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PIPLAN, A Treatment-Planning Code for Pions

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PIPLAN, A TREATMENT-PLANNING CODE FOR PION RADIATION THERAPY

by

William J. Shlaer

ABSTRACT

Piplan is a computer code for use in planning pion radiation therapy treatments. An introduction to the code and instructions for its use are given and illustrated by an example.

INTRODUCTION

The central problem in planning radiation therapy treatments is to find a combination of beams that will deliver an adequately uniform dose to the tumor-bearing volume while sparing the surrounding tissues to a degree dependent on their sensitivity to radiation. One of the most useful tools available to the treatment planner is the treatment-planning code, a computer program that, given the beam combination under consideration, quickly and conveniently calculates the radiation dose distribution that the beams would give to the patient. It is then the responsibility of the planner, using his judgment and experience, to evaluate the results from several trial beam combinations and to select the best, or if necessary, to further modify the beams to improve the dose distribution.

The Los Alamos treatment planning code, PIPLAN, is adapted to the special properties of pions used in radiation therapy. Information about the patient and the beams to be used for a possible treatment are used as input to PIPLAN. PIPLAN calculates the dose distribution that would be given by selected pion beams and makes it available for convenient display. In the process, the code takes general specifications of the beams and generates the complete details necessary for actually performing the treatment.

The unique features of pions and the versatility of pion radiation therapy make necessary certain sophistications in the code that are much less

important when dealing with a conventional modality. The pion beam that will be available for therapy at Los Alamos will be scanned in two dimensions to control irradiation of the desired volume. The basic beam is reasonably monoenergetic with a cross section that is longer than it is wide so that the beam stops at a definite depth and produces a long, thin, cylindrical region of stopped pions at the end of its range. This cylindrical region contains most of the high-LET dose. The entering pions deliver a predominantly low-LET dose. The cylindrical region is scanned in depth, perpendicular to its long axis, by a variable thickness degrader to sweep out an area irradiated with stopped pions. The patient is very slowly translated under the beam in a direction perpendicular to this swept area so that a volume is filled with stopped pions. During this dual scan process, the length and position of the cylinder along its own axis can be varied by an independent jaw collimator. The speed of the scan can also be varied. This allows an almost arbitrary volume to be given a uniform density of stopped pions. The entering pions deliver an appreciable dose before they stop, which, for some volumes, makes it impossible to obtain a completely uniform absorbed dose from a single beam; often, a good approximation to uniformity is possible. This versatility in the ability to deal with quite irregular treatment volumes is reflected in two features of the code. The first feature is that the calculation is done in three dimensions. This allows the use of complex

shapes for the treatment volume and a realistic representation of the patient's anatomy; also, the beams used need not be a co-planar but can enter from any direction. The second feature is that the code calculates the details of the beam scan and can preserve this information for use in the actual irradiation. The shape of the treatment volume is specified by contours as is the patient's surface and internal structure. The entrance direction and dose but not the field size is given for each beam. Using the information on the shape of the treatment volume, the code calculates the size, position, and number of pions for each cylinder in the scan pattern; for each beam, this is computed to give as uniform a dose as possible from that beam's direction.

Pions for radiation therapy are charged particles. This leads to two physical phenomena that are reflected in features of the code, finite range and multiple coulomb scattering. The finite range of pions, along with star production by stopped pions, leads to a depth dose distribution that has a rather narrow peak at the end of the range where the particles stop. This effect is further exaggerated by the increased biological effect of the high-LET radiation that is concentrated in this peak. The distance the pions penetrate matter before stopping is primarily a function of the total mass along the path, although there is a dependence on atomic number as well. This means that the predicted distribution of radiation will be accurate only if account is taken of internal inhomogeneities as well as the patient's surface shape. This code traces rays of pion through regions of different density until the total mass is sufficient to stop them. Multiple coulomb scattering makes the beam spread slightly as it penetrates to the treatment volume. The finite emittance of the beam means that pions stopping at a point enter not along a single line but within a narrow, elliptical cone. These effects produce a complex fall-off pattern at the beam edges. The code includes an approximate treatment of edge effects.

The pion dose is calculated with an analytic beam model that is suitable for relatively rapid calculation while taking account of inhomogeneities. Parameters in the model control the width and depth distribution of the beam. These parameters will be adjusted and the model improved to fit dose

distributions given by Monte-Carlo calculations and, ultimately, to fit actual dose distribution measurements. Treatment planning for beams other than pions is also possible with this code while retaining such features as the three-dimensional calculation and accurate treatment of inhomogeneities. For this, calculation modules for models of other types of beams must be added to the code.

The code is designed to run interactively on a PDP-11/45 provided with such special devices as a contour digitizer, display scope, plotter, control knobs, and control buttons as well as a keyboard. The program is also available on a CDC 7600 at the LASL central computing facility (CCF) with input from cards and output to film and printer. Because the full computation may take a prohibitive amount of time on a small computer, it will be easy to restrict the magnitude of the calculation. Inhomogeneities can be ignored; the number of points at which dose is calculated may be reduced; and the calculation can even be restricted to two dimensions. The PDP-11 may be coupled to the large computer at the CCF to permit a plan that looks good in approximate calculation on the PDP-11 to be computed more accurately in a reasonable amount of time. Input is done interactively on the PDP-11; the calculation is done by the large computer, and the results of the computation are returned to the PDP-11 to be viewed on the scope under interactive control. A direct computer-to-computer link may be used, but the communication could be by magnetic tape.

As of this writing, some of the features planned for the code remain for future implementation. The code is available only on the CDC 7600's at the CCF. The interactive version on the PDP-11/45 is not yet ready. The PDP-11 is also the control computer for the biomedical beam. The generation of a stored file of data, containing the details of the beam to be used for executing the plan, must wait until the code is running on the PDP-11. Still further in the future is a storage and retrieval system which will allow recall of the patient's anatomical data and beam plans for a previously entered case. Computer-to-computer link by magnetic tape remains for the future, and a direct link may never exist. A link may not be necessary if the calculation runs fast enough on the PDP-11. There is no true two-dimensional restriction of the

calculation at present, and the scheme that designs the beam scan pattern is subject to improvement. The beam model parameters have not yet been adjusted to fit actual pion dose distribution data and beam edge effects are especially uncertain. Calculation modules that model gamma and electron beams are not in the code, although commands to use them are included.

USING THE CODE

General

The code requires input information about the patient, the beams used, the type of calculation to be done, and the kind of output to be generated. It provides output information on the distribution of radiation delivered by the beams to the patient. Input information is conveyed by a series of commands and numerical data. On the interactive PDP-11 system some of this data can come from transducers instead of being keyed in or entered on punched cards. There may be special command buttons, knobs to position a beam, a digitizing table for contour entry, and knobs to control the position and angle of the plane in which contours are entered and the output dose distribution map is plotted. The use of the transducers is optional; the same data can be entered in numerical form from the keyboard or on punched cards. On the CDC 7600, all input must come from punched cards.

Output is both alphanumeric and graphic. The PDP-11 has a scope that can present temporary displays of either type of output. There is a printer for alphanumeric output and a plotter for graphic output in permanent form. On the CDC 7600, graphic output is by 35-mm film; alphanumeric output is by lineprinter.

Administrative Data

The first section of input the code requires is the administrative data that identify the case. These data consist of the case number, patient's name, doctor's name, treatment site, and date. The administrative data are presented as output for verification and to guide the user in filling in any missing items.

In the future it may be possible to store patient information. Entry of a stored case's number would recall the administrative data, patient contours, and any previously developed plans for that

case. Once a case was recalled, it would then be possible to modify any of the data, develop new plans, and return the case to storage, or purge it from memory if it were no longer of interest.

Patient Contours

The next section of input is the patient's anatomy; this is entered as contours on up to 30 parallel planes, to permit the representation of three-dimensional structures. Although all planes, or sheets, of contours must be parallel, they can be at any orientation to a reference system of coordinate axes that are fixed in any convenient relationship to the patient; each sheet's position in the parallel stack of planes must be given.

Before contours are entered on a sheet, two special points 10 cm apart are entered; the code uses these points to align the sheet with the others and to correct any magnification in the data. The data for the contours entered on the sheet can come as direct values from a digitizing table or as numerical information from keyboard or cards. The contours are displayed as they are entered on the sheet. Each contour is assigned a number less than 30 that is used to associate corresponding contours on different planes. Each contour is also assigned a density that specifies the degree to which the structure within slows pions. The density may be ignored, in which case the contour appears on output for reference only and the density within is taken to be that specified by other contours. There are two special types of contours, surface and treatment volume. Surface contours give the patient's outline and must appear on every sheet with the same contour number. Treatment volume contours give the size of the region to be dosed by the beams but do not specify a density and they must appear on at least two adjacent sheets.

It is possible to select a sheet, change its position in the parallel stack of planes, and add, modify, or delete contours. A sheet is recalled and displayed by its number. Its position relative to other planes can then be changed. On that sheet any contour can be modified by calling it up by number. This deletes any old data and allows a new contour to be entered under that number. If no data are entered, the contour remains deleted. If the angular orientation of any sheet relative to the reference system is changed, the change affects the orientation

of the entire stack of parallel planes on which contours are entered.

If data are entered for one plane only, that sheet is duplicated on two others spaced 30 mm to either side of it. This gives a pseudo-two-dimensional calculation in which data need be entered in only one plane and calculated doses are valid in that plane only.

Plans and Beams

After the patient data are entered, the treatment plans for which doses are to be calculated must be specified by input to the code. Each plan has a number and consists of one or more numbered beams. A beam can enter from any direction relative to the patient-fixed reference system, and it can have any weight of dose relative to other beams. These parameters must be given as input to the code; they may be controlled by a special knob or entered numerically. Patient contours with the beams drawn in as lines are displayed in two views to guide adjustment of beam direction. A beam may be converted to a rotational or partial rotational treatment. Compensating material, or bolus, may be placed in a beam to reduce the effect of patient surface shape and internal inhomogeneities between the beam's entrance port and the treatment volume.

It is possible to select plans and beams by number for deletion or modification of any parameter with guidance by appropriate displays. A beam of zero weight is dropped; a plan with no beams disappears. At any stage, it is possible to save a duplicate of a plan under another number then continue the development of the original plan.

The Calculation

Before computation begins on a plan, the nature of the calculation is specified. The number and spacing of the points at which the dose is to be computed are set. The type of radiation in the beam is given. In the case of pions, the dose can be the total absorbed dose, the absorbed dose given by the high-LET component of the radiation only, or a weighted combination of high- and low-LET doses as an approximation to biological effective dose. Inhomogeneities and curvature are included or excluded from the calculation. A file that contains the details of the scans of the pion beams and of the bolus needed for each beam can be saved. Such a file could be used for later execution of the

plan under manual or computer control. All these changes generate appropriate displays.

Finally, the calculation must be started or exported to a larger and faster machine. During computation the code attempts to design beams that give the treatment volume a uniform high dose of radiation, and displays of the beam scan and bolus are generated. A message indicates when calculation is finished. If necessary, the calculation can be aborted before its conclusion. A calculation performed by a larger machine must be imported upon completion for display of the results.

Display of Results

After the distribution of radiation dose has been calculated, the results are displayed under control of input commands. The basic display is a map showing patient contours and isodoses. The orientation and position of the map are specified relative to the patient-fixed reference system. The isodose values can be changed, or a dot density display can be substituted. There is also a three-dimensional display of either isodoses or dots that is viewed in plane projection from any orientation (even with only one isodose this display is almost incomprehensible).

Any display of input data or results is copied onto a permanent plot on command; this is most useful for getting a record of the isodose maps of the results.

CONVENTIONS

Input

The basic unit of input is the record, consisting of one punched card or one line from the keyboard. Within the record, data are free field; items can be located anywhere in the record. Data items, or fields, are separated by one or more blanks or by a comma with or without adjacent blanks; commas can set off blank fields. A data field can contain any group of characters as long as it does not contain commas or blanks; fields cannot cross record boundaries. A blank record is equivalent to one blank field.

Commands

A command is an asterisk followed by two significant letters and any number of ignored characters. This allows the use of complete words, two-letter abbreviations, or commands with added comments as

long as there are no blanks or commas.

For example,

*BEAM

*BE

*BEAM-ADDS-A-NEW-BEAM-TO-THE-PLAN

all have the same effect because they all start with an asterisk and the same two characters.

Defaults

Many commands are followed by one or more fields of numerical data that the code will use as input. However, in some instances there are default values that will be used if numerical data are not supplied. The default will occur if there is a blank field set off by commas, if there are no data before the end of the record, or if there are no data before the next command. The details of each default option are described in the section on commands.

Units

Numerical input data must be integers. Distances are given in millimeters, angles in degrees, and relative values are in percent of a standard. The section on commands gives the units for each item of numerical data input.

Coordinate Systems

There is a basic reference system, fixed with respect to the patient, from which all positions and angles are measured. The reference system can be fixed in the most convenient relationship to the patient for each case. For example, it is often convenient to take the Z-axis in the supine patient's midline, with the positive end toward the head; the Y-axis vertical near the treatment volume, with the positive end pointing upward; and the X-axis horizontal, with the positive end toward the patient's right.

Sheets of contours, beams, and isodose maps are all fixed with respect to another coordinate system, the working system, whose origin may be displaced from the origin of the reference system and whose axes may make angles with the axes of the reference system. To relate these two systems, it is convenient to develop the transformation that will carry the reference system of axes into the working system, regardless of the angle and position of the working system.

The first part of such a transformation is the rotation of the axes to the new angles; this is done in three stages and defines three angles. First is

a rotation of the reference system about its Z-axis to give the primary system with X_1 -, Y_1 - and Z_1 -axes. The angle of this rotation will be called ϕ ; a positive direction of rotation carries the Y-axis toward the X-axis. Next is a rotation of the primary system about its X_1 -axis to give the secondary system with X_2 -, Y_2 - and Z_2 -axes. This angle is called θ , and is positive when the rotation carries the Z_1 -axis toward the Y_1 -axis. Finally there is a rotation of the secondary system about either its Y_2 - or Z_2 -axis to give the tertiary system with X_3 -, Y_3 - and Z_3 -axes. If the rotation is about the Y_2 -axis, the angle is called α and is positive if the rotation carries the X_2 -axis toward the Z_2 -axis. If the rotation is about the Z_2 -axis, the angle is called β and is positive when the Y_2 -axis is carried toward the X_2 -axis. These rotations are illustrated in Fig. 1.

The angles ϕ and θ can be given another meaning if a globe is imagined centered on the reference system with the Z-axis as its north pole and the

Fig. 1. The rotation of the coordinate system. Rotation about the Z-axis by angle ϕ gives the X_1 - Y_1 - Z_1 system; rotation, by angle θ , about the X_1 -axis yields the X_2 - Y_2 - Z_2 system. The third rotation can either be about the Y_2 -axis by angle α or about the Z_2 -axis by angle β .

Y-axis defining the zero meridian of longitude. If ϕ is less than 180° and θ less than 90° , the secondary system, the one where only ϕ and θ rotations have been applied, will have its positive Y_2 -axis at longitude ϕ West and latitude θ South. The Z_2 -axis will also be at longitude ϕ West but at latitude $90-\theta$ North; its angle from the pole, or co-latitude, is θ . The tertiary system will still have one of these relationships; the axis about which the third rotation occurs retains its position in latitude and longitude.

To complete the transformation from the reference to the working system, displacement of the tertiary system without rotation is all that is necessary. The tertiary system origin is moved to the point $X=x, Y=y, Z=z$ in the reference system without changing the angles of the axes; this gives the quarternary system with X_4 -, Y_4 -, and Z_4 -axes. This is sufficient to carry the reference system to any system of the same handedness, but for convenience, one redundant stage is added to the transformation. The quarternary system is translated along its own Z_4 -axis to a point $Z_4=s$, finally giving the working system with X_w -, Y_w -, and Z_w -axes. The displacement of the origin and the translation along the Z_4 -axis are shown in Fig. 2.

Fig. 2. The positioning of the coordinate system. After rotation, applying the displacement vector, D , gives the X_4 - Y_4 - Z_4 system with origin at the point (x, y, z) in the reference system, and then translation along the Z_4 -axis by the scan distance, s , yields the working coordinate system.

The seven quantities $x, y, z, \phi, \theta, \psi$, and s , where ψ is related to α or β as appropriate, define the working system's position and angle with respect to the reference system. The vector triplet x, y , and z are called the displacements; ϕ, θ , and ψ are the rotations, and s is called the scan distance. The scan distance is useful whenever a group of parallel planes occur, for example, in the entry of contours.

The plane in which contours are entered is defined to be the X_w - Y_w plane of the working system. In this case, the third rotation occurs about the Z_2 -axis, and ψ is related to β and is measured from the position where the X_3 -axis is parallel to the X - Z plane of the reference system, not from the X_2 -axis position. This leaves the Z -axis, which can be taken as the perpendicular line of sight for viewing this plane, at longitude ϕ and co-latitude θ with the X -axis of the viewed plane parallel to the X - Z plane of the reference system if $\psi=0$.

Exactly the same thing is true for the isodose maps. They are drawn to represent the X_w - Y_w plane of the working system under the transformation described above for contour entry sheets.

The beam entrance direction is given by the Y_w -axis of the working system. For the beam, the third rotation is about the Y_2 -axis and is measured from X_2 ; ψ is just α in this case. The stopping cylinder of pions lies in the X_w - Y_w plane parallel to the X_w -axis; the pions enter, and are swept in range, along the Y_w -axis. To fill a three-dimensional volume the beam is also swept longitudinally along the Z -axis; such motion can be represented by changes of the scan distances.

The beam pattern is read out by diagrams showing the length and range of the cylinder of stopped pions as well as the bolus at each plane in the longitudinal sweep. The diagrams are in the X_w - Y_w plane of a working coordinate system that is given by the same rotational transformation as is used for specifying the beam. A displacement is also used to locate the first plane's position in the reference system. Successive planes of the longitudinal sweep are related to the first plane by the scan distance.

Contours

The contours entered on parallel planes are an attempt to represent three-dimensional objects. To

enable the computer program to reconstruct the three-dimensional objects from the contours, certain restrictions and conventions are necessary.

A contour, in a plane, consists of any number of segments all having the same contour number and surrounding regions of the same density. Each segment consists of an ordered collection of points in the plane that defines a closed path that does not intersect itself. The last point of a segment is automatically made the same as the first so that the contour closes even if the entered data left a gap.

Contour segments should not intersect each other, because regions of ambiguous density then occur. Even if the intersecting segments are of the same density, errors will be caused. The one exception to this rule is that contour segments whose density is to be ignored may intersect other contours with assigned or ignored densities.

Contours that belong to the same three-dimensional object as sectioned by different planes must be given the same number and must have the same density. Contour numbers must be unique to each object. The same number must not be re-used for a second object even if it is of the same density, or the two objects will be joined into one. The exception is that a contour number may be re-used if there is a plane of contours separating the two objects that does not have a contour of that number. To get a meaningful representation of a three-dimensional object, at least two adjacent planes must have contours for that object. If an object extends over many planes each one must have a contour representing the cross section of the object in that plane.

In entering the data for contour segments that belong to the same object on several planes, the segments must always be entered in the same order if there is more than one per plane. That is, the first segment of the contour should connect with the first segment on any other plane to represent one branch of the object. The same is true for the other segments. The number of segments for a contour must remain the same from plane to plane. If an object bifurcates, it must be represented by two segments on every plane on which it appears at all. The two segments can be closely adjacent to represent the object on planes where its cross section is single.

Segments representing the same object on different planes need not have the same number of points; they are connected by joining each point with a straight line to the appropriate point on adjacent planes. For example, if the total numbers of points in the segments on two sheets are 24 and 32, some connected points will be 1 to 1, 24 to 32, 12 to 16, 6 to 8, 3 to 4, and 2 to both 2 and 3.

If the joining lines are to approximate the surface of the actual object, the order of points in the segments must go around in the same direction, clockwise or counterclockwise. Also, the starting points of the segment in each plane must be corresponding points in the object. Finally, the points must not be inappropriately bunched on one side of the object in one plane and on the other side in the next plane.

The contours are given on a stack of parallel planes; to be parallel, their transformations must have the same rotation angles. Each plane can have its own scan distance, and, if necessary, it can have its own displacement vector. Whenever the rotations are changed for a plane, the new angles are entered in the transformations for all planes in the stack.

COMMANDS

Administrative Data

The following commands are used in entering and changing the administrative data concerning the patient.

*CASE n p₁ p₂ p₃ d s t initializes the program to begin a new case. It may be followed by up to seven fields giving the administrative data. The first field, n, is the case number; the next three, p₁ p₂ p₃, are the patient's name; there is one field, d, for the doctor's name, one, s, for the treatment site and one, t, for the date. The first twelve characters of each field are used; the rest are ignored. The data fields, including the case number, can contain any characters or be left completely blank; there is no restriction to alphabetic or numeric information. Of course, no blanks or commas can occur within a field, so, for example, the date must be given as 5JUL73 or 5/JUL/73. The data can be entered one item at a time if the code is running on an interactive computer. If another command is

issued before all seven fields of administrative data have been entered, the rest of the data are left blank; the three patient name fields must be on one record.

If the system for storage and retrieval of patient information is implemented, the case number is supposed to provide unique identification used for the storage and recall of all information about the case. Giving the case number will recall the rest of the administrative data, the patient contours, and any treatment plans that may have been developed previously and stored under that number; the case data remains in storage until purged. If the number is not encountered in storage, a new case is set up and entered. Once a case is recalled, administrative data, contours, and plans can be changed and new plans can be developed and added. The case number must be unique not only to the patient and site, but to the set of patient contours used. This allows the storage of several descriptions of the same patient with, for example, differing orientations of the stacks of planes of contours or differing degrees of contour detail.

*NAME $p_1 p_2 p_3$ enters up to three twelve-character fields of data to be stored as the patient's name. All of the fields that are to be entered must be on one record; the remaining fields are left unchanged.

*DOCTOR d enters one twelve-character field to be stored as the physician's identification.

*SITE s enters one twelve-character field to describe the treatment site.

*DATE t enters one twelve-character field, the date.

Coordinate Transformation

These three commands are used to enter the parameters of the coordinate transformation from the reference system to the working system. These commands are applied with respect to a specific working system such as that of a plane of contours or of a beam. The effect of the transformation varies with the application.

*DISPLACE x y z sets the displacement vector so that the origin of the working system is at the point $X=x$, $Y=y$, $Z=z$ in the reference system. The three required fields of numerical data are measured in millimeters and must be in the same record as the command itself.

*ROTATE $\phi \theta \psi$ sets the three rotation angles.

The interpretation of the third angle, ψ , depends on what the system being rotated refers to. The first angle, ϕ , is a rotation about the Z-axis of the reference system. The resulting system is then rotated about its X-axis by the second angle, θ . If the rotation applies to a beam, the third angle, ψ , is α , a rotation about the Y-axis of the twice rotated system. If it applies to a plane of contours or an isodose map, the third angle is another rotation about the Z-axis, β , and is measured from the position where the X-axis of the working system is parallel to the X-Z plane of the reference system. The angles are measured in degrees and must be given in the same record as the command.

*SCAN s sets the value of the scan distance, the amount by which the working system is displaced along its own Z-axis after the displacements and rotations are applied. The value is in millimeters and must be in the same record as the command.

Contour Input

These commands allow the input of patient contours to the program. Contours are given on a stack of up to 30, numbered parallel planes, or sheets, to describe the three-dimensional structure of the patient in the region of the treatment site.

*SHEET n creates or calls up plane number n ; if n is greater than 30 or is not specified on the same record as the command, a sheet is created and assigned the first unused number. If the sheet existed previously, all contours on it are displayed along with the displacements, rotations, and scan parameter of the sheet. If the sheet did not exist, it is created with the same displacement and rotation as the sheet of next lower number but with the scan parameter increased by 30 mm. The first sheet created has displacement, rotation and scan set to zero initially. The coordinate transformation commands *DISPLACE, *ROTATE, AND *SCAN, can be used to set the position of the sheets. The contour plane is always the X-Y plane of the working coordinate system. Each sheet can have its own displacement if desired, but it is usually sufficient to have the same displacement vector for all sheets and to use the scan distance alone to give the position of the sheet in the stack. Since all the sheets are parallel, any change in the rotation produced by *ROTATE $\phi \theta \psi$ command applies to all sheets in the

stack. The rotation angles ϕ and θ give the longitude and co-latitude of the Z-axis of the working system on a globe whose pole is the Z-axis of the reference system. The Z-axis of the working system is perpendicular to the sheets of contours and may be taken as a line-of-sight in visualizing the sheets. The angle ψ is the rotation about the Z-axis from the point where the X-axis was parallel to the X-Z plane of the reference system. Three sheets of contours are shown in Fig. 3.

When entering contours from the digitizing table, it is necessary to relate position on the table to coordinates in the X-Y plane of the working system. This is done by digitizing two special points for each sheet of contours, the first will be at the origin and the second will be at the 10-cm point on the positive X-axis of the working system. This makes the digitized values independent of the position and rotation of the drawing placed on the table. Since the two points need not be 10 cm apart

Fig. 3. Three sheets of contours; each sheet is entered as the X_W - Y_W plane of a working coordinate system. The three sheets shown all have the same rotations and displacements, but they are separated by having different values of the scan parameter. Each sheet shows the origin-point and the ten-centimeter-point that are used to relate the X_W - Y_W plane to position on the digitizing table.

on the table, a magnified or reduced drawing can be used; the points should represent an actual 10 cm on the patient. Each point is entered by positioning the digitizing cursor correctly and then pressing its button or giving a carriage return on the keyboard. The same information can be entered numerically from keyboard or cards by giving the X and Y value in digitizer units, first for the origin-point and then for the ten-centimeter-point. If these are given in the same record as the *SHEET command, the first field following the command will be taken as the sheet number and must be set off by commas if it is to be blank. These points will be set to $X=0$, $Y=0$, and $X=100$, $Y=0$ if nothing is entered either numerically or from the digitizing table before the command following *SHEET is given.

*DUPLICATE n makes a duplicate of the current sheet, the one called up by the last *SHEET command, and stores it as sheet number n. If another sheet existed as sheet number n, it is lost; if n is the same as the current sheet number, the current sheet is lost. If n is not specified on the same record as the command, the first unused sheet number is assigned. The current sheet remains current and unchanged after a *DUPLICATE command.

*ORIGIN allows the origin-point to be reset. Following this command the data can be entered numerically as X and Y values in millimeters or from the digitizing table using its button or a keyboard carriage return. This command is useful in correcting erroneous data, or if the undesired default values for the origin-point were invoked, for example, by giving one of the coordinate transformation commands to position the sheet before entering the correct origin-point.

*TEN-CM allows revision of the point at 10 cm in the working system; it functions exactly like *ORIGIN.

*CONTOUR n d prepares for the entry of data as contour number n; if n is not given on the same record as the command, the number is assigned to be one greater than the highest contour number in use on the current sheet. If n is given and corresponds to a previously existing contour number on the current sheet, all data pertaining to that contour is immediately eliminated; if no further data is entered, the contour disappears. The effective density of the material within the contour is given by d.

This value is specified as a percentage of the pion stopping power for muscle tissue. If $\cdot$ is not given in the second numerical field of the same record as the command, the default value of 100% is assigned. If a negative value is given, the density is ignored.

The actual contour data can be entered either from the digitizing table or numerically. If the digitizing table is used, the cursor is positioned at the first point of the contour, and data input is initiated by pressing its button or by giving a carriage return from the keyboard. Tracing around the contour segment will enter points with a separation given by the `*SPACING` command; the end of data is indicated by pressing the button again, giving another carriage return, or giving any command. This completes the entry of one contour segment; the segment is automatically closed by joining the last point to the first point. Another push of the digitizer button or another carriage return from the keyboard will start the entry of data for the next segment of the same contour with the same density; this procedure can be repeated for any number of segments. It is also possible to enter discrete points from the digitizing table instead of tracing the contour. To do this, the `*SPACING` command is used to set the separation to zero; one point is then entered each time the digitizer button is pushed or a carriage return is given. If the data for the first contour segment is to be entered numerically, it follows the `*CONTOUR` command on any number of records but with no interspersed blank fields or records. The X and Y values of the points are given in digitizer units; the order is $X_1, Y_1, X_2, Y_2, \dots$ and so on. The contour segment is automatically closed; it is not necessary for the first and last points to be identical. To indicate the end of a segment, a blank field or any command may be given; the command that is given to end the segment is executed. Giving `*CONTOUR` causes the program to go directly on to the next contour, and `*SHEET` brings up another sheet for contour entry. If more than one segment is to be entered for the contour, the command `*START` readies the computer for input of the next segment; `*END` does the same thing but also generates a display of the sheet that includes the segments already entered.

`*SURFACE n d` acts exactly like a `*CONTOUR` command, but the contour entered is flagged as marking

the outline of the patient; a surface contour must be given on every sheet of contours. The default density is 100% of soft tissue and occurs if no density is given in the same record as the command. The density outside the surface is taken to be zero except for any holes present.

`*TREATMENT-VOLUME n d` also acts like a `*CONTOUR` command, but the contour entered is flagged to indicate that it marks the treatment volume. The program will attempt to design beams that deliver a uniformly high dose to the treatment volume. A treatment volume must be specified, and its contours must occur on at least two adjacent sheets, or the code will not generate meaningful beams. If no density is given in the same record as the command, the density is ignored. This default differs from all other contours where the default density is 100%.

`*START` immediately readies the code for entry of another segment of the same contour. The contour segment can be entered from the digitizing table or numerically; this is done the same way as if entry follows a `*CONTOUR` command except that there is no opportunity to specify a new contour number or density.

`*END` is used to mark the end of a contour segment and to generate an updated display of the sheet that includes the segments just entered. It also readies the code for the entry of the next segment of the same contour.

`*DENSITY d` allows the density of the current contour to be changed; it may be given either before or after the entry of the data for any segment; the value of d is given as the percentage of the pion stopping power for muscle tissue. It must be given in the same record as the command, or it is set to the default value of 100%. If the given density is less than zero, the density for that contour is ignored. A density of zero is perfectly acceptable and is a good approximation for air-filled spaces.

`*IGNORE-DENSITY` flags the current contour so that its density will be ignored. The density within the current contour is given by other contours that surround the same region just as if the contour were not present at all. This is the only type of contour that is allowed to intersect other contours since no confusion can result. This command can be given before or after the entry of data for any segment.

*SPACING s resets the minimum spacing between points taken from the digitizing table. The value of s is given in digitizer units. Every time a *CONTOUR command is given, the value of s is reset to 10. It is not necessary to give s in the same record as the *SPACING command. The default, which happens if another command or a blank field occurs before the value of s is given, is to leave the value of s the same as it was before. Setting the spacing to zero is used as a special flag to indicate that discrete points are to be entered from the digitizing table, one each time a carriage return is given from the keyboard or the digitizer button is pushed.

Plans and Beams

This group of commands enters the parameters of the beams used to dose the treatment volume. One or more beams constitute a plan; the doses from all beams in a plan are summed to get the final dose distribution. It is possible to store up to 22 plans in the computer, although results can be computed and displayed for only one plan at a time.

*PLAN n calls up and displays plan number n . If the plan did not previously exist, it is created. If n is greater than 22 or is not given in the same record as the command, a new plan is created and assigned the first unused plan number. The display of the plan includes identification by case number and patient name as well as a list with the parameters of all the beams currently in the plan.

*SAVE n makes a duplicate of the current plan, the one called up by the last *PLAN command, and saves it as plan number n . If another plan existed as plan number n , it is lost. If n is the same as the current plan number n , the current plan is lost. If n is not specified on the same record as the command, the first unused plan number is assigned. After issuing a *SAVE command, the current plan remains available for modification while the saved copy preserves its present state of development.

*BEAM n w adds a beam to the plan as beam number n with weight w . If beam number n previously existed, it is recalled and its parameters are available for modification. The beams are displayed on two cross sections at right angles through the treatment volume with the current beam drawn more heavily than the others. If n and w are not given in the same record as the command, the default options are

used. The beam number is assigned to be one greater than the highest number previously used in the current plan, and the weight is set to 100. The weight, w , is given in arbitrary units, but they do correspond to the isodose levels used in the output of the results. A beam with a weight of 100 will have a maximum dose of approximately 100 units on the isodose map.

The pion beam gives a cylindrical region of stopped pions. To fill a volume with stopped pions the cylinder is scanned, rapidly in depth to give an area, and slowly in the longitudinal direction perpendicular to this area. The coordinate transformation command, *ROTATE, controls the direction of the beam. The cylinder of stopped pions lies in the X - Y plane of the working coordinate system parallel to the X -axis; the pions enter along lines that are parallel to the Y -axis. The depth scan is parallel to the Y -axis, and the longitudinal scan is in the direction of the Z -axis. This is shown in Fig. 4.

Fig. 4. The beam has pions entering parallel to the Y -axis of the working system and stopping to form a cylinder parallel to the X -axis. The range scan is parallel to the X -axis and fills an area in the X - Y plane with beam; the longitudinal scan is parallel to the Z -axis and fills a volume with stopped pions.

Since the treatment volume is defined by contours and fixes the aiming point of the beam, the *DISPLACE and *SCAN commands are irrelevant. Only the entrance angles given by *ROTATE ϕ θ ψ are necessary to define the beam. Starting from the reference system, ϕ is a rotation about the Z-axis, θ is a rotation about the new X-axis, and ψ is α , a final rotation about the resulting Y-axis. The rotations yield a working system with the beam entering along the positive Y-axis and the longitudinal scan along the Z-axis. Related to a globe whose pole is the Z-axis of the reference system, the beam entrance direction is at longitude ϕ and latitude θ . If ψ is zero, the longitudinal scan is parallel to an axis through longitude ϕ and co-latitude θ . The scan direction is rotated about the beam entrance direction if ψ is not zero.

*WEIGHT w changes the weight assigned to the current beam, the beam produced or recalled by the last *BEAM command. If w is not given in the same record as the command, a default value of 100 is assigned. The units used for the weight are arbitrary, but they do correspond approximately to the maximum dose that the beam will contribute on an isodose map of the results.

*BOLUS f is a command to flag the current beam so that, during computation, bolus is added to correct for internal inhomogeneities and patient surface curvature between the beam port and the treatment volume. If this command is not given, no bolus is used for a beam. The amount of bolus is not specified; it is computed automatically so that the total pion stopping power is the same for every ray entering the treatment volume. If field f contains the word NO or anything beginning with the letter N, the flag is reset and bolus is not used.

*ARC s ϕ θ k m converts the current beam into a rotational treatment. All parameters must be in the same record as the command or the defaults will be used. The code simulates true rotation by summing a finite number of beams; the angular spacing of which is given by s . The value is given in degrees and the default is 20° . The axis of rotation is at longitude ϕ and co-latitude θ on a globe with the pole at the reference system Z-axis. The values are in degrees and the defaults are zero for both angles. For a partial rotation, the lower limit is k , and the upper limit is m . The units are degrees and the

defaults are 0° and 360° giving a complete rotation.

*XIS ϕ θ sets the longitude, ϕ , and co-latitude, θ , of the axis of rotation. The values are in degrees, and the defaults are zero for both angles.

*LIMITS k m gives the lower limit, k , and upper limit, m , for a partial rotation. The values are in degrees, and the defaults are 0° and 360° which gives a complete rotation.

The Calculation

The following commands control the nature of the calculation and its execution. Whenever a *CASE command is given, all parameters specified by these commands are set to their default value, otherwise, they remain as last set.

*VOLUME X_L X_H X_S Y_L Y_H Y_S Z_L Z_H Z_S specifies the number, position, and spacing of points at which the dose is to be calculated. The volume that these points occupy is given in the reference coordinate system. There are points spaced every X_S millimeters starting from the lower X-limit, X_L , to the upper limit, X_H ; the Y and Z directions are similar. The values are all given in millimeters, and the defaults for each new case are a lower limit of -100 mm, an upper limit of 100 mm, and a spacing of 20 mm in all three directions. The values need not be given in the same record as the command; on an interactive system, the data can be entered one item at a time. A blank record or field results in the default value being used for that item; giving another command results in defaults for any remaining items.

*PION sets the code for calculation with pion beams; this is the default particle type for each case. Once a particle is specified by command, all calculations will be done for that particle until a command is given to use another type of particle, or a *CASE command is given to restore the default option of pions.

*GAMMA e sets the code for calculation with gamma-ray beams of characteristic energy e .[†] The energy is given in kilovolts and the default value is 1200 keV.

*ELECTRON e sets the code for calculation with electron beams of energy e .[†] The energy is given in kilovolts and the default value is 6,000 keV.

*RAD specifies that the output from the calculation is to be the absorbed dose. This is the

[†]This command is not yet implemented.

default option and is invoked for each new case.

***HI-LET** specifies that the output from the calculation is to be the absorbed dose delivered by the high-LET component of the radiation only.

***REM r** specifies that the output from the calculation is to be a weighted combination of high- and low-LET doses as an approximation to biological effective dose. The parameter *r*, expressed as a percent, is the ratio of the biological effect for high- to low-LET radiation. The default value is 300% occurring if a blank field, blank record, or another command is given before the parameter is specified.

***INHOMOGENEITIES f** causes the computation to include the effects of internal inhomogeneities as well as surface curvature unless the first character of the following field, *f*, is N as in the word NO. In that case, both internal inhomogeneities and surface curvature are ignored. Field *f* need not be in the same record as the command, but a blank record, a blank field, or another command will cause the inclusion of the inhomogeneity effects. For each new case, the default option is inclusion of the effects of both surface curvature and internal inhomogeneities.

***CURVATURE f** causes the computation to include the effects of surface curvature only and to ignore the effects of internal inhomogeneities. If the first character of field *f* is the letter N as in the word NO, the effects of surface curvature are ignored as well. As with the command ***INHOMOGENEITIES**, field *f* need not be in the same record as the command.

***FILE f** causes the generation of a file of data that can be used for the actual execution of the plan.[†] If field *f* contains the word NO or anything that starts with the letter N, the file is not generated, the field *f* obeys all the same rules as the corresponding field for the command ***INHOMOGENEITIES**. The default option, for each new case, is that the file is not generated.

For each beam in the plan, the file will contain information on the bolus, if used, and on how the cylinder of stopped pions is to be scanned to fill the treatment volume. The longitudinal beam scan is divided into successive planes, and for each plane, information is given to locate the plane in space and to specify the details of the depth scan

and the bolus for that plane. The depth, length, and position for each cylinder of stopped pions in the plane is given, as well as the relative entrance dose delivered by the pions that must stop in the cylinder to give the correct dose. If bolus is used, the amount necessary is given for each entering beam ray in the plane.

***GO n** starts the calculation on plan number *n*. If *n* is not given in the same record as the command, the plan specified by the preceding ***PLAN** command is used. Absence of a preceding ***PLAN** command or certain intervening commands will cause the default plan number to become undefined. In this case, the code gives an error message instead of proceeding with the calculation.

The code calculates for one beam at a time. A rotational treatment is replaced by several fixed beams evenly spaced in angle over the arc to be covered. For each beam, the code attempts to design a beam scan pattern that will result in a uniform dose over the treatment volume. If bolus is used, the code computes the amount required in each ray to equalize the total stopping power between the beam port and the treatment volume. The same information about beam scan and bolus that is saved in response to a ***FILE** command is presented diagrammatically and transiently on the display scope as the calculation proceeds; if the ***FILE** command was given, permanent copies of these diagrams are made on the plotter. (These diagrams are illustrated by Figs. 22 and 23 of the example.) For each longitudinal scan plane of each beam, one diagram is generated, identified by case number, patient name, plan number, and beam number. The weight of the beam appears on the display as well as the parameters of the coordinate transformation to a working system; the rotation angles are those used to specify the beam, with rotation ϕ about the Z-axis then θ about the new X-axis and ψ about the resulting Y-axis. The diagram that appears represents, almost, the X-Y plane of the working system with the central vertical line being the Y-axis. There is one important difference from a true X-Y plane; the vertical coordinate is the range of the pion beam, the distance the pions would travel in muscle tissue before stopping. For this reason the vertical line is not quite the Y-axis, but it truly gives the locus where X is zero. The ticks on the edges represent centimeters of

[†]This command is not yet implemented.

X-position and of range. On this diagram, there is a horizontal line for each cylinder of stopped pions; its location, measured down from the top, gives the range of the pions in the cylinder. The length and position of the horizontal line, measured from the vertical axis on the diagram, gives the length and position of the cylinder, measured from the Y-axis of the working coordinate system. There is a numerical value associated with each horizontal line; this gives the relative entrance dose delivered by the pions necessary to bring the cylinder up to the desired dose. If bolus is used, there is also a group of vertical lines on this diagram; these give the bolus required between the beam port and the treatment volume to equalize the range for each ray in this plane. The position of the line relative to the vertical axis gives the X-position of the ray, and the length of the line gives the range that must be made up in bolus for that ray.

When the calculation is completed, the code displays a message to that effect.

*FLUSH stops the calculation before it is completed; all work done on the computation since giving the *GO command is lost. Administrative data, patient contours, and beam plans remain for use by another calculation, but it must be started from scratch with another *GO command. This is the only command that is effective after a *GO command before the computation is completed. If another command is given during a calculation, it is ignored until the calculation is completed. Input to the code is held up at that command, and a following *FLUSH command will have no effect.

*EXPORT n sends the calculation of plan number n off to a larger and faster computer for execution.[†] The plan number must be given in the same record as the command, or the number specified by a preceding *PLAN command is used. This is subject to the same restrictions as with a *GO command.

The actual transmission of data to the other computer may be done by a direct computer-to-computer link, or by generating a magnetic tape to be read by the other computer. If the PDP-11/45 is fast enough to handle all calculations actually required in reasonable time, no exporting may ever have to be done.

[†]This command is not yet implemented.

*IMPORT n recovers the results of a calculation done on plan number n by another computer; the results are then available for display just as if they had been computed by a *GO command.[†] The plan number need not be given in the same record as the command. A blank record or field results in the importation of the first plan found in the file of completed calculations. If plan number n is not found among the completed calculations, an error message will be displayed.

Display of Results

The following commands control the presentation of the results of the calculation and allow display of the distribution of radiation dose delivered to the patient by the beams.

*MAP calls up a scope display of a map showing both the distribution of radiation dose and the patient contours. The map shows the X-Y plane of the working system of coordinates automatically centered on the screen. The coordinate transformation commands *DISPLACE, *ROTATE, and *SCAN are used to change the angle and position of this plane. The rotation angles have the same interpretation as for a sheet of contours. For the command *ROTATE ϕ θ ψ , the angles ϕ and θ give the longitude and co-latitude of the Z-axis of the working system on a globe whose pole is the Z-axis of the reference system and whose zero meridian is its Y-axis. The Z-axis of the working system is perpendicular to the plane of the map and may be taken as the line-of-sight in viewing the map. The angle ψ is related to β and gives the rotation of the map about this Z-axis line-of-sight, measured from the position where the X-axis of the working system is parallel to the X-Z plane of the reference system. On an interactive computer, it may be possible to control the coordinate transformation parameters with knobs. Since it takes some time to recompute the display, the new values of the parameters are displayed numerically on the old map. After the parameters have stopped changing, the new map is generated.

The display of the map includes a list of the coordinate transformation parameters for that map, the patient contours as sectioned by the X-Y plane of the working coordinate system, and a representation of the radiation dose distribution given by the beams to that plane. The type of dose is set by the *RAD, *HI-LET, and *REM commands, and its

distribution is shown on the map by isodose lines. The levels of dose at which the isodoses are drawn is controlled by a list of levels with default values of 50, 100, 150, 200, 250, and 300 dose units. These units correspond to the units used for beam weights. The maximum dose in the treatment volume should be about equal to the sum of the weights of all the beams. Other levels are added to the list by entering them following the *MAP command after which isodose lines immediately appear on the map and remain in the list for future maps. The additional levels need not be given on the same record as the command and blank fields and records in the list are ignored. The list of levels is cleared and replaced by a new list using the *LEVELS command. Levels need not be given with this command but may be added one at a time following a subsequent *MAP command so they can be seen as they are added. To aid in identifying the isodoses, a numbered list of levels appears on the display, and small numbers are superimposed on the isodose lines. These small numbers give the position, in the list, of the level that corresponds to each isodose. The distribution of radiation can also be shown by a dot plot. The density of dots on this plot is proportional to the effective dose in each region. The constant of proportionality is shown on the display and can serve as a guide in case it has to be changed. The dot-plot option is invoked by a *POINTS command, which also can reset the constant of proportionality. All future maps are dot plots until a *LEVELS command restores the isodose option.

*LEVELS $k_1 k_2 \dots$ clears the old list of isodose levels and enters the new levels $k_1 k_2 \dots$ given following the command. The new levels must be given in the same record as the command with no blank fields interspersed. However, if the *LEVELS command is given following a *MAP or *ISOMETRIC command, the map is immediately redrawn with those isodose levels that were given on the same record as the *LEVEL command; if no levels were given with the *LEVEL command, the map is redrawn with no isodoses displayed. In either case, new levels can be added one at a time as if they followed a *MAP command. The command *LEVELS also cancels the dot-plot option. All maps following a *LEVELS command will use the new list of levels until another *LEVELS or a *POINTS command is given. Of course the new list is expanded

by levels entered following *MAP commands, and subsequent maps use the expanded list. There is a limit of 30 levels, after which each new level replaces the last level entered into the list.

*POINTS d sets up the dot-plot option for maps; the constant of proportionality between dose and dot density is set by d . The density constant, d , must be given in the same record as the command; if not, the default value is 20 which gives a reasonable dot density for a maximum dose that is around 100 dose units. After a *POINTS command, all subsequent maps are dot plots until a *LEVELS command is given. If the *POINTS command follows a *MAP or *ISOMETRIC command, the map is immediately redrawn as a dot plot.

*ISOMETRIC causes a scope display of an isometric-like plot of patient contours and the distribution of radiation. The *ROTATE command sets the angle of view of the display, but *DISPLACE and *SCAN are irrelevant. The line-of-sight is the Z-axis of the working coordinate system. The three-dimensional data is all projected onto the X-Y plane of the working system by ignoring the Z-coordinate, and the display is automatically centered on the screen. The patient contours are drawn on their sheets of entry and then projected onto the X-Y plane of the working system. The isodoses are drawn on the X-Y planes of the reference system defined by Z_L , Z_M and Z_S of the *VOLUME command; there is a plane of doses every Z_S millimeters starting at Z_L and going to Z_M . The isodoses are then projected onto the X-Y plane of the working system. A dot plot is generated by placing dots, with density proportional to effective dose, throughout the volume of dose computation defined by the *VOLUME command, and then projecting the dots onto the X-Y plane of the working system. The displays produced by the *ISOMETRIC command are usually impossibly confusing even if only one level of isodose is drawn.

With regard to changes of angle, changes of isodose levels, and the use of the dot-plot option, the command *ISOMETRIC behaves just like the *MAP command.

Miscellaneous

*OUTPUT causes the current scope or printer display to be recorded permanently on the plotter. It is most useful for the maps of the results, but it can be used with any display.

*PRESERVE n causes the administrative data, patient contours, and beam plans of the current case to be stored as case number n.[†] The number, n, must be given in the same record as the command, or storage takes place under an assigned number. The assigned number is displayed, and it does not correspond to any case currently in storage. Even if the case to be stored was previously in storage, it is not assigned the same number and overwritten; it is stored under a new assigned number. If a number is given that corresponds to any case currently in storage, the *PRESERVE command is ignored, and an error message will be displayed. The exception occurs if the given number is the same as the number under which this case was previously stored. Then the previously stored case is overwritten and lost, and the new version, which may have been modified, is stored under the same number.

*PURGE n removes the current case, as set by a *CASE command, from storage if it had been previously preserved.[†] The case number, n, must be given in the same record as the command. As a check, the given number must agree with the number under which the case was previously stored and it will then also agree with the number given in the *CASE command that recalled the case. If such agreement is not found, no purging takes place, and an error message is displayed.

*UNLOAD causes the treatment planning code to stop running and relinquish control and its computer memory space to the system monitor for other uses.

*PASS is a no-operation command; it is used to terminate the execution of a previous command of the type that continues to accept input until it encounters another command.

EXAMPLE

General

The use of the treatment planning code on the CDC-7600 is demonstrated in the following example in which some reference will be made to interactive operation on the PDP-11. A complete listing of the example, including CDC-7600 control cards, is found in the Appendix. The head and neck region is chosen, and a treatment volume is arbitrarily drawn in lateral to the pharynx. A plan consisting of two

opposed beams is used; the total delivered dose and the high-LET component of the dose are computed and displayed. For comparison, a plan with only one beam is also tried.

Administrative Data

The required information is the case number, patient's name, doctor's name, site and date; this can all be entered as a single record or divided among several records.

```
*CASE 1128
VICTIM, JOHN Q.
KLIGERMAN
HEAD+NECK
20/JUL/73
```

This information is displayed for verification as shown in Fig. 5.

```
CASE- 1128
NAME- VICTIM      JOHN      Q.
DR. - KLIGERMAN
SITE- HEAD+NECK
DATE- 20/JUL/73
PLANS- 0
```

Fig. 5. The display of the administrative data for this case.

If the input of administrative data is divided among several records, the display is generated one line at a time after each record is entered, showing all information entered to that point and indicating the next item required. If the storage and retrieval system for patient data is implemented, entering the number of a previously stored case will recall the rest of the administrative data, the patient contours and any plans that may have been generated for that case.

Patient Contours

The basic data used here is freely adapted from Secs. 12 through 18 in "A Cross-Section Anatomy" by Eycleshymer and Schoemaker. The sections are used as if they were parallel although they are not quite so; the dorsal edges are slightly closer together than the ventral edges. Artistic license is used in symmetrizing the sections, and in assigning contours to adjacent pieces of complex bone as if they were a single simple piece. The contours are digitized on a machine that gives about 394 counts per centimeter on the drawing and, since the drawings are 4/5 scale, about 315 counts per centimeter of actual distance.

[†]This command is not implemented.

The reference system chosen for this case has its origin at the center of the spinal cord at the level of Sec. 15 near the lower edge of the second cervical vertebra. The positive Z-axis extends in a cranial direction; the X- and Y-axes extend to the right and ventrally, respectively, and lie in the plane of Sec. 15.

The first sheet of contours corresponds to Sec. 12 which lies about 39 mm above Sec. 15.

*SHEET 1

04083 03609 07229 03609

*SCAN 39

The *SHEET command creates this sheet of contours. The four numbers following the command are the digitized X and Y values of the origin of the plane and a point corresponding to 10 cm of actual distance on the positive X-axis. The *SCAN command sets the location of this sheet on the Z-axis of the reference system; since no rotation or displacement is applied the *SCAN command moves the sheet along the Z-axis but leaves it parallel to the X-Y plane of the reference system. The parameters of the first sheet are shown in the display of Fig. 6.

Contour 1 is the patient's outline.

*SURFACE 1

04070 07268 . . .

. . .

. . . 03672 07164

*END

The display now shows the contour that was just entered (Fig. 7). Contour 2 represents the left ramus of the mandible.

*CONTOUR 2

02634 05539 . . .

. . .

. . . 02596 05505

*END

*DENSITY 175

SHEET-	1		
DISPLACE-	0	0	0
ROTATE-	0	0	0
SCAN-	39		
ORIGIN PT OK			
TEN-CM PT OK			

Fig. 6. The parameters of Sheet 1.

SHEET- 1
CONTOUR- 1
DENSITY- 100
START

Fig. 7. Sheet 1 after the entry of the surface contour.

As each contour is entered, a new display is generated when *CONTOUR command is given. This display shows the new contour number, but until the entry of the new contour segment is completed, it can only show previously entered segments. When the *END command is received, the display is redrawn with the new segment included. At this point, the density still has the default value of 100%. In the example above, bone is arbitrarily assigned 175% of the soft tissue stopping power for pions, regardless of the relative amounts of compact and trabecular bone. The *DENSITY command resets the density assigned to this contour. It is echoed back at the bottom of the display, below a line of asterisks, just before the display is redrawn with the new density for the contour (Fig. 8). Contour 3 is the right ramus of the mandible, and Contour 4 is a section of the hard palate. The hard palate, the approximated upper and lower teeth, and the central portion of the mandible are all represented by Contour 4 as if they were a single piece of bone; the two rami of the mandible are represented by separate contours since, by convention, a contour cannot join or divide in passing from one sheet to another. Both Contours 3 and 4 are given a density of 175%.

SHEET- 1
 CONTOUR- 2
 DENSITY- 100
 START

 DENSITY- 175

Fig. 8. Contour 2 has its density changed from 100 to 175 by the command shown below the line of asterisks.

```
*CONTOUR 3
05569 05516 . . .
          . . .
          . . . 05523 05500

*END
*DENSITY 175
*CONTOUR 4
04065 06848 . . .
          . . .
          . . . 03862 06805

*END
*DENSITY 175
```

The display of the contours just after entering Contour 4 and changing its density is shown in Fig. 9. Contour 5 outlines the pharyngeal air space, and is assigned a density of zero. Contour 6 is the spinal cord, and, since its density is the same as that of the surrounding medium, its effect on density is canceled by using an *IGNORE-DENSITY command.

```
*CONTOUR 5
. . . . .
*END
*DENSITY 0
*CONTOUR 6
. . . . .
*END
*IGNORE-DENSITY
```

SHEET- 1
 CONTOUR- 4
 DENSITY- 175
 START

Fig. 9. Sheet 1 with Contours 1-4 entered.

Contours 7 and 8 represent the occipital condyles and part of the first cervical vertebra on the right and left, respectively. These contours have a density of 175%.

```
*CONTOUR 7
. . . . .
*END
*DENSITY 175
*CONTOUR 8
. . . . .
*END
*DENSITY 175
```

This completes contour entry on Sheet 1 for the moment. The result is shown in Fig. 10.

SHEET- 1
 CONTOUR- 8
 DENSITY- 175
 START

Fig. 10. Sheet 1 with Contours 1-8.

The second sheet of contours corresponds to Sec. 13 and lies 25 mm above the origin of the reference system.

*SHEET 2

04099 03558 07239 03559

*SCAN 25

Again, two points must be digitized to relate digitizing table position to coordinates in the plane of contours being entered. Contour entry then proceeds just as for Sheet 1. In this plane, Contour 4 represents the teeth, and Contours 7 and 8 represent the first cervical vertebra. The bodies of the second through the fourth cervical vertebrae are treated as one piece of bone and appear on Sheet 2 as Contour 9 immediately anterior to the cord. The treatment volume is assigned contour number 13 and appears in this plane just to the left of the pharynx.

*TREATMENT-VOLUME 13

.....

*END

The treatment-volume density is ignored, the default case. The completed Sheet 2 after entry of the treatment volume is shown in Fig. 11.

Sheet 3 corresponds to Sec. 14 in Eycleshymer and Schoemaker and is 11 mm above the origin. On this sheet, Contours 2, 3, and 4 together represent a cross section of the mandible. Contours 7 and 8 are no longer present, but Contour 10 has appeared to represent part of the arch and processes of the second cervical vertebra. Sheet 3 is shown in Fig. 12.

SHEET-
CONTOUR-
DENSITY-
START

Fig. 11. Sheet 2 after entering the last contour, number 13, the treatment-volume.

SHEET-
CONTOUR-
DENSITY-
START

Fig. 12. Sheet 3 after all contours have been entered.

Sheet 4 corresponds to Sec. 15 and passes through the origin of the reference system and has a scan parameter value of zero. The contours are shown in Fig. 13 and represent the same structures as in Sheet 3.

Sheet 5 corresponds to Sec. 16. It is 14 mm below the reference system origin. Contour 4 alone remains at this level to represent the mandible. Contour 10 is no longer present, but Contour 12, similarly located, represents parts of the third and fourth cervical vertebrae treated as one piece of bone. Contour 11 represents the hyoid bone. Sheet 5 is shown in Fig. 14.

Sheet 6 corresponds to Sec. 17. It is 24 mm below the origin. Because this section is completely below the mandible, Contour 4 does not appear. The other contours and structures are the same as on Sheet 5. Sheet 6 is shown in Fig. 15.

Sheet 7 corresponds to Sec. 18 of Eycleshymer and Schoemaker. It is 34 mm below Sheet 4 which was Sec. 15 and contained the origin of the reference coordinate system. Contour 13, the treatment volume, and Contour 11, the hyoid, do not appear on this level. The pharynx and vestibule of the larynx are represented by Contour 5. Contour 6, the spinal cord, and Contour 9, the vertebral body, are present. Contour 12 represents the remainder of the vertebra at this level. From anterior to posterior, or top to bottom on Fig. 16, the contours are numbers 5, 9, 6,

and 12; they are all surrounded by Contour 1, the surface.

SHEET- 4
CONTOUR- 13
DENSITY- IGNORED
START

Fig. 13. Sheet 4 after all contours have been entered.

SHEET- 5
CONTOUR- 13
DENSITY- IGNORED
START

Fig. 14. Sheet 5 after all contours have been entered.

SHEET- 6
CONTOUR- 13
DENSITY- IGNORED
START

Fig. 15. Sheet 6 after all contours have been entered.

SHEET- 7
CONTOUR- 12
DENSITY- 175
START

Fig. 16. Sheet 7 after all contours have been entered.

The vertebral bodies do not actually intersect Sheet 1, Sec. 12 of Eycleshymer and Schoemaker, but they come close enough to make it desirable to represent them on that sheet. By free use of the imagination, a suitable contour to represent the vertebral body is added to a piece of graph paper containing the other contours of Sheet 1; and, not wanting to bother with the digitizing table, the values of the contour points are read off to the nearest millimeter. To avoid negative numbers in the X-Y pairs of the contour, the values are read relative to a point

20 mm to the left of the origin point that was used for the rest of the contours on the digitizing table; this gives an origin point of X=20, Y=0 to be entered when the sheet is recalled. The 10-cm point is only 80 mm further to the right since the scale of the drawing is 4/5.

```
*SHEET 1
20,0 100,0
```

This recalls the first sheet and displays the contours already present, Fig. 17.

```
*CONTOUR 9
20,22 23,21 26,19 28,16 25,13
25,10 23,7 20,6 17,7 15,10
15,13 12,16 14,19 17,21
*END
*DENSITY 175
```

This adds Contour 9 to the sheet, the result of which is shown in Fig. 18.

```
SHEET-      1      0      0
DISPLACE-    0      0      0
ROTATE-      39
SCAN-
ORIGEN PT OK
TEN-CM PT OK
```

Fig. 17. Sheet 1 as recalled.

```
SHEET-      1
CONTOUR-    9
DENSITY-   175
START
```

Fig. 18. Sheet 1 after Contour 9 has been added.

Plans and Beams

A plan is a collection of beams that is built up and specified by appropriate commands.

```
*PLAN 1
*BEAM 1
*ROTATE -90 0 0
*BOLUS
*SAVE 2
```

The *PLAN command creates Plan 1 and displays it, or if Plan 1 had previously existed it would be recalled and displayed. Of course, a newly created plan is empty; as yet having no beams. The *BEAM command adds Beam 1 to the plan. If Beam 1 existed previously, it would be recalled. A display is generated showing two cross-sections at right angles to each other through the treatment volume. All beams in the plan are displayed as lines at appropriate angles on these cross sections. A beam coming straight out of the display appears to go up or down; the other cross section shows the true situation. The beam referenced by the last *BEAM command is displayed more heavily for identification. A newly created beam is parallel to the Y-axis of the reference system and has a weight of 100. The *ROTATE command changes the entrance angle of the beam; the beam now enters parallel to the X-axis from the negative side. The new angle of the beam is shown in an updated display. The beam's weight remains at the default value of 100. The *BOLUS command adds material to each beam ray so that they all have the same

total stopping power between the entrance port and the treatment volume. The *BOLUS command doesn't affect the display. The *SAVE command makes a copy of the plan as it currently exists, with one beam at -90° , and saves it as Plan 2. The *SAVE command generates a display that lists the beams in the plan and their parameters (Fig. 19). Plan 1 is still current and changes can be made to it.

```
*BEAM 2
*ROTATE 90  0  0
*BOLUS
```

These commands add a second beam entering from the opposite side. It is possible to go back to any beam in the plan and change it.

```
*BEAM 1
*WEIGHT 140
```

This returns to Beam 1 and raises the dose it will deliver to 140 units; Beam 2 retains the default value of 100 units. The two beams of the plan are shown in Fig. 20.

```
PLAN-      1
CASE-  1128      VICTIM
      BEAM WEIGHT  PHI  THETA
      1      100   -90    0  BOL
SAVED AS PLAN      2
```

Fig. 19. A copy of Plan 1 is made and saved as Plan 2.

```
BEAM-      1  BOL
WEIGHT-    140
```

Fig. 20. Two perpendicular cross sections through the patient, showing the two beams after they have been rotated to their final directions.

The Calculation

Any parameters of the calculation can be changed from their default values if desired.

```
*VOLUME -80 80 5   -20 70 5   -40 40 5
*GO 1
```

The array of points at which the dose is to be calculated is changed, and a display is generated showing the old values for the calculation parameters to guide the interactive user in entering the changes. Calculation is then started on Plan 1. The calculation parameters are displayed with a message that the calculation has begun, Fig. 21. This display is immediately followed by displays of the scan patterns for all the beams in the plan. For each plane of the longitudinal scan there is one display showing each cylinder of stopping pions and the bolus for each entering ray. Samples of these displays are shown in Fig. 22 for Beam 1 and Fig. 23 for Beam 2. When the calculation is finished, the parameters are again displayed with a message that computation is done.

```
PLAN-      1
CASE-  1128      VICTIM
      BEAM WEIGHT  PHI  THETA
      2      100   -90    0  BOL
      1      140   -90    0  BOL
```

```
PIONS
RAD
USE SURFACE AND INHOMOGENEITIES
COMPUTATION VOLUME
X-   -80    80    5
Y-   -20    70    5
Z-   -40    40    5
```

```
*****
BEGIN CALCULATION ON PLAN      1
```

Fig. 21. The calculation parameter display at the start of calculation.

```

CASE 1128
NAME VICTIM
PLAN 1
BEAM 1
WEIGHT 140
X-ZERO -6
Y-ZERO 26
Z-ZERO 28
PHI -90
THETA 0
PSI 0
SCAN -15

```

Fig. 22. The range scan pattern for one plane of the longitudinal scan of Beam 1. The plane is identified by case, plan, beam, displacements, rotations and scan. The display shows each stopping cylinder with its entrance dose; also shown is the bolus required for each entering beam ray in this plane.

```

CASE 1128
NAME VICTIM
PLAN 1
BEAM 2
WEIGHT 100
X-ZERO -56
Y-ZERO 28
Z-ZERO 28
PHI 90
THETA 0
PSI 0
SCAN -15

```

Fig. 23. The range scan pattern for one plane of the longitudinal scan of Beam 2.

Display of Results

The results are displayed under control of commands.

*MAP

An isodose map is displayed using the default levels for an X-Y plane with rotations, displacements, and scan all zero (Fig. 24).

*SCAN 38

*SCAN 24

*SCAN 11

*SCAN -14

*SCAN -23

*SCAN -33

*SCAN 0

Each of these commands produces a map of a plane parallel to the first map but displaced from it by the number of millimeters specified. The last command returns to the original plane.

*ROTATE 90 90 0

*DISPLACE -30 25 0

The first command changes the angle of the mapped plane so that it is perpendicular to its former orientation, and the second moves it so that it passes through the center of the treatment volume (Fig. 25).

X	Y	Z	PHI	THETA	PSI	SCAN
0	0	0	0	0	0	0

NO-DOSE
1-50
2-100
3-150
4-200
5-250
6-300

SCAN- 38

Fig. 24. An isodose map superimposed on the patient contours; the transformation that gives this as the X-Y plane is displayed above the map.

	X	Y	Z	PHI	THETA	PSI	SCAN
	-30	.25	0	90	90	0	0

NO-DOSE
1-50
2-100
3-150
4-200
5-250
6-300

ROTATE- 0 90 0

Fig. 25. A map of a plane at right angles to the one in Fig. 24 and passing through the center of the treatment volume.

```
*ROTATE 0 90 0
*POINTS
*ROTATE 0 0 0
*DISPLACE 0 0 0
```

The first command gives the third perpendicular view, the *POINTS command replaces the isodose map with a dot plot where the number of dots in a region is proportional to the dose. The last two commands restore the plane to its original angle and position as shown in Fig. 26.

	X	Y	Z	PHI	THETA	PSI	SCAN
	0	0	0	0	0	0	0

DENSITY
20

Fig. 26. A dot plot where the density of points is proportional to effective dose.

	X	Y	Z	PHI	THETA	PSI	SCAN
	0	0	0	60	60	0	0

NO-DOSE
1-150

Fig. 27. An isometric-like projected view of the patient contours and the three-dimensional isodose plot using a single level.

```
*ISOMETRIC
*LEVELS 150
*ROTATE 60 30 0
*ROTATE 60 60 0
```

These commands produce an isometric-like projected view of the three-dimensional data, replace the dot plot with a single isodose level, and display several angles of the projected view. The last such display is shown in Fig. 27.

Further Calculation, Displays, and Termination

The calculation can be redone with different parameters or for another plan.

```
*HI-LET
*GO 1
```

This repeats the calculation using the high-LET component of the dose only.

```
*LEVELS 50 100 150 200 250 300
*MAP
*SCAN 24
*SCAN -23
```

The first command restores the six standard levels that were used in early isodose maps. Then the map is displayed for three parallel planes at the center and ends of the treatment volume. The calculation initiated by a *GO command resets to zero the displacement, rotations, and scan parameters of the transformation to the working coordinate system, and the first map is of the X-Y plane of this reset system.

*RAD

*GO 2

*LEVELS 25 50 75 100 125 150

*MAP

*SCAN 24

*SCAN -23

The first two commands calculate the total absorbed dose, in rad, for Plan 2 which has only one beam.

The last four commands reset the isodose levels and display three maps of the results.

*UNLOAD

This command causes termination of code operation and an exit to the computer operating system.

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APPENDIX

THE COMPLETE INPUT DECK OF THE EXAMPLE

\$JOBNAME=SHLAER, AC=MO36HLAER, UA=8903F689 SHL, CL=U, LC=400000, TL=1M, PL=50, PR=111
\$OPERMIFS=PIPLAN, FSI=MFSI, OAC=MOO
\$LDG01=PIPLAN, M=NONE, LC=165000
\$FM.

```
*CASE 1128
VICTIM, JOHN Q.
KLIGERMAN
HEAD+ NECK
20/JUL/73
*SHEET 1
04083 03609 07229 03609
*SCAN 39
*SURFACE 1
04070 07268 04444 07233 04860 06975 05244 06750 05641 06532
06007 06185 06167 05768 06255 06371 06324 04978 06421 04596
06516 04158 06345 04073 06299 03696 06201 03295 05975 02888
05656 02371 05263 01846 04865 01528 04479 01446 04070 01555
03689 01508 03288 01581 02920 01902 02506 02276 02129 02827
01979 03232 01899 03617 01809 04145 01833 04251 01775 04893
01804 05108 01886 05463 02013 05887 02200 06265 02504 06616
02889 06769 03272 06923 03672 07184
*END
*CONTOUR 2
02634 05539 02678 05466 02692 05329 02693 05161 02627 04988
02534 04846 02504 04669 02501 04455 02413 04451 02380 04634
02384 01798 02471 04973 02558 05142 02575 05313 02596 05505
*END
*DENSITY 175
*CONTOUR 3
05569 05516 05618 05483 05572 05311 05571 05121 05649 04949
05715 04736 05791 04572 05654 04413 05643 04580 05574 04785
05466 04977 05455 05170 05485 05347 05523 05500
*END
*DENSITY 175
*CONTOUR 4
04065 06848 04272 06824 04456 06777 04665 06660 04851 06456
04973 06313 05040 06116 04985 05926 04950 05728 04873 05529
04720 05502 04713 05736 04687 05928 04638 06124 04502 06355
04356 06407 04214 06223 04063 06253 03927 06353 03751 06315
03608 06116 03539 05921 03577 05703 03571 05527 03496 05381
03333 05378 03263 05568 03194 05774 03190 05969 03236 06155
03312 06350 03460 06548 03680 06711 03862 06805
*END
*DENSITY 175
*CONTOUR 5
04081 04837 04283 04797 04476 04725 04471 04619 04280 04612
04067 04621 03870 04649 03681 04674 03690 04781 03853 04841
*END
*DENSITY 0
*CONTOUR 6
04087 03753 04193 03731 04290 03650 04295 03508 04180 03421
04064 03417 03966 03448 03880 03519 03893 03648 03959 03726
*END
*IGNORE- DENSITY
*CONTOUR 7
04854 03859 04807 03694 04669 03623 04552 03637 04489 03808
04411 03995 04352 04142 04435 04193 04613 04130 04779 04013
*END
*DENSITY 175
*CONTOUR 8
03294 03835 03328 03976 03432 04078 03533 04152 03675 04200
03760 04142 03767 03590 03750 03869 03657 03755 03552 03633
03456 03562 03373 03610 03315 03713
*END
*DENSITY 175
*SHEET 2
04099 03558 07239 03559
*SCAN 25
*SURFACE 1
04067 07030 04470 06925 04771 06727 05255 06545 05645 06232
05884 05942 06096 05566 06163 05177 06248 04783 06354 04381
06354 04001 06202 03605 06038 03216 05858 02823 05511 02432
05276 02029 04900 01584 04495 01525 04107 01580 03710 01604
03318 01701 03063 02017 02724 02422 02295 02809 02078 03205
02006 03596 01821 03991 01822 04376 01870 04770 01993 05168
02099 05557 02225 05945 02510 06337 02907 06636 03284 06765
03691 06941
*END
*CONTOUR 2
02765 05377 02838 05339 02928 05164 02756 04952 02560 04859
02591 04631 02597 04439 02500 04442 02466 04596 02475 04796
02517 04978 02592 05157 02710 05337
*END
*DENSITY 175
*CONTOUR 3
05467 05277 05517 05227 05597 05007 05661 04818 05699 04623
05726 04423 05680 04275 05629 04350 05582 04558 05469 04765
05281 04938 05264 05085 05382 05221
*END
*DENSITY 175
*CONTOUR 4
04086 06636 04275 06624 04489 06564 04656 06453 04872 06258
04973 06089 05044 05876 05037 05698 05047 05498 04908 05361
04875 05564 04844 05753 04796 05962 04712 06147 04541 06348
04333 06451 04092 06503 03872 06461 03690 06339 03563 06143
03529 05953 03494 05752 03489 05547 03481 05344 03366 05242
03302 05385 03305 05557 03320 05746 03346 05956 03402 06149
03492 06326 03678 06506 03870 06592
*END
*DENSITY 175
```

The example was run on the Los Alamos computer center "cafeteria," a quick turnaround service for jobs that run on the CDC 7600. Bold face cards with a "\$" in the first column are 7600 control cards. The treatment planning code, PIPLAN, is kept on a resident fileset of the same name. The two cards following the \$JOB card access this fileset, load the code, and start it running. All cards with a * in the first column are PIPLAN commands; the remaining cards are data. Column 1 need not be left blank on these cards but this is done here to provide visual separation of the commands.

*CONTOUR 5
04089 04792 04217 04799 04293 04853 04357 04812 04427 04707
04420 04837 04271 04631 04085 04629 03891 04634 03702 04628
03690 04699 03849 04748 03908 04809 04003 04817
*END
*DENSITY 0
*CONTOUR 6
04092 03727 04177 03713 04229 03655 04237 03567 04210 03492
04141 03488 04050 03486 03965 03486 03902 03538 03908 03634
03951 03700 04012 03729
*END
*IGNORE- DENSITY
*CONTOUR 7
05529 03723 05383 03778 05199 03845 05067 03754 04878 03553
04896 03348 04489 03232 04289 03142 04131 03148 04140 03230
04287 03314 04486 03384 04620 03603 04560 03793 04461 03996
04329 04179 04140 04282 04189 04378 04378 04384 04619 04368
04846 04305 05067 04231 05261 04123 05441 03980
*END
*DENSITY 175
*CONTOUR 8
02637 03912 02788 04032 02971 04184 03159 04234 03371 04284
03556 04326 03727 04332 03891 04338 04048 04364 04049 04274
03906 04156 03769 03985 03660 03805 03534 03599 03569 03412
03703 03318 03887 03292 04051 03268 04063 03149 03906 03171
03710 03210 03509 03297 03320 03492 03197 03636 03043 03845
02868 03910 02671 03798
*END
*DENSITY 175
*CONTOUR 9
04116 04224 04176 04205 04235 04156 04289 04100 04318 04037
04324 03957 04316 03873 04267 03837 04157 03837 04087 03837
03895 03837 03945 03886 03912 03966 03928 04044 03952 04104
04003 04160 04058 04193
*END
*DENSITY 175
*TREATMENT- VOLUME 13
03701 04476 03516 04385 03306 04353 03122 04330 02922 04327
02858 04491 02922 04656 03108 04752 03300 04759 03508 04695
03688 04595
*END
*SHEET 3
03901 03756 07039 03756
*SCAN 11
*SURFACE 1
03884 07273 04270 07180 04655 08917 05088 06574 05456 08119
05635 05797 05796 05400 05901 05004 05991 04315 08043 04217
05961 03829 05784 03449 05559 03058 05290 02649 05127 02318
04736 02177 04321 02011 03951 02020 03546 01987 03185 02221
02790 02655 02281 03050 02035 03453 01864 03842 01742 04226
01708 04631 01742 05017 01789 05386 01916 05790 02141 06182
02533 06577 03038 06968 03470 07250
*END
*CONTOUR 2
02826 05772 02921 05641 02801 05492 02632 05341 02609 05189
02452 05019 02396 04804 02317 04811 02316 05021 02348 05226
02463 05400 02484 05592 02670 05728 02763 05780
*END
*DENSITY 175
*CONTOUR 3
04907 05748 05069 05730 05175 05596 05281 05403 05339 05200
05384 04981 05337 04829 05249 04857 05178 05023 05088 05211
04987 05397 04855 05490 04672 05561 04675 05714 04776 05742
*END
*DENSITY 175
*CONTOUR 4
03909 06982 04085 06982 04286 06926 04466 06812 04609 06588
04712 06377 04819 06177 04883 05977 04841 05828 04725 05857
04635 05992 04529 06185 04427 06390 04354 06569 04271 06702
04089 06780 03891 06786 03699 06768 03512 06634 03373 06544
03265 06371 03149 06164 03070 05977 02977 05825 02846 05832
02846 05988 02924 06177 03014 06358 03121 06583 03263 06765
03359 06913 03513 06961 03704 06967
*END
*DENSITY 175
*CONTOUR 5
03881 05324 03988 05224 04096 05192 04244 05203 04234 05109
04138 05063 04110 04880 04030 04781 03889 04772 03777 04798
03631 04772 03561 04835 03585 04996 03493 05098 03617 05134
03645 05161 03768 05230
*END
*DENSITY 0
*CONTOUR 6
03888 03980 03977 03965 04040 03907 04076 03826 04039 03743
03955 03715 03889 03703 03790 03723 03737 03774 03736 03876
03777 03916 03833 03947

*END
*IGNORE- DENSITY
*CONTOUR 9
03890 04572 04083 04578 04286 04577 04477 04540 04612 04424
04647 04218 04610 04026 04463 03940 04283 04029 04096 04123
03892 04136 03659 04063 03521 03930 03391 03893 03273 03983
03218 04124 03252 04320 03364 04484 03523 04548 03711 04557
*END
*DENSITY 175
*CONTOUR 10
03870 03563 03949 03583 04039 03576 04087 03556 04001 03490
03952 03479 03921 03400 03873 03374 03835 03447 03783 03468
03694 03510 03706 03555 03786 03561
*END
*DENSITY 175
*TREATMENT- VOLUME 13
03445 04608 03306 04502 03107 04353 02911 04270 02711 04226
02506 04256 02371 04425 02361 04607 02443 04812 02521 04980
02708 05090 02901 05110 03107 05113 03307 05047 03439 04928
03473 04770
*END
*SHEET 4
03924 03541 07059 03541
*SCAN 0
*SURFACE 1
03903 07102 04310 07055 04695 06729 05118 06309 05432 05897
05655 05520 05796 05128 05915 04717 06000 04338 06000 03933
05891 03552 05688 03157 05512 02776 05279 02355 04904 02008
04516 01828 04117 01759 03737 01759 03333 01894 02969 02101
02679 02380 02398 02779 02177 03152 02002 03563 01918 03952
01894 04344 01940 04745 02001 05110 02115 05515 02349 05901
02731 06335 03128 06729 03517 06996
*END
*CONTOUR 2
02851 05774 02942 05711 03013 05648 02994 05541 02888 05421
02753 05236 02629 05035 02562 04865 02501 04667 02434 04667
02434 04869 02473 05043 02527 05243 02585 05468 02691 05648
02774 05761
*END
*DENSITY 175
*CONTOUR 3
05108 05630 05181 05583 05250 05441 05287 05248 05337 05079
05384 04884 05409 04673 05413 04489 05364 04488 05278 04673
05210 04885 05133 05088 05044 05284 04950 05454 04973 5570
05051 05617
*END
*DENSITY 175
*CONTOUR 4
03918 06696 04093 06702 04313 06646 04497 06518 04685 06296
04826 08100 04972 05902 05089 05724 04935 05640 04811 05684
04694 05898 04537 06089 04365 06295 04230 06445 04032 06502
03847 06445 03677 06344 03516 06193 03392 06038 03218 05847
03084 05893 02910 05819 02908 05569 03038 06101 03230 06301
03437 06474 03570 06569 03762 06658
*END
*DENSITY 175
*CONTOUR 5
03912 04903 04041 04847 04171 04782 04317 04810 04440 04788
04442 04732 04315 04607 04124 04514 03920 04419 03754 04428
03585 04574 03371 04654 03334 04761 03420 04807 03583 04785
03706 04790 03812 04867
*END
*DENSITY 0
*CONTOUR 6
03927 03675 04002 03864 04064 03657 04100 03561 04105 03487
04035 03427 03947 03421 03871 03418 03791 03437 03752 03511
03766 03615 03816 03660 03868 03672
*END
*IGNORE- DENSITY
*CONTOUR 9
03936 04281 04117 04249 04248 04149 04313 03940 04270 03841
04081 03818 03918 03806 03740 03805 03614 03811 03577 03914
03621 04089 03702 04228 03815 04269
*END
*DENSITY 175
*CONTOUR 10
03925 03275 04117 03356 04305 03550 04475 03749 04701 03950
04839 04002 04915 03935 04802 03724 04784 03546 04680 03403
04485 03338 04276 03231 04133 03042 04012 02915 03690 02791
03783 02785 03689 02950 03573 03154 03400 03307 03233 03419
03047 03510 02989 03847 02980 03818 03029 03953 03133 03961
03239 03912 03329 03805 04346 03617 03548 03519 03730 03316
*END
*DENSITY 175

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*TREATMENT- VOLUME 13
03525 04001 03353 03940 03146 04009 02940 04024 02752 03996
02538 04000 02401 04077 02388 04255 02463 04479 02616 04678
02759 04797 02955 04828 03135 04720 03333 04811 03526 04433
03604 04321 03593 04168
*END
*SHEET 5
03943 03506 07085 03506
*SCAN - 14
*SURFACE 1
03953 07150 04337 07116 04721 06845 04932 06575 05142 06168
05346 05789 05493 05390 05627 04987 05809 04588 05935 04199
05977 03810 05876 03418 05661 03041 05474 02641 05125 02212
04738 01908 04340 01787 03965 01754 03560 01847 03178 02026
02774 02322 02390 02840 02129 03225 01987 03618 01963 04013
01980 04355 02079 04788 02155 05173 02332 05573 02579 05968
02817 06342 03134 06737 03423 07003 03684 07166
*END
*CONTOUR 4
03942 06847 04135 06847 04341 06821 04518 06760 04864 06571
04749 06368 04829 06169 04926 05985 04927 05857 04857 05805
04728 05900 04636 06108 04539 06294 04418 06498 04298 06651
04116 06680 03929 06677 03758 06608 03555 06445 03418 06267
03223 06069 03091 05968 03030 06021 03080 06172 03212 06357
03331 06555 03546 06720 03734 06818
*END
*DENSITY 175
*CONTOUR 5
03932 04594 04021 04514 04110 04502 04208 04574 04318 04581
04334 04505 04232 04412 04091 04365 03932 04352 03806 04360
03626 04379 03484 04435 03440 04542 03485 04604 03574 04546
03664 04494 03768 04495 03844 04585
*END
*DENSITY 0
*CONTOUR 6
03938 03562 04050 03557 04145 03501 04151 03389 04064 03360
03945 03336 03821 03338 03741 03403 03798 03497 03867 03555
*END
*IGNORE- DENSITY
*CONTOUR 9
03958 04066 04122 04072 04310 04007 04378 03812 04260 03678
04054 03637 03873 03678 03665 03711 03586 03819 03652 04022
03780 04062 03888 04059
*END
*DENSITY 175
*CONTOUR 11
03957 05640 04123 05607 04298 05487 04358 05359 04360 05281
04287 05312 04141 05447 03996 05511 03377 05497 03750 05405
03593 05299 03532 05263 03532 05313 03589 05411 03683 05355
03811 05596
*END
*DENSITY 175
*CONTOUR 12
03958 03252 04140 03294 04313 03426 04402 03617 04485 03817
04637 03835 04720 03993 04797 04013 04829 03821 04823 03622
04794 03426 04734 03233 04588 03238 04470 03314 04341 03232
04161 03111 03957 03073 03763 03131 03561 03265 03410 03274
03244 03215 03165 03372 03176 03571 03217 03763 03234 03943
03301 03973 03346 03897 03397 03804 03534 03811 03575 03701
03562 03588 03613 03414 03754 03301
*END
*DENSITY 175
*TREATMENT- VOLUME 13
03546 04111 03343 04009 03168 04040 02958 04016 02767 04009
02561 03953 02372 04103 02320 04343 02367 04542 02574 04775
02757 04865 02949 04864 03154 04793 03285 04610 03403 04407
03547 04197
*END
*SHEET 6
03944 03576 07086 03576
*SCAN - 24
*SURFACE 1
03957 06671 04339 06621 04663 06394 04934 05981 05170 05607
05373 05212 05627 04812 05791 04421 05876 04049 05855 03631
05696 03242 05473 02860 05285 02471 04930 02130 04541 01949
04143 01907 03737 01955 03361 02096 02976 02244 02577 02510
02389 02860 02209 03274 02055 03657 01997 04051 02067 04435
02171 04838 02330 05232 02596 05612 02973 06009 03351 06376
03617 06601
*END
*CONTOUR 5
03945 04891 04084 04810 04163 04697 04310 04688 04408 04737
04473 04617 04337 04489 04150 04402 03957 04402 03765 04422
03560 04488 03388 04636 03426 04786 03573 04763 03677 04721
03812 04849
*END
*DENSITY 0
*CONTOUR 6
03951 03578 04068 03577 04147 03525 04151 03428 04099 03340
04005 03294 03892 03301 03781 03344 03748 03430 03773 03547
03850 03587
*END
*IGNORE- DENSITY
*CONTOUR 9
03988 04244 04159 04236 04332 04151 04526 04012 04675 03825
04720 03640 04719 03499 04573 03510 04410 03641 04281 03751
04087 03660 03949 03671 03754 03698 03653 03741 03563 03810
03436 03485 03283 03490 03189 03614 03244 03760 03376 03901
03573 04019 03769 04185
*END
*DENSITY 175
*CONTOUR 11
03958 05637 04167 05611 04353 05417 04485 05197 04509 05051
04447 05002 04341 05172 04179 05426 04013 05512 03873 05508
03690 05368 03596 05195 03496 05027 03375 05017 03347 05103
03541 05361 03762 05612
*END
*DENSITY 175
*CONTOUR 12
03971 03190 04145 03213 04345 03291 04530 03336 04697 03347
04717 03265 04536 03183 04346 03125 04140 03088 03947 03081
03742 03118 03560 03176 03355 03233 03184 03299 03182 03372
03325 03408 03523 03320 03705 03245 03873 03199
*END
*DENSITY 175
*TREATMENT- VOLUME 13
03552 04115 03367 03993 03161 03962 02965 03967 02767 03973
02627 04223 02644 04432 02784 04561 02974 04607 03163 04570
03355 04412 03542 04323
*END
*SHEET 7
04096 03602 07233 03602
*SCAN - 34
*SURFACE 1
04085 05805 04484 05656 04875 05464 05355 05057 05698 04666
05900 04280 05919 03877 05863 03497 05797 03094 05662 02717
05273 02287 04885 02054 04487 01822 04085 01911 03708 01983
03320 02161 02837 02506 02597 02913 02396 03287 02285 03706
02265 04076 02421 04473 02708 04858 02954 05168 03319 05575
03708 05762
*END
*CONTOUR 5
04086 05014 04290 04999 04440 05020 04441 04963 04285 04822
04248 04718 04316 04680 04489 04789 04675 04861 04782 04804
04705 04601 04480 04451 04277 04390 04087 04353 03884 04384
03703 04411 03512 04568 03388 04694 03382 04813 03515 04814
03709 04740 03896 04640 03984 04695 03932 04758 03815 04848
03745 04943 03903 04985
*END
*DENSITY 0
*CONTOUR 6
04097 03621 04183 03634 04262 03580 04273 03471 04231 03401
04148 03353 04085 03358 04007 03365 03953 03427 03926 03512
03952 03585 04018 03629
*END
*IGNORE- DENSITY
*CONTOUR 9
04080 04249 04288 04199 04390 04068 04424 03867 04283 03754
04085 03680 03895 03708 03743 03872 03781 04081 03906 04219
*END
*DENSITY 175
*CONTOUR 12
04108 03250 04296 03340 04485 03492 04681 03659 04897 03793
05032 03688 05029 03518 04892 03413 04671 03385 04480 03390
04299 03239 04276 03086 04251 02933 04095 02897 03953 02945
03976 03091 03977 03203 03815 03318 03702 03404 03540 03417
03316 03428 03135 03482 03177 03684 03305 03766 03505 03696
03699 03510 03906 03359
*END
*DENSITY 175
*SHEET 1
20,0 100,0
*CONTOUR 9
20,22 23,21 26,19 28,16 25,13
25,10 23,7 20,6 17,7 15,10
15,13 12,16 14,19 17,21
*END
*DENSITY 175
*PLAN 1
*BEAM 1
*ROTATE -90 0 0
*80LUS

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*SAVE 2
*BEAM 2
*ROTATE 90 0 0
*BOLUS
*BEAM 1
*WEIGHT 140
*VOLUME -80 80 5 -20 70 5 -40 40 5
*GO 1
*MAP
*SCAN 38
*SCAN 24
*SCAN 11
*SCAN -14
*SCAN -23
*SCAN -33
*SCAN 0
*ROTATE 90 90 0
*DISPLACE -30 25 0
*ROTATE 0 90 0
*POINTS

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*ROTATE 0 0 0
*DISPLACE 0 0 0
*ISOMETRIC
*LEVELS 150
*ROTATE 60 30 0
*ROTATE 60 60 0
*HI-LET
*GO 1
*LEVELS 50 100 150 200 250 300
*MAP
*SCAN 24
*SCAN -23
*RAD
*GO 2
*LEVELS 25 50 75 100 125 150
*MAP
*SCAN 24
*SCAN -23
*UNLOAD
$EJ.

```