HeatWave
Three-dimensional steady-state and dynamic thermal transport with temperature-dependent materials

1.2. Test run

A quick way to understand the solution procedure is to step through an example. We shall determine dynamic temperature profiles for an array of four thermal probes inserted into tissue. In additional to **HeatWave** procedures, the example illustrates the effective use of symmetry boundaries and a variable-resolution mesh to find accurate thermal flux values on small objects. Figure 1.1 shows the geometry of a single probe. The cylindrical metal probe at a fixed temperature of 100 °C has a diameter of 1.0 mm. The exposed region of the probe extends from spherical tip at $z = 20.5$ mm to $z = 0.0$ mm. A 1.5 mm diameter sheath with poor thermal conductivity covers the probe from the solution boundary at $z = -10.0$ mm to $z = 0.0$ mm. The four probes in the array have centers at ($x = 5.0$ mm, $y = 5.0$ mm), ($x = -5.0$ mm, $y = 5.0$ mm), ($x = -5.0$ mm, $y = -5.0$ mm) and ($x = 5.0$ mm, $y = -5.0$ mm). By symmetry, we need model only the probe in the first quadrant and apply the boundary condition $\partial T/\partial \mathbf{n} = 0.0$ along the lines $x = 0.0$ and $y = 0.0$. The condition means that there is no thermal flux across the boundary. We can apply the same condition at $z = -10.0$ mm to approximate the effect of an infinite extension of the sheathed probe in the $-z$ direction. The solution volume has relatively large dimensions in x and y: $x_{max} = y_{max} = 25.0$ mm. The condition $T = 0.0$ °C is applied on these boundaries to approximate the effect of a large mass of exterior tissue at ambient temperature.

To begin, transfer the example files `WALKTHROUGH.MIN`, `WALKTHROUGH.WIN` and `WALKTHROUGH.SCR` to a working directory like `\AMAZE\BUFFER`. Run the program launcher `AMAZE.EXE` and make sure the program and data directories are set correctly (*i.e.*, to `\AMAZE` and `\AMAZE\BUFFER`). Run **MetaMesh** and click the command *LOAD MIN FILE* in the *FILE* menu. Pick `WALKTHROUGH.MIN` in the dialog and click *OK*. You can view or edit the script with the *EDIT MIN FILE* command in the *FILE* menu. Table 1.1 shows the contents of the file. Note that variable element resolution has been applied along all directions to ensure accurate representations of the cylindrical and spherical surfaces of the probe Click on the *PROCESS MESH* command. **MetaMesh** sets up a foundation mesh, divides the volume into regions that represent physical entities, and then fits
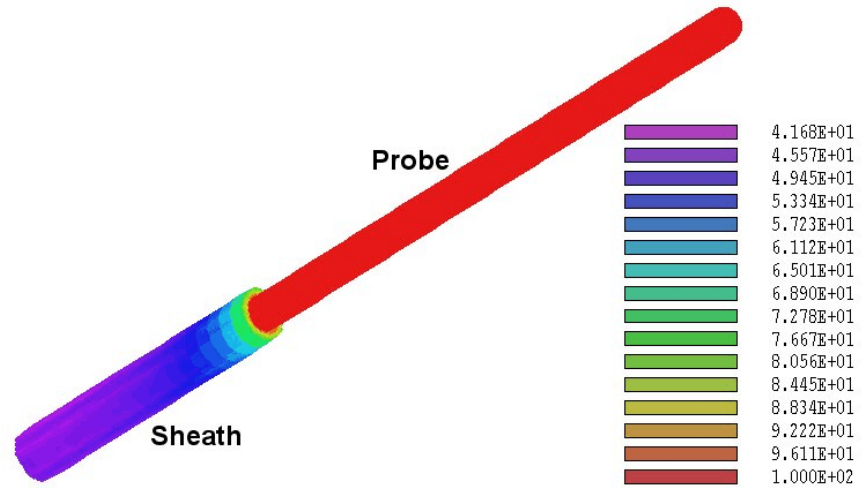
	4.168E+01
	4.557E+01
	4.945E+01
	5.334E+01
	5.723E+01
	6.112E+01
	6.501E+01
	6.890E+01
	7.278E+01
	7.667E+01
	8.056E+01
	8.445E+01
	8.834E+01
	9.222E+01
	9.611E+01
	1.000E+02

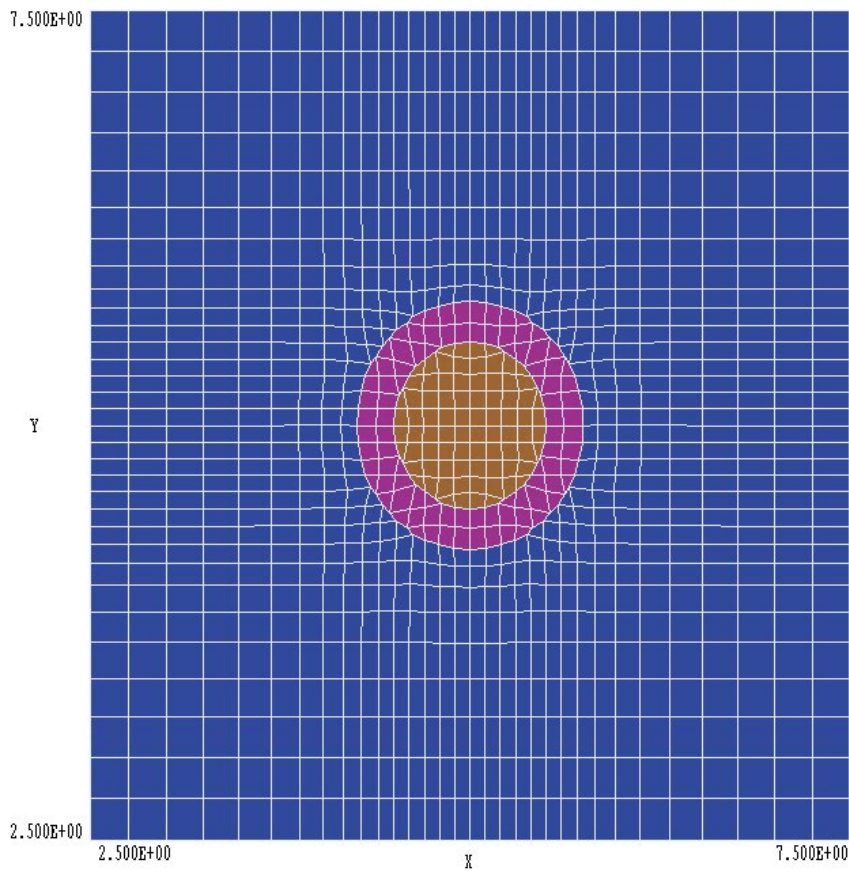**Figure 1.1.** Probe geometry for the *WALKTHROUGH* example, surfaces color-coded by temperature.

Figure 1.2. Detail of mesh for the *WALKTHROUGH* example in the plane z = -5.0 mm near x = 5.0, y = 5.0

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designated surfaces. The program requires about 10 seconds to create a mesh with 890,847 nodes. Click on the *SAVE MESH* command in the *FILE* menu. The resulting file WALKTHROUGH.MDF will be used as input by **HeatWave**. At this point you may want to experiment with some of the plotting capabilities of **MetaMesh** before proceeding to the next step. Figure 1.2 shows a detailed cross section of the mesh near the probe normal to the z axis at $z = -5.0$ mm.

Table 1.1. Contents of the file WALKTHROUGH.MIN

```
* File WALKTHROUGH.MIN
* Dimensions in mm
Global
  XMesh
     0.00   4.00   0.25
     4.00   6.00   0.10
     6.00  15.00   0.25
    15.00  25.00   0.50
  End
  YMesh
     0.00    4.00    0.25
     4.00    6.00    0.10
     6.00   15.00    0.25
    15.00   25.00    0.50
  End
  ZMesh
  -10.00   18.00    0.50
   18.00   22.00    0.20
   22.00   35.00    0.50
  End
  RegName(1) = Tissue
  RegName(2) = Sleeve
  RegName(3) = Probe
  RegName(4) = Boundary
End

Part
  Region Tissue
  Type Box
  Fab  50.00  50.00  70.00
End
```

```
PPart
  Region Sleeve
  Type Cylinder
  Fab 0.75  10.00
  Shift 5.00   5.00   -5.00
  Surface Region Tissue
End
Part
  Region Probe
  Name ProbeBody
  Type Turning
   L -20.0 -0.5  20.0 -0.5 S
   A  20.0 -0.5  20.5  0.0 20.0 0.0 S
   A  20.5  0.0  20.0  0.5 20.0 0.0 S
   L  20.0  0.5 -20.0  0.5 S
   L -20.0  0.5 -20.0 -0.5
  End
  Shift 5.00  5.00  0.00
  Surface Region Tissue
  Surface Region Sleeve
End
Part
  Region Boundary
  Type BoundXUp
End
Part
  Region Boundary
  Type BoundYUp
End
Part
  Region Boundary
  Type BoundZUp
End

ENDFILE
```

Table 1.2. Contents of the file WALKTHROUGH.WIN

```
* File WALKTHROUGH.WIN
* -------------- Run parameters --------------
DUNIT 1000.0
MODE TVAR
TMAX 252.0
DTMIN 0.001
DTMAX 1.000

* ------------- Material properties ------------
* Tissue
COND(1) = 0.5
DENS(1) = 1000.0
CP(1) = 4800.00
* Sleeve
COND(2) = 0.05
DENS(2) = 1000.0
CP(2) = 4800.00
* Probe
FIXED(3) = 100.0
* Boundary
FIXED(4) = 0.0
* ------------- Region assignments -------------
REGION(1) = 1
REGION(2) = 2
REGION(3) = 3
REGION(4) = 4
* ------------- Diagnostic commands -------------
SETTIME 20.0
SETTIME 50.0
SETTIME 100.0
SETTIME 250.0
HISTORY 0.00 0.00 25.00
ENDFILE
```

The next step is to run **HeatWave** from the **AMaze** program launcher. The program requires two files: the MDF file generated by **MetaMesh** and a script to control the solution. Table 1.2 shows the contents of the file WALKTHROUGH.WIN (the suffix stands for Heat**W**ave **IN**put). You can also view the file using the *EDIT SCRIPT FILE* command in the *FILE* menu. The first group of commands sets general run parameters. For
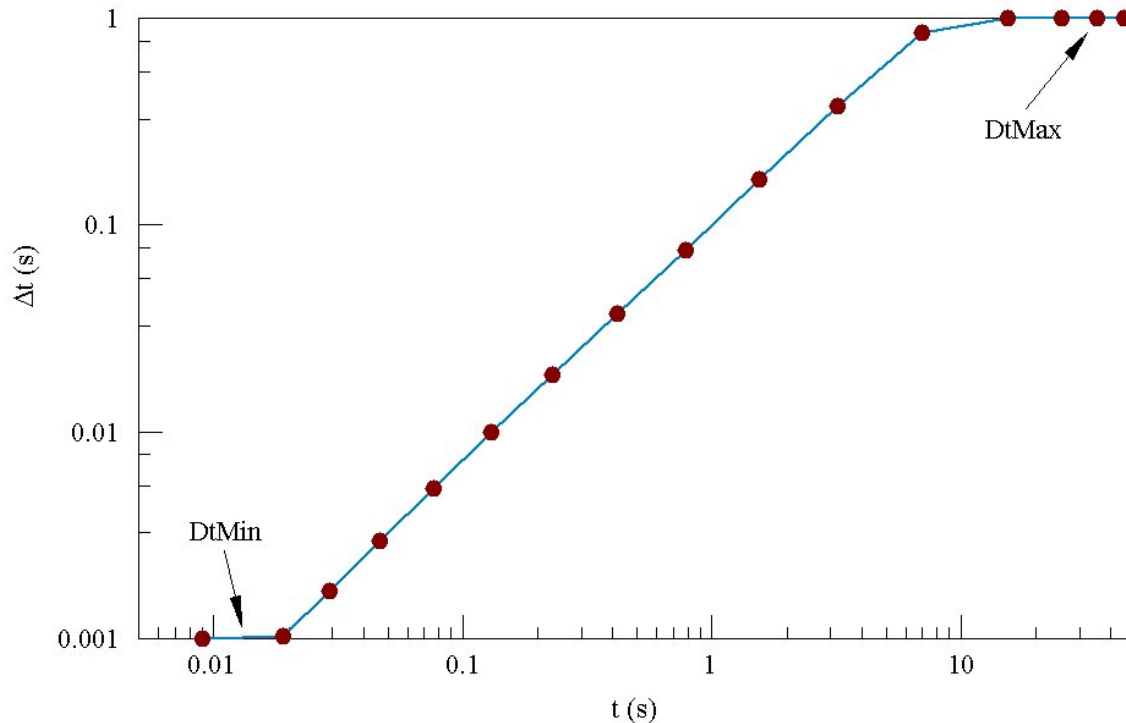
Figure 1.3. Automatic adjustment of time step in the *WALKTHROUGH* example.

example *DUNIT 1000.0* indicates that coordinates in the **MetaMesh** file are in millimeters and **MODE DYNAMIC** specifies a dynamic solution. The command *TMAX 252.0* gives the total simulation time. The *DTMIN* and *DTMAX* commands control the automatic time-step feature for the initial-value solution. The next command group assigns physical properties to materials. The tissue has $k = 0.5$ W/m-°C, $\rho = 1000$ kg/m^3 and $C_p = 4800$ J/kg-°C. The conductivity of the sheath is 10 per cent that of the tissue. The probe and outer boundaries are fixed-temperature materials with values 100 °C and 0 °C. The *REGION* commands associate material properties with the regions defined in **MetaMesh**. The final set of commands instructs the program to create data files at times 20, 50, 100 and 250 seconds and to place a probe on-axis at position $z = 25.0$ mm.

Choose the command *START RUN* in the *RUN* menu. In the dialog pick the file WALKTHOUGH.WIN and click *OK*. The program reads the mesh file, analyzes parameters in the script, calculates coupling coefficients for the finite-element calculation, advances the diffusion equation and creates
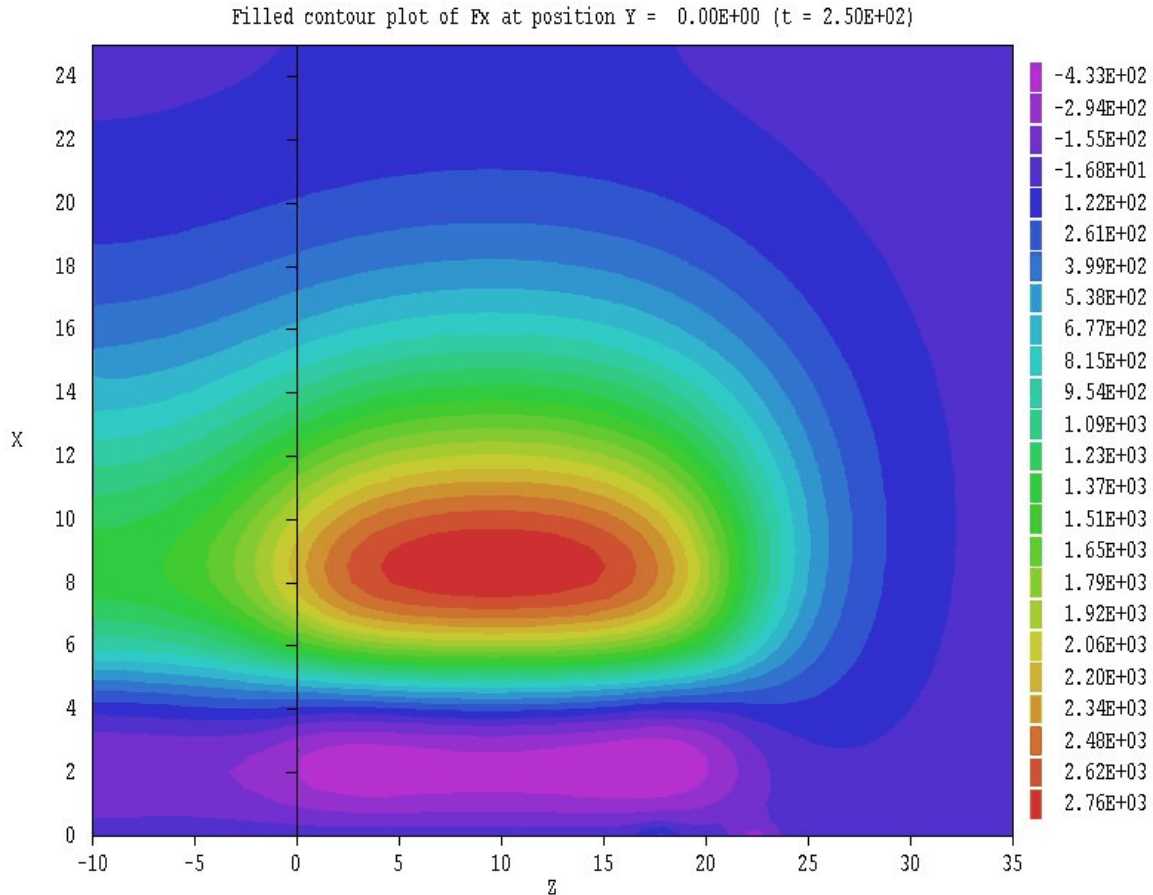
Filled contour plot of Fx at position Y = 0.00E+00 (t = 2.50E+02)

Figure 1.4. Example of a plane plot – thermal flux f_x in the plane $y = 0.0$.

the files `WALKTHROUGH.001, WALKTHROUGH.002, WALKTHROUGH.003, WALKTHROUGH.004` and `WALKTHROUGH.P01.` The first four files are data records at the specified times and the final file is the probe record. The on-screen display shows the progress of the run. Initially the time step is quite small in order to resolve the strong temperature gradient near the probe at 100 °C in the tissue at 0°C. **HeatWave** automatically increases the time step while maintaining accuracy as the temperature profile spreads (Fig. 1.3). The entire solution process takes about 238 seconds on a 2.6 GHz computer.

Run the **HWV** program to analyze the data files. Click the *SET SOLUTION SERIES* command in the *FILE OPERATIONS* menu. Pick `WALKTHROUGH.001` and click *OK*. The *LOAD NUMBERED SOLUTION IN SERIES* command is now active. Pick the command and enter the number 4 in the dialog. The program loads data from the file
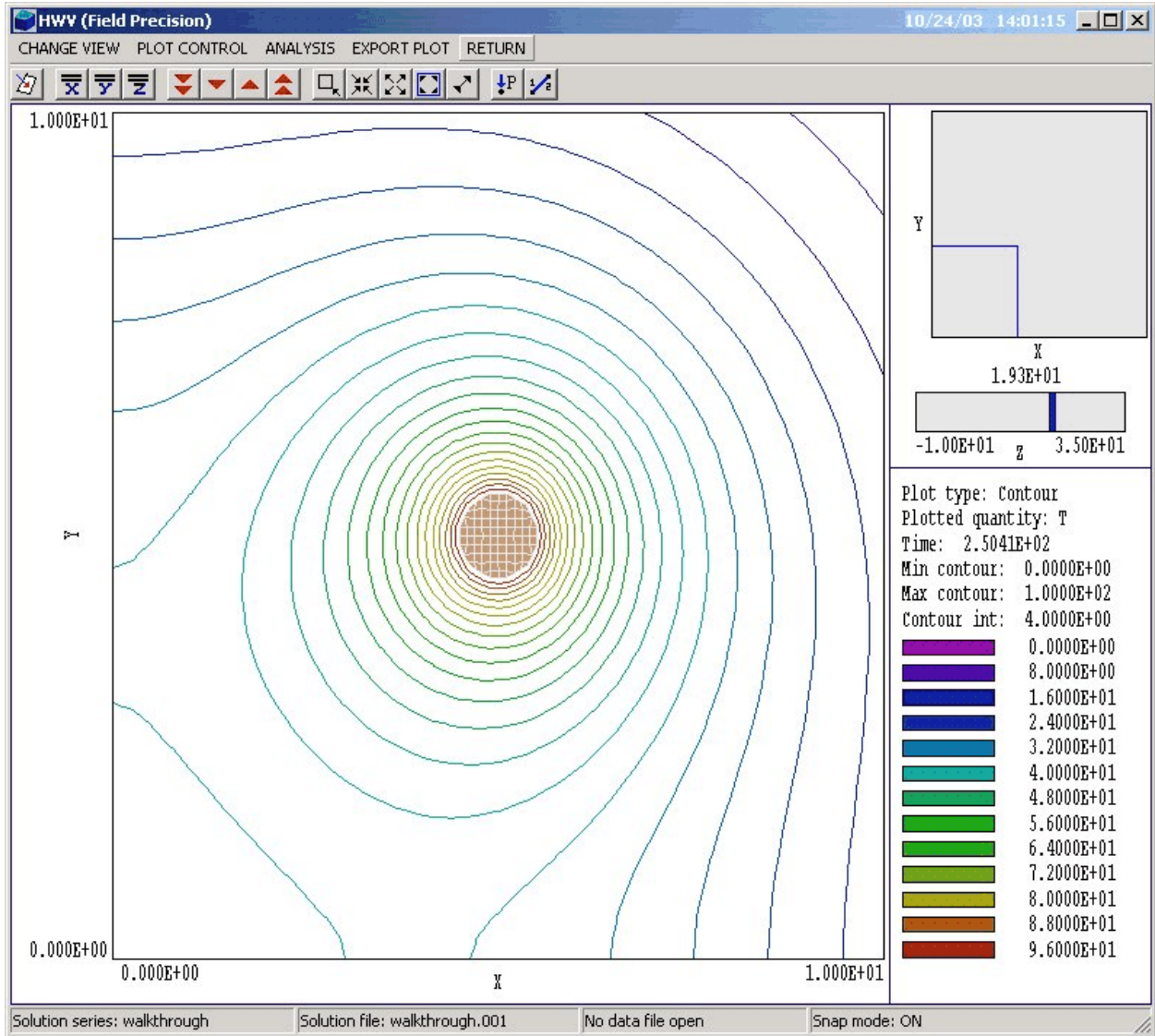
Figure 1.5. **HWV** working environment in the slice plot menu.

WALKTHROUGH.004 created near the end of the run at $t = 250$ seconds. After the data is loaded the *PLANE PLOTS, SLICE PLOTS* and *SURFACE PLOTS* menus become active. Click on the *PLANE PLOTS* menu. Plane plots show the variation of quantities in a specified plane normal to one of the axes. The plot is constructed by projecting interpolated quantities on a regular rectangular mesh. Plane plots achieve dramatic effects but may not show small details of the conformal mesh solution. Take the following actions to construct the thermal flux plot of Fig. 1.4:

■ Click the *SET PLANE* command. In the dialog, choose *Y* as the normal axis and move the slider to *Y* = 0.0.

■ Click the *PLOT STYLE* command in the *PLOT CONTROL* menu and choose *FILLED CONTOURS 2D*.

■ Click the *PLOT QUANTITY* command in the *PLOT CONTROL* menu and choose *FX*.

The plot shows the value of the *x*-component of thermal flux (f_x in W/m^2) in the plane *y* = 0.0. To export a copy to the default Windows printer, click the command *DEFAULT PRINTER* in the *EXPORT PLOT* menu.

Click *RETURN* to return to the main menu and then choose *SLICE PLOTS*. Like plane plots, slice plots show the variation of quantities in a plane normal to one of the axes. The difference is that slice plots compute plot quantities directly from the conformal mesh. The procedures are more difficult but can show small details in the solution. Figure 1.5 shows the working environment for slice plots. The main plot area shows a zoomed view of isotherms in a plane normal to *z* near the probe. The upper area on the right shows an outline of the view region in the normal plane and the location of the slice along the normal axis. The lower area gives information on the plot.

Because slice plots are referenced to the conformal mesh, you can control visual operations (such as zooming and panning) with the mouse. It is also possible to find information on thermal quantities at a point or along a scan line by pointing and clicking. As a final activity, we shall determine the variation of temperature along a radial line from (*x* = 0.0, *y* = 0.0) to (*x* = 10.0, *y* = 10.0) in the plane *z* = 20.09. Take the following actions:

■ If you changed the default slice view, click on *SLICE NORMAL TO Z* in the *CHANGE VIEW* menu. Use the red arrows in the toolbar to move to the plane *z* = 20.9. Finally, click on *GLOBAL VIEW* in the *CHANGE VIEW* menu.

■ Click the *OPEN HISTORY* command in the *ANALYSIS* menu. Click *OK* to accept the default file prefix of *WALKTHROUGH*. **HWV** will write a record of the scan calculation to the file `WALKTHROUGH.DAT`.
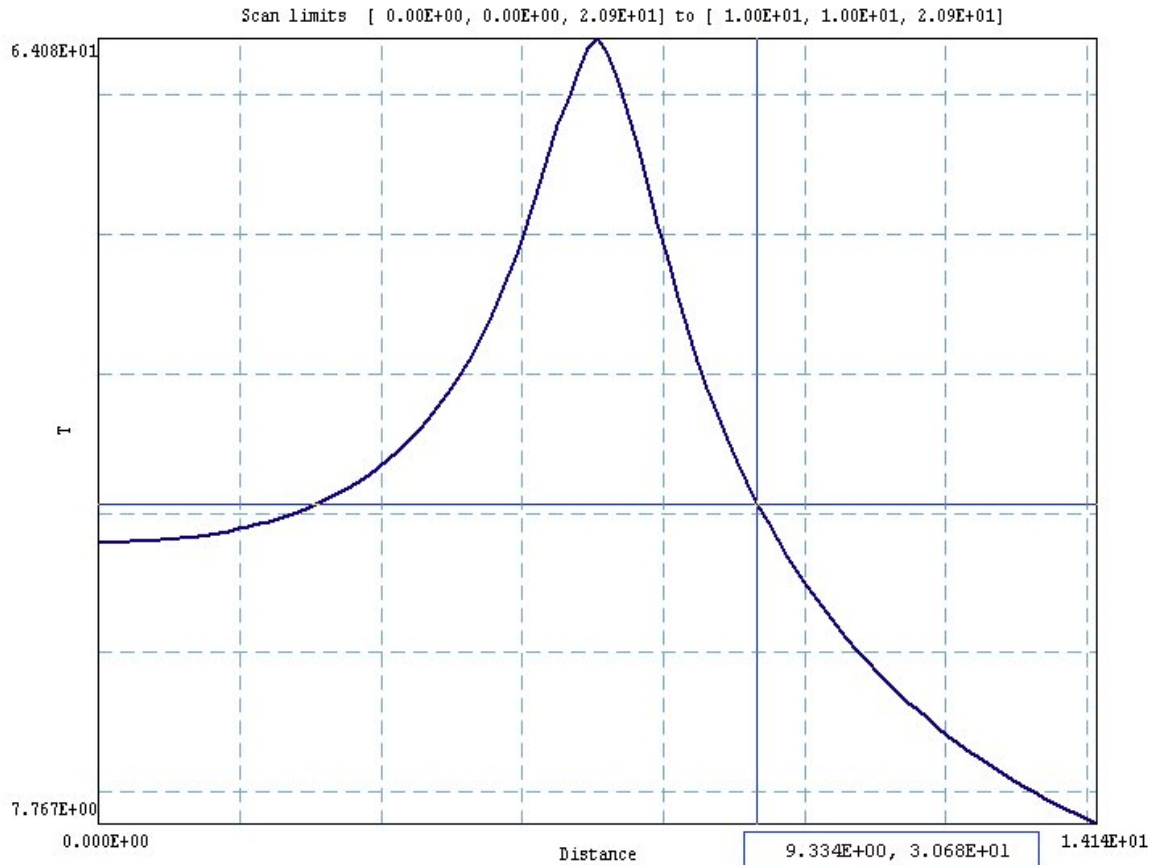
Figure 1.6. Scan plot in the oscilloscope mode.

■ Click the command *LINE SCAN* in the *ANALYSIS* menu and move the mouse into the plot area. The cursor changes to a cross-hair pattern to show that pointing is active. Move the mouse toward the lower-left corner of the plot until the entries in the status bar at the bottom of the screen read $x = 0.0$ and $y = 0.0$. (Note that the values change discontinuously – mouse pointing is set to the snap mode by default.) When the mouse is positioned, click the left button.

■ Next move the mouse to the position ($x = 10.0$, $y = 10.0$) and click the left button. The program computes 100 values along the scan line, enters the scan menu and creates the plot shown in Fig. 1.6.

■ Click on *the OSCILLOSCOPE MODE* command. In this mode you can drag cross-hairs with the mouse to query specific points on the plot. Values are listed at the bottom of the plot area.

■ Click the right mouse button to exit the oscilloscope mode and click *RETURN* to exit the scan menu. Click *RETURN* again to return to the main menu.

Because a data file (WALKTHROUGH.DAT) has been opened, the *ANALYSIS* submenu in the main menu is active. Choose the command *FULL ANALYSIS* in the *ANALYSIS* menu. There will be a significant delay while **HWV** performs a complex set of volume and surface integrations to find average temperature, thermal fluxes and other quantities. When the program has completed the task, click on the *CLOSE DATA FILE* command in the *FILE* menu and then choose the command *EDIT DATA FILE*. Choose *WALKTHROUGH.DAT* in the dialog and click *OK*. The data file contains quantitative information on the line scan and the global analysis. Exit the editor when you are finished. This discussion covered only a fraction of the capabilities of **HWV**. Chapters 11 through 15 cover operation of the program in detail.