XEG(NGP,NGP,2),UV(NPR1,2),Q(NPR1),WTG(NGP,NGP),
```

```
     &HEL(4,4),PEL(4),TE(4),TOLD(NPOIN),PELQS(3,LL),DENCPS(NDATA),
     &CONDS(NDATA),PELQ(4,4),QE(4),SSA(2,4),NUVQ(NENDR1,4)
      DIMENSION         SFN(4),AJ(2,2),ZETA(4,2),AJI(2,2),DELN(2,4)
      IF(N.GT.NENDR1) GO TO 10
      DO 160 I=1,LL
      DO 160 J=1,LL
  160 PELQ(I,J)=0.
   10 CONTINUE
      DO 40 II=1,NGP
      DO 40 JJ=1,NGP
      WT=WTG(II,JJ)
      XZ=XEG(II,JJ,1)
      YZ=XEG(II,JJ,2)
C
C     COMPUTING SHAPE FUNCTIONS AND THEIR DERIVATIVES
C
      SFN(1)= (1.-XZ)*(1.-YZ)/4.
      SFN(2)= (1.+XZ)*(1.-YZ)/4.
      SFN(3)= (1.+XZ)*(1.+YZ)/4.
      SFN(4)= (1.-XZ)*(1.+YZ)/4.
      DO 60 I=1,LL
      DELN(1,I)= ZETA(I,1)*(1.+YZ*ZETA(I,2))/4.
   60 DELN(2,I)= ZETA(I,2)*(1.+XZ*ZETA(I,1))/4.
C
C     COMPUTING JACOBIAN MATRIX, IT'S DETM AND INVERSE
C
      CALL MULT(DELN,XE,AJ,2,LL,2)
      DETJ= AJ(1,1)*AJ(2,2)-AJ(2,1)*AJ(1,2)
      AJI(1,1)= AJ(2,2)/DETJ
      AJI(1,2)=-AJ(1,2)/DETJ
      AJI(2,1)=-AJ(2,1)/DETJ
```

```
      AJI(2,2)= AJ(1,1)/DETJ
      CALL MULT(AJI,DELN,SSA,2,2,LL)
      TZ= 0.
      DO 120 1=1,LL
  120 TZ=TZ+SFN(I)*TE(I)
      CALL    PROPTY(DENCPS,CONDS,NDATA,TZ,DENCP,COND,N,NENDR3,
     & NENDR4)
C     COMPUTING ELEMENT STIFNESS MATRIX
      IF(N-GT.NENDRl) GO TO 90
      UZ=0.
      VZ= 0-
      QZ=O.
      DO 50 1=1,LL
      NN=NUVQ(N,I)
      QE(I)=Q{NN)
      UZ=UZ+SFN(I)*UV(NN,l)
      VZ=VZ+SFN(I)*UV(NN,2)
   50 CONTINUE
      SO 81 1=11LL
      BO 81 J=l,LL
   81 PELQ(I,J)=PELQ(I,J)+SFM(I)*SFM(J)*DETJ«WT
      GO TO 91
   90 IF(H.GT.KENBR2) O3 TO 92
      UZ=VCX
      VZ=VCY
      GO TO 91
   92 IF(N*GT,NEMBR3) GO TO 93
      UZ=iJ
      VZ=O.
   91 COITIIUE
      SA= (UZ*AJI(1,1)+VZ*AJI(2,1))*DETJ
```

```
      SB= (UZ*AJI(1,2)+VZ*AJI(2,2))*DETJ
      DO 80 I=1,LL
      DO 80 J=1,LL
      SCONV= DENCP*SFN(I)*(SA*DELN(1,J)+SB*DELN(2,J))
      SCOND= COND*DETJ*(SSA(1,I)*SSA(1,J)+SSA(2,I)*SSA(2,J))
   80 HEL(I,J)=HEL(I,J)+WT*(SCONV+SCOND)
      GO TO 40
   93 CONTINUE
      DO 110 I=1,LL
      DO 110 J=1,LL
      SCOND= COND*DETJ*(SSA(1,I)*SSA(1,J)+SSA(2,I)*SSA(2,J))
  110 HEL(I,J)=HEL(I,J)+WT*SCOND
   40 CONTINUE
      CALL MULT(PELQ,QE,PEL,LL,LL,1)
      IF(N.LT.NITL1) GO TO 1000
      IF(N.GT.NITL2) GO TO 1000
      KNTL=KNTL+1
      DO 130 J=1,LL
      IF(NUVQ(N,J).EQ.IQTL) GO TO 140
  130 CONTINUE
  140 DO 150 I=1,LL
  150 PELQS(KNTL,I)=PELQ(I,J)
 1000 CONTINUE
      RETURN
      END
C*************************************************************************
      SUBROUTINE QRATE(Q,GAMMA,GAMMAD,NPR1,TOLD,NPOIN,NELSL1,NX1,NY1,
     &QITL,IQTL,IHCWT,ITER,ITST,NXBT1,NITL2,NOD,NELEM,NSTEEL,DELTAU)
C
C     COMPUTING HEAT GENERATION RATE AT POINTS IN THE PRIMARY ZONE
C     IF ITER = 1 THE FIRST APPROXIMATION TO Q(I) WILL BE USED
```

```
C
      DIMENSION GAMMA(NPR1),GAMMAD(NPR1),TOLD(NPOIN),NELSL1(27)
      DIMENSION Q(NPR1),NOD(NELEM,4)
      WRITE (3,3)
    3 FORMAT(/'   JJ   NODE',T18,'GAMMA',T33,'GAMMA-DOT',T47,'  K1  '
     &,T63,'EXPN',T77,' TAU  ',T92,'Q(JJ)',T107,'QDIFF',T123,'TEMP')
      JJ=0
      NIT=NITL2+NY1-2
      DO 12 I=1,NY1
      IF(I.EQ.3) NELSL1(NXBT1)=NITL2
      DO 10 J=1,NX1
      JJ=JJ+1
      IF(I.NE.1) GO TO 500
      NEL=NELSL1(J)
      NN=NOD(NEL,4)
      GO TO 510
  500 NEL=NELSL1(J)+I-2
      IF(I.NE.NY1) GO TO 520
      IF(NEL.NE.NIT) GO TO 520
      NEL=NITL2
      NELSL1(NXBT1)=NIT
  520 NN=NOD(NEL,1)
  510 CONTINUE
      GAM=GAMMA(JJ)
      GAMDOT=GAMMAD(JJ)
      IF(GAMDOT.GT.0.1) GO TO 40
      Q(JJ)=0.
      IF(JJ.EQ.IQTL) QITL=Q(JJ)
      GO TO 10
   40 CONTINUE
      CALL STRESS(GAMDOT,NSTEEL,TAU)
      TAU1=TAU + DELTAU
      EXPN = 0.001
C        STRAIN HARDENING IS CONSIDERED NEGLIGIBLE FOR THE PRESENT
C        MATERIAL, SO EXPONENT N IS GIVEN A VERY SMALL VALUE.
```

```
      TAU=TAU1*GAM**EXPN
      QOLD=Q(JJ)
      TEMP=TOLD(NN)
      Q(JJ)= TAU*GAMDOT/16800.
      QDIFF=Q(JJ)-QOLD
      IF(JJ.EQ.IQTL) QITL=Q(JJ)
   11 WRITE (3,4) JJ,NN,GAM,GAMDOT,TAU1,EXPN,TAU,Q(JJ),QDIFF,TEMP
    4 FORMAT(I5,I7,8E15.7)
   10 CONTINUE
   12 CONTINUE
      JJ=JJ+1
      DO 50 I=JJ,NPR1
   50 Q(I)= 0.
      RETURN
      END
C***********************************************************************
      SUBROUTINE ASMBLY(H,LH,NOD,ND,NELEM,NPOIN,HEL,PEL,LL,N,T,NENDR1)
C
C     ASSEMBLYING ELEMENT MATRICES INTO PROBLEM MATRIX
C
      DIMENSION H(LH),NOD(NELEM,4),ND(NPOIN),HEL(4,4),PEL(4),T(NPOIN)
      DO 10 I=1,LL
      II=NOD(N,I)
      IF(N.GT.NENDR1) GO TO 20
      T(II)=T(II)+PEL(I)
   20 CONTINUE
      DO 10 J=1,LL
      JJ=NOD(N,J)-II+ND(II)
   10 H(JJ)=H(JJ)+HEL(I,J)
      RETURN
      END
C***********************************************************************
      SUBROUTINE    ASM(H,LH,NOD,ND,NELEM,NPOIN,HEL,PEL,LL,N,T)
```

```
C
C      SUBTRACTING ELEMENT MATRIX HEL FOR SIMPLE SLIDING FRICTION
C      FROM PROBLEM MATRIX H.
C
       DIMENSION H(LH),N0D(NELEM,4),ND(NPOIN),HEL(4,4),PEL(4),T(NPOIN)
       DO 10 1=1,LL
       II=NOD(N,I)
       DO 10 J=1,LL
       JJ=NOD(N,J)-II+ND(II)
    10 H(JJ)=H(JJ)-HEL(I,J)
       RETURN
       END
C*******************************************************************************
       SUBROUTINE ASMBL(H,LH,NOD,ND,NELEM,NPOIN,HEL,PEL,LL,N,T)
C
C      ASSEMBLING ELEMENT MATRIX HEL FOR ACTUAL INTERFACE VELOCITY
C      DISTRIBUTION INTO PROBLEM MATRIX H.
C
       DIMENSION H(LH),NOD(NELEM,4),HD(HPOIM),HEL(4,4),PEL(4),T(NPOIN)
       DO 10 1=1,LL
       II=NOD(N,I)
       K) 10 J=1,LL
       JJ=NOD(K,J)-II+ND(11)
    10 H(JJ)»H(JJ)+HEL(I,J)
       RETURN
       EHD
C******************************************************************************
       SUBROUTINE HSECP (NOD,X,NELEM,NPOIH,MT1PE,NPE,DENCPS,CONDS,
      &^,¥TG,VC,U,ALPHR,MENDR1,NENDR2,NENDR3,NENDR4,NFE,NGP,T,UV,Q,IPR1,
      &XEG,H,LH,ND,TOLD,QTOT,NITL1,NITL2,NFLUX,NUVQ,IQTL,NDATA,ITER,NBANR
      &,QSEC,XSB:,NFE1,NX1MBT,CL,MY,VSEC,I)T2,PELQS,SUMA,ISHAPE,QSITL,
      & IFHALF,PCL,TMIIT)
C
```

```
C     SUBROUTINE MODIFIES (H) & (P) FROM THE PLANE UNIFORM FRICTION
C     SOURCE ANALYSIS TO ALLOW FOR SECONDARY PLASTIC DEFORMATION.
C     THE INTERFACE CHIP VELOCITY VARIES WITH DRAG-BACK, STARTING AT
C     VC/3 AT THE TOOL EDGE, & REACHING VC AT THE END OF PLASTIC
C     CONTACT.
C
      DOUBLE PRECISION XE(4,2),XX,YY,A1,A2,B1,B2,C1,C2,D1,D2,EE,FF,GG,
     &EGG,FF2
      DIMENSION DENCPS(NDATA),CONDS(NDATA)
      DIMENSION NOD(NELEM,4),X(NPOIN,2),WTG(NGP,NGP),
     &XEG(NGP,NGP,2),H(LH),ND(NPOIN),UV(NPR1,2),Q(NPR1),TOLD(NPOIN),TE(4
     &),PELQS(3,4),T(NPOIN),NUVQ(NENDR1,4),NFLUX(NFE,2),NBANR(NPOIN)
      DIMENSION XK(4,2),NPE(3),ZETA(4,2),HEL(4,4),PEL(4)
      DIMENSION QSEC(NFE,4),XSEC(NFE1,2),VSEC(NFE1),SFN(4),DELN(2,4),
     &AJ(2,2),XES(4,2)
      VCX=VC*SIN(ALPHR)
      VCY=VC*COS(ALPHR)
      TCOS=COS(ALPHR)
      TSIN=SIN(ALPHR)
      ZETA(1,1)=-1.
      ZETA(1,2)=-1.
      ZETA(2,1)= 1.
      ZETA(2,2)=-1.
      ZETA(3,1)= 1.
      ZETA(3,2)= 1.
      ZETA(4,1)=-1.
      ZETA(4,2)= 1.
C
C     MODIFYING  (H)  AND  (P)
C
      VSEC(1) = VC/3.
      Q1 = TAUINT*VC/3./16800.-QC
      SDS=0.
      DO 60 K=1,NFE
      J1= NFLUX(K,1)
```

```
      J2=NFLUX(K,2)
      DIST= SQRT((X(J1,1)-X(J2,1))**2+(X(J1,2)-X(J2,2))**2)
      SDS=SDS+DIST
      FUN = SQRT(1.+8.*SDS/PCL)/3.
      Q2 = TAUINT*VC*FUN/16800.-QC
      VSEC(K+1)=VC*FUN
      IF(DT2.LT.0.0001)Q2=QC/3.
      IF(SDS.LE.PCL)GO TO 62
      VSEC(K+1)=VC
      Q2 = TAUINT*VC*2.*(1.-SDS/CL)/16800.-QC
   62 CONTINUE
      WRITE (3,74) J1,J2,DIST,SDS,VSEC(K+1)
   74 FORMAT(/' J1 =',I10,'     J2 =',I10,'     DIST =',F12.6,
     & '     SDS =',F12.6,'     VSEC(K+1) =',F12.6)
      T(J1)= T(J1) + (Q1/3.+Q2/6.)*DIST
      T(J2)= T(J2) + (Q2/3.+Q1/6.)*DIST
   60 Q1=Q2
C
C     DOES A SECONDARY ZONE EXIST?
C
      IF(DT2.LT.0.0001) RETURN
      DO 20 NT=1,2
      DO 78 IS=1,NFHALF
      N=NITL1+1+NY*IS
      IF(IS.EQ.1) N=NITL2
      LL=NPE(NTYPE)
      DO 51 I=1,LL
      PEL(I)= 0.
      DO 51 J=1,LL
   51 HEL(I,J)= 0.
      DO 30 I=1,LL
      JJ=NOD(N,I)
      TE(I)=TOLD(JJ)
      XK(I,1)=X(JJ,1)
   30 XK(I,2)=X(JJ,2)
```

```
      CALL    EQ4SCM(XK,XEG,LL,UV,Q,NPR1,NGP,HEL,PEL,DENCPS,CONDS,
     &NDATA,WTG,NENDR1,NENDR2,NENDR3,NENDR4,VCX,VCY,U,2ETA,N,TOLD,TE
     &fNITLlfNITL2,PELQSrKNTLrIQTL#NPOIN,NUVQ,VSEC#NFEl,TSIN,TCOS#NT/IS)
      IF(NT.NE.l) GO TO 79
      CALL         A. ^(H/LHrNOD.NDrNELEM^NPOIN^HELrPELrLLrN.T)
      GO TO 78
   79 CALL        ASMBL(HrLH,NODrNDrNELEMfNPOIN#HELfPELfLLfNfT)
   78 CONTINUE
   20 CONTINUE
C
C     MODIFYING  (P)   ACCORDING TO Q DISTRIBUTION IN SECONDARY ZONE
C     TRIANGULAR SECONDARY DEFORMATION ZONE ASSUMED
C
      QDTFF=QSITL-Q(IQTL)
      Q(IQTL)= QSITL
      DO 120 1=1,3
      N=NITL1+I-1
      DO 120 J=lf4
      II=NOD(NfJ)
  120 T(II)=T(II)+PELQS(I,J)*QDIFF
      DO 90 IS=1#NFHALF
      N=NITL1+1+NY*IS
      IF(IS.EQ.l)  N=NITL2
      IX) 98  1=1,4
   98 PEL(I)=  0.
      DO 91  1*1,2
      IX) 91 J*l,2 *
   91 XES(IffJ)«X(MOD(X,X),J)
      IX5 92 J«1.2
      XES(3,J)=XSEC(IS+1,J)
   92 XES(4fJ)«ZSBC(IS,J)
```

```
      DO 97 1=1,4
      DO 97 J=l,2
   97 XE(I,J)=X(NOD(N,I),J)
      DO 93 11=1,NGP
      DO 93 JJ=1,NGP
      WT=WTG(II,JJ)
      XZ=XEG(II,JJ,1)
      YZ=XEG(11,JJ,2)
      SFN(l)=(l.-XZ)*(l.-YZ)/4*
      SFN(2)=(l.+XZ)*(l.-YZ)/4-
      SFN(3)=(l-+XZ)*(l-+YZ)/4.
      SFN(4)=(l.-XZ)*(l.+YZ)/4.
      QZ=O.
      DO 94 1=1,4
   94 QZ=QZ+SFM(I)*QSEC(IS,I)
      DO 95 1=1,4
      DELN(l,I)=ZETA(I,l)*(l.+YZ*ZETA(I,2))/4-
   95 DELN(2,I)=ZETA(I,2)*(l.+XZ*ZETA(I,l))/4*
      CALL MHLT(DELN,XES,AJ,2,4,2)
      DETJ=AJ(l,l)*AJ(2,2)-AJ(2,l)*AJ(l,2)
      Xlt=O.
      II«0.
      DO 96 I«l,4
      XX«XX+SFM(I)*XES(I,1)
   96 YMI+SFM(I)»XES(I,2)
      Al«4**XK-XE(l,l)-XE(2,l)-XE(3,l)-XE(4,l)
      A2«4.*XT-ZE(lr2)-ZE(2,2)-ZE(3,2)-XE(4,2)
      Bl«XE(l,l)+XE(2fl)-XE(3,l)-XE(4,l}
      B2=XE(1,2)+XE(2,2)-XE(3,2)-XE(4,2)
      Cl«ZB(2,2)-ZE(lf2)"»-ZB(3,2)-*XE(4,2)
```

```
      C2=XE(2,1)-XE(1,1)+XE(3,1)-XE(4,1)
      D1=XE(1,2)-XE(2,2)+XE(3,2)-XE(4,2)
      D2=XE(1,1)-XE(2,1)+XE(3,1)-XE(4,1)
      EE=B1*D1-B2*D2
      FF=B1*C1+A1*D1-B2*C2-A2*D2
      GG=A1*C1-A2*C2
      EGG=4.*EE*GG
      FF2=FF*FF
      IF(N.GT.NENDR1) GO TO 72
      IF(DABS(EE).LT.0.1D-30) GO TO 72
      YYZ=(DSQRT(FF2-EGG)-FF)/2./EE
      IF(ABS(YYZ).LT.1.) GO TO 99
      YYZ=-(FF/EE+YYZ)
      GO TO 99
   72 YYZ=-GG/(B1*C1-B2*C2)
   99 XXZ=(4.*XX-(XE(1,1)+XE(2,1))*(1.-YYZ)-(XE(3,1)+XE(4,1))*(1.+YYZ))/
     &((XE(2,1)-XE(1,1))*(1.-YYZ)+(XE(3,1)-XE(4,1))*(1.+YYZ))
      WJQ=WT*DETJ*QZ
      PEL(1)=PEL(1)+WJQ*(1.-XXZ)*(1.-YYZ)/4.
      PEL(2)=PEL(2)+WJQ*(1.+XXZ)*(1.-YYZ)/4.
      PEL(3)=PEL(3)+WJQ*(1.+XXZ)*(1.+YYZ)/4.
      PEL(4)=PEL(4)+WJQ*(1.-XXZ)*(1.+YYZ)/4.
   93 CONTINUE
      DO 70 I=1,4
      JJ=NOD(N,I)
      T(JJ)=T(JJ)+PEL(I)
   70 CONTINUE
   90 CONTINUE
      RETURN
      END
```

```
C***********************************************************************
      SUBROUTINE EQ4SCM(XE,XEG,LL,UV,Q,NPR1,NGP,HEL,PEL,DENCPS,CONDS,
     &NDATA,WTG,NENDR1,NENDR2,NENDR3,NENDR4,VCX,VCY,U,ZETA,N,TOLD,TE
     &,NITL1,NITL2,PELQS,KNTL,IQTL,NPOIN,NUVQ,VSEC,NFE1,TSIN,TCOS,NT,IS)
C
C     COMPUTING STIFFNESS MATRIX OF A SECONDARY ZONE ELEMENT FOR
C      MODIFYING (H) ACCORDING TO ACTUAL INTERFACE VELOCITY
C     DISTRIBUTION. LOCAL VALUES OF MATERIAL PROPERTIES ARE USED.
C
      DIMENSION  VSEC(NFE1)
      DIMENSION XE( 4,2),XEG(NGP,NGP,2),UV(NPR1,2),Q(NPR1),WTG(NGP,NGP),
     &HEL(4,4),PEL(4),TE(4),TOLD(NPOIN),PELQS(3,LL),DENCPS(NDATA),
     &CONDS(NDATA),PELQ(4,4),QE(4),SSA(2,4),NUVQ(NENDR1,4)
      DIMENSION        SFN(4),AJ(2,2),ZETA(4,2),AJI(2,2),DELN(2,4)
      DO 40 II=1,NGP
      DO 40 JJ=1,NGP
      WT=WTG(II,JJ)
      XZ=XEG(II,JJ,1)
      YZ=XEG(II,JJ,2)
C
C     COMPUTING SHAPE FUNCTIONS AND THEIR DERIVATIVES
C
      SFN(1)= (1.-XZ)*(1.-YZ)/4.
      SFN(2)= (1.+XZ)*(1.-YZ)/4.
      SFN(3)= (1.+XZ)*(1.+YZ)/4.
      SFN(4)= (1.-XZ)*(1.+YZ)/4.
      DO 60 I=1,LL
      DELN(1,I)= ZETA(I,1)*(1.+YZ*ZETA(I,2))/4.
   60 DELN(2,I)= ZETA(I,2)*(1.+XZ*ZETA(I,1))/4.
C
C     COMPUTING JACOBIAN MATRIX, IT'S DETM AND INVERSE
C
      CALL MULT(DELN,XE,AJ,2,LL,2)
      DETJ= AJ(1,1)*AJ(2,2)-AJ(2,1)*AJ(1,2)
```

```
      AJI(1,1)= AJ(2,2)/DETJ
      AJI(1,2)=-AJ(1,2)/DETJ
      AJI(2,1)=-AJ(2,1)/DETJ
      AJI(2,2)= AJ(1,1)/DETJ
      CALL MULT(AJI,DELN,SSA,2,2,LL)
      TZ= 0.
      DO 120 I=1,LL
  120 TZ=TZ+SFN(I)*TE(I)
      CALL        PROPTY(DENCPS,CONDS,NDATA,TZ,DENCP,COND,N,NENDR3,
     & NENDR4)
C
C     COMPUTING ELEMENT STIFNESS MATRIX
      IF(N.GT.NENDR1) GO TO 90
      IF(NT.EQ.1) GO TO 51
      UZ=(SFN(1)*VSEC(IS)+SFN(2)*VSEC(IS+1))*TSIN+SFN(3)*UV(NUVQ(N,3),1)
     &+SFN(4)*UV(NUVQ(N,4),1)
      VZ=(SFN(1)*VSEC(IS)+SFN(2)*VSEC(IS+1))*TCOS+SFN(3)*UV(NUVQ(N,3),2)
     &+SFN(4)*UV(NUVQ(N,4),2)
      GO TO 91
   51 CONTINUE
      UZ=0.
      VZ= 0.
      DO 50 I=1,LL
      NN=NUVQ(N,I)
      UZ=UZ+SFN(I)*UV(NN,1)
      VZ=VZ+SFN(I)*UV(NN,2)
   50 CONTINUE
      GO TO 91
   90 IF(NT.EQ.1) GO TO 30
      UZ=SFN(1)*VSEC(IS)*TSIN+SFN(2)*VSEC(IS+1)*TSIN+(SFN(3)+SFN(4))*VCX
      VZ=SFN(1)*VSEC(IS)*TCOS+SFN(2)*VSEC(IS+1)*TCOS+(SFN(3)+SFN(4))*VCY
```

```
      GO TO 91
   30 CONTINUE
      UZ=VCX
      VZ=VCY
   91 CONTINUE
      SA= (UZ*AJI(1,1)+VZ*AJI(2,1))*DETJ
      SB= (UZ*AJI(1,2)+VZ*AJI(2,2))*DETJ
      DO 80 I=1,LL
      DO 80 J=1,LL
      SCONV= DENCP*SFN(I)*(SA*DELN(1,J)+SB*DELN(2,J))
      SCOND= COND*DETJ*(SSA(1,I)*SSA(1,J)+SSA(2,I)*SSA(2,J))
   80 HEL(I,J)=HEL(I,J)+WT*(SCONV+SCOND)
      GO TO 40
   93 CONTINUE
      DO 110 I=1,LL
      DO 110 J=1,LL
      SCOND= COND*DETJ*(SSA(1,I)*SSA(1,J)+SSA(2,I)*SSA(2,J))
  110 HEL(I,J)=HEL(I,J)+WT*SCOND
   40 CONTINUE
      RETURN
      END
C***********************************************************************
      SUBROUTINE PROPTY(DENCPS,CONDS,NDATA,TEMP,DENCP,COND,N,NENDR3,
     &NENDR4)
C
C     INTERPOLATING FOR MATERIAL PROPERTIES AT VARIOUS TEMPERATURES
C        LINEAR INTERPOLATION USED
C     STEP SIZE =50 DEGC, U ALWAYS < 1
C
      DIMENSION DENCPS(NDATA),CONDS(NDATA)
      IF(TEMP.LT.22.)TEMP=22.
      IF(N.GT.NENDR3) GO TO 10
      NSTEP=TEMP/50.
      I1=NSTEP+1
```

```
      IF(I1 .GE. NDATA) GO TO 6
      U= TEMP/50. -FLOAT(NSTEP)
      IF(U.LE. 0.0001 ) GO TO 5

      DENCP=QINTER(DENCPS,NDATA,I1,U)

      COND=QINTER(CONDS,NDATA,I1,U)
      GO TO 9

    5 DENCP=DENCPS(I1)

      COND=CONDS(I1)
      GO TO 9
    6 DENCP=DENCPS(NDATA)
      COND=CONDS(NDATA)
      GO TO 9
   10 IF(TEMP.GT.1200.) TEMP=1200.
      COND=0.00101-0.320E-06 * (TEMP-22.)
    9 RETURN
      END

C**********************************************************************
      SUBROUTINE     BC(H,LH,NKNOW,NBOUN,ND,NBANR,T,NPOIN,X,NHCWT,IHCWT,

     &HCWT,TROOM,IHST,IHEND,HINTF,TSHANK)

C

C     IMPOSING BOUNDARY CONDITIONS

C

      DIMENSION H(LH),NKNOW(NBOUN),ND(NPOIN),NBANR(NPOIN),X(NPOIN,2),T(N

     &POIN),NHCWT(IHCWT,2),HCWT(IHCWT)

C

C     BOUNDARY WHERE THE TEMPERATURE IS SPECIFIED:
C

      L1= 1

      DO 200 K=1,NBOUN

      I=NKNOW(K)

      ID= ND(I)

      IF(I.EQ.1) GO TO 110

      L1= ND(I-1)+NBANR(I-1)

  110 L2= ID+NBANR(I)-1

      DO 101 J=L1,L2

  101 H(J)= 0.

      H(ID)=1.
```

```
      T(I)= TROOM
  200 CONTINUE
C
C     WHERE CONTACT CONDUCTANCE OCCURS:
C
      DO 10  I=IHST,IHEND
      Jl= NHCWT(I,1)
      J2= NHCWT(I,2)
      DIST=  SQRT((X(Jl,l)-X(J2,l))**2+(X(Jl,2)-X(J2,2))**2)
      HADD= HINTF*DIST/3-
      WRITE (3,2) HADD
    2 FORMAT(4E20.7)
      DO 20 K=l,2
      II=NHCWT(I,K)
      ID=ND(II)
      IDR=ID+(J1-J2)*(-1)**K
      WRITE (3,1)  ID,IDR
    1 FORMAT(8110)
      T(II)=T(II)+HINTF*TSHANK*DIST/2.
      H(ID)=H(ID)+HADD
   20 H(IDR)= H(IDR)+HADD/2-
   10 O3NTINUE
      RETURN
      EMD
C*****                                                  ************
      SUBROUTINE  GBMD(NPOIN,H,LH,ND,P,NBANR)
C
C     SUBROUTINE TOR SOLVING A GENERAL BANDED MATRIX
C     GAUSSIAN  ELIMINATION AND BACK SUBSTITUTION  EMPLOYED
C     ELEMENTS OF BAID STORED HORIZONTALLY  IN   H(I)
C     K)SITION OF DIAGONAL ELEMENT GIVEN BY KD(I)
```

```
C      LH = LENGTH OF VECTOR HKD
C
       DOUBLE PRECISION S
       DIMENSION  H(LH),ND(NPOIN),P(NPOIN),NBANR(NPOIN)
       NM= NPOIN-1
       DO 10 N=1,NM
       NN= NBANR(N)-1
       ID= ND(N)
       S= H(ID)
       DO 20 J=1,NN
   20  H(ID+J)= H(ID+J)/S
       P(N)= P(N)/S
C
C      GAUSSIAN ELIMINATION
C
       DO 30 1=1,NN
       IDI= HD(M-H)-I
       IF(H(IDI)) 70,30,70
   70 S=H(IDI)
       DO 40 J=1,NN
       JJ= IDI+J
   40  H(JJ)= H(JJ)-  S*H(IB+J)
       P(N+I}= P(M4-I)- S*PCD
   30 CXMTINUE
   10  O3NTIN1IE
C
C      BACK SUBSTITUTIOM
C
       P(IK)IM)S= P(NPOIN)/H(LH)
       DO 50 I*1,NM
```

```
      N= NPOIN-I
      ID= ND(N)
      NN= NBANR(N)-1
      SUM= 0.
      DO 60 J=1,NN
   60 SUM= SUM + H(ID+J)*P(N+J)
   50 P(N)= P(N)-SUM
      RETURN
      END
C***********************************************************************
      FUNCTION QINTER(F,NDATA,I1,U)
C
C     LINEAR INTERPOLATION FUNCTION
C
      DIMENSION F(NDATA)
      Y1=F(I1)
      Y2=F(I1+1)
      QINTER=Y1 +(Y2-Y1)*U
      RETURN
      END
C***********************************************************************
      SUBROUTINE BANWTH(NELEM,NPOIN,NTYPE,NPE,NOD,ND,NBANR,LH,NBANL)
C
C       SUBROUTINE TO DETERMINE BANDWIDTHS & DIAGONAL POSITIONS
C       OF THE PROBLEM MATRIX ROWS IN THE VECTOR H.
C
      DIMENSION NPE(8),NOD(NELEM,4),ND(NPOIN),NBANR(NPOIN),
     & NBANL(NPOIN),LR(8),LL(8)
      DO 10 I=1,NPOIN
      NBANR(I)=1
      NBANL(I)=0
   10 CONTINUE
      LT=NPE(NTYPE)
      DO 20 N=1,NELEM
      NR=1
      NL=1
      DO 30 J=2,LT
      IF(NOD(N,J).GT.NOD(N,NR))NR=J
      IF(NOD(N,J).LT.NOD(N,NL))NL=J
   30 CONTINUE
      DO 40 J=1,LT
```

```
      LR(J)=NOD(N,NR)-NOD(N,J)+1
      LL(J)=NOD(N,J)-NOD(N,NL)
   40 CONTINUE
      DO 50 J=1,LT
      JJ=NOD(N,J)
      IF(NBANR(JJ).LT.LR(J))NBANR(JJ)==LR(J)
      IF(NBANL(JJ).LT.LL(J))NBANL(JJ)=LL(J)
   50 CONTINUE
   20 CONTINUE
      DO 60 N=2,NPOIN
      I=NPOIN-N+1
      IF(NBANR(N-l)-NBANR(N).GT.1)NBANR(N)=NBANR(N-l)-1
      IF(NBANL(I+1)-NBANL(I).GT.1)NBANL(I)=NBANL(I+l)-l
   60 CONTINUE
      LH=0
      DO 70 N=1,NPOIN
      LH=LH+NBANR(N)+NBANL(N)
   70 ND(N)=LH-NBANR(N)+1
      RETURN
      END
C*********************************>.<*************************xx********
      SUBROUTINE  STRESS(GAMDOT,MSTEEL,TAU)
C
C     CALCULATION OF SHEAR STRESS FROM EMPIRICAL EQUATIONS,
C     BASED ON TORSIONAL HOPKINSON BAR TESTS.
C
      STRLOG=ALOG10(GAMDOT)
      IF (NSTEEL.EQ.1020) GO TO 10
      IF (NSTEEL.EQ.1114) GO TO 20
      WRITE(3#5)
    5 FORMAT(' STEEL PROPERTIES NOT AVAILABLE, 1020 DATA USED1)
   10 IF (GAMDOT.LT.200.) TAU=52647. + 788.*STRLOG
      IF (GAMDOT.GE.200.) TAU=39159. + 6672.*STRLOG
      GO TO 100
   20 IF (GAMDOT.LT.200.) TAU=45975. + 778.*STRLOG
      IF (GAMDOT.GE.200.) TAU=36258. + 5221*STRLOG
  100 CONTINUE
      RETURN
      END
C*x*xx*xxx*xxxxxxxx*x*xxxxxxxxxxxxx*xxxxx*xxxxxxx*xxxxxxx***xxxxxxxx
      SUBROUTINE TEMPLT(NPOINr»iXEM#MHCWTfKKNOWrNODrX,TfIHCfIHW,IHT,
     & NBOUN,NENDR3,IHCWT)
C
C     PLOTTING TEMPERATURE DISTRIBUTIONS FOR ORTHOGOHAL MACHIIIMG?
C     QUADRILATERAL, ELEMENTS ARE DIVIDED INTO TWO TRIURGLES ST
C     LINEAR INTERPOLATION USED WITH1H TOESE-
C
      LOGICAL IPRNT(IOO)

      DIMENSION  NHCWT(IHCWT,2) rSX3IOH(22) vMOD(HELEK,4) fZ(llPOIHf 2) ,
     & T(MPOIN),ITC20)
      DATA IT/50,100,150,200,250g300g400f 500g600,650# 700 * 750r800g850,
     & 900,1000f1100,1200,1300,1400/
      CALL PLOTS(0.0t0*0f26)
C

      SFAO0.0100
      YDWN=-0.012
      TMRHT=0.08
      ITPLT=1
```

```
C        CHANGE ITPLT TO 1 IF A PLOT OF CONTOURS THROUGHOUT THE TOOL
C        IS REQUIRED; TO 0 IF IT IS NOT.
      IHCW=IHC+IHW

      IHCW1=IHCW+1

C

C     CHIP _ WORKPIECE _ TOOL

C

      CALCF=2.54
      XLIM=11.0
      YLIM=8.0
      ACTFAC=CALCF/SFAC
      CALL FACTOR(ACTFAC)
      YUP=YLIM*SFAC

      HT=TNRHT*SFAC
      CALL PLOT(0.060,0.030,-3)
      XLIM=XLIM*SFAC

C     PLOTTING OUTLINES OF WORK & CHIP.
      CALL PLOT(X(1,1),X(1,2),3)
      DO 10 I=1,IHCW

      DO 10 J=1,2

      NN=NHCWT(I,J)

      IF(X(NN,1).GT.XLIM.OR.X(NN,2).GT.YUP)GO TO 10
      CALL PLOT(X(NN,1),X(NN,2),2)

   10 CONTINUE

C     PLOTTING THE BOUNDARY BETWEEN PRIMARYZONE & WORK.
      NN=NKNOW(1)
      CALL PLOT(X(NN,1),X(NN,2),3)
      DO 20 I=1,NBOUN

      NN=NKNOW(I)

       IF (X(NN,1).GT.XLIM.OR.X(NN,2).GT.YUP)GO TO 20
      CALL PLOT(X(NN,1),X(NN,2),2)

   20 CONTINUE

C     PLOTTING PART OF TOOL OUTLINE.
      NN=NHCWT(IHCW1,1)

      CALL PLOT(X(NN,1),X(NN,2),3)

      ICLEAR=IHCW1+22
      DO 40 I=IHCW1,ICLEAR

      NN=NHCWT(I,2)

      IF (X(NN,1).GT.XLIM) GO TO 40
      CALL PLOT(X(NN,1),X(NN,2),2)
```

```
   40 CONTINUE
      NN=NHCWT(IHCWT,2)
      CALL PLOT(X(NN,1),X(NN,2),3)
      DO 50 I=IHCWT,140,-1
      NN=NHCWT(Irl)
      IF(X(NN,2).GT-YUP) GO TO 50
      CALL PLOT(X(NN,l)rX(NN,2),2)
   50 CONTINUE
C     PLOTTING THE ISOTHERMALS:

      DO 130 1=1,100

  130 IPRNT(I)=wFALSE,

      DO 30 N=1,NELEM

      XJ=X(N0D(N,4)rl)

      YJ=X(NOD(N,4),2)

      IF(yj-GT.YUP.AND.XJ,GT.XLIM-AND.N-GT.NENDR3) GO TO 120

      IF(YJ.GT-YUP) GO TO 30

      IF(XJ.GT-XLIM) GO TO 30

      IF(YJ.LT.YDWN) GO TO 30

      CALL       ISOT(N,T,NODfNELiM,IT,XtNPOIN,IPRNT,HT)

   30 CONTINUE
C

C     TOOL (CONTOURS NOT ALREADY PLOTTED ABOVE)
C

  120 IF(ITPLT.EQ.O) GO TO 80
      im^NHCWT(IHCW1t1)

      XTL=X(NM,1)

      SFAC=SFAC*5.
      HT=TNRHT*SFAC
      ACTXF=CALCF/SFAC
      CALL FACTOR(ACTXF)
      CALL PLOT(0.60#0.00,-3)
      CALL PLQT(X(NI!,l)fX(NM,2K3)

      IX) 70 I*IHCWlr IHCWT

      NN=NHCWT(I,2)

   70 CALL PLOT(X(NN,1)#X(NNf2)f2)

      CALL PLOT(X(NMfl)rX(NMf2)f2)

      DO 140 1*1,100

  140 IPRNT(I)=.FALSE-
```

```
      NN=N
      DO 80 N=NN,NELEM
      CALL        ISOT(N,T,NOD,NELEM,IT,X,NPOIN,IPRNT,HT)
   80 CONTINUE
      CALL PLOT(0.0,0.0,-999)
      RETURN
      END
C************************************************************************
      SUBROUTINE  ISOT(N,T,NOD,NELEM,IT,X,NPOIN,IPRNT,HT)
C
C     PLOTTING ISOTHERMALS WITHIN QUADRILATERAL ELEMENT
C
      LOGICAL TEST,IPRNT(100)
      DIMENSION T(NPOIN),NOD(NELEM,4),IT(15),IE(50),XIT(100),X(NPOIN,2)
      I1=NOD(N,1)
      I2=NOD(N,2)
      I3=NOD(N,3)
      I4=NOD(N,4)
      T1=T(I1)
      T2=T(I2)
      T3=T(I3)
      T4=T(I4)
      IF(IT(1).GT.AMAX1(T1,T2,T3,T4)) RETURN
      ITMIN=MIN1(T1,T2,T3,T4)
      ITMIN=ITMIN/10+1
      ITMIN=ITMIN*10
      IL=0
   10 IL=IL+1
      IF(IT(IL)-ITMIN) 10,20,20
   20 JJ=0
      IH=IL
```

```
      CALL TCORD(T1,T2,I1,I2,X,NPOIN,IL,IE,XIT,JJ,IT,IH)
      CALL TCORD(T2,T3,I2,I3,X,NPOIN,IL,IE,XIT,JJ.IT,IH)
      CALL TCORD(T3,T1,I3,I1,X,NPOIN,IL,IE,XIT,JJ,IT,IH)
      CALL TCORD(T1,T4,I1,I4,X,NPOIN,IL,IE,XIT,JJ,IT,IH)
      CALL TCORD(T4,T3,I4,I3,X,NPOIN,IL,IE,XIT,JJ,IT,IH)
      TEST=.FALSE.
      DO 40 I=IL,IH
      IPEN=3
      IF(JJ.EQ.0) RETURN
      DO 40 J=1,JJ
      IF(IE(J).NE.I) GO TO 40
      CALL PLOT(XIT(J),XIT(50+J),IPEN)
      IPEN=2
      IF(IPRNT(I).OR.TEST) GO TO 40
      IPRNT(I)=.TRUE.
      TEST=.TRUE.
      TLEVEL=FLOAT(IT(I))
      CALL NUMBER(XIT(J),XIT(50+J),HT,TLEVEL,90.,-1)
      CALL PLOT(XIT(J),XIT(50+J),3)
   40 CONTINUE
      RETURN
      END
C************************************************************************
      SUBROUTINE  TCORD(T1,T2,I1,I2,X,NPOIN,IL,IE,XIT,JJ,IT,IH)
C
C     CALCULATING CO-ORD OF ISOTHERMALS AT SIDE I1 - I2
C
      DIMENSION IE(50),XIT(100),X(NPOIN,2),IT(15)
      I=IL-1
   30 I=I+1
      TP=IT(I)
```

```
      IF(TP.GT.AMAX1(T1,T2)) GO TO 100
      IF((TP-T1)*(TP-T2)) 20,20,30
   20 JJ=JJ+1
      IE(JJ)=I
      IF(I.GT.IH) IH=I
      XIT(JJ)=X(I1,1)+(X(I2,1)-X(I1,1))*(TP-T1)/(T2-T1)
      XIT(50+JJ)=X(I1,2)+(X(I2,2)-X(I1,2))*(TP-T1)/(T2-T1)
      GO TO 30
  100 RETURN
      END
```

```
      PROGRAM MESHPL
C
C PLOTTING THE FEM MESH IN THE PRIMARY ZONE, CHIP & TOOL.
C
      DIMENSION X(769,2),NOD(679,4)
      OPEN(UNIT=7,DEVICE='DSK',FILE='XYTST3.DAT')
      OPEN(UNIT=9,DEVICE='DSK',FILE='NOD.DAT')
      READ(7,950)((X(I,J),J=1,2),I=1,769)
  950 FORMAT(8F10.6)
      READ(9,920)((NOD(I,J),J=1,4),I=1,679)
  920 FORMAT(16I5)
      CALL PLOTS(0.0,0.0,27)
      TNRHT=0.08
C
C PRIMARY ZONE & PART OF CHIP.
C
      SFAC=0.004
      XORIGN=0.016
      YORIGN=0.002
      NSTART=1
      NSTOP=222
      CALL ELEMPL(X,NOD,SFAC,TNRHT,XORIGN,YORIGN,NSTART,NSTOP)
C
C TOOL TIP TO ELEMENT 582
C
      SFAC=0.002
      XORIGN=0.000
      YORIGN=0.000
      NSTART=448
      NSTOP=582
      CALL ELEMPL (X,NOD,SFAC,TNRHT,XORIGN,YORIGN,NSTART,NSTOP)
C
C ELEMENTS 583 TO 620
C
      SFAC=0.008
      XORIGN=0.275
      YORIGN=0.000
      NSTART=583
      NSTOP=620
      CALL  ELEMPL(X,NOD,SFAC,TNRHT,XORIGN,YORIGN,NSTART,NSTOP)
C
C REMAINDER OF TOOL
C
      SFAC=0.04
      XORIGN=0.558
      YORIGN=0.000
      NSTART=621
      NSTOP=679
      CALL  ELEMPL(X,NOD,SFAC,TNRHT,XORIGN,YORIGN,NSTART,NSTOP)
      CALL PLOT(0.0,0.0,-999)
      STOP
      END
C**************************************************************************
      SUBROUTINE ELEMPL(X,NOD,SFAC,TNRHT,XORIGN,YORIGN,NSTART,NSTOP)
      DIMENSION X(769,2),NOD(679,4)
      ACTFAC=2.54/SFAC
      HT=TNRHT*SFAC
      CALL  FACTOR (ACTFAC)
      CALL  PLOT(XORIGN,YORIGN,-3)
      N4=MOD(NSTART,4)
```

```
      CALL PLOT(X(N4,1),X(N4,2),3)
      DO 50 N=NSTART,NSTOP
      J4=NOD(N,4)
      CALL PLOT(X(J4,1),X(J4,2),3)
      SUMX=0.
      SUMY=0.
      DO 100 I=1,4
      J=NOD(N,I)
      SUMX=SUMX+X(J,1)
      SUMY=SUMY+X(J,2)
      CALL PLOT(X(J,1),X(J,2),2)
  100 CONTINUE
      XM=SUMX/4.
      YM=SUMY/4.
      XELEM=FLOAT(N)
      CALL NUMBER(XM,YM,HT,XELEM,45.,-1)
   50 CONTINUE
      RETURN
      END
```

PRIMD.DAT

α	t_1	U	t_2	h	C
-5.000000	0.010400	60.000000	0.022000	0.010000	4.670000

ICLEAR

1	7	15	25	37	51	69	91	119	120	147	176	207	237	238	268	269	292	293	294
317	341	365	366	386	387	403	421	441	461	483	507	529	551	574	595	596	612	613	614
627	628	640	652	664	676	690	706	728	734	740	746	752	758	764	2	8	16	26	38
52	70	92	93	121	148	177	208	209	239	240	270	271	272	295	318	342	343	367	368
388	404	422	442	462	484	508	530	552	575	576	597	598	599	615	616	629	641	653	665
677	691	707	729	735	741	747	753	759	765	3	9	17	27	39	53	71	72	94	122
149	178	179	210	211	241	242	243	273	296	319	320	344	345	369	389	405	423	443	463
485	509	531	553	554	577	578	579	600	601	617	630	642	654	666	678	692	708	730	736
742	748	754	.760	766	4	10	18	28	40	54	55	73	95	123	150	151	180	181	212
213	214	244	274	297	298	321	322	346	370	390	406	424	444	464	486	510	532	533	555
556	557	580	581	602	618	631	643	655	667	679	693	709	731	737	743	749	755	761	767
5	11	19	29	41	42	56	74	96	124	125	152	153	182	183	184	215	245	275	276
299	300	323	347	371	391	407	425	445	465	487	511	512	534	535	536	558	559	582	603
619	632	644	656	668	680	694	710	732	738	744	750	756	762	768	6	12	20	30	31
43	57	75	97	98	126	127	154	155	156	185	216	246	247	277	278	301	324	348	372
392	408	426	446	466	488	489	513	514	515	537	538	560	583	604	620	633	645	657	669
681	695	711	733	739	745	751	757	763	769	21	22	32	44	58	76	77	99	100	128
129	130	131																	

NOD

2	8	7	1	3	9	8	2	4	10	9	3	5	11	10	4
6	12	11	5	8	16	15	7	9	17	16	8	10	18	17	9
11	19	18	10	12	20	19	11	16	26	25	15	17	27	26	16
18	28	27	17	19	29	28	18	20	30	29	19	21	22	30	20
26	38	37	25	27	39	38	26	28	40	39	27	29	41	40	28
30	31	41	29	22	32	31	30	38	52	51	37	39	53	52	38
40	54	53	39	41	42	54	40	31	43	42	41	32	44	43	31
52	70	69	51	53	71	70	52	54	55	71	53	42	56	55	54
43	57	56	42	44	58	57	43	70	92	91	69	71	72	92	70
55	73	72	71	56	74	73	55	57	75	74	56	58	76	75	57
92	93	119	91	72	94	93	92	73	95	94	72	74	96	95	73
75	97	96	74	76	77	97	75	93	121	120	119	94	122	121	93
95	123	122	94	96	124	123	95	97	98	124	96	77	99	98	97
121	148	147	120	122	149	148	121	123	150	149	122	124	125	150	123
98	126	125	124	99	100	126	98	148	177	176	147	149	178	177	148
150	151	178	149	125	152	151	150	126	127	152	125	100	128	127	126
177	208	207	.176	178	179	208	177	151	180	179	178	152	153	180	151
127	154	153	152	128	129	154	127	208	209	237	207	179	210	209	208
180	181	210	179	153	182	181	180	154	155	182	153	129	130	155	154
209	239	238	237	210	211	239	209	181	212	211	210	182	183	212	181
155	156	183	182	130	131	156	155	156	185	184	183	211	241	240	239
212	213	241	211	183	184	213	212	239	240	268	238	240	270	269	268
241	242	270	240	213	214	242	241	184	215	214	213	185	216	215	184
270	271	292	269	242	243	271	270	214	244	243	242	215	245	244	214
216	246	245	215	271	272	293	292	243	273	272	271	244	274	273	243
245	275	274	244	246	247	275	245	272	295	294	293	273	296	295	272
274	297	296	273	275	276	297	274	247	277	276	275	295	318	317	294
296	319	318	295	297	298	319	296	276	299	298	297	277	278	299	276
318	342	341	317	319	320	342	318	298	321	320	319	299	300	321	298
278	301	300	299	342	343	365	341	320	344	343	342	321	322	344	320
300	323	322	321	301	324	323	300	343	367	366	365	344	345	367	343
322	346	345	344	323	347	346	322	324	348	347	323	367	368	386	366
345	369	368	367	346	370	369	345	347	371	370	346	348	372	371	347
368	388	387	386	369	389	388	368	370	390	389	369	371	391	390	370
372	392	391	371	388	404	403	387	389	405	404	388	390	406	405	389
391	407	406	390	392	408	407	391	404	422	421	403	405	423	422	404
406	424	423	405	407	425	424	406	408	426	425	407	422	442	441	421
423	443	442	422	424	444	443	423	425	445	444	424	426	446	445	425
442	462	461	441	443	463	462	442	444	464	463	443	445	465	464	444
446	466	465	445	462	484	483	461	463	485	484	462	464	486	485	463
465	487	486	464	466	488	487	465	484	506	507	483	485	509	508	484
486	510	509	485	487	511	510	486	488	489	511	487	506	530	529	507
509	531	530	508	510	532	531	509	511	512	532	510	489	513	512	511
530	552	551	529	531	553	552	530	532	533	553	531	512	534	533	532

513	514	534	512	552	575	574	551	553	554	575	552	533	555	554	553
534	535	555	533	514	515	535	534	575	576	595	574	554	577	576	575
555	556	577	554	535	536	556	555	515	537	536	535	576	597	596	595
577	578	597	576	556	557	578	577	536	558	557	556	537	538	558	536
597	598	612	596	578	579	598	597	557	580	579	578	558	559	580	557
538	560	559	558	598	599	613	612	579	600	599	598	580	581	600	579
559	582	581	580	560	583	582	559	599	615	614	613	600	601	615	599
581	602	601	600	582	603	602	581	583	604	603	582	615	616	627	614
601	617	616	615	602	618	617	601	603	619	618	602	604	620	619	603
616	629	628	627	617	630	629	616	618	631	630	617	619	632	631	618
620	633	632	619	629	641	640	628	630	642	641	629	631	643	642	630
632	644	643	631	633	645	644	632	641	653	652	640	642	654	653	641
643	655	654	642	644	656	655	643	645	657	656	644	653	665	664	652
654	666	665	653	655	667	666	654	656	668	667	655	657	669	668	656
665	677	676	664	666	678	677	665	667	679	678	666	668	680	679	667
669	681	680	668	677	691	690	676	678	692	691	677	679	693	692	678
680	694	693	679	681	695	694	680	691	707	706	690	692	708	707	691
693	709	708	692	694	710	709	693	695	711	710	694	707	729	728	706
708	730	729	707	709	731	730	708	710	732	731	709	711	733	732	710
729	735	734	728	730	736	735	729	731	737	736	730	732	738	737	731
733	739	738	732	735	741	740	734	736	742	741	735	737	743	742	736
738	744	743	737	739	745	744	738	741	747	746	740	742	748	747	741
743	749	748	742	744	750	749	743	745	751	750	744	747	753	752	746
748	754	753	747	749	755	754	748	750	756	755	749	751	757	756	750
753	759	758	752	754	760	759	753	755	761	760	754	756	762	761	755
757	763	762	756	759	765	764	758	760	766	765	759	761	767	766	760
762	768	767	761	763	769	768	762	14	13	12	6	13	21	20	12
13	23	22	21	14	24	23	13	23	33	32	22	24	34	33	23
33	45	44	32	34	46	45	33	34	35	47	46	24	36	35	34
45	59	58	44	46	47	59	45	59	60	76	58	47	61	60	59
60	78	77	76	61	62	78	60	48	62	61	47	35	49	48	47
36	50	49	35	78	79	99	77	62	80	79	78	79	101	100	99
80	81	101	79	62	63	81	80	48	64	63	62	49	65	64	48
50	66	65	49	101	102	128	100	81	82	102	101	102	103	129	128
82	83	103	102	81	63	83	82	103	104	130	129	83	105	104	103
104	132	131	130	105	106	132	104	83	84	106	105	64	84	83	63
65	85	84	64	66	86	85	65	66	67	87	86	50	68	67	66
131	158	157	156	132	133	158	131	106	107	133	132	158	159	188	157
133	134	159	158	107	108	134	133	84	108	107	106	85	109	108	84
85	111	110	109	86	87	111	85	159	160	189	188	134	135	160	159
108	136	135	134	109	110	136	108	160	161	190	189	135	162	161	160
136	137	162	135	110	138	137	136	111	112	138	110	87	113	112	111
161	192	191	190	162	163	192	161	137	164	163	162	192	193	221	191
163	194	193	192	164	165	194	163	137	138	165	164	193	223	222	221
194	195	223	193	165	166	195	194	138	139	166	165	112	113	139	138
223	224	253	222	195	196	224	223	166	167	196	195	139	140	167	166
113	114	140	139	87	88	114	113	67	89	88	87	68	90	89	67
224	225	254	253	196	197	225	224	167	168	197	196	140	141	168	167
114	115	141	140	88	116	115	114	89	117	116	88	90	118	117	89
225	226	255	254	197	198	226	225	168	169	198	197	141	142	169	168
115	143	142	141	116	144	143	115	117	145	144	116	118	146	145	117
226	227	256	255	198	199	227	226	169	170	199	198	142	171	170	169
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227	228	257	256	199	200	228	227	170	201	200	199	171	202	201	170
172	203	202	171	173	204	203	172	174	205	204	173	175	206	205	174
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229	260	259	258	230	261	260	229	231	262	261	230	232	263	262	231
233	264	263	232	234	265	264	233	235	266	265	234	236	267	266	235
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288	289	312	287	310	334	333	309	311	335	334	310	312	313	335	311
289	314	313	312	290	315	314	289	291	316	315	290	334	358	357	333
335	336	358	334	313	337	336	335	314	338	337	313	315	339	338	314

316	340	339	315	358	359	381	357	336	360	359	358	337	361	360	336
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360	384	383	382	361	385	384	360	362	363	385	361	187	186	185	156
ie6	217	216	185	217	218	246	216	219	218	217	186	220	219	186	187
218	248	247	246	248	249	277	247	218	250	2*9	248	219	251	250	218
252	251	£19	220	249	279	278	277	250	280	£79	249	251	281	280	250
252	282	281	251	279	302	301	278	280	302	302	279	305	304	303	280
281	306	305	280	282	307	306	281	302	325	324	301	303	326	325	302
304	327	326	303	329	328	327	304	330	329	30*	305	331	330	305	306
332	331	306	307	325	349	348	324	326	350	349	325	327	351	350	326
328	352	351	327	354	328	329	330	355	35*	330	331	356	355	331	332
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427	447	*46	426	428	448	447	427	429	430	*48	428	411	431	430	429
412	413	431	411	447	467	466	446	448	449	*67	447	430	450	449	448
431	432	450	430	413	433	432	431	414	43*	433	413	415	435	434	414
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432	452	*51	450	433	453	452	432	434	45*	453	433	435	455	454	434
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458	480	479	457	459	481	480	458	460	482	AB1	459	492	516	515	514
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540	541	562	561	520	542	541	540	521	522	542	520	499	500	522	521
477	501	500	499	479	501	477	478	541	56*	563	562	542	543	564	541
522	523	543	542	500	524	523	522	501	502	524	500	479	503	502	501
480	504	503	479	481	505	504	480	482	506	505	481	564	565	584	563
543	544	565	564	523	545	544	543	524	525	5*5	523	503	525	524	502
504	526	525	503	505	527	526	504	506	528	527	505	565	566	585	58*
544	567	566	565	545	546	567	544	525	547	546	545	526	548	547	525
527	549	548	526	528	550	549	527	566	587	586	585	567	568	587	566
546	569	568	567	547	570	569	546	5*8	571	570	547	549	572	571	548
550	573	572	549	587	588	605	586	568	589	$38	587	569	590	589	568
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672	664	683	671	673	685	664	672	67*	666	685	673	663	697	696	682
684	698	697	663	665	686	690	664	697	713	712	696	696	699	713	697
686	700	699	690	675	689	688	674	674	688	687	686	689	705	704	693
686	687	701	700	687	703	702	701	6B8	70*	703	687	713	715	714	712.
699	716	715	713	700	717	716	699	701	702	717	700	716	720	721	715
717	719	720	716	702	718	719	717	715	721	722	714	721	726	727	722
720	725	726	721	719	724	725	720	718	723	724	719				
156	185	166	187	216	217	218	219	220	246	2A7	248	249	250	251	252"
277	278	£79	280	281	282	301	302	303	30*	305"	306	307	324	325	326
327	328	329	330	331	332	*348	349	350	351	352	353	354	355	356	372
373	374	375	376	377	376	379	380	392	393	394	395	396	397	39B	399
400	401	*02	408	409	410	411	412	413	41*	415	416	417	418	419	420
426	427	*28	429	430	431	432	433	434	435	436	437	43S	439	440	446
447	448	-i49	450	451	452	453	454	455	456	457	458	45*? '	460	466	467
468	469	470	471	472	473	474	475	476	477	478	479	460	401	482	488
489	490	491	492	493	494	495	496	497	498	*99	500	501	502	503	50*
505	506	313	514	515	516	517	518	319	520	321	522	523	524	525	526
527	526	537	938	539	540	541	542	543	54*	545	546	547	548	549	550
561	562	563	564	565	566	567	568	569	570	371	372	373	584	385	566
587	588	589	390	391	392	393	394	603	606	607	600	609	610	6S1	621
622	623	&24	625	626	634	633	636	637	636	639	646	647	646	649	650
651	656	659	660	661	662	663	670	671	672	673	674	675	682	683	684
683	666	487	688	689	696	697	698	699	700	701	702	703	704	705	712
713	714	713	716	717	718	719	720	721	722	723	724	725	726	727	

FINREV.DAT

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2/84          1114
          1          6
        0.5000000E-01 -t1        -t2         -α          -FT          -Fc               -h            -w
U~ 60.0000      0.0104      0.0220     -5.0000    196.7000     420.4000        0.0100        0.2000
   30.0000     80.0000      0.0000      0.0100 -p
        0.2840000E 00 -ρ        0.1120000E 00 -S        0.7840000E-03 -Kw       0.1010000E-01 -KT
         24
        0.3053062E-01           0.3189376E-01           0.3324758E-01           0.3459156E-01 ┐
        0.3592976E-01           0.3697618E-01           0.3773230E-01           0.3890935E-01 │
        0.4063421E-01           0.4276305E-01           0.4501979E-01           0.4754213E-01 │ ρS
        0.5059785E-01           0.5431928E-01           0.6559843E-01           0.6872702E-01 │
        0.5971587E-01           0.5510997E-01           0.4801293E-01           0.4267611E-01 │
        0.4278518E-01           0.4276211E-01           0.4274374E-01           0.4271867E-01 ┘
        0.7951334E-03           0.7839343E-03           0.7727351E-03           0.7391381E-03 ┐
        0.7167398E-03           0.6887424E-03           0.6607445E-03           0.6383467E-03 │
        0.5991496E-03           0.5655524E-03           0.5375550E-03           0.5095573E-03 │ Kw
        0.4815599E-03           0.4535618E-03           0.4255639E-03           0.3975665E-03 │
        0.3807680E-03           0.3639697E-03           0.3583704E-03           0.3639697E-03 │
        0.3695693E-03           0.3751689E-03           0.3807684E-03           0.3919676E-03 ┘
        769          679        175          142        282          447        679          22
         72           22         54
        150           27          6           81         83           15
        121          125
        0.1710000E-02 —hf
          3            4          4
          3
       -0.7745967E 00           0.0000000E 00           0.7745967E 00           0.5555556E 00
        0.8888889E 00           0.5555556E 00
   1    6   11   17   23   29   35   41   47   53   59   65   71   77   87   88 ┐ NELSLI
  93   98  103  108  113  118  123  128  133  138  143                        ┘
   2    8    7    1    3    9    8    2    4   10    9    3    5   11   10    4 ┐
   6   12   11    5    8   16   15    7    9   17   16    8   10   18   17    9 │
  11   19   18   10   12   20   19   11   16   26   25   15   17   27   26   16 │ NOD
  18   28   27   17   19   29   28   18   20   30   29   19   21   22   30   20 │
  26   38   37   25   27   39   38   26   28   40   39   27   29   41   40   28 │
  30   31   41   29   22   32   31   30   38   52   51   37   39   53   52   38 ↓
  40   54   53   39   41   42   54   40   31   43   42   41   32   44   43   31
  52   70   69   51   53   71   70   52   54   55   71   53   42   56   55   54
  43   57   56   42   44   58   57   43   70   92   91   69   71   72   92   70
  55   73   72   71   56   74   73   55   57   75   74   56   58   76   75   57
  92   93  119   91   72   94   93   92   73   95   94   72   74   96   95   73
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 345  369  368  367  346  370  369  345  347  371  370  346  348  372  371  347
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .
```

(NOD IS THE SAME AS IN PRIMD.DAT, SO THE FULL LISTING IS NOT SHOWN.)

684	698	697	683	685	686	698	684	697	713	712	696	698	699	713	697j	
636	700	699	6VU	673	68?	6S«	674	674	6©S	687	686	68V	703	704	688	Q
686	687	701	700	687	703	702	701	638	704	703	687	712	715	714	712	O
699	716	715	713	700	717	716	699	701	702	717	700	716	720	721	715	Z
717	719	720	716	702	718	719	717	715	721	722	714	721	726	727	722	
720	725	726	721	719	724	725	720	718	723	724	719					
1	2	3	4	5	6	14	24	36	5G	6B	90	118	146	175	206	ijt/NOW
236	267	291	316	340-	364											
1	7	7	15	15	25	25	37	37	51	51	69	69	91	91	119	
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269	292	292	293	293	294	294	317	317	341	341	365	365	366	366	386	
386	387	387	403	403	421	421	441	441	461	461	483	483	507	507	529	
529	551	551	574	574	595	595	596	596	612	6V2	613	613	614	614	627	
627	628	628	640	640	652	652	664	664	676	676	690	690	706	706	726	
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757	751	751	745	745	739	739	733	733	711	711	695	695	681	681	669	
669	657	657	645	645	633	633	620	620	604	604	583	583	560	560	538	
156	157	157	188	188	189	189	190	190	191	191	221	221	222	222	253	
253	254	254	255	255	256	256	257	257	256	258	259	259	283	283	308	NHCWT
308	309	309	333	333	357	357	381	381	382	382	383	156	187	187	220	
220	252	252	282	282	307	307	332	332	356	356	380	380	402	402	420	
420	440	440	460	460	482	482	506	506	52S	528	550	550	573	573	594	
594	611	611	626	626	639	639	651	651	663	663	675	675	689	689	705	
705	704	704	703	703	702	702	718	718	723	723	724	724	725	725	726	
726	727	727	722	722	714	714	712	712	696	696	682	682	670	6.70	658	
658	646	646	634	634	621	621	606	606	605	605	586	586	585	585	584	
584	563	563	562	562	561	561	538									
156	185	185	216	216	246	246	247	247	277	277	278	278	301	301	324	X
324	348	348	372	372	392	392	408	408	426	426	446	446	466	466	488	∇
488	489	489	513	513	514	514	515	515	537	537	538					N
28	29	2	1	55	56	29	28	82	83	56	55	109	110	83		H
136	137	110	109	29	30	3	2	56	57	30	29	83	84	57	56	
110	111	84	83	137	138	111	110	30	31	4	3	57	58	31	30	
84	85	58	57	111	112	85	84	138	139	112	111	163	164	139	133	
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86	87	60	59	113	114	87	B6	140	141	114	113	165	166	141	140	
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147	148	121	120	172	173	148	147	40	41	14	13	67	68	41	40	
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78	79	52	51	105	106	79	78	132	133	106	105	159	160	133	132	
52	53	26	25	79	80	53	52	106	107	BO	79	133	134	107	106	
160	161	134	133	53	54	27	26	80	81	54	53	107	108	81	80	
134	135	108	107	161	162	135	134									