CNWRA 97-002

FAULTING VERSION 1.0 – A CODE FOR SIMULATION OF DIRECT FAULT DISRUPTION

TECHNICAL DESCRIPTION AND USER'S GUIDE

Prepared for

Nuclear Regulatory Commission
Contract NRC-02-93-005

Prepared by

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ABSTRACT

The FAULTING code has been developed at the Center for Nuclear Waste Regulatory Analyses (CNWRA) for evaluating the impact of geologic faulting as a disruptive event on repository performance. This code uses published field data to simulate timing and amount of both largest credible and cumulative displacements along existing (but not adequately characterized) and new faults within the proposed high-level waste (HLW) repository at Yucca Mountain (YM), Nevada. The FAULTING code calculates the percentage of repository area and the number of waste packages (WPs) disrupted and timing of disruption, if it occurs. This user's guide describes the theory and application of the FAULTING code. It is anticipated that the FAULTING code will be used by the Nuclear Regulatory Commission (NRC) as a tool for an independent assessment of information provided by the U.S. Department of Energy (DOE) on fault displacement hazards and potential effects and consequences of fault displacement in the proposed repository block. At present, the FAULTING code is a stand-alone code suited for sensitivity analyses of different input parameters on the final results. This code will become part of version 3.0 of the Total-system Performance Assessment (TPA) code currently under development by CNWRA

Fault displacement is generated in the FAULTING code along a randomly located fault zone inside the simulation area. These randomly generated fault zones represent those that are known to exist but are not adequately characterized, as well as new faults that may develop in the future during the 10,000-yr time frame of regulatory interest. Although the time frame considered here is 10,000 yr, the approach is amenable to analysis over longer periods should the need arise. In the current version of the code, it is assumed that the computer generated fault zones generally possess attributes similar to those of Ghost Dance and Sundance faults which have been mapped in the proposed repository block. Strike direction is determined as either northwest or north-northeast commensurate with fault trace orientations observed in the field at and near YM. Considering the relatively small diameter of emplacement drifts ($\sim$5m) and the steep (60–90°) dip of most near-surface faults at YM, it is assumed that local variation in dip of the fault has little influence on number of WPs disrupted. Therefore, the model is two dimensional (plan view) in the plane of emplacement horizon. Whether a fault intersects the potential repository depends on location, orientation, and trace length of the fault in the simulation area. Based on published field data, the following variables for the fault zone are selected randomly from ranges of possible values represented as probability distribution functions: location, trace orientation, geometry (fault length, dip, and width), fault activity, time of largest credible displacement and cumulative displacement faulting event, and magnitude of largest credible displacement and rate of cumulative displacement. Whether WP disruption occurs is dependent upon fault displacement exceeding a threshold value governed by repository and WP design and WP emplacement geometry. If the threshold displacement is exceeded by either largest credible displacement in a single event or by cumulative displacement due to fault creep, the number and locations of WPs intersected and disrupted are calculated based on length of intersection of the fault zone within the repository and corresponding fault zone width.

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ACKNOWLEDGMENTS

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The authors wish to thank D.A. Ferrill, R.W. Janetzke, and B. Sagar for their valuable technical and programmatic reviews of this report. The authors appreciate the able assistance of B. Russell for drafting some of the figures, K. Poor for compilation assistance, B. Long for editorial review, and C. Garcia for secretarial support.

QUALITY OF DATA AND SOFTWARE

DATA: Data used to describe faulting events in the FAULTING code were taken from the published sources referenced in this report. Basic field information was acquired from the map of Scott and Bonk (1984) and from the report of Spengler et al. (1994). Data, derived from field investigations and published by the Electric Power Research Institute (EPRI) in the expert judgment elicitation report (Electric Power Research Institute, 1993) on earthquakes and tectonic issues, provided an additional source of information. Data from the EPRI (1993) report were drawn from information provided by the scientists on the elicitation panel who are familiar with field relationships at Yucca Mountain (YM). While the earlier data of Scott and Bonk (1984) were not collected under a formal quality assurance (QA) program, use of standard methods for collection and analysis of geological information and mapping of lithologic units and structures assures those data are acceptable for incorporation into the description of variables that define faulting events at YM. The later data extracted from Spengler et al. (1994) and the EPRI (1993) report, were collected either by the U.S. Department of Energy (DOE) funded geologists under established QA procedures or by non-DOE scientists using standard methods. The code development effort relied mainly on data presented in the EPRI (1993) report rather than overall interpretations and scientific opinions of the expert panel because the data provided published values for certain of the parameters needed to describe faulting event variables in the code. As new data become available from the DOE site characterization program, these can be incorporated to refine the variables associated with prediction of faulting events in the FAULTING code.

The FAULTING Code Version 1.0 has been developed following the procedures described in CNWRA Technical Operating Procedure 018 which follows the guidance contained in CNWRA QA Manual (CQAM).

1 INTRODUCTION

1.1 REGULATORY BASIS AND TECHNICAL BACKGROUND

The primary purpose of performance assessment (PA) is to determine whether the proposed geological repository system satisfies applicable regulatory standards of the U.S. Environmental Protection Agency (EPA) and the Nuclear Regulatory Commission (NRC). This determination is accomplished by comparing estimated values of the regulatory performance measures derived from PA analyses with acceptable values of the same performance measures specified in the regulations. Hence, PA models are developed to estimate future repository performance. In addition to this regulatory function, results of PA will also be used by the NRC to evaluate site characterization activities and design options developed by the U.S. Department of Energy (DOE). To meet these objectives, the Total-system Performance Assessment (TPA) code has been developed to provide computational algorithms for estimating various performance measures (Sagar and Janetzke, 1993). To estimate performance measures, the TPA code contains a set of consequence modules that are largely independent computational units. The FAULTING code is planned to be a new consequence module of the TPA code used to evaluate potential consequences of primary faulting events in the proposed repository block at Yucca Mountain (YM).

1.2 PURPOSE OF THE FAULTING CODE

The FAULTING code is developed to evaluate the potential of direct disruption of waste packages (WPs) due to fault displacement in the proposed repository block at YM. Potential effects of seismic shaking are addressed in a separate code. The code does not include any indirect effects of faulting (e.g., possible effects of fault displacement on groundwater hydrology and flow pathways). In this code, faulting is treated as occurring in a block containing the repository without regard for tectonic mechanisms responsible for driving the faulting process. In the future, it may be possible to consider how different tectonic models affect fault occurrence and characteristics. For example, a listric-detachment fault system is one tectonic model proposed for the Yucca Mountain region (YMR) (Scott, 1990; Young et al., 1992; Ofoegbu and Ferrill, 1995, 1996) that could logically result in linked displacements. As the code is presently configured, planar decoupled faults are considered and slip is assumed to occur along either single or multiple slip surfaces within the fault zone. The code will permit an independent assessment by the NRC of information provided by the DOE on fault displacement hazards and potential effects of fault displacement in the repository block. It is anticipated this type of information will be used to evaluate the DOE site viability assessment planned in FY98 (U.S. Department of Energy, 1994).

Because of the abundance of the faults in and around the potential repository site at YM (Scott and Bonk, 1984; Scott, 1990; Spengler et al., 1994), and evidence of Quaternary displacement on many of these faults, faulting processes are potentially important considerations for the performance of the proposed repository. Faults in and around the proposed repository site at YM constitute two dominant sets, one consisting of northwest-trending faults and the other consisting of north-northeast-trending faults. Faults in the north-northeast-trending fault system in the vicinity of YM have long been interpreted to exhibit Quaternary displacement (Swadley et al., 1984). Northwest-trending faults have also been mapped in and north of the repository block (Scott and Bonk, 1984; Scott, 1990; Spengler et al., 1994). While it is reasonable to assume that WPs will be emplaced in the potential repository in accordance with a prescribed setback distance from known and well-characterized faults, there are uncertainties related to consequences of displacement along yet unknown fault zones (including faults not distinguished or

adequately characterized, and possible new faults). Considering the complex nature of faults mapped in the proposed repository block (Spengler et al., 1994) relative to possible width of the fault zones, occurrence of multiple slip surfaces, and lack of data on amount and timing of displacement, it may be difficult to distinguish and adequately characterize a wide fault zone cutting volcanic rock units. If a fault zone penetrating subsurface excavations are not adequately characterized, then the zone may not be recognized and an appropriate setback may not be applied. It is also uncertain whether new faults may develop over the 10,000-yr regulatory time frame under consideration. The FAULTING code provides a tool for evaluation of the potential consequences of fault displacement in the proposed repository block and for analyzing sensitivity of faulting consequence to uncertainties of input parameters.

1.3 REPORT CONTENT

The FAULTING code is a stand-alone code that will be used for sensitivity analyses of different parameters on the predicted percentage of repository area being disrupted due to faulting events. Results of these analyses will be used for further refinement of the code which will be incorporated into the TPA code. This report is the user's guide for the stand-alone version of the FAULTING code.

A description of the technical design of the FAULTING displacement consequence software is presented in the subsequent chapters along with the input parameters and output results. Description of the model concepts and parameter distributions is presented in chapter 2. Chapter 3 provides specifics of computer software and hardware requirements for installing the code and running it. Chapter 4 describes input files and chapter 5 describes the output files. Supporting mathematical models and subroutines used in the code are described in appendix A. Results of verification exercises are included in appendix B.

2 FAULTING CODE DESIGN

2.1 GENERAL BASIS FOR DESIGN

It is assumed that WPs will be appropriately set back from known faults and present no hazard. The FAULTING code is designed to evaluate hazard related to presently unknown fault zones in a simulation area centered on the proposed repository (Stirewalt et al., 1995, 1996). Unknown fault zones include those not distinguished or adequately characterized and new faults that may develop during the 10,000-yr time frame of regulatory interest. The unknown fault zones are assumed to have geometries and displacements comparable to those of the north-northeast- and north- northwest-trending faults already defined in and near the proposed repository block (e.g., Ghost Dance and Sundance faults) by Spengler et al. (1994).

Although parts of the data set developed by the Electric Power Research Institute (EPRI) are used to define certain parameters for the FAULTING code, the approach implemented in the FAULTING code for assessing fault displacement differs from that undertaken by EPRI (1993). Potential effects from both the largest credible fault displacement and cumulative fault displacements are being considered in the FAULTING code, whereas the EPRI (1993) analysis does not take into account cumulative slip.

2.2 DETAILED TECHNICAL DESIGN BASIS AND ASSUMPTIONS

Preliminary field data from Ghost Dance and Sundance faults provide the information base for describing faulting events in the vicinity of the proposed repository. Data uncertainty is represented using probability distributions. Additional information on characteristics of faulting in the proposed repository block, which will become available as site characterization proceeds, will be used to refine the variables as appropriate. The following variables are considered for describing faults and faulting events in the proposed repository block (Stirewalt et al., 1995):

- Fault zone location
- Fault zone trace orientation (north-northeast or northwest)
- Fault zone geometry (i.e., strike, dip, trace length, width, and number and location of multiple slip surfaces)
- Fault activity (active or inactive)
- Number of largest credible displacement faulting events over 10,000 yr
- Time of occurrence of largest credible displacement faulting events
- Amount of largest credible displacement per faulting event
- Amount of cumulative displacement during 10,000-yr time period
- Time cumulative displacement exceeds threshold displacement

A 50 × 50 km simulation area, roughly centered around the proposed repository, is considered in this code. This simulation area was selected for compatibility with the area being considered for use in the VOLCANO module (Lin, et al., 1993). From information provided by the user on areal mass loading (AML) (i.e., waste emplacement in tons per acre), the code checks whether the primary upper region of the repository would be sufficient to emplace 70,000 MTU of waste. If the available emplacement area in the primary upper region is insufficient, other regions are included in the calculation in this sequence: Primary Lower, Optional Area A, Optional Area B, Optional Area C, and Optional Area D. Figure 2-1 is from TRW Environmental Safety Systems, Inc. (1995) indicating the

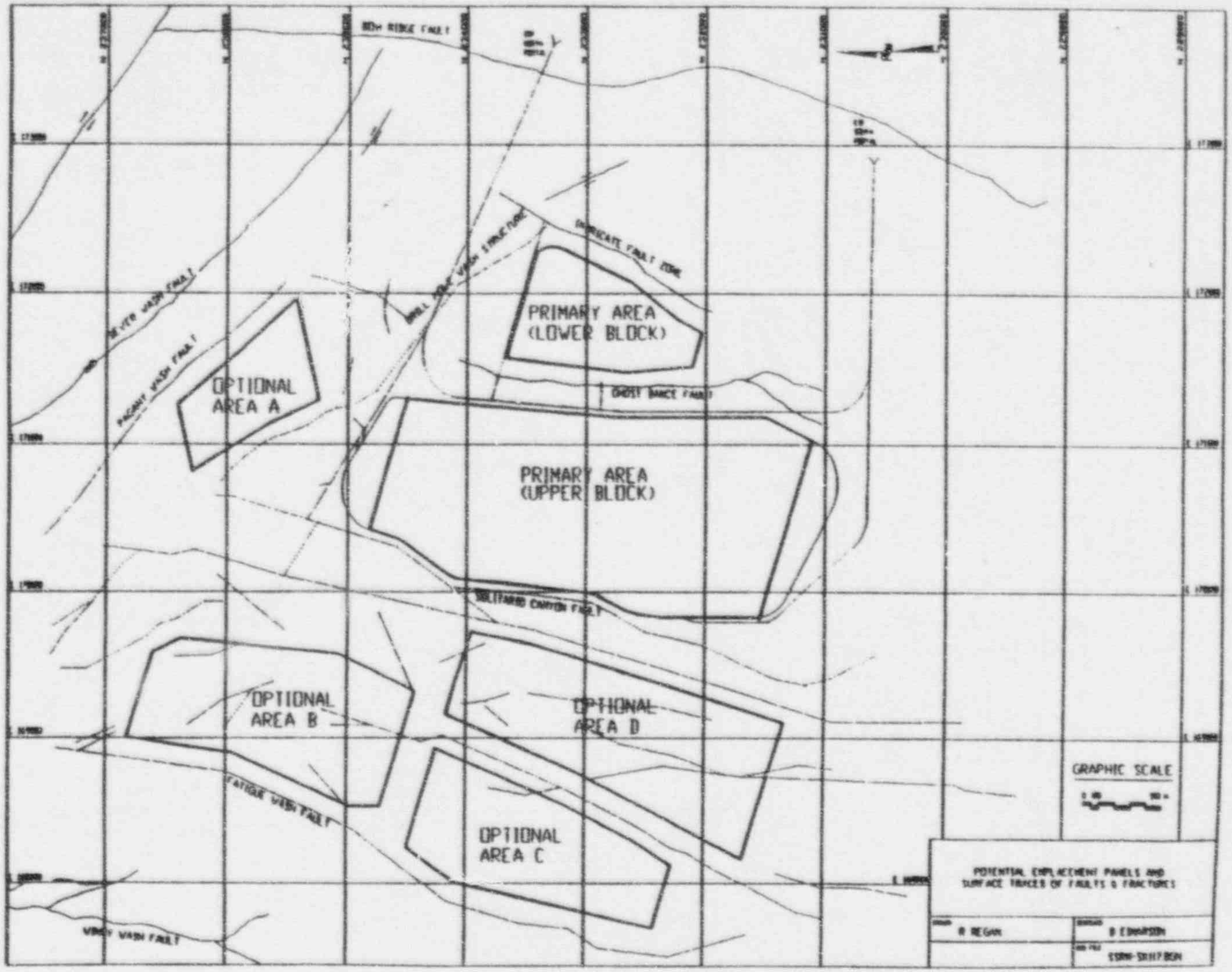

Figure 2-1. Different repository blocks (TRW Environmental Safety Systems Inc., 1995)

emplacement regions. Figure 2-2 shows the plots of the regions used in the FAULTING code. More discussion of the regions is in section 4.1

The following sections describe input parameters which are discussed in further detail in Stirewalt et. al. (1995, 1996). Any deviation from that proposed by Stirewalt et al. (1995, 1996) is also described.

2.2.1 Fault Zone Midpoint Location

It is assumed that the middle point of a fault zone (fl_x and fl_y) is uniformly distributed within the 50×50 km simulation region. In the FAULTING code, the origin of the simulation area was taken as 170,500 m East and 233,000 m North, which falls in the middle of the primary emplacement area. Random sampling of two values from the uniform probability distribution function (PDF) (145,500 m $\leq$ x $\leq$ 195,500 m and 208,000 m $\leq$ y $\leq$ 258,000 m) is used to locate the coordinates of the middle point of the fault zone within the simulation region. As discussed previously, the FAULTING code considers the fault zone at the repository level.

2.2.2 Fault Zone Trace Orientation

Trace orientations (fo) of faults simulated in the FAULTING code are selected from distributions derived from faults identified at YMR. Whether a north-northeast- or northwest-trending fault trace orientation is encountered is determined in the code assuming that north-northeast striking faults are three times as probable as northwest faults in the YM area. The distribution of faults shown on the geologic map of the proposed repository area by Scott and Bonk (1984) suggests this weighting relationship (75 percent north-northeast and 25 percent northwest). This weighting can be changed if later site characterization indicates a different relationship should be used.

2.2.3 Fault Zone Geometry

Fault zone geometry is described by four variables: strike, trace length, dip, and width. Methodologies used in the FAULTING code to simulate each of these variables are discussed in the following sections.

2.2.3.1 Strike

Strike of the fault (north-northeast strike sNE and northwest strike sNW) is determined by random sampling from normal PDFs of most probable fault trends as indicated by field evidence. For the two primary fault sets mapped by Scott and Bonk (1984) in the YM area, ranges for strike are N25°–40°W for northwest-trending set of faults and N25°E to N5°W for north-northeast set. These ranges are represented in the PDFs so that 90 percent of the faults lie within these ranges. This approach allows for consideration in the code of lower-probability faults having other strike orientations. In the FAULTING code, this variable is measured counterclockwise in a system of geographic axes with 0° to the east, 90° to the north, and 180° to the west. Therefore, these orientation ranges will be represented in the code to lie most probably between 115° and 130° for the northwest-trending set (i.e., N25°–40°W faults) and between 65° and 95° for the north-northeast-trending set (i.e., N25°E to N5°W faults).

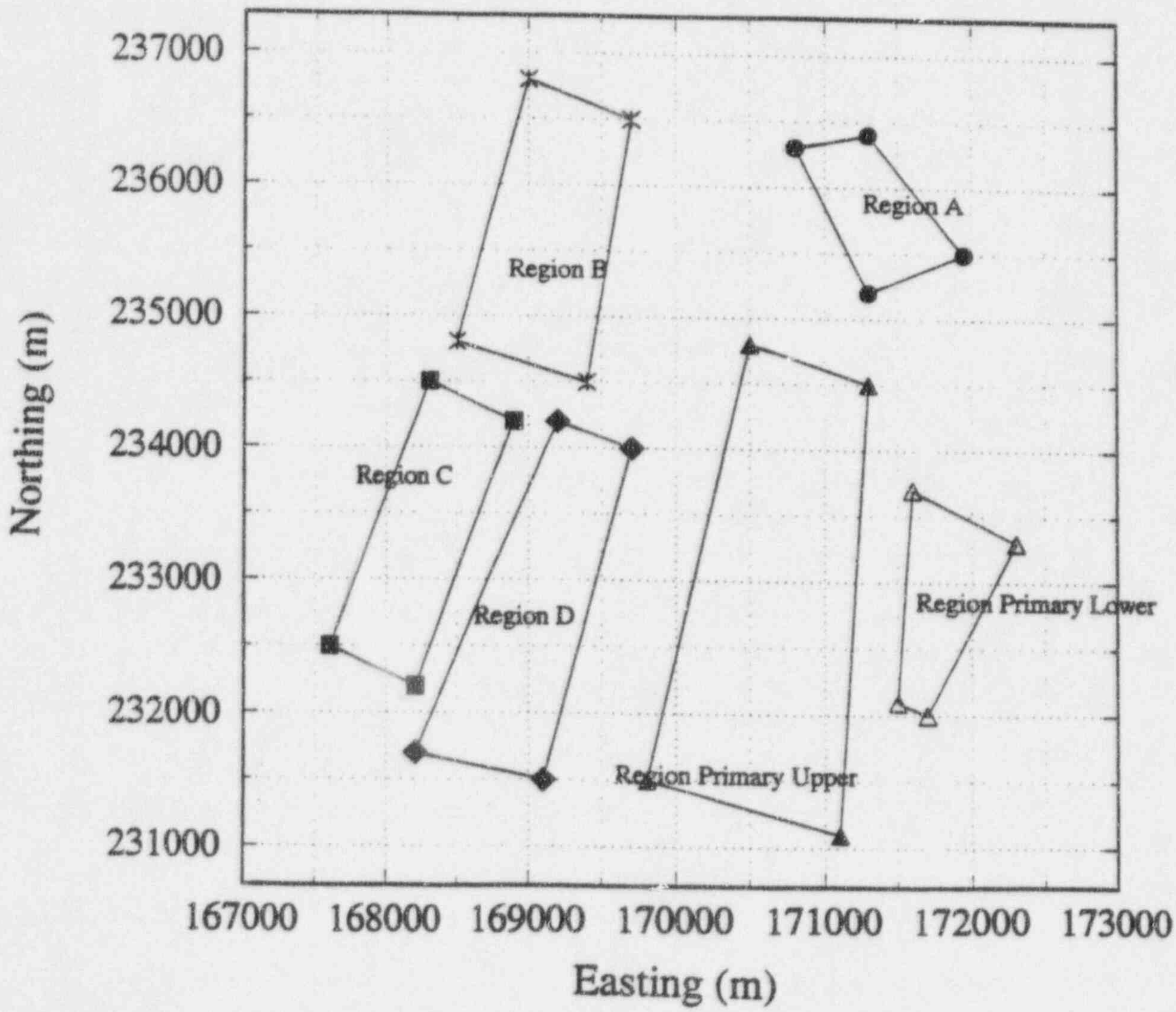

Figure 2-2. Different repository blocks as modeled in the FAULTING code

2.2.3.2 Trace Length

A fault zone is centered on the midpoint randomly selected as discussed in section 2.2.1. The fault zone is extended from this midpoint equally in both directions along the strike direction of the fault based on fault trace length, ltNW or ltNE, depending on the orientation. Fault trace length is determined by random sampling of values from uniform PDFs. Faults that extend outside the simulation area (50×50 km) are truncated at the boundary of that area. Based on lengths of faults mapped by Scott and Bonk (1984) in the potential repository area, fault trace length ltNE may vary between 3 and 12 km in the north-northeast-trending fault set and ltNW may vary between 2 and 10 km in the northwest set.

2.2.3.3 Dip

Dip angle of a fault (θ_NW or θ_NE) zone is not necessary in the FAULTING code as it is two dimensional and limited to the proposed repository horizon. Dip angle is generated only to complete the description of the geometry of a given fault zone. Future analysis may incorporate dip angle.

Scott and Bonk (1984) recognized that faults at YM have steep dip angles varying between 80°NW and 80°NE for the northwest-trending set and between 60° W and 90° for the north-northeast-trending set. Fault dip is represented in the PDFs so that 90 percent of the faults have dips in these ranges, an approach that allows faults having other dips with a low probability. However, it is not considered very likely that low-angle faults either presently occur or will develop at the proposed repository horizon level.

Because faults in YMR generally strike either north-northeast or northwest and dip either eastward or westward, it was possible to set up a simple scheme in the FAULTING code for designating dip without indicating dip direction. In this approach, dip angle is always measured from horizontal in the east direction. For example, a dip angle of 0°E is recorded as 0° and a dip of 0°W is recorded as 180°. Likewise, a dip of 60°E is shown as 60° while a dip of 60°W is 120°. This scheme is not completely general and will not work if a fault has other orientation, such as east-west strike.

2.2.3.4 Width

Fault zone width, wNW or wNE, may be considered to vary within the range observed for the two primary fault sets. Width for the northwest-trending faults, wNW, ranges from 0.5 to 275 m with the maximum being that reported for Sundance fault by Spengler et al. (1994) based on ground surface observations. Similarly, width for the north-northeast-trending faults, wNE, may vary between 0.5 and 365 m with the maximum width being that reported by Spengler et al. (1994) for Ghost Dance fault. Fault zone width is determined by sampling values from a logbeta distribution with the PDF skewed toward the narrow fault zone widths. This type of PDF is used since field data do not definitively indicate that fault zones having width close to the maximum values should be abundant at YM. Width of the fault zone provides a measure of the width of the zone of secondary faulting effects, but these effects are not directly considered in the code at this time. New data from the Exploratory Studies Facility (ESF) will be used to refine the fault zone width PDF.

2.2.3.5 Number and Location of Multiple Slip Surfaces

A fault zone may have multiple slip surfaces. In the FAULTING code, both single and multiple surfaces are modeled. The number of possible slip surfaces n is assumed to vary uniformly among 1, 2,

3, and 4. This maximum value is based on data from Spengler et al. (1993) who mapped three additional surfaces exhibiting displacement adjacent to the main trace of the Ghost Dance fault zone. In the FAULTING code, it is assumed that the slip surfaces can be located uniformly within the width of the faulting zone. A uniform PDF is used to locate these surfaces within the fault zone.

2.2.4 Fault Activity

Whether a fault is classified as active or inactive is addressed by assuming that the probability of movement on modeled faults in the proposed repository block is one during the next 10,000 yr. That is, all faults are assumed to be active in this time frame. While a value of unity is used in current application of the FAULTING code at YM, other values may be used in the future.

2.2.5 Number of Largest Credible Displacement Faulting Events

Number of largest credible displacement faulting events is determined using information on faulting recurrence intervals. At YM, this information was taken from the expert elicitation report prepared by EPRI (1993). Information on recurrence intervals presented for Ghost Dance fault in the EPRI (1993) report is used for both northwest- and north-northeast-trending faults. These numbers can be refined as additional data become available for specific faults. This approach is being used, even though major block-bounding faults outside the proposed repository block may have shorter recurrence intervals, since it is thought to provide a reasonable estimate for interval of recurrence of faulting in the proposed repository block. Therefore, for the two primary fault sets observed at YM, recurrence intervals can be selected by random sampling from PDFs defined by the recurrence intervals (Electric Power Research Institute, 1993) for largest credible displacement events along the Ghost Dance fault as shown in table 2-1. Given these recurrence intervals for the current time period of interest at YM (10,000 yr), only a single largest credible displacement event is probable. The probability of a second event occurring within 10,000 yr is miniscule. Because it is not known where in the recurrence sequence the faults may lie, the single largest credible displacement event (for each modeled fault) may occur at any time during the 10,000-yr period. PDF of largest credible displacement will be modified using new data acquired by the DOE.

2.2.6 Time of Occurrence of Largest Credible Displacement Faulting Events

As discussed earlier in this report, the FAULTING code provides a framework for determining if either largest credible displacement or cumulative displacement in yet unknown fault zones could induce WP disruption. The unknown fault zones include those not distinguished or adequately characterized as well as new faults that may develop during the regulatory time period of interest. The logic for simulating the time of occurrence of largest credible displacement or start of cumulative displacement in the FAULTING code differs from that in Stirewalt et al. (1995, 1996). The time of occurrence of faulting event (t) is modeled as having an exponential distribution

$$Prob\,(T \leq t \leq T + \delta T) = \lambda e^{-\lambda t}\,\delta T \tag{2-1}$$

where, t is the time in year, δT is the time period of interest, and λ is the number of events per year. As the distribution is exponential, both mean and standard deviation are equal to $1/\lambda$. Now $1/\lambda$ is equal to the recurrence interval (ri) of the faulting event having a uniform distribution between 60,000 and 275,000 yr (Electric Power Research Institute, 1993).

Table 2-1. Recurrence intervals used in the FAULTING code for north-northeast- and northeast-trending faults at Yucca Mountain

Recurrence Interval (yr)	Estimated Cumulative Probability of Occurrence
60,000	(min)
100,000	(0.03)
150,000	(0.10)
230,000	(0.50)
275,000	(0.95)

Simulation of the time of occurrence t of largest credible displacement faulting event in the FAULTING code is a two-step process. First, a random value of λ is selected from the uniform distribution between 60,000 and 275,000 yr. Next, the value of t is generated by sampling an exponential distribution with this λ as its parameter. If this random number is less than 10,000 yr, that is, if the simulated time of occurrence of largest credible displacement faulting event is less than the time period of interest, then this time is accepted for subsequent simulation of faulting phenomenon. As the recurrence interval for the faulting event is quite large compared to the time of interest, the resulting distribution of time of occurrence may be approximated as uniform as was done by Stirewalt et al. (1995, 1996).

2.2.7 Amount of Largest Credible Displacement and Partitioning of Displacement along Multiple Slip Surfaces

In the EPRI expert elicitation report (Electric Power Research Institute, 1993), Arabasz defined the cumulative probability of occurrence for magnitude of largest credible displacement per faulting event for the northwest-trending fault set. The data are given in table 2-2. Table 2-2 also shows corresponding cumulative probability of occurrence for northwest-tending faults as given by Whitney in EPRI (1993). Both PDFs are assumed to be uniform. For northwest-trending faults, the magnitude of largest credible displacement ldNW varies uniformly between 0.045 and 0.250 m. Similarly, for north-northeast-trending faults, the magnitude ldNE varies uniformly between 0.060 and 0.450 m. In this case, the maximum probable value is considered to be 0.45 m for computational purposes since that is the highest probability value provided in the data (Electric Power Research Institute, 1993). Concentration of slip along a single surface is considered to be the most conservative case for assessing potential effects of fault displacement.

When largest credible displacements intersect the repository and cause WP disruption, both single and multiple slip surfaces are modeled in the FAULTING code. The largest credible displacement along a fault zone is partitioned among the multiple slip surfaces using uniformly distributed random numbers. For example, if there are three surfaces, two uniformly distributed random numbers between

Table 2-2. Amount of largest credible displacement per faulting event used in the FAULTING code for northwest (NW)- and north-northeast (NNE)-trending faults at Yucca Mountain

Largest Credible NW Displacement (cm)	Estimated Cumulative Probability of Occurrence (NW)	Largest Credible NE Displacement (cm)	Estimated Cumulative Probability of Occurrence (NNE)
4.5	0.05	6	0.1
9	0.5	12	0.5
18	0.95	20	0.8
25	max	30	0.9
—	—	45	0.95
The values are derived from information on the northwest-trending Pagany Wash and Drill Hole Wash faults and the northeast-trending Ghost Dance fault as presented in the elicitation report of EPRI (1993).			

0 and 1, RN1 and RN2, are generated. The first surface receives RN1 times the largest credible displacement, second surface has (RN2 - RN1) times the largest credible displacement, and the third surface has (1 - RN2) times the largest credible displacement.

2.2.8 Amount of Cumulative Fault Displacement during 10,000 yrs and Partitioning of Displacement Rate along Multiple Slip Surfaces

Possible cumulative fault displacement is determined by considering suggested slip rates, cdNW or cdNE, over the time frame of 10,000 yr. Because little information exists to quantify number of cumulative slip events or timing of such events, which in this analysis is considered to represent amounts of displacement less than possible maximum slip, cumulative slip will be assessed to determine if and when it exceeds a threshold displacement value leading to WP disruption. Slip rates are selected by random sampling from PDFs defined by the slip rate values presented (by Arabasz) in the EPRI expert elicitation report (Electric Power Research Institute, 1993) as shown in table 2-3 for northwest- and north-northeast-trending fault sets. The rate of cumulative fault displacement is also partitioned among the multiple slip surfaces using logic similar to that for largest credible displacement. PDF of cumulative fault displacement rate will be modified using new data acquired by the DOE.

2.2.9 Threshold Displacement

It is assumed that a minimum amount of fault displacement is needed to disrupt a WP. There is insufficient quantitative information available at present to specify this threshold displacement (TD) for WPs to be emplaced in the proposed repository at YM. Stirewalt et al. (1995, 1996) have assumed

Table 2-3. Amount of cumulative fault displacement used in the FAULTING code for northwest (NW)- and north-northeast (NNE)-trending faults at Yucca Mountain

NW Slip Rate (mm/yr)	Estimated Cumulative Probability of Occurrence (NW)	NE Slip Rate (mm/yr)	Estimated Cumulative Probability of Occurrence (NNE)
0.0	min	0.00004	min
0.00004	0.05	0.0004	0.05
0.001	0.5	0.0007	0.5
0.002	0.95	0.002	0.95
0.01	max	0.007	max
Values are derived from information on the northwest-trending Pagany Wash and Drill Hole Wash faults and the northeast-trending Ghost Dance fault as presented in the elicitation report of EPRI (1993).			

a uniform PDF varying between 0.1 and 0.5 m. Because this parameter is not physically related to faulting events, it is taken as input from the user. This approach also facilitates sensitivity analysis of this parameter on final results.

2.2.10 Time Cumulative Fault Displacement Exceeds Threshold Displacement

The time that cumulative displacement, tcNW or tcNE, exceeds a TD and results in WP disruption is calculated as TD divided by slip rate. If the time is beyond the time period of interest, (e.g., 10,000 yr), then cumulative displacement will not affect proposed repository performance.

2.3 SIMULATION PROCESS AND CONSEQUENCE ANALYSIS

Description of a faulting event in the FAULTING code is based on geometric considerations for a fault lying within the 50×50 km simulation region centered around the proposed repository. Two implicit assumptions have been made to describe the faulting event at YMR: probability of a faulting event is homogeneous in the simulation region and invariant in time, and characteristics of a new or undiscovered fault trend can be adequately described by existing information on known faults at YM.

Before starting the simulation, the code reads the coordinates of the simulation region and maximum and minimum values of each parameter from the file *fault.inc*. The code then receives the names of detailed output file, file for data written in a format for further processing, and file to write information for plotting the faults from the user through the keyboard. The analyst supplies an initial seed value for random number generation and number of realizations to be carried out. From information on AML in metric ton of uranium per acre (MTU/acre) provided by the user, the code checks whether the Primary Upper region would be sufficient to emplace 70,000 MTU of waste. If the available area is

inadequate, other regions are included in the calculation in this sequence: Primary Lower, Optional Area A, Optional Area B, Optional Area C, and Optional Area D. The proposed repository blocks and areas are described in chapter 4.

The simulation process of stochastically generating fault zones and subsequent consequence analysis are illustrated in the flow chart in figures 2-1a and b. Table 2-4 describes the PDF of each parameter along with maximum and minimum values. Simulation starts with the determination of time of occurrence of the faulting event. If the faulting event takes place within the 10,000 yr time period of interest, then subsequent steps of simulation are carried out. The fault zone is described by the location of its middle point, length, orientation, dip, and width by sampling randomly from respective PDFs. As was described, there are two PDFs for each parameter to represent the characteristics of both north-northeast- and northwest-trending faults observed at YM. The next step is to determine whether the simulated fault plane intersects the proposed repository and, if it does, the length of the fault within the proposed repository boundaries. The proposed repository boundaries have been determined from the area of each emplacement region (i.e., Primary Upper, Primary Lower, Optional Area A, Optional Area B, Optional Area C, and Optional Area D) and the area necessary to emplace 70,000 MTU of waste at a given AML. To avoid unnecessary calculations, simulation of fault zone dip and width are carried out only if the fault zone intersects the proposed repository region. In the next step of the simulation process, it is decided whether the slip takes place along single or multiple slip surfaces (two, three, or four), in the fault zone by randomly selecting from a uniform PDF. The positions of these slip surfaces are determined as a function of the width using uniformly distributed random numbers between 0 and 1.

Determination of potential for WP disruption starts with random selection of amount of largest credible displacement per faulting event using uniform PDF. If this displacement exceeds the specified threshold displacement, then it is assumed that all WPs within the fault zone (width times length of fault zone within the proposed repository) are disrupted. The code has a provision for including any standoff distance from the fault zone boundaries where there is potential for WP disruption if fault movement takes place. This standoff distance has to be supplied by the user through the include file *fault.inc*. In the next step, total displacement along the fault zone is partitioned over multiple slip surfaces generated previously. The exact amount of slip distributed to any one surface is proportional to the fraction of total slip bourn by this surface. The potential for WP disruption is checked in a fashion similar to the entire fault zone. If a particular fault zone does not have a potential for WP damage due to largest credible displacement, its susceptibility to WP damage due to cumulative slipping is assessed. Slip rates are selected by random sampling from PDFs defined by the slip rate values presented in EPRI (1993). Time required for cumulative slip to exceed the specified threshold displacement is calculated. If the time necessary for failure is less than the remaining time of 10,000 yr period of interest, it is assumed that WP disruption takes place in the entire fault zone. The cumulative fault displacement is partitioned among the multiple slip surfaces. If the cumulative fault displacement in any one of the multiple slip surfaces exceeds the threshold displacement within 10,000 yr time period, number and percentage of WP disrupted, along with area and percentage of emplacement area disrupted are calculated. Width of the disrupted zone due to movement along any slip surface is proportional to the fraction of total cumulative displacement of the fault partitioned to this slip surface.

It should be pointed out that the algorithm for estimating the consequence of a faulting event, as presently encoded, will always give conservative results. In this algorithm, whether or not a fault intersects a given emplacement region is determined by checking the intersection of the fault trace with the emplacement region. As each fault is assigned a finite width, the fault trace becomes a line along the middle of the fault zone. Therefore, it is possible that the trace of a wide fault may not intersect the

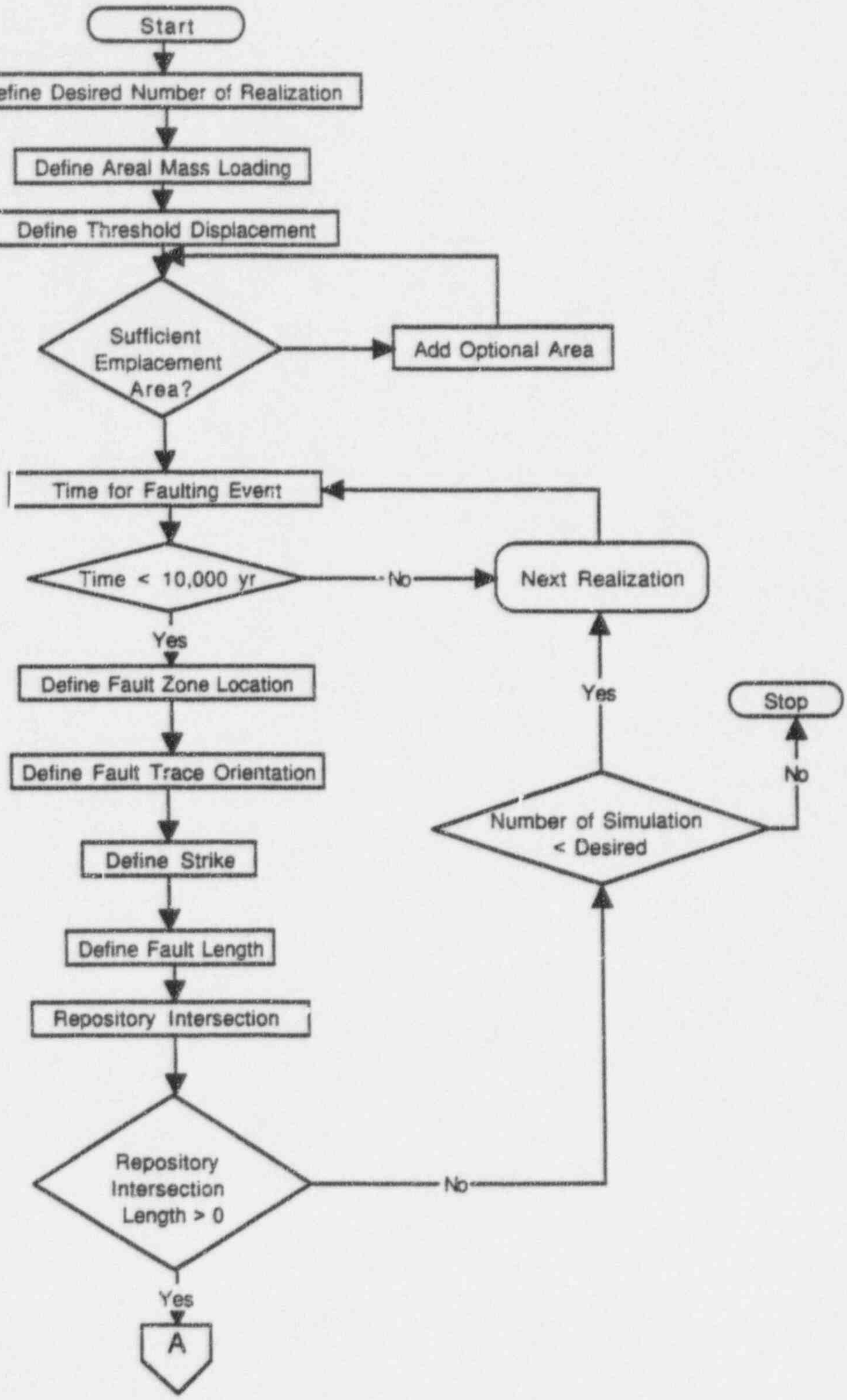

Figure 2-3a. Flow diagram illustrating sequential steps for describing faulting events

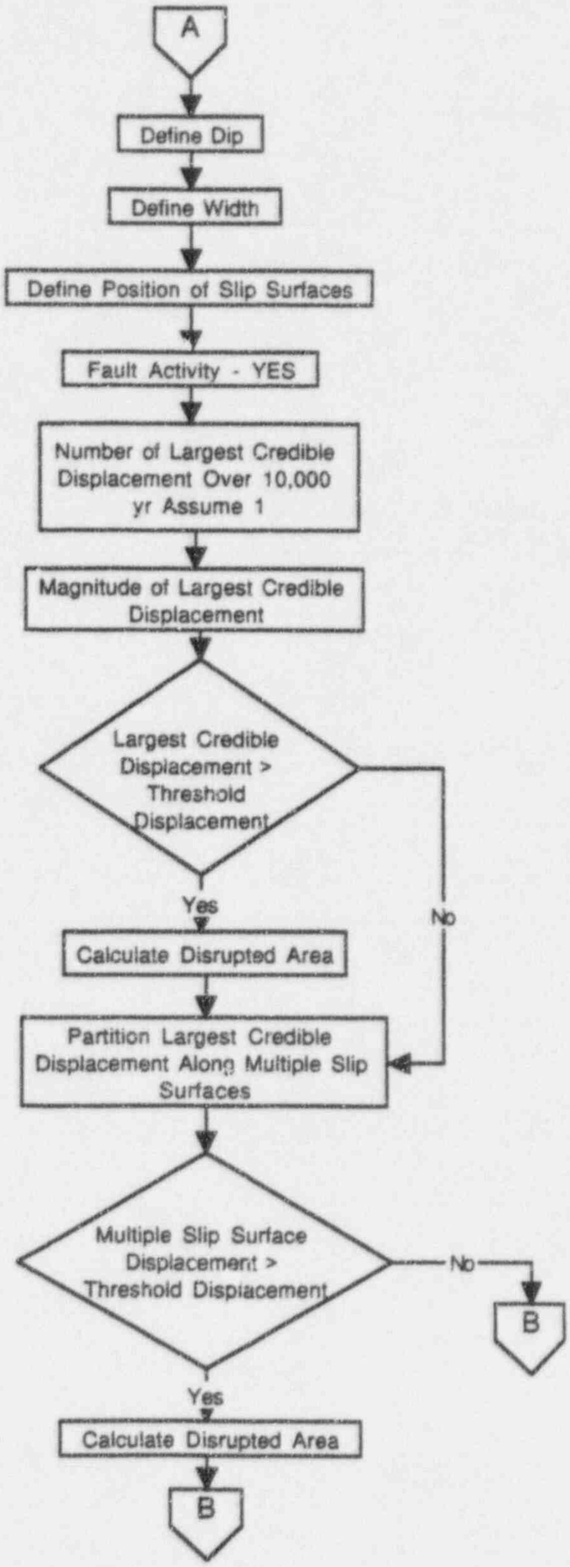

Figure 2-3b. Flow diagram illustrating sequential steps for describing faulting events (cont'd)

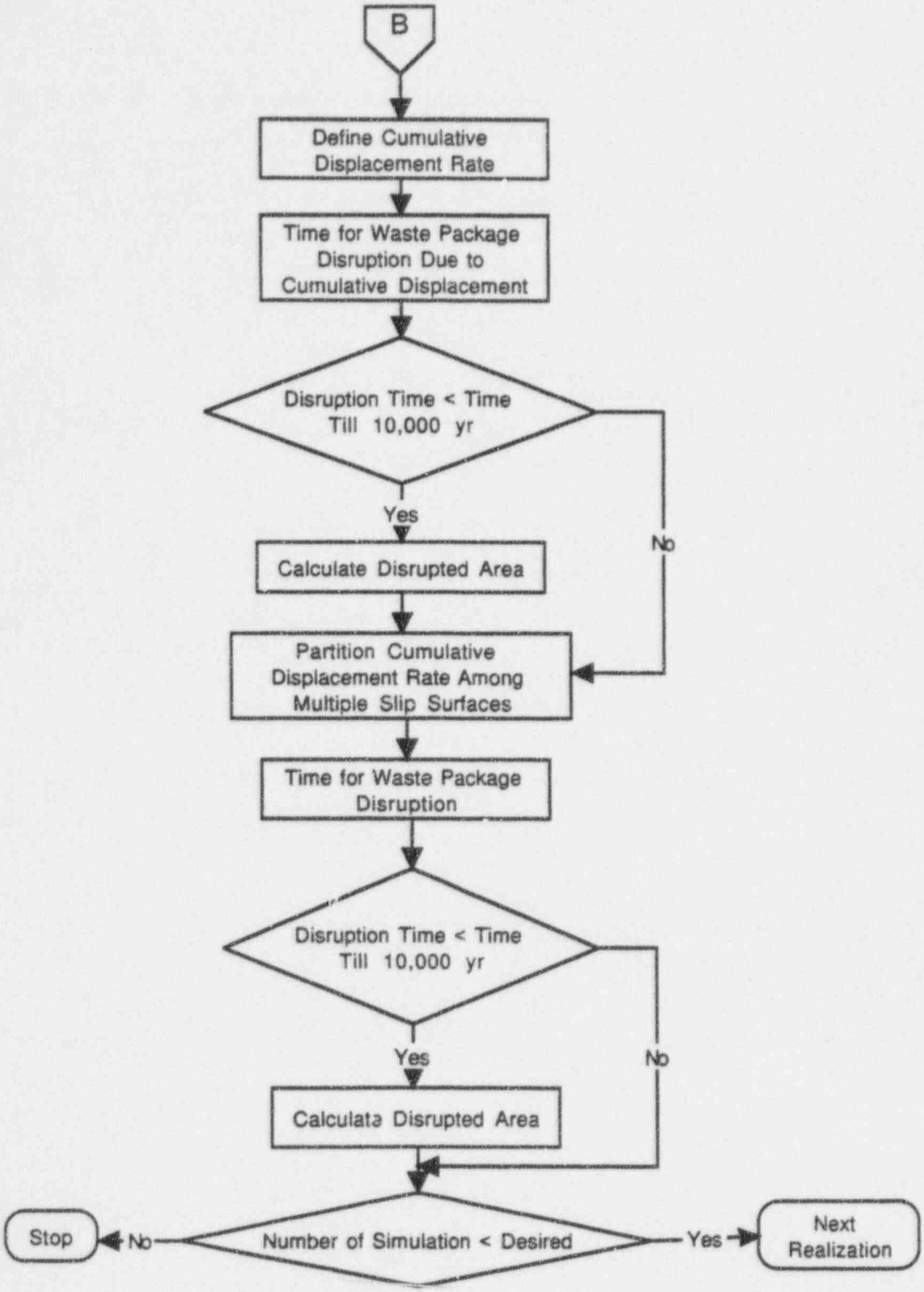

Figure 2-3c. Flow diagram illustrating sequential steps for describing faulting events (cont'd)

Table 2-4. Variables sampled in the FAULTING code and their distributions

Variable Description	Symbol	Probability Distribution Function (PDF)
Center of fault	fl_x fl_y	Uniform PDF 145500 m < x < 195500 m Uniform PDF 208000 m < y < 258000 m
Orientation	fo fo	Uniform PDF 25% of time NW Uniform PDF 75% of time NE
Strike orientation	sNW sNE	Normal PDF, 90% probability N25°W ≤ sNW ≤ N40°W N25°E ≤ sNE ≤ N5°W
Trace length	ltNW ltNE	Uniform PDF 2000 m ≤ ltNW ≤ 10000 m 3000 m ≤ ltNE ≤ 12000 m
Dip angle	θ_NW θ_NE	Normal PDF, 90% probability 80° NE < θ_NW > 80° SW 60° NW ≤ θ_NE ≤ 90°
Fault zone width	wNW wNE	Logbeta, PDF α=1.5, β=3.0 0.5 m ≤ wNW ≤ 275 m 0.5 m ≤ wNE ≤ 365 m
Number of slip surfaces	n	Uniform probability n={1,2,3,4}
Recurrence interval	riNW riNE	Uniform PDF 60,000 yr ≤ ri ≤ 275,000 yr
Number of faulting events	—	FE=1 time period of interest (10,000 yr) is short compared to recurrence intervals
Time of first largest credible event	t1	Uniform PDF 0 < t1 < 10,000 yr
Amount of largest credible displacement	ldNW ldNE	Uniform PDF 0.045 m ≤ ldNW ≤ 0.250 m 0.060 m ≤ ldNE ≤ 0.450 m
Largest displacement partitioned among slip surfaces	ldpNWn ldpNEn	Uniform partitioning of ld along n slip surfaces
Amount of cumulative displacement rate	cdNW cdNE	Uniform PDF 0.0 mm/yr ≤ cdNW ≤ 0.00001 mm/yr 0.00000004 mm/yr ≤ cdNE ≤ 0.000007 mm/yr
Cummulative displacement rate partitioned among slip surfaces	cdpNWn cdpNEn	Uniform partitioning along n slip surfaces

emplacement region, but a small part of the repository is actually within the fault zone. The FAULTING code does not account for these regions and, as a result, gives a slightly conservative estimate of the area affected by the faulting event. If faulting is found to be important, then the algorithm can be modified to be more realistic.

3 FAULTING SOFTWARE AND HARDWARE

The FAULTING code is written in FORTRAN 77, compiled with a SUN f77 compiler (Version 2.0.1) and functions on a SUNOS 4.1 operating system. The code works with both small and large values, hence, all real variables are declared as double precision (REAL*8) and all calculations are carried out in double precision.

FAULTING is a stochastic simulation code that randomly samples parameters in each realization. Many of the parameters have been specified as having uniform PDF. Moreover, parameters with other statistical distributions for their PDFs need uniformly distributed random numbers between 0 and 1 for stochastic simulation. The FAULTING code uses the *drand(k)* function of the FORTRAN compiler (SUN Microsystems, Inc., 1992) to generate the uniformly distributed random numbers. This is a compiler and machine-dependent function and may need to be changed if the code is ported to another computer system. A portable congruential random number generator discussed by Ripley (1987) and used widely is included with the code.

FAULTING also uses the machine-dependent function, *fdate()*, to stamp the output with date and time. In another type of machine and compiler, this call should be directed to a similar function that is specific to that compiler and machine.

There are two somewhat arbitrarily placed limitations on the array sizes. Arrays related to WP disruption due to maximum credible displacement are limited to 100,000 elements through PARAMETER *maxsim2*. Similarly, arrays related to cumulative displacement are limited to 5,000 elements through PARAMETER *maxsim*. If the need arises to increase the size of these arrays, the values for *maxsim* and *maxsim2* should be changed at the beginning of the source code. The code should be recompiled after making the changes.

Input parameters used to define the simulation region and maximum and minimum values of the parameter PDFs are described in the file *fault.inc*. Any changes to these values should be made in this file only. This file is included during compilation and needs to reside in the same directory for successful compilation. Therefore, any changes to this file will be active only after recompilation of the source code.

The main program of the FAULTING code reads input files, defines the simulation system configuration, calls subroutines to locate and characterize faulting events, and outputs the results. Subroutines used by the FAULTING code and the function of each subroutine are listed in table 3-1.

3.1 COMPILATION

The source code for FAULTING is called fault.f, written in standard FORTRAN 77 except for two functions *fdate()* and *drand(k)* of the SUN Fortran Compiler (SUN Microsystems, 1992). The include file *fault.inc* should be in the same directory as *fault.f* during compilation. The source code has been compiled without any optimization performed by the compiler. The commands are standard for SUN machines (and many other Unix-based machines):

faulting% f77 fault.f -o fault

This will produce the executable file *fault* in the current directory **faulting**. No compiler optimization scheme is used in compiling the code.

Table 3-1. Name and function of subroutines in the FAULTING code

Subroutine	Purpose
intersection	Calculates intersection point of two straight lines
inlength	Determines whether the intersection is real for each side of the repository boundary
checkin	Determines whether a point is inside a given region
check_area	Calculates area of a quadrilateral bounded by points (x_1,y_1), (x_2,y_2), (x_3,y_3), and (x_4,y_4).
triangle	Calculates area of a triangle bounded by points (x_1,y_1), (x_2,y_2), and (x_3,y_3)
segment	Determines whether a fault intersects a repository using the end coordinates of a line (fault) and a pointer for a particular repository
check_disrupt	Calculates area of the repository along with the number and percentage of waste packages disrupted in a faulting event
gauss	Accepts two values of uniformly distributed random numbers and produces two independent standard normal numbers
betad	Generates a random number following the beta distribution, Beta(α, β), where α and β are shape parameters of the distribution
logbeta	Produces logbeta distributed random numbers within the interval [lower, upper] using beta distributed random numbers from the betad subroutine
exponential	Generates exponentially distributed random numbers
sort	Sorts an array of length *n* into ascending order using the Heapsort algorithm

3.2 USER SUPPORT

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4 INPUT DATA

4.1 SIMULATION AND REPOSITORY REGIONS

Input data for the FAULTING code can be divided into two groups: those needed to define PDFs for different parameters and those needed to describe a particular run of the code. As discussed before, the first set of data is given in the include file *fault.inc*. The second set of data is input from the user interactively. The FAULTING code requires definition of the repository region. In this code, all six emplacement regions are approximated by four-sided polygons. It is tedious to input the coordinates of each of the four corners of a region interactively. Moreover, this approach is error-prone. Therefore, the coordinates of each emplacement region are included in *fault.f* through DATA statements. The origin of the simulation area was taken as 170,500 m East and 233,000 m North, which falls in the middle of the primary emplacement area. The following coordinates for each corner of different emplacement regions are developed from the site plan given by TRW Environmental Safety Systems Inc. (1995):

Region Primary Upper:
[(170500 E, 234800 N), (171300 E, 234500 N), (171100 E, 231100 N), (169800 N, 231500 E)]

Region Primary Lower:
[(171600 E, 233700 N), (172300 E, 233300 N), (171700 E, 232000 N), (171500 E, 232100 N)]

Optional Region A:
[(170800 E, 236300 N), (171300 E, 236400 N), (171950 E, 235500 N), (171300 E, 235200 N)]

Optional Region B:
[(169000 E, 236800 N), (169700 E, 236500 N), (169400 E, 234500 N), (168500 E, 234800 N)]

Optional Region C:
[(168300 E, 234500 N), (168900 E, 234200 N), (168200 E, 232200 N), (167600 E, 232500 N)]

Optional Region D:
[(169200 E, 234200 N), (169700 E, 234000 N), (169100 E, 231500 N), (168200 E, 231700 N)]

Figure 2-2 shows the plots of the regions given by the coordinate points. It should be realized that representation of a repository region by a four-sided polygon is an approximation. As a result, the area calculated using these coordinate values does not exactly match with the area given in TRW Environmental Safety Systems Inc. (1995). Table 4-1 gives both the actual and calculated areas of each of the emplacement regions. The difference is negligible for the analysis performed by the FAULTING code.

4.2 DESCRIPTION OF PARAMETER FILE *fault.inc*

The FAULTING code requires site-specific values for different parameters to describe the PDFs and the simulation region. These parameters are declared in a separate file called *fault.inc* included in this code at the beginning of compilation. Any modification to the parameters can be done independently in the file *fault.inc* without any possibility of modifying any part of the code accidently. An example of *fault.inc* file is provided in table 4-2.

Table 4-1. Comparison of calculated and actual areas of each emplacement region

Region	Calculated Area (acre)	Actual Area (acre)
Primary Upper	908	931
Primary Lower	179	218
Optional Area A	171	157
Optional Area B	425	439
Optional Area C	348	363
Optional Area D	472	585

Table 4-2. Example of *fault.inc* file

```
c
c....C***********************************************************
c      This file contains values of different variables used in the
c      FAULTING code. Any change to the data should be done here
c      so that the program remains unaffected.
c....C***********************************************************
c

c
c... Coordinates of the square region (meter)
c
c
c      Define the coordinates of the square region
c      Origin is defined in the middle of the Primary Area (Upper Block)
c      x0 = 170500 East = 170500m, y0 = 233000 North = 233000 m
c      The simulation block is 50 km x 50 km centered at (x0,y0)
c

       xleft   = 145500.0
       xright  = 195500.0
       ybottom = 208000.0
       ytop    = 258000.0

c
c...  Probability of fault zone orientation
c

       pforient = 0.25

c
c...  Strike of fault zone (degree, measured from North)
c
```

```
      min_sNW = 115.0d0
      max_sNW = 130.0d0

      min_sNE = 65.0d0
      max_sNE = 95.0d0

c
c...  Total trace length (meter)
c

      min_ltNW = 2000.0d0
      max_ltNW = 10000.0d0

      min_ltNE = 3000.0d0
      max_ltNE = 12000.0d0

c
c...  Dip angle (degree, measured from East)
c

      min_thetaNW = 80.0d0
      max_thetaNW = 100.0d0

      min_thetaNE = 90.0d0
      max_thetaNE = 120.0d0

c
c...  Fault width (meter)
c

      min_wNW = 0.5d0
      max_wNW = 275.0d0

      min_wNE = 0.5d0
      max_wNE = 365.0d0

      alpha = 1.5d0
      beta = 3.0d0

c
c...  Time of occurrence of largest credible displacement faulting event (year)
c     Changed from 0 and 10,000 years to 60,000 and 275,000 years
c

      min_t1 = 60000.0d0
      max_t1 = 275000.0d0

c
c...  Amount of largest credible displacement per faulting event (meter)
c

      min_ldNW = 4.5d-2
      max_ldNW = 25.0d-2

      min_ldNE = 6.0d-2
      max_ldNE = 45.0d-2

c
c...  Largest credible displacement along multiple slip surfaces (meter)
c
```

```
        ld_max = 45.0d-2

c
c...  Amount of cumulative displacement rate (meter/year)
c

        min_cdNW = 0.0d-3
        max_cdNW = 0.01d-3

        min_cdNE = 0.00004d-3
        max_cdNE = 0.007d-3

c
c...  Define standoff distance
c

        standoff = 0.0

c
c...  Define MTU per WP
c

        MTU_wp = 9.0
```

4.3 SAMPLE INTERACTIVE INPUT

As discussed before, values of different parameters necessary to carry out a simulation are taken interactively from the user. A typical input session is given in table 4-3.

Table 4-3. Example input session of the FAULTING code

```
faulting%  fault

Output file => fault_test.out

File for plotting fault traces => fault_test.plt

Output Data file => fault_test.dat
Thu Dec 19 10:15:33 1996

Need a verbose output on screen (y/n)=>n

Integer Seed for Random Number Generation (>1) => 3

Number of Simulation Run Desired => 1000
Input Areal Mass Loading AML in MTU/acre

50

Emplacement Area Needed = 1400.00 acre

Number of WPs = 7778

Area of Primary Upper Region = 908.08 acre
Additional Area Needed = 491.92 acre

Area of Primary Lower Region = 182.85 acre
Additional Area Needed =    309.07 acre

Area of Optional Region A = 170.50 acre
```

```
Additional Area Needed = 138.57 acre

To emplace 70,000 MTU, following regions are necessary:

Primary Upper Region
Primary Lower Region
Optional Region A
Optional Region B

Threshold Displacement for WP (m) => .1
```

5 DESCRIPTION OF OUTPUT

The FAULTING code produces three output files in addition to output on the screen. The first output file records detailed information about every fault that intersects the emplacement region(s) in addition to the information about selection of emplacement region(s). Output is somewhat verbose and can be used for obtaining detailed information of the simulation process. In most cases, the primary interest will be on faults that can disrupt WPs. These results are summarized in tabular form in a separate output file—one line per fault. If multiple slip surfaces of a particular fault are activated, one additional line is used for each slip surface. In a separate file, information about trace of faults intersecting the emplacement region(s) is given for plotting. The format for this output file conforms to the requirements of PLOTMTV code (Toh, 1995), a freeware software for plotting on xwindows systems. In addition, the code writes important information about faults on the screen. Amount of information about the faults can be increased substantially by selecting "y" or "Y" when prompted for verbose output at the beginning of the run. Example output files are described in the following sections. Name of the output files are selected by the user—maximum 80 characters in length. Any symbol, legal for file naming in SUNOS system, can be used. If the selected file name matches with any existing files in the directory, user will be prompted to select another name. In no case will an existing file be overwritten.

5.1 DETAILED OUTPUT FILE

At the end of the file, information about number of realizations, number of faults intersecting the repository, and number of faults disrupting the WPs are given. A sample output file is given in table 5-1.

Table 5-1. A sample detailed output file of the FAULTING code

```
  ***********************************************
      FAULTING CODE
      Wed Dec 18 14:49:05 1996
  ***********************************************
Areal Mass Loading AML = 50.000000000000 MTU/acre

Emplacement Area Needed = 1400.00 acre

Number of WPs = 7778

Area of Primary Upper Region = 908.08 acre
Additional Area Needed = 491.92 acre

Area of Primary Lower Region = 182.85 acre
Additional Area Needed = 309.07 acre

Area of Optional Region A = 170.50 acre
Additional Area Needed = 138.57 acre

To emplace 70,000 MTU, following regions are necessary:

Primary Upper Region
Primary Lower Region
Optional Region A
Optional Region B

Threshold Displacement = 0.10000 m
```

```
Fault: 696 Time of Fault Activation = 12.383943739843 years

The Fault has NW orientation
Strike of the Fault Zone:   125.3868 degree

Fault Trace Length:  2480.4113 m
Fault: 696     170388.2   235191.5   171824.6   233169.3   1343.596

Fault Width: 50.479583 m

Slip Surface: 1 Position: 29.4740 m

Slip Surface: 2 Position: 15.8730 m

Cumulative Displacement of the Fault = 0.00000262 m

... No surface has exceeded the cumulative displacement exceeding threshold ...
Fault: 797 Time of Fault Activation = 4639.6484236231 years

The Fault has NE orientation
Strike of the Fault Zone: 75.5030 degree

Fault Trace Length: 10461.1739 m
Fault: 797     172540.6   239418.3   169921.8   229290.2   3987.446

Fault Width: 163.970541 m

Slip Surface: 1 Position: 128.5298 m

Slip Surface: 2 Position: 58.4283 m

Slip Surface: 3 Position: 149.5059 m

Slip Surface: 4 Position: 74.1511 m
Fault (Disrupting): 1 Time for Fault Activation = 4639.6484236231 years


Mid-point Coordinates of the Fault:
x = 171231.2076 m;  y = 234354.2706 m
Strike of the Fault Zone: 75.5030 degree

Fault Trace Length: 10461.1739 m
Fault: 797     172540.6   239418.3   169921.8   229290.2   3987.446

Fault Width: 163.970541 m

Threshold Displacement =  0.10000 m

Largest Credible Displacement Per Faulting Event: Fault NE 0.175559 m

At time = 4639.6 years, number of WPs failed = 898 IE 11.55% Area Disrupted =
161.56    Acre OR  11.54 %

Cumulative Displacement of the Fault = 0.00000449 m

... No surface has exceeded the cumulative displacement exceeding threshold ...
Fault: 2193 Time of Fault Activation = 18.318516923872 years

The Fault has NE orientation
Strike of the Fault Zone: 90.9146 degree

Fault Trace Length: 7916.1388 m
Fault: 2193     170602.6   235643.0   170729.0   227727.8   3525.287
```

```
Fault Width: 99.871866 m

Slip Surface: 1 Position: 88.7058 m

Slip Surface: 2 Position: 87.3908 m

Cumulative Displacement of the Fault = 0.00000366 m

... No surface has exceeded the cumulative displacement exceeding threshold ...
Fault: 3602 Time of Fault Activation = 5946.8966261762 years

The Fault has NW orientation
Strike of the Fault Zone: 119.2013 degree

Fault Trace Length:  6984.7316 m
Fault: 3602     169062.7    239378.3    172470.4    233281.3    1034.505

Fault Width: 96.298132 m

Slip Surface: 1 Position: 44.7583 m

Slip Surface: 2 Position: 7.6050 m

Slip Surface: 3 Position: 77.8871 m

Slip Surface: 4 Position: 85.5902 m

Cumulative Displacement of the Fault = 0.00000148 m

... No surface has exceeded the cumulative displacement exceeding threshold ...
Fault: 4223 Time of Fault Activation = 7775.3980134803 years

The Fault has NE orientation
Strike of the Fault Zone: 72.7878 degree

Fault Trace Length: 11952.7576 m
Fault: 4223     173064.4    242746.0    169527.5    231328.5    1493.093

Fault Width: 101.877913 m

Slip Surface: 1 Position: 85.3410 m

Slip Surface: 2 Position: 91.8620 m
Fault (Disrupting): 2 Time for Fault Activation = 7775.3980134803 years

Mid-point Coordinates of the Fault:
x = 171295.9663 m;  y = 237037.2331 m
Strike of the Fault Zone: 72.7878 degree

Fault Trace Length: 11952.7576 m
Fault: 4223     173064.4    242746.0    169527.5    231328.5    1493.093

Fault Width: 101.877913 m

Threshold Displacement = 0.10000 m

Largest Credible Displacement Per Faulting Event: Fault NE 0.385201 m

At time = 7775.4 years, number of WPs failed = 209 IE  2.69% Area Disrupted =
37.59  Acre OR 2.68 %

Slip Surface: 1 Position: 85.3410 m
```

```
At time = 7775.4 years, number of WPs failed = 62 IE  0.80% Area Disrupted =
10.99 Acre  OR 0.78 % Multiple Plane 1

Slip Surface: 2 Position: 91.8620 m

At time = 7775.4 years, number of WPs failed = 148 IE  1.90% Area Disrupted =
26.60  Acre OR 1.90 % Multiple Plane 2

Fault 4223Slip Fault No. 2 Number of Slip Surfaces Exceeding Threshold Slip
Displacement = 2
Time = 7775.3980134803 year

Cumulative Displacement of the Fault = 0.00000670 m

... No surface has exceeded the cumulative displacement exceeding threshold ...
Number of Realizations = 5000
Number of Simulated Faults Intersecting the Repository = 5
Number of Simulated Faults Disrupting WPs = 2
```

5.2 Output File of Summarized Results

This output file contains information about those faults that can disrupt the WPs. For each of these faults, following information is written to this output file:

- time of occurrence
- coordinates of midpoint
- orientation
- strike
- fault length
- fault length within emplacement region
- fault width
- largest credible fault displacement
- threshold displacement
- number of WPs disrupted
- percentage of WPs disrupted
- area of emplacement region disrupted
- percentage of area of emplacement region disrupted
- multiple slip surface number, if any.

A sample output file is given in table 5-2.

Table 5-2. A sample output file of the FAULTING code with summarized results

```
  ************************************************
              FAULTING CODE
          Wed Dec 18 14:49:05 1996
  ************************************************
Time X0 YC Orient  Strike Length Length_repo width Disp  Threshold  wp_dis
wp_dis% area_dis area_dis%

4639.6 171231.2 234354.3 NE  75.50  10461.2 3987.4 163.97  0.17556  0.10000  898
11.55  161.6 11.54
```

```
7775.4 171296.0 237037.2 NE  72.79  11952.8 1493.1 101.88  0.38520  0.10000  209
2.69   37.6   2.68
7775.4 171296.0 237037.2 NE  72.79  11952.8 1493.1 101.88  0.38520  0.10000
62  0.80   11.0   .78 Surface 1

7775.4 171296.0 237037.2 NE  72.79  11952.8 1493.1 101.88  0.38520  0.10000
148  1.90   26.6    1.90 Surface 2
```

5.3 Output File for Plotting Fault Traces

Information about fault traces is written in this file in a format compatible with the PLOTMTV program (Toh, 1995). This output file is ready to be processed without any modification. If this file is invoked as the input file for the PLOTMTV program, a screen plot for all the fault traces will be generated. Details about the PLOTMTV program are given in Toh (1995). A sample plot is given in figure 5-1.

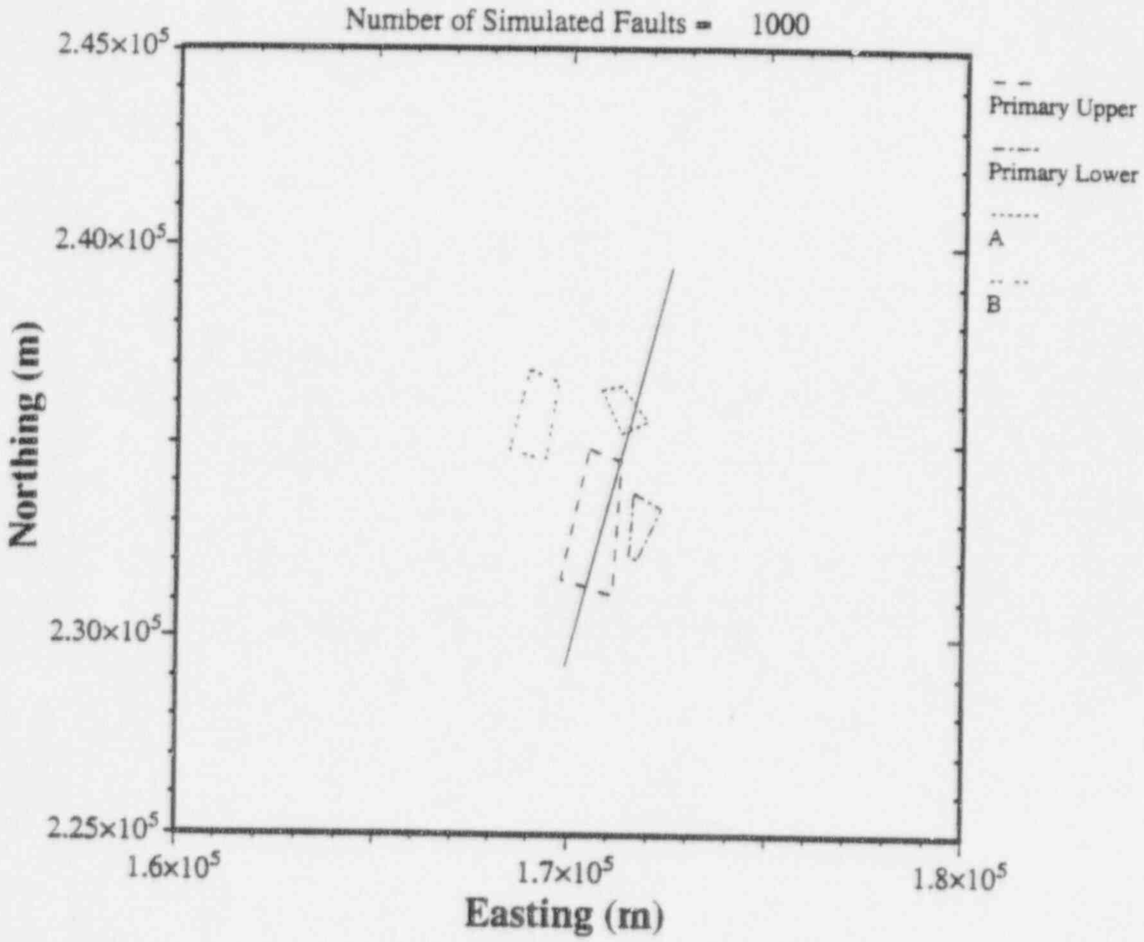

Figure 5-1. Sample plot of simulated fault traces along with emplacement regions

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APPENDIX A

MATHEMATICAL MODELS AND SUBROUTINE DESCRIPTIONS

This section describes the mathematical models and subroutines used in developing the FAULTING code. Table 3-1 gives a short description of each subroutine. More detail is provided here. The current version of the code uses subroutines to generate random samples for a given statistical distribution. Other programs may alternately be used to generate the required sample parameters [e.g., program LHS94 Version 1.1 (Iman and Shortencarier, 1984)].

A.1 SUBROUTINE *intersection*

Subroutine *intersection* calculates the coordinates of the intersection point (x_i,y_i) of two straight lines. Line 1 passes through (x_1,y_1) and (x_2,y_2). Line 2 passes through (x_3,y_3) and (x_4,y_4). This subroutine takes (x_1,y_1), (x_2,y_2), (x_3,y_3), and (x_4,y_4) as input and produces (x_i,y_i) as the output.

Equation of line 1 is

$$\frac{y-y_1}{x-x_1}=\frac{y_2-y_1}{x_2-x_1} \tag{A-1}$$

it goes through (x_i,y_i). Therefore,

$$\frac{y_i-y_1}{x_i-x_1}=\frac{y_2-y_1}{x_2-x_1} \tag{A-2}$$

Similarly,

$$\frac{y_i-y_3}{x_i-x_3}=\frac{y_4-y_3}{x_4-x_3} \tag{A-3}$$

Solving (A-2) and (A-3) for x_i and y_i,

$$x_i = \frac{-x_2x_4y_3+x_1x_4y_3+x_2x_4y_1-x_2x_3y_1-x_1x_4y_2+x_1x_3y_2+x_2x_3y_4-x_1x_3y_4}{-x_3y_1+x_4y_1+x_3y_2-x_4y_2+x_1y_3-x_2y_3-x_1y_4+x_2y_4} \tag{A-4}$$

$$y_i=-\frac{x_2y_1y_3+x_4y_1y_3+x_1y_2y_3-x_4y_2y_3+x_2y_1y_4-x_3y_1y_4-x_1y_2y_4+x_3y_2y_4}{-x_3y_1+x_4y_1+x_3y_2-x_4y_2+x_1y_3-x_2y_3-x_1y_4+x_2y_4} \tag{A-5}$$

A.2 SUBROUTINE *inlength*

Equations (A-4) and (A-5) do not guarantee that the point of intersection of these lines is real, that is, the point lies on both the lines as shown in figure A-1, but the denominator of equations (A-4) or (A-5) may be zero, hence parallel lines. Subroutine *inlength* checks if the intersection point between two straight lines is real. This subroutine takes as input end coordinates of a line (fault trace), coordinates

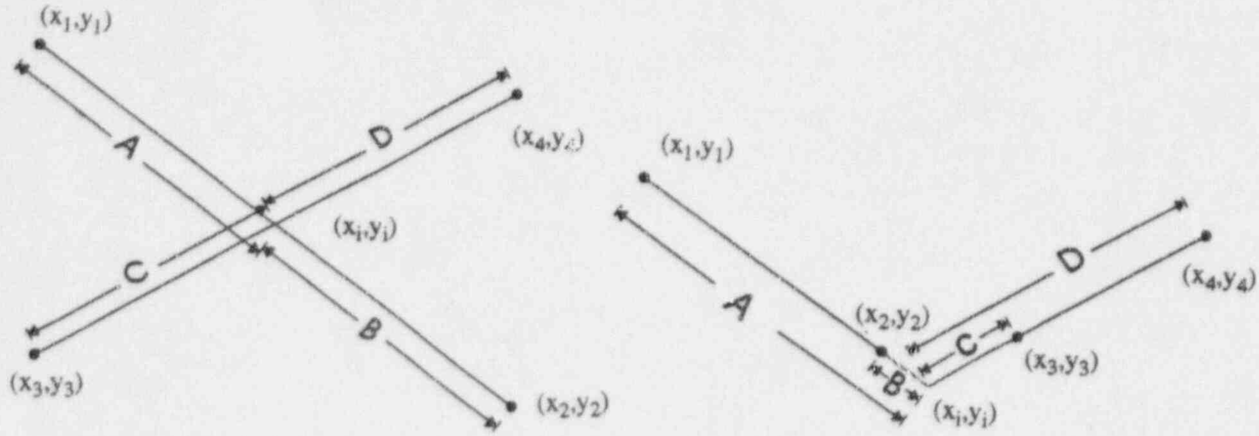

Figure A-1. Determination of real intersection point of two finite straight lines

of vertices of the polygon (emplacement region), number of sides of the quadrilateral, a counter to keep track of the number of intersections between a fault, and a four-sided emplacement region. *Inlength* actually calls the subroutine *intersection* to calculate the coordinates (x_i,y_i) given the fault and one side of the polygon representing the emplacement region. Output of this subroutine are the intersection point coordinates and a flag to indicate real intersection (ints_flag = 1 for real intersection, and 0 otherwise).

The algorithm for checking the real intersection consists of computation of six lengths:

A = length of the line joining (x_1,y_1) and (x_i,y_i)
B = length of the line joining (x_2,y_2) and (x_i,y_i)
C = length of the line joining (x_3,y_3) and (x_i,y_i)
D = length of the line joining (x_4,y_4) and (x_i,y_i)
E = length of the line joining (x_1,y_1) and (x_2,y_2)
F = length of the line joining (x_3,y_3) and (x_4,y_4)

For the intersection to be real, the following two conditions need to be true:

$$A + B = E \Rightarrow (A + B) - E = 0 \qquad \text{(A-6)}$$

and

$$C + D = F \Rightarrow (C + D) - F = 0 \qquad \text{(A-7)}$$

It should be recognized that comparison of real numbers (length dimension) having very similar magnitudes is problematic due to round off errors. Therefore, an acceptable tolerance should be used. A value of 0.0001 m has been taken for tolerance considering typical values of fault length and double precision calculations used in the model.

A.3 SUBROUTINE *checkin*

Subroutine *checkin* determines whether a point (x_p, y_p) falls inside a given quadrilateral (emplacement region). The quadrilateral is defined by the coordinates of its vertices (x_1,y_1), (x_2,y_2), (x_3,y_3), and (x_4,y_4). Coordinates of the given point and corners of the quadrilateral are the input to the subroutine. Output of this subroutine is the flag IN equal to 1 if the given point falls within the quadrilateral, and 0 otherwise.

The algorithm for checking if a given point falls within the quadrilateral begins by computing five areas:

A1: area of triangle (x_1,y_1), (x_2,y_2), (x_p,y_p)
A2: area of triangle (x_2,y_2), (x_3,y_3), (x_p,y_p)
A3: area of triangle (x_3,y_3), (x_4,y_4), (x_p,y_p)
A4: area of triangle (x_4,y_4), (x_1,y_1), (x_p,y_p)
A: area of quadrilateral (x_1,y_1), (x_2,y_2), (x_3,y_3), and (x_4,y_4)

The area of quadrilateral (x_1,y_1), (x_2,y_2), (x_3,y_3), (x_4,y_4) is given by the sum of two triangular areas:

A = area of [triangle (x_1,y_1), $x_2,y_2)$, (x_3,y_3) + triangle (x_3,y_3), (x_4,y_4) (x_1,y_1)]

If the point (x_p,y_p) is inside the quadrilateral (figure A-2), then

$$A = A_1 + A_2 + A_3 + A_4 \qquad \text{(A-8)}$$

If outside, then

$$A < (A_1 + A_2 + A_3 + A_4) \qquad \text{(A-9)}$$

A.4 SUBROUTINE *cal_area/triangle*

Subroutine *cal_area* calculates the area of a polygon. The polygon is defined by the coordinates of each vertex. These coordinates and the number of sides of the polygon are the input for this subroutine. The calculated area is the output. The following formula is used to calculate the area A of a n-sided polygon:

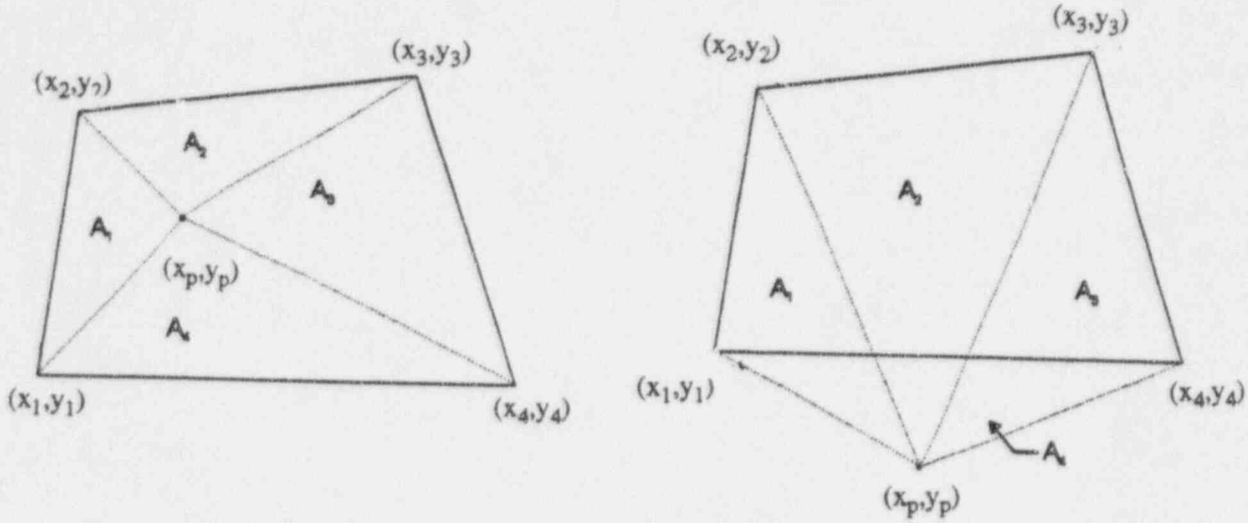

Figure A-2. Determination if a given point falls within a given quadrilateral

$$A = \frac{1}{2}\sum_{i=1}^{n} \begin{vmatrix} x_i & x_{i+1} \\ y_i & y_{i+1} \end{vmatrix} \qquad \text{(A-10)}$$

where, $i = 1, \ldots, n$, and $x_{n+1} = x_1$, and $y_{n+1} = y_1$. In expanded form, this equation becomes

$$A = \frac{1}{2}\left[(x_1 y_2 + x_2 y_3 + \ldots + x_n y_1) - (x_2 y_1 + x_3 y_2 + \ldots + x_1 y_n)\right] \qquad \text{(A-11)}$$

Absolute value of the expression in parenthesis is used to calculate the area. The subroutine *triangle* uses the same equation and calculates only the area of a triangle given by (x_1,y_1), (x_2,y_2), and (x_3,y_3).

A.5 SUBROUTINE *segment*

The subroutine *segment* takes as input the coordinates of end points of a given line (fault) and the vertices of a quadrilateral (emplacement region). It then uses each segment of the boundary of the emplacement area and checks if there is a real intersection. The subroutine *segment* calls the subroutine *intersection* to calculate the coordinates of the intersection point. The length of the fault within the given emplacement region is the output from this subroutine. The algorithm is given in the following section.

Figure A-3 illustrates different cases that may arise while determining the length of the fault inside a repository block. In figure A-3,

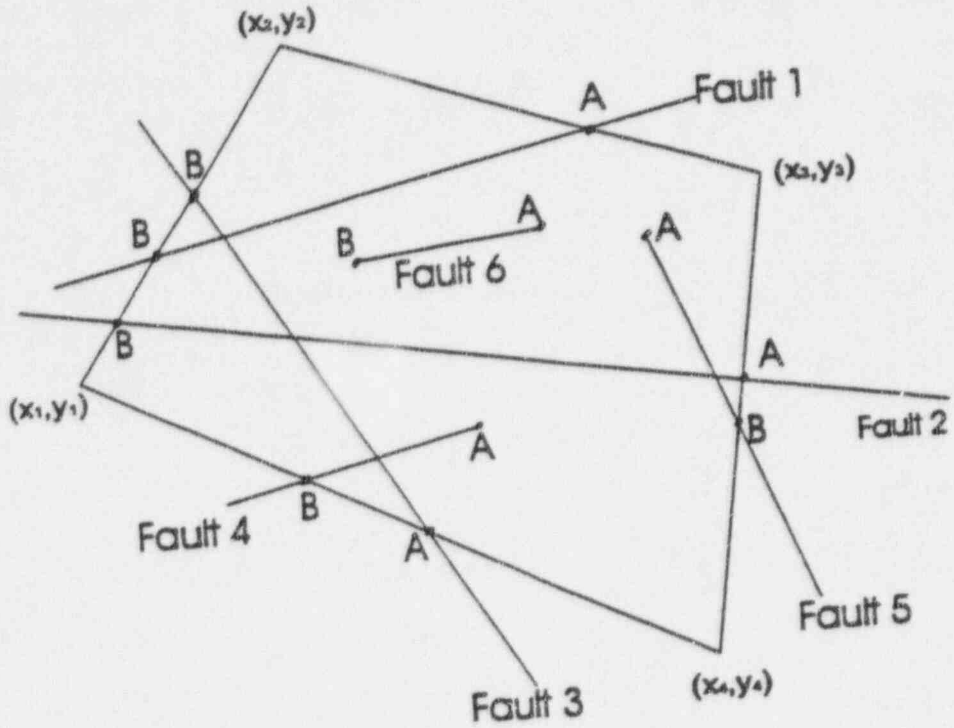

Figure A-3. Different cases while determining the length of the fault inside a repository block

• Fault 6:	Intersection length = fault length
• Faults 4 and 5:	Intersection length = AB: need to find only B
• Faults 1, 2, and 3:	Intersection length = AB: need to know both A and B.

The three following steps are necessary to determine length of the fault within the block:

Step 1: Determine if each end of the fault is within the boundary;
if yes, intersection length equal fault length

Step 2: If one end is within the boundary, determine
(i) which segment it intersects
(ii) calculate length AB

Step 3: If both ends are outside the boundary, determine
(i) which segments it intersects
(ii) calculate length AB

The length of the portion of a randomly generated fault intersected by a given repository region is calculated following the previously mentioned algorithm. Subroutine *checkin* is used to determine whether both ends of the fault fall within the given region. If both ends of the fault are within the given region then the intersected length is the length of the fault. If one end or both ends fall outside the given

region, then subroutine *inlength* is used to determine first the intersection point(s) of the fault and then the sides of the quadrilateral region. There will be one or two real intersection points depending on if one or two end points fall outside the region. The intersected length for the first case is the distance between the real intersection point and the other end point of the fault that falls within the region. The intersected length for the second case is the distance between the two intersection points.

A.6 SUBROUTINE *check_disrupt*

Subroutine *check_disrupt* calculates the consequence of a faulting event. It calculates the number and percentage of WPs, and area of emplacement disrupted for each faulting event. Input to this subroutine are the length and width of the fault, areal mass loading (MTU/acre), MTU per WP, number of WPs in the emplacement region, and the standoff distance. Standoff distance is the distance normal to the fault assumed to be affected by the movement along the fault plane.

A.7 SUBROUTINE *gauss*

The probability distribution function (PDF) of the normal or Gaussian distribution is (Scheaffer and McClave, 1982)

$$f(x;\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}} \exp[-\frac{(x-\mu)^2}{2\sigma^2}], \quad -\infty<x<\infty, \quad -\infty<\mu<\infty, \quad \sigma>0 \qquad \text{(A-12)}$$

where, μ and σ are the location and scale parameters of the distribution. It can be shown that μ and σ are equal to the mean and standard deviation of x. Subroutine *gauss* generates random numbers x having standard normal distribution (mean $\mu = 0$ and standard deviation $\sigma = 1$) with lower and upper cut-off A and B. There is a 90 percent probability that the random number will fall between A and B, that is, $A \leq x \leq B$.

Mean of the random numbers with desired truncated normal distribution is

$$\mu = \frac{A+B}{2}$$

Now, the probabilities are

$$P(x \leq A) = \frac{100-90}{2}\% = 5\% = 0.05 \qquad \text{(A-13)}$$

and

$$P(X \geq B) = 0.05 \qquad \text{(A-14)}$$

for a standard normal variate Z,

$$P(Z \leq 1.645) = 0.05 \tag{A-15}$$

Therefore, standard deviation of the desired truncated normal distribution is $\sigma = \frac{A-\mu}{1.645} = \frac{B-\mu}{1.645} = \frac{B-A}{3.29}$.

Generation of normally distributed random numbers is determined out following Ang and Tang (1984). If U_1 and U_2 are two uncorrelated uniformly distributed random numbers between 0 and 1, then two normally distributed random numbers with mean μ and standard deviation σ are

$$x_1 = \mu + \sigma\sqrt{-2lnU_1}\,\mathrm{Cos}2\pi U_2 \tag{A-16}$$

and

$$x_2 = \mu + \sigma\sqrt{-2lnU_1}\,\mathrm{Sin}2\pi U_2 \tag{A-17}$$

A.8 SUBROUTINE *betad*

The PDF of Beta distribution within 0 and 1 (standard Beta distribution) is

$$f(x;\alpha,\beta) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)}x^{\alpha-1}(1-x)^{\beta-1}, \qquad 0 < x < 1 \tag{A-18}$$

where, α and β are shape parameters of the distribution and $\Gamma(\eta)$ is the Gamma function of η. $\Gamma(\eta)$ is defined as

$$\Gamma(\eta) = \int_0^\infty x^{\eta-1}e^{-z}dz \tag{A-19}$$

taking z as a dummy variable.

Mean μ and variance σ^2 of the distribution are

$$\mu = \frac{\alpha}{\alpha+\beta} \tag{A-20}$$

and

$$\sigma^2 = \frac{\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)} \tag{A-21}$$

Random sample y from a general Beta distribution with lower and upper bounds A and B may be obtained through

$$y = \frac{x-A}{B-A} \tag{A-22}$$

where x is the corresponding random sample for the standard Beta distribution.

Therefore,

$$\mu_y = (B-A)\mu + A = \frac{A\beta + B\alpha}{\alpha + \beta} \tag{A-23}$$

and

$$\sigma_y^2 = (B-A)^2\sigma^2 = \frac{(B-A)^2\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)} \tag{A-24}$$

Generation of Beta distributed random numbers is carried out following Ang and Tang (1984). A random sample x with PDF of the standard Beta distribution with shape parameters α and β can be generated from

$$x = \frac{U_1^{1/\alpha}}{U_1^{1/\alpha} + U_2^{1/\beta}} \tag{A-25}$$

where U_1 and U_2 are two random numbers having the standard uniform distribution provided

$$U_1^{1/\alpha} + U_2^{1/\beta} \le 1 \tag{A-26}$$

A.9 SUBROUTINE *logbeta*

If x is standard Beta distributed with mean equal to 0 and standard deviation equal to 1, then y has logbeta distribution if

$$y = e^x \tag{A-27}$$

which means

$$\ln y = x \tag{A-28}$$

has beta distribution. Consequently, the lower and upper limits A and B will be

$$a^* = \ln a \tag{A-29}$$

Now, a standard beta distribution needs to be generated with lower and upper limits a^* and b^*.

$$b^* = \ln b \qquad \text{(A-30)}$$

Mean of logbeta distribution $\mu = e^{\frac{\alpha}{\alpha+\beta}}$

Variance of logbeta distribution $\sigma^2 = e^{\frac{\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)}}$

Given $\alpha = 1.5$, and $\beta = 3.0$, then

$\mu = e^{\frac{1.5}{4.5}} = 1.3956$

and

$\sigma = e^{\frac{1.5x3}{4.5^2 x(5.5)}} = 1.0412$

Minimum value $e^0 = 1$

Maximum value $e^1 = 2.71828$

Therefore, random sample B standard Beta distribution (i.e., within the interval 0 and 1), when converted to logbeta distribution y, will be within the interval 1 and 2.71828; hence

$$y = \frac{x-a}{b-a} = \frac{x-1}{1.71828} \qquad \text{(A-31)}$$

y will be logbeta distributed with interval between 0 and 1. If, for example, random numbers are needed, which is logbeta within interval (A,B), then

$Z = y(B-A) + A$

$Z = \frac{x-a}{b-a} \cdot (B-A) + A$

$= \frac{(x-a)(B-A)+A(b-A)}{b-a} = \frac{x(B-A)}{b-a} - \frac{a(B-A)}{b-a} + A$

$= x\frac{B-A}{b-a} + \frac{-aB+aA+bA-aA}{b-a}$

$$= x\frac{B-A}{b-a} + \frac{bA-aB}{b-a} \qquad \text{(A-32)}$$

A.10 SUBROUTINE *exponential*

Subroutine *exponential* generates a random sample x that is exponentially distributed with the parameter λ. The PDF of exponential distribution is

$$f(x;\lambda) = \lambda e^{-\lambda x} \qquad x \geq 0 \tag{A-33}$$

where λ is a constant. The mean and standard deviation of the exponential distribution are equal to $1/\lambda$.

The exponentially distributed random number y is generated using u, a uniformly distributed random number between 0 and 1 (Ang and Tang, 1984):

$$y = -\frac{1}{\lambda}\log(1 - u) \tag{A-34}$$

A.11 SUBROUTINE *sort*

Subroutine sort has been adopted from Press et al. (1986). It sorts a real array of a given length into an ascending order using the Heapsort algorithm. The array is replaced by its sorted rearrangement. Details of the algorithm are available in Press et al. (1986)

A.12 REFERENCES

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APPENDIX B

SUBROUTINE VERIFICATION RESULTS

B.1 VERIFICATION OF SUBROUTINES *intersection, inlength, checkin, cal_area, and segment*

Subroutines *intersection*, *inlength*, *checkin*, *cal_area*, and *segment* were verified individually by solving a simple problem described in the following section. The problem has also been solved by hand to compare with the calculated results. Figure B-1 shows four faults along with the boundary of Optional Area A. Faults 1 and 2 fall completely within the proposed repository region: in this case Area A. One end of Fault 3 intersects the area (only one end inside the area). Both ends of Fault 4 are outside the region, as shown in Figure A-1. The coordinates of both ends of the faults are provided along with fault length and length of the fault intersected by the proposed repository Area A.

Fault 1:
End 1: [171200 m, 236200 m] End 2: [171400 m, 235600 m]
Length = 632.456 m
Intersected Length = 632.456 m

Fault 2:
End 1: [171300 m, 235600 m] End 2: [171300 m, 235300 m]
Length = 300.000 m
Intersected Length = 300.000 m

Fault 3:
End 1: [170900 m, 235400 m] End 2: [171000 m, 236000 m]
Length = 608.276 m
Intersected Length = 103.852 m

Fault 4:
End 1: [171500 m, 235200 m] End 2: [171750 m, 236000 m]
Length = 838.153 m
Intersected Length = 562.013 m

Four corners of Optional Area A:
(170800 m, 236300 m), (171300 m, 236400 m), (171950 m, 235500 m), and (171300 m, 235200 m)

Figures B-2 and B-3 show Faults 3 and 4 and the segments of the region they intersect (real intersection). The following results are from the subroutines that show good agreement with the actual (hand-calculated) results.

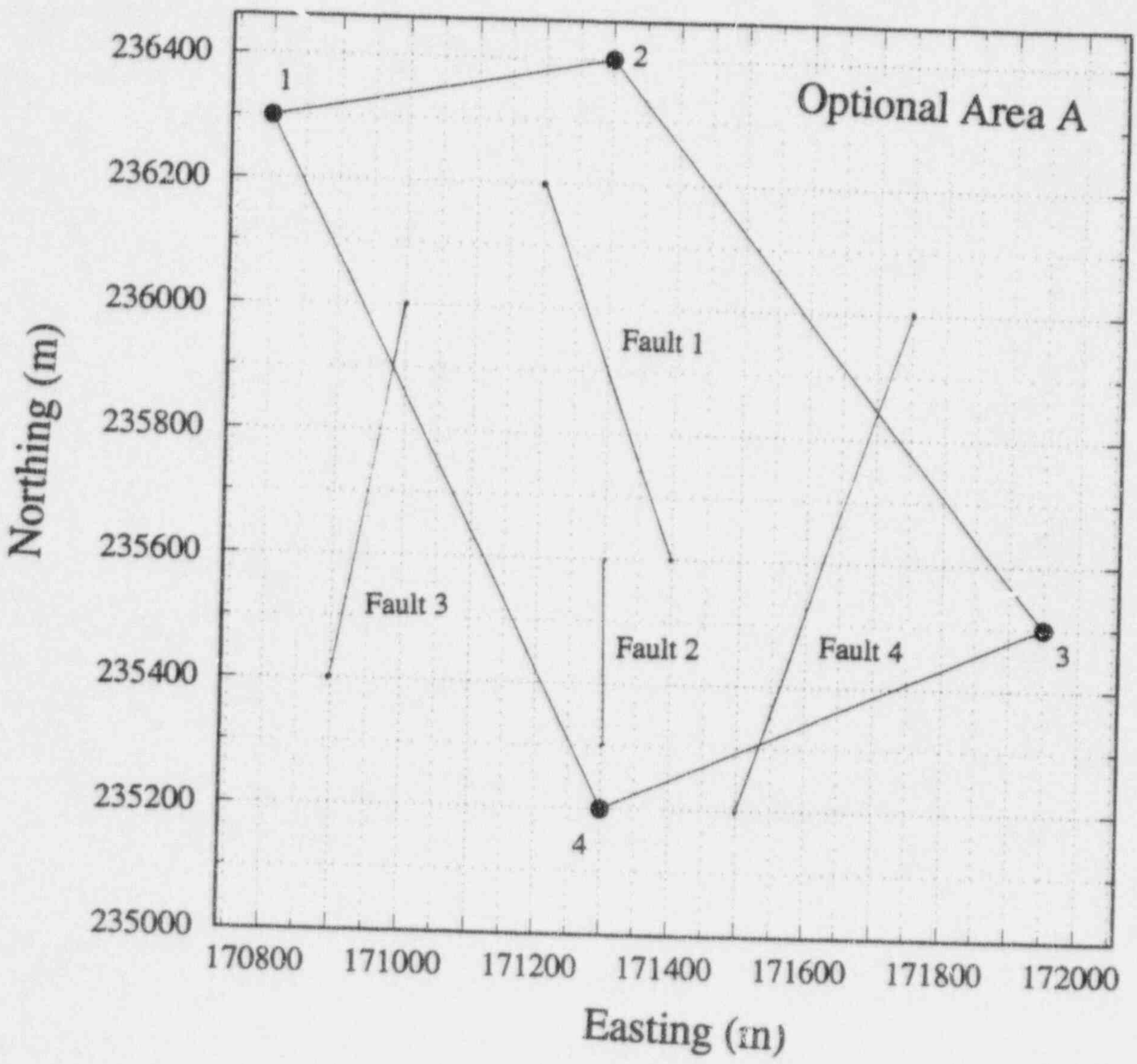

Figure B-1. Optional Area A with four fault planes used in verification of the code

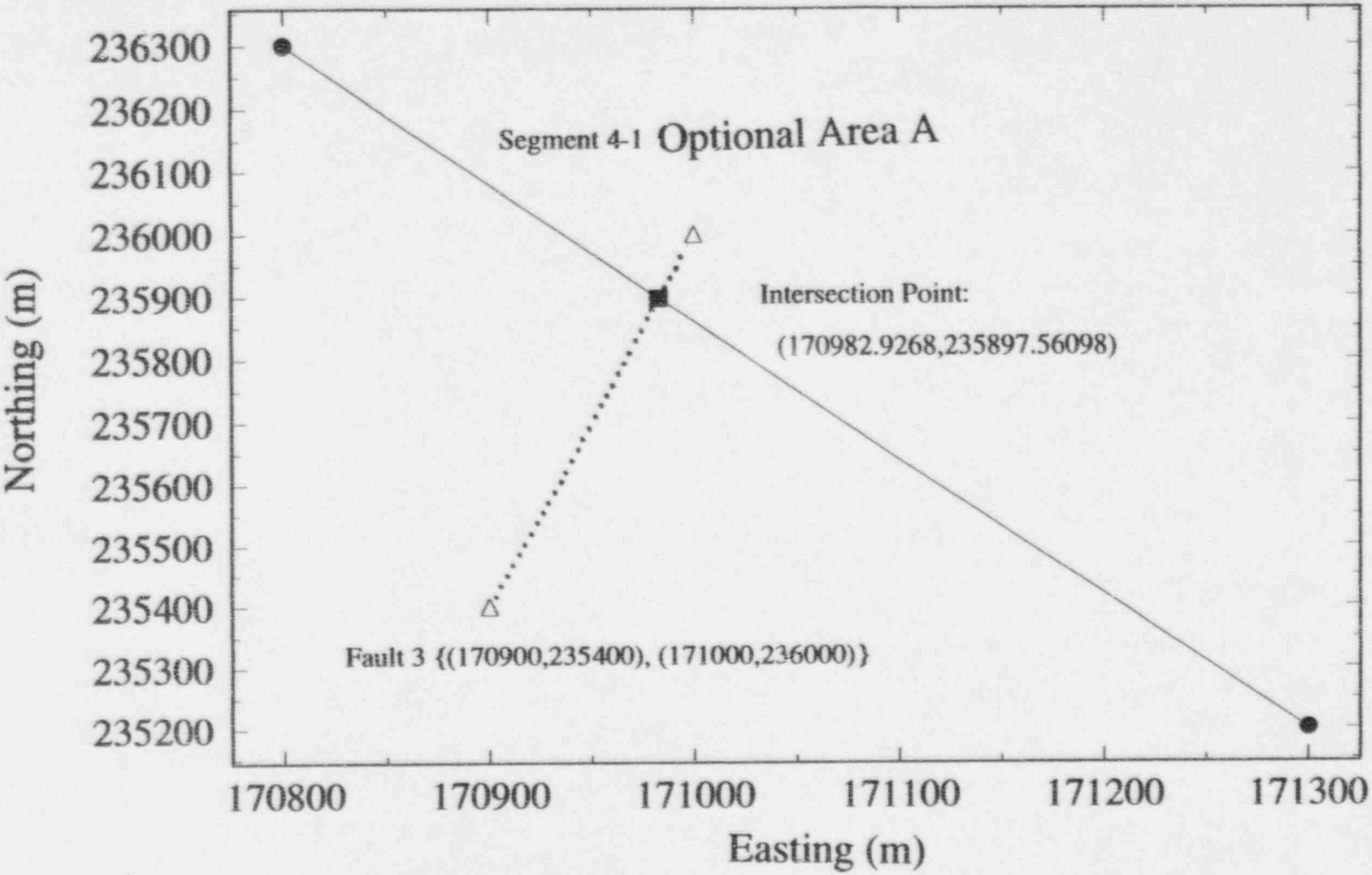

Figure B-2. Intersection point of Fault 3 and segments of Optional Area A

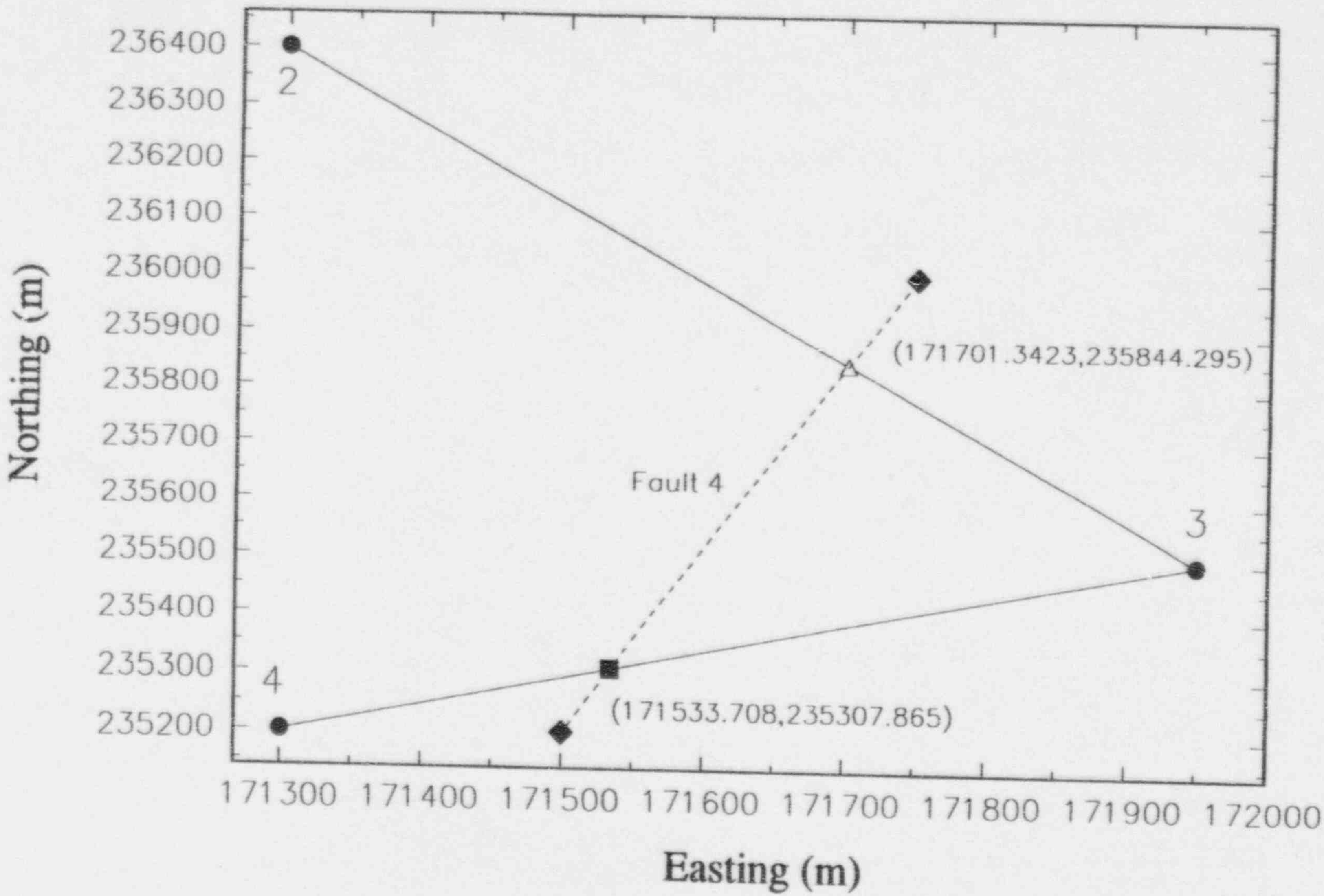

Figure B-3. Intersection points of Fault 4 and segments of Optional Area A

FAULT 1:

```
x1 of fault => 171200
y1 of fault => 236200
x2 of fault => 171400
y2 of fault => 235600
Region (PU,PL,A,B,C,D) => A

... Fault Plane ...
End 1: x = 171200.00000000 y = 236200.00000000
End 2: x = 171400.00000000 y = 235600.00000000
Region: A

x(1) = 170800.0  y(1) = 236300.0
x(2) = 171300.0  y(2) = 236400.0
x(3) = 171950.0  y(3) = 235500.0
x(4) = 171300.0  y(4) = 235200.0
x(5) = 170800.0  y(5) = 236300.0

171200.00000000    236200.00000000 falls inside the region
171400.00000000    235600.00000000 falls inside the region

Intersection Points:
Point 1: 171200.00000000    236200.00000000
Point 2: 171400.00000000    235600.00000000
Intersected length = 632.45553203368

Another run => y
```

FAULT 2:

```
x1 of fault => 171300
y1 of fault => 235600
x2 of fault => 171300
y2 of fault => 235300
Region (PU,PL,A,B,C,D) => A

... Fault Plane ...
End 1: x = 171300.00000000 y = 235600.00000000
End 2: x = 171300.00000000 y = 235300.00000000
Region: A

x(1) =   170800.0  y(1) =   236300.0
x(2) =   171300.0  y(2) =   236400.0
x(3) =   171950.0  y(3) =   235500.0
x(4) =   171300.0  y(4) =   235200.0
x(5) =   170800.0  y(5) =   236300.0

171300.00000000    235600.00000000 falls inside the region
171300.00000000    235300.00000000 falls inside the region
```

```
Intersection Points:
Point 1:      171300.00000000    235600.00000000
Point 2:      171300.00000000    235300.00000000
Intersected length = 300.00000000000

Another run => y
```

FAULT 3:

```
x1 of fault => 170900
y1 of fault => 235400
x2 of fault => 171000
y2 of fault => 236000
Region (PU,PL,A,B,C,D) => A

 ... Fault Plane ...
End 1: x = 170900.00000000 y = 235400.00000000
End 2: x = 171000.00000000 y = 236000.00000000
Region: A

x(1) = 170800.0  y(1) = 236300.0
x(2) = 171300.0  y(2) = 236400.0
x(3) = 171950.0  y(3) = 235500.0
x(4) = 171300.0  y(4) = 235200.0
x(5) = 170800.0  y(5) = 236300.0

170900.00000000    235400.00000000 falls outside the region
171000.00000000    236000.00000000 falls inside the region

In subroutine Intersection
x1 = 170800.00000000 y1 = 236300.00000000
x2 = 171300.00000000 y2 = 236400.00000000
x3 = 170900.00000000 y3 = 235400.00000000
x4 = 171000.00000000 y4 = 236000.00000000
Part 1 = -16078881000000.  Part 2 = 16128488000000.
Part 4 = -27817218000000.  Part 5 = 27885760000000.
Part 6 = -10000.0000000000  Part 7 = 300000.00000000
xi = 171058.62068966  yi = 236351.72413793

Subroutine Inlength
Data about Intersection:
Segment: 1
x1 = 170800.00000000 y1 = 236300.00000000
x2 = 171300.00000000 y2 = 236400.00000000
Intersection Point:
xi = 171058.62068966 yi = 236351.72413793
A =  356.57573453473 B =  264.85198756455 C = 246.15956272518
D = 263.74238863410 E = 509.90195135928 F =  608.27625302982

In subroutine Intersection
x1 = 171300.00000000 y1 = 236400.00000000
x2 = 171950.0000000 y2 = 235500.00000000
```

```
x3 = 170900.00000000 y3 = 235400.00000000
x4 = 171000.00000000 y4 = 236000.00000000
Part 1 = -22099812000000.  Part 2 = 22181945000000.
Part 4 =  -36235122000000.  Part 5 = 36348720000000.
Part 6 = 90000.000000000  Part 7 = 390000.00000000
xi = 171110.41666667  yi = 236662.50000000

Subroutine Inlength
Data about Intersection:
Segment: 2
x1 = 171300.00000000 y1 = 236400.00000000
x2 = 171950.00000000 y2 = 235500.00000000
Intersection Point:
xi = 171110.41666667 yi = 236662.50000000
A = 671.63836272043 B = 1279.9146157502 C = 1433.9827138467
D = 323.80254828797 E = 1110.1801655587 F = 608.27625302982

In subroutine Intersection
x1 = 171950.00000000 y1 = 235500.00000000
x2 = 171300.00000000 y2 = 235200.00000000
x3 = 170900.00000000 y3 = 235400.00000000
x4 = 171000.00000000 y4 = 236000.00000000
Part 1 = 30198825000000.  Part 2 = -30260324000000.
Part 4 = 35966766000000.  Part 5 = -36051360000000.
Part 6 = 30000.000000000  Part 7 = -390000.00000000
xi = 170830.55555556  yi = 234983.33333333

Subroutine Inlength
Data about Intersection:
Segment: 3
x1 = 171950.00000000 y1 = 235500.00000000
x2 = 171300.00000000 y2 = 235200.00000000
Intersection Point:
xi = 170830.55555556 yi = 234983.33333333
A = 1030.6903176339 B = 422.41406460403 C = 517.03242728497
D = 1232.9234804488 E = 715.89105316382 F = 608.27625302982

In subroutine Intersection
x1 = 171300.00000000 y1 = 235200.00000000
x2 = 170800.00000000 y2 = 236300.00000000
x3 = 170900.00000000 y3 = 235400.00000000
x4 = 171000.00000000 y4 = 236000.00000000
Part 1 = 24143916000000.  Part 2 = -24214019000000.
Part 4 = 27760722000000.  Part 5 = -27857440000000.
Part 6 = -110000.00000000  Part 7 = -300000.00000000
xi = 170982.92682927  yi = 235897.56097561

Subroutine Inlength
Data about Intersection:
Segment: 4
x1 = 171300.00000000 y1 = 235200.00000000
x2 = 170800.00000000 y2 = 236300.00000000
```

```
Intersection Point:
xi = 170982.92682927 yi = 235897.56097561
A = 103.852043200217 B = 504.42420982961 C = 442.06265757053
D = 766.24193978893 E = 1208.3045973595 F = 608.27625302982
Intersection is real

k = 2 xin(k) = 170982.92682927 yin(k) = 235897.56097561

Intersection Points (In subroutine segment):
Point 1: 171000.00000000    236000.00000000
Point 2: 170982.92682927    235897.56097561
Intersection Points:
Point 1: 171000.00000000    236000.00000000
Point 2: 170982.92682927    235897.56097561
Intersected length = 103.852043200217

Another run => y
```

FAULT 4:

```
x1 of fault => 171500
y1 of fault => 235200
x2 of fault => 171750
y2 of fault => 236000
Region (PU,PL,A,B,C,D) => A

... Fault Plane ...
End 1: x = 171500.00000000 y = 235200.00000000
End 2: x = 171750.00000000 y = 236000.00000000
Region: A

x(1) = 170800.0  y(1) = 236300.0
x(2) = 171300.0  y(2) = 236400.0
x(3) = 171950.0  y(3) = 235500.0
x(4) = 171300.0  y(4) = 235200.0
x(5) = 170800.0  y(5) = 236300.0

171500.00000000    235200.00000000 falls outside the region
171750.00000000    236000.00000000 falls outside the region

In subroutine Intersection
x1 = 170800.00000000 y1 = 236300.00000000
x2 = 171300.00000000 y2 = 236400.00000000
x3 = 171500.00000000 y3 = 235200.00000000
x4 = 171750.00000000 y4 = 236000.00000000
Part 1 = -10078252500000.0  Part 2 = 10142720000000.0
Part 4 = -27811224000000.  Part 5 = 27899920000000.
Part 6 = -25000.000000000  Part 7 = 400000.00000000
xi = 171913.33333333  yi = 236522.66666667

Subroutine Inlength
Data about Intersection:
```

```
Segment: 1
x1 = 170800.00000000 y1 = 236300.00000000
x2 = 171300.00000000 y2 = 236400.00000000
Intersection Point:
xi = 171913.33333333 yi = 236522.66666667
A = 547.59311739851 B = 1385.7458481105 C = 625.47972700072
D = 1135.3816783600 E = 509.90195135928 F = 838.15273071201

In subroutine Intersection
x1 = 171300.00000000 y1 = 236400.00000000
x2 = 171950.00000000 y2 = 235500.00000000
x3 = 171500.00000000 y3 = 235200.00000000
x4 = 171750.00000000 y4 = 236000.00000000
Part 1 = -16094895000000.  Part 2 = 16222812500000.
Part 4 = -36045576000000.  Part 5 = 36221280000000.
Part 6 = 225000.00000000  Part 7 = 520000.00000000
xi =  171701.34228188  yi = 235844.29530201

Subroutine Inlength
Data about Intersection:
Segment: 2
x1 = 171300.00000000 y1 =  236400.00000000
x2 = 171950.00000000 y2 =  235500.00000000
Intersection Point:
xi = 171701.34228188 yi = 235844.29530201
A = 163.13039725267 B = 675.02233345934 C = 424.69979487818
D = 685.48037068055 E = 1110.1801655587 F = 838.15273071201
Intersection is real

k = 1 xin(k) = 171701.34228188 yin(k) = 235844.29530201

In subroutine Intersection
x1 = 171950.00000000 y1 = 235500.00000000
x2 = 171300.00000000 y2 = 235200.00000000
x3 = 171500.00000000 y3 = 235200.00000000
x4 = 171750.00000000 y4 = 236000.00000000
Part 1 = 36342427500000.  Part 2 = -36418760000000.
Part 4 = 35989128000000.  Part 5 = -36093840000000.
Part 6 = 75000.000000000  Part 7 = -520000.00000000
xi = 171533.70786517  yi = 235307.86516854

Subroutine Inlength
Data about Intersection:
Segment: 3
x1 = 171950.00000000 y1 = 235500.00000000
x2 = 171300.00000000 y2 = 235200.00000000
Intersection Point:
xi = 171533.70786517 yi = 235307.86516854
A = 725.14337376209 B = 113.00935694992 C = 257.39903035103
D = 458.49202281278 E = 715.89105316382 F = 838.15273071201
Intersection is real
```

```
k = 2 xin(k) = 171533.70786517 yin(k) = 235307.86516854

In subroutine Intersection
x1 = 171300.00000000 y1 = 235200.00000000
x2 = 170800.00000000 y2 = 236300.00000000
x3 = 171500.00000000 y3 = 235200.00000000
x4 = 171750.00000000 y4 = 236000.00000000
Part 1 = 30240840000000.  Part 2 = -30356547500000.
Part 4 = 27543096000000.  Part 5 = -27701680000000.
Part 6 = -275000.00000000  Part 7 = -400000.00000000
xi = 171418.51851852  yi = 234939.25925926

Subroutine Inlength
Data about Intersection:
Segment: 4
x1 = 171300.00000000 y1 = 235200.00000000
x2 = 170800.00000000 y2 = 236300.00000000
Intersection Point:
xi = 171418.51851852 yi = 234939.25925926
A = 1111.3284355367 B = 273.17570482465 C = 1494.7175389558
D = 286.41294159630 E = 1208.3045973595 F = 838.15273071201
Intersection Points:
Point 1: 171701.34228188    235844.29530201
Point 2: 171533.70786517    235307.86516854

Intersected length = 562.01297650942
Another run => n
```

B.2 VERIFICATION OF SUBROUTINE *gauss*

Subroutine *gauss* has been developed following the mathematical guideline given in appendix A. section A.7, and adopting the routine provided in Ghosh and Kulatilake (1987). A set of 500 normally distributed random numbers with a probability 90 percent falling between -1 and 1 was generated. The statistics of the generated numbers are

	Input Data	Normal Distribution
Minimum	-1.584767	
Maximum	1.966892	
Mode	-0.128587	3.743165e-3
Mean	3.743165e-3	3.743165e-3
Standard Deviation	0.586337	0.586337
Variance	0.343791	0.343791
Skewness	0.119546	0.0
Kurtosis	3.05641	3.0
Best Fit Results		
Chi-Square Test	57.136959	
Kolmogorov-Smirnov Test	0.023695	
Anderson-Darling Test	0.231722	

Figure B-4 shows the histogram of random numbers with a fitted normal distribution with mean and standard deviation equal to 0.0037 and 0.5863. They compare very well with the population mean and standard deviation equal to 0.0 and 0.6079. The skewness and kurtosis of the data set indicate normality. Figure B-5 shows the cumulative distribution of these numbers. The numbers were tested for normality. The data set passes Chi-Square, Kolmogorov-Smirnov, and Anderson-Darling tests for goodness-of-fit with $\alpha = 0.05$. As expected, with a larger set of random numbers, the sample mean and standard deviation become closer to the population mean and standard deviation. This has been tested with different data sets. For example, when the number of generated random numbers is 1,000, the sample mean and standard deviation are 0.0012 and 0.5987. The skewness and kurtosis of the generated data set have improved. As before, the generated data set can be taken as normal as shown by the results of Chi-Square, Kolmogorov-Smirnov, and Anderson-Darling tests with $\alpha = 0.05$.

	Input Data	**Normal Distribution**
Minimum	-2.051897	
Maximum	1.859709	
Mode	-0.056978	1.249021e-3
Mean	1.249021e-3	1.249021e-3
Standard Deviation	0.598718	0.598718
Variance	0.358463	0.358463
Skewness	-0.012203	0.0
Kurtosis	2.969442	3.0
Best Fit Results		
Chi-Square Test	37.568098	
Kolmogorov-Smirnov Test	8.731377e-3	
Anderson-Darling Test	0.077632	

B.3 VERIFICATION OF SUBROUTINE *betad*

Subroutine *betad* has been developed following the mathematical guideline given in appendix A.8, with any acceptable values of α and β. In the file *fault.inc*, the values of α and β are fixed at 1.5 and 3.0, as given in Stirewalt et al. (1995). A set of 1,000 random numbers between 0 and 1 was generated. Sample statistics show that sample α and β are 1.50 and 3.11. Sample mean and variance are 0.3279 and 0.0390, which compare very well with population mean of 0.3333 and population variance of 0.0404. The set of random numbers were fitted with Beta distribution. The statistics are provided following this paragraph. The data set is Beta distributed as shown by the Chi-Square, Kolmogorov-Smirnov, and Anderson-Darling tests with $\alpha = 0.05$. Figure B-6 shows the histogram of random numbers with Beta distribution overlay.

	Input Data	**Beta Distribution**
Minimum	2.91705e-3	
Maximum	0.92994	
Mode	0.206862	0.191073
Mean	0.327924	0.325007
Standard Deviation	0.197694	0.197694

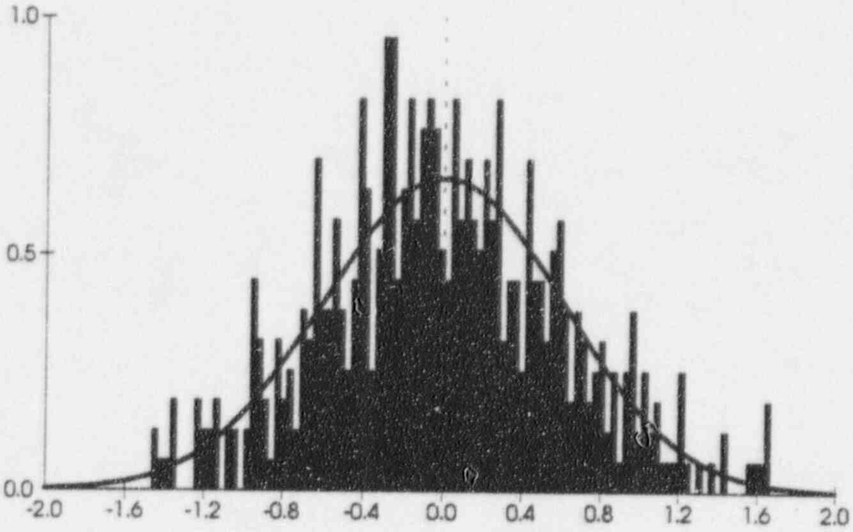

Figure B-4. Histogram of random numbers generated by *gauss* having normal distribution along with the fitted normal distribution curve

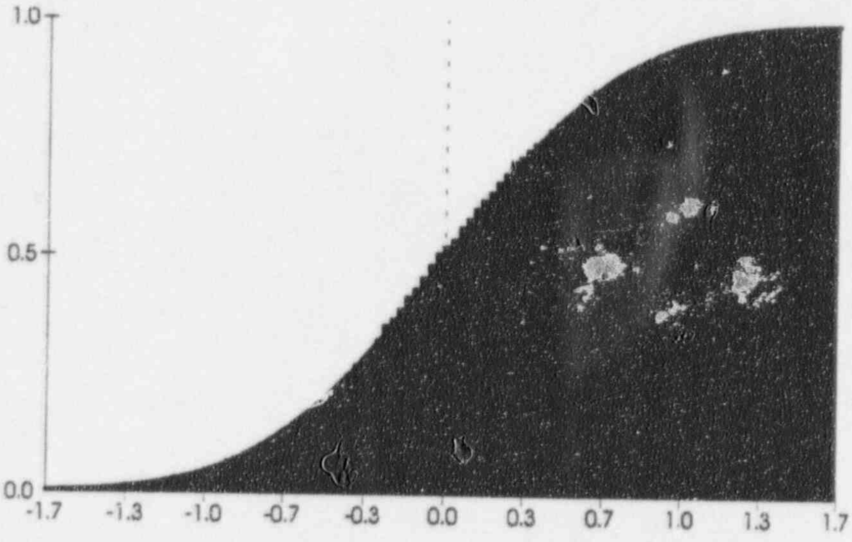

Figure B-5. Cumulative distribution of random numbers generated by *gauss* having normal distribution

Variance	0.039083	0.039083
Skewness	0.485402	0.535402
Kurtosis	2.421904	3.38095

Best Fit Results	
Chi-Square Test	13.767742
Kolmogorov-Smirnov Test	0.013351
Anderson-Darling Test	0.258163

B.4 VERIFICATION OF SUBROUTINE *exponential*

Random numbers following the exponential distribution with the parameter λ are simulated using the subroutine *exponential*. The equation used in the subroutine *exponential* is given in Appendix A, section A.10. A set of 1,000 random numbers with λ equal to 10 (mean and standard deviation equal to 0.1) were generated. The statistics of the generated numbers are

	Input Data	Exponential Distribution
Minimum	1.85602e-4	
Maximum	0.62722	
Mode	9.59108e-3	
Mean	0.09888	0.09888
Standard Deviation	0.095711	0.09888
Variance	9.16051e-3	9.77780e-3
Skewness	1.75468	2.0
Kurtosis	6.97331	9.0

Best Fit Results	
Chi-Square Test	113.74484
Kolmogorov-Smirnov Test	0.02051
Anderson-Darling Test	0.31278

Figure B-7 shows the histogram of generated random numbers with a fitted exponential distribution. The mean and standard deviation compare very well with the given λ. Goodness-of-fit analysis with Chi-Square, Kolmogorov-Smirnov, and Anderson-Darling tests show that the data set is exponential with $\alpha = 0.05$.

B.5 VERIFICATION OF SUBROUTINE *check_disrupt*

Subroutine *check_disrupt* has been verified by developing a small test program that basically supplies the values of all input variables of the subroutine and prints the output on the screen. These results were checked using hand calculation.

The following is typical output for verification run of the subroutine *check_disrupt*. For this particular run, a fault having a length of 1,000 m within the given repository was assumed. The fault had a width of 10 m. Each waste package (WP) contained 10 MTU of waste. WPs were emplaced at an areal

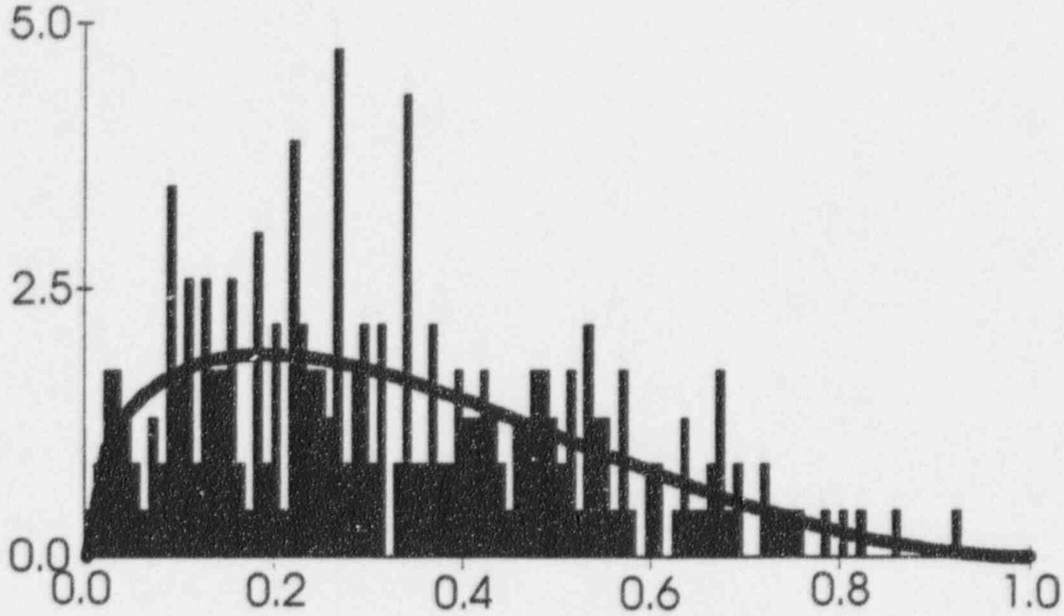

Figure B-6. Histogram of random numbers generated by *betad* having beta distribution

mass loading of 100 MTU/acre. There is no standoff distance. The area affected should be equal to 10,000 m^2 or 2.47097 acre. Number of WPs disrupted should be equal to 25 or 0.36 percent of all WPs.

```
                    length => 1000

                     width => 10

                  standoff => 0

                       AML => 100

                    MTU_wp => 10
Number of waste packages disrupted = 25
Percent of waste packages disrupted = 0.35709184408188 percent
Area disrupted =      2.4709700000000 acre
```

B.6 VERIFICATION OF SUBROUTINE *sort*

Subroutine *sort* of Press et al. (1986) has been verified using a small test program that takes the values of all elements in an array and calls the subroutine *sort* to rearrange them in an ascending order. *Sort* then prints the rearranged values on the screen. This is a typical example of the verification run:

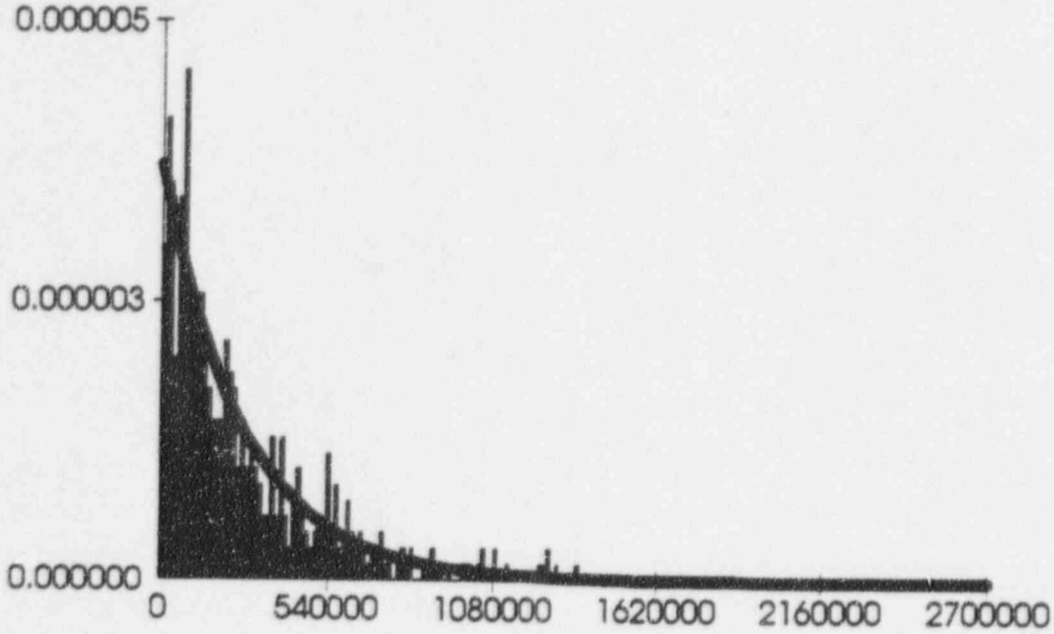

Figure B-7. Histogram of random numbers generated by exponential distribution

```
                              number of data => 20
 Data  1 => 1
 Data  2 => 4
 Data  3 => 5
 Data  4 => 6
 Data  5 => 7
 Data  6 => 8
 Data  7 => 2
 Data  8 => 3
 Data  9 => 20
 Data 10 => 19
 Data 11 => 18
 Data 12 => 10
 Data 13 => 11
 Data 14 => 12
 Data 15 => 17
 Data 16 => 16
 Data 17 => 13
 Data 18 => 15
 Data 19 => 14
 Data 20 => 0
   0.
      1.0000000000000
      2.0000000000000
      3.0000000000000
      4.0000000000000
      5.0000000000000
      6.0000000000000
      7.0000000000000
      8.0000000000000
     10.0000000000000
```

```
11.000000000000
12.000000000000
13.000000000000
14.000000000000
15.000000000000
16.000000000000
17.000000000000
18.000000000000
19.000000000000
20.000000000000
```

B.7 REFERENCES

Ghosh, A., and P.H.S.W. Kulatilake. 1987. A FORTRAN program for generation of multivariate normally distributed random numbers. *Computers & Geosciences* 13(3): 221–233.

Press, W.H., B.P. Flannery, S.A. Tekolsky, and W.T. Vetterling. 1986. *Numerical Recipes in FORTRAN*. Cambridge, United Kingdom: Cambridge University Press.

Stirewalt, G.L., S.M. McDuffie, R.D. Manteufel, and R.W. Janetzke. 1995. *Technical Specifications for a Fault Displacement Module*. Report to Nuclear Regulatory Commission. San Antonio, TX: Center for Nuclear Waste Regulatory Analyses.

CNWRA 97-002

FAULTING VERSION 1.0 – A CODE FOR SIMULATION OF DIRECT FAULT DISRUPTION

TECHNICAL DESCRIPTION AND USER'S GUIDE