TECHNICAL SPECIFICATIONS FOR A FAULT DISPLACEMENT MODULE

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ABSTRACT

The FAULTING consequence module described in this report generates a faulting event in a simulation area measuring 50×50 km centered around the potential repository block at Yucca Mountain, Nevada. It was created at the Center for Nuclear Waste Regulatory Analyses (CNWRA) for evaluation of faulting as a disruptive event in Phase 3 of the Nuclear Regulatory Commission (NRC) Iterative Performance Assessment (IPA) activity. Taking into account published field data for timing and amount of both largest credible and cumulative types of displacement, the module provides a framework for determining if primary fault displacement (i.e., displacement along the main fault trace rather than along associated secondary fractures) in the repository block could induce waste package disruption, the timing of that disruption (if it occurs), and the number of waste packages disrupted. Therefore, it is anticipated that the FAULTING module will permit 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 repository block.

Fault displacement is generated in the FAULTING module along an assumed, unknown, randomly located fault zone inside the simulation area. These unknown fault zones include those not distinguished or adequately characterized, as well as new faults which may develop during the 10,000-yr regulatory time frame of interest. Although the time frame considered is 10,000 yr, the approach is amenable to analysis over longer periods should the need arise. Strike direction is determined as either northwest or northeast parallel to the fault trace orientations observed in the field at and near Yucca Mountain. Whether the fault intersects the potential repository depends on location and orientation of the fault in the simulation area and total fault trace length. Whether waste packages are disrupted is dependent upon amount of displacement exceeding a threshold value which is governed by repository and waste package design and waste package emplacement geometry. If the threshold displacement is exceeded by either largest credible displacement in a single event or by smaller cumulative displacements with time through multiple events, then number and locations of waste packages intersected and disrupted can be calculated based on length of intersection of the fault zone with the repository, repository design, and waste package emplacement geometry.

The following variables for defining the fault zone are chosen randomly from ranges of values, based on published field data, which are represented as probability distribution functions (PDFs): location, trace orientation, geometry, activity, number and time and amount of largest credible displacement faulting events, and amount and time of cumulative displacements. It is assumed that the unknown fault zones can possess attributes similar to those of the Ghost Dance and Sundance faults, which have been mapped in the repository block. The fault zone is assigned a randomly selected width, and displacement in the zone is considered along both single and multiple slip surfaces. It is assumed that variation in dip of the fault has little influence on number of waste packages disrupted, considering horizontal waste package emplacement, because faults are observed to dip steeply (i.e., between 60 and 90°) at the surface and similar dips are thought to occur at repository level. However, the module permits consideration of faults with dips less than 60° as well. If waste package disruption occurs as a result of either a largest credible displacement event or cumulative displacement, the timing of that disruption is relayed to the SOurce TErm Code (SOTEC) for calculation of radionuclide release.

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QUALITY OF DATA AND SOFTWARE

DATA: Data used for description of variables associated with defining faulting events in the FAULTING consequence module 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). Field data incorporated into the expert judgment elicitation on earthquakes and tectonics issues conducted by the Electric Power Research Institute (EPRI)—data which were derived from field investigations and published by EPRI in the elicitation report (Electric Power Research Institute, 1993)—provided a very important source of information as well. Data from the EPRI (1993) report were drawn from information provided by those scientists on the elicitation panel who were most familiar with field relationships at Yucca Mountain. 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 which define faulting events at Yucca Mountain. The later data extracted from Spengler et al. (1994) and the EPRI (1993) report, selected for use in development of the FAULTING consequence module because of their pertinence for describing faulting at Yucca Mountain, were collected either by U.S. Department of Energy (DOE)-funded geologists under established QA procedures or by non-DOE scientists using standard methods. The module development effort relied mainly on the data presented in the EPRI (1993) report rather than the 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 module. As new data become available from the DOE site characterization program, they can be incorporated to refine the variables associated with definition of faulting events in the FAULTING consequence module.

SOFTWARE: No software was used for describing the variables associated with defining faulting events in the FAULTING consequence module. Any software developed for analyzing consequences of fault displacement in the repository block will be qualified appropriately in the final report containing the model and code description and software user guide.

1 INTRODUCTION

1.1 REGULATORY BASIS FOR THE FAULTING CONSEQUENCE MODULE

Performance assessment (PA) analyses will play an important role in determining if the geological repository system being designed for possible construction at Yucca Mountain, Nevada, by the U.S. Department of Energy (DOE) will satisfy the applicable regulatory standards specified in 10 CFR Part 60. This determination is to be accomplished, after completion of adequate site characterization efforts by DOE, by comparing estimated values of the regulatory performance measures with minimum values for the same performance measures as specified in the regulations. Hence, PA models are being designed and developed for use in prediction of future repository performance. Two PAs for Yucca Mountain have been completed to date. The first, Iterative Performance Assessment (IPA) Phase 1 (Nuclear Regulatory Commission, 1992), was conducted to demonstrate the Nuclear Regulatory Commission (NRC) PA methodology. The second PA, IPA Phase 2 (Nuclear Regulatory Commission, 1995), broadened the scope and included more site-specific models and data. Scenarios are a key component of these and future PAs which have motivated development of consequence modules as well as methods for screening scenarios (Bonano and Baca, 1994).

The Total-System Performance Assessment (TPA) code has been developed to assist the NRC with analyzing information DOE will provide for proving compliance with the applicable regulatory standards of 10 CFR Part 60. The TPA code is comprised of a set of independent computational units, or consequence modules, that provide computational algorithms for estimating future repository performance (Sagar and Janetzke, 1993). Execution of the independent consequence modules contained in the TPA code is controlled by an executive module (EXEC) which assures the consequence modules are executed in the proper sequence and appropriate values of the common parameters are passed to the consequence modules (Sagar and Janetzke, 1993). The new FAULTING consequence module discussed in this report is being designed for incorporation into the TPA code during IPA Phase 3.

1.2 PURPOSE OF THE FAULTING CONSEQUENCE MODULE

Scenarios involving faulting are important for consideration in assessment of performance of the potential repository site at Yucca Mountain because a series of northeast-trending, west-dipping, normal faults or fault zones both occur in the repository block and bound the block to the east and west (Scott and Bonk, 1984; Scott, 1990; Spengler et al., 1994). Faults in the northeast-trending fault system in the vicinity of Yucca Mountain 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 waste packages 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 unknown fault zones (including faults either not distinguished or adequately characterized, and possible new faults). Considering the complex nature of faults mapped in the repository block (Spengler et al., 1994) relative to possible width of the 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 homogeneous volcanic units. If a fault zone penetrated in subsurface excavations were not adequately characterized, then the importance of setback from the zone may not be recognized. It is also uncertain whether new faults may develop over the 10,000-yr regulatory time frame under consideration. Therefore, it is deemed pertinent to develop a module to evaluate potential consequences of fault displacement in the repository block.

The FAULTING consequence module is being developed to evaluate potential consequences of direct mechanical disruption of waste packages due to fault displacement in the potential repository block. Potential effects of seismic shaking are not addressed in the module at this time. Also, the module does not include any indirect effects of faulting (e.g., possible effects of fault displacement on groundwater hydrology and flow pathways or possible long-term effects of fault displacement on waste package weakening or corrosion). In addition, the existing module does not presently distinguish between the different tectonic models which could be used to drive the faulting process. Rather, faulting is treated as occurring in a block containing the repository without regard for deeper-seated tectonic mechanisms which cause faulting to occur. It is possible that alternative tectonic models can be factored in to consider distributed faulted and linked displacements at a later date. For example, a listric-detachment fault system is one tectonic model that has been proposed for the Yucca Mountain region (Scott, 1990; Young et al., 1992) that could logically result in linked displacements. As the module is presently configured, planar decoupled faults are considered and slip is assumed to occur along both single and multiple slip surfaces within the fault zone. As designed, the module will permit an independent assessment of information provided by DOE on fault displacement hazards and potential effects of fault displacement in the repository block. It is anticipated that this type of information will be submitted by DOE in FY98 to support its determination of technical site suitability (U.S. Department of Energy, 1994). Descriptions of the concepts and data upon which the FAULTING consequence module is based are presented in Chapter 2.

2 TECHNICAL DESIGN OF THE FAULT DISPLACEMENT CONSEQUENCE MODULE

2.1 GENERAL CONCEPTS AND BASIS FOR TECHNICAL DESIGN OF THE MODULE

The basic framework for analyzing fault displacement in the repository block is considered to include both northwest- and northeast-trending primary fault zones which are assumed to be presently unknown and randomly located in a simulation area around the repository. The unknown fault zones are assumed to have geometries and displacements comparable to those of the northeast- and northwest-trending faults already defined in the repository block (i.e., the Ghost Dance and Sundance faults) by Spengler et al. (1994). These unknown fault zones ideally can include those not distinguished or adequately characterized and faults which may develop during the 10,000-yr time frame of regulatory interest. Although some parts of the same data set were used both to drive the elicitation conducted by the Electric Power Research Institute (EPRI) on earthquakes and tectonics (Electric Power Research Institute, 1993) and to define certain variables for faulting events for the FAULTING consequence module, the approach taken in development of the FAULTING module for assessing fault displacement differs from that undertaken by EPRI (1993). Unknown primary faults were not considered in the EPRI (1993) elicitation analysis. Potential effects from both the largest credible fault displacement and cumulative fault displacements are being considered, whereas the EPRI (1993) analysis did not take into account cumulative slip. This approach was chosen to make it possible to analyze the potential effects of displacement along such structures, as well as to set up a framework in which potential hydrologic effects of faulting and long-term effects of fault displacement on waste package corrosion and weakening could be assessed at a later time when appropriate data become available. One goal of the module construction effort is to formulate a means of providing an independent assessment of fault displacement hazards and potential consequences of fault displacement in the repository block, and use of the same database in an alternative approach different from that of EPRI (1993) makes it possible to conduct a useful comparative assessment.

The sequence for consideration of variables in development of the FAULTING consequence module is illustrated in the flow diagram of Figure 2-1. The logic diagrams for description of variables are illustrated and discussed in Section 2.2 to define the detailed technical design basis and assumptions involved in development of the FAULTING consequence module. Outside of and prior to execution of the FAULTING consequence module, the EXEC module of the TPA code will determine how frequently this new module is to be executed, taking into account the likelihood of a randomly generated fault in the simulation area intersecting the potential repository.

2.2 DETAILED TECHNICAL DESIGN BASIS AND ASSUMPTIONS

Implementation of the module in IPA Phase 3 analyses will be based on field data for consideration of fault geometry and attributes of potential faulting events in the repository block—events which may result in intersection of a fault with waste packages and consequent release of radionuclides from damaged packages. The following variables, presented in the sequence in which they should be addressed in the module (Figure 2-1), are considered to be those essential and sufficient for describing faults and faulting events in the repository block:

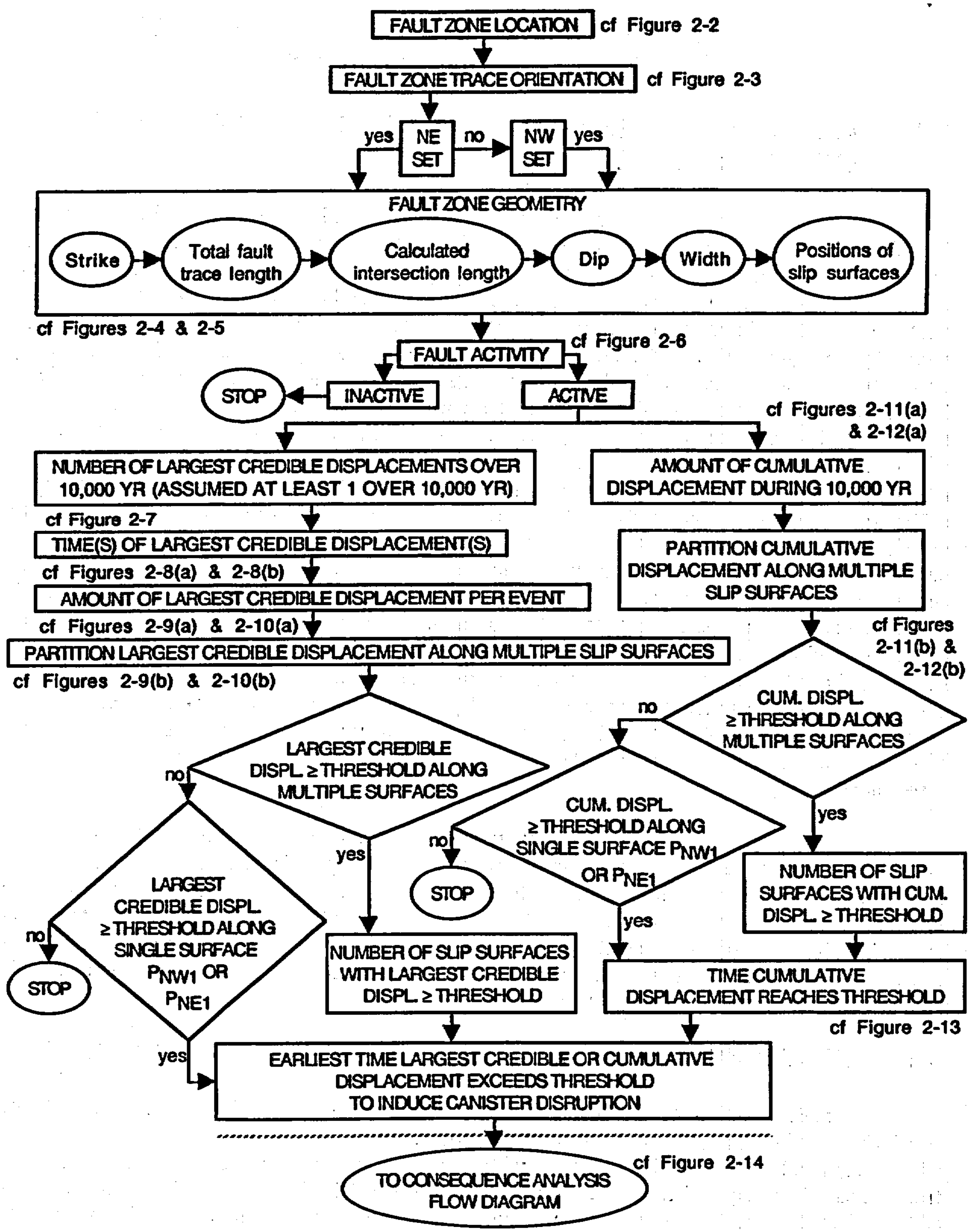


Figure 2-1. Flow diagram illustrating sequential steps for consideration of variables to describe faulting events in IPA Phase 3

- Fault zone location
- Fault zone trace orientation (northeast or northwest)
- Fault zone geometry (i.e., strike, total trace length, intersection length, dip, width, and positions of 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 cumulative displacement exceeds threshold displacement

Because field data which provide the information base for the variables may be incomplete, uncertainties may exist in the variables which render it feasible to represent certain of them as probability distributions. Additional information on characteristics of faulting in the repository block which may come to light as site characterization proceeds will be used to refine the variables as appropriate.

2.2.1 Fault Zone Location

Random sampling of values from uniform probability distribution functions (PDFs) will be used to locate the fault zone within the simulation area by determining (x,y) coordinates of the midpoint of the zone. Figure 2-2 illustrates the logic diagram for describing the fault zone location variable. (The fault will be extended from its midpoint equally in both directions along the strike of the fault based on total fault length, l_t, one of the fault zone geometry variables discussed in Section 2.2.3.) The fault is considered at repository level for analysis in the FAULTING consequence module and not at the ground surface where fault locations are frequently identified in the field. A 50×50-km simulation area around the repository will be considered with the repository footprint forming the boundary within which waste package disruption directly due to fault displacement can occur. This simulation area was selected, in part, to make the area used for the FAULTING module compatible with that being considered for use in the VOLCANO module by Center for Nuclear Waste Regulatory Analyses (CNWRA) volcanologists.[1]

This approach for location of faults in the repository block assures suitable assessment of potential unknown faults with orientations similar to those for the known Ghost Dance (northeast-striking) and Sundance (northwest-striking) faults in the Yucca Mountain area which may be encountered in the repository block as site characterization proceeds. The unknown fault zones can include those not distinguished or adequately characterized, as well as new faults which may develop during the 10,000-yr time frame of regulatory interest. Since the locations of the Ghost Dance and Sundance faults are known, it is assumed that efforts will be made by DOE to apply a set-back distance for these faults. Thus, the greatest potential hazard lies in fault zones which remain to be detected in the repository block. The Ghost Dance and Sundance faults can also be analyzed using the FAULTING consequence module, if desired, to determine possible effects of slip on these two faults if no set-back distance was implemented.

[1] Connor, C. Personal communication to S. McDuffie, RE: Acceptable size of simulation area for the VOLCANO consequence module. March, 1995.

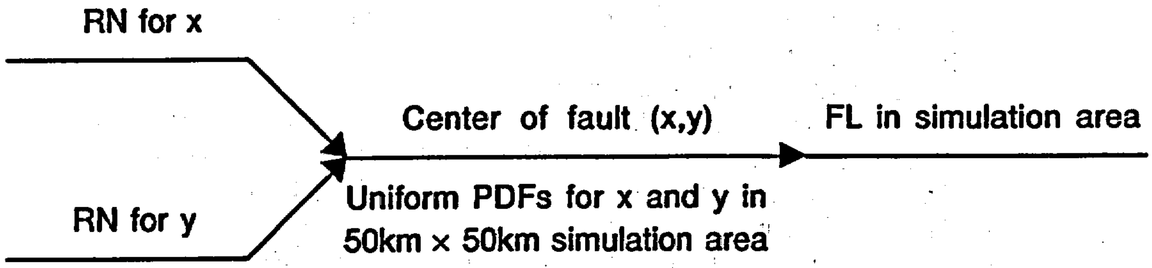


Figure 2-2. Logic diagram summarizing the fault zone location variable (FL) for NW and NE fault sets where RN=Random Number and PDF=Probability Distribution Function

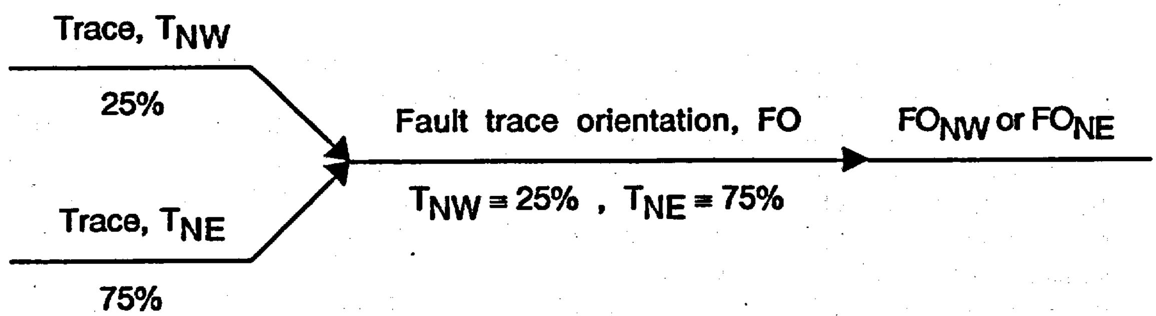


Figure 2-3. Logic diagram summarizing the fault zone trace orientation variable (FO_{NW} or FO_{NE}) for NW or NE fault sets

2.2.2 Fault Zone Trace Orientation

Whether a northeast- or northwest-trending fault trace direction is to be encountered will be determined in the module by considering northeast faults to occur 75 percent of the time, and northwest faults 25 percent of the time. That is, northeast-striking faults are considered to be three times more numerous than northwest faults in the repository area. The distribution of faults shown on the geologic map of the repository area by Scott and Bonk (1984) suggests this weighting relationship. Furthermore, slip tendency analysis (Morris et al., 1994; Ferrill et al., 1995), a new technique for assessing the tendency of a surface to experience displacement in response to a given stress state, supports the concept that northeast-trending faults are most likely to develop in the present stress field. The weighting, however, can be changed if later detailed mapping indicates a different relationship should be used. Figure 2-3 shows the logic diagram for describing this variable.

2.2.3 Fault Zone Geometry

Fault geometry (i.e., strike, total trace length, intersection length, dip, width, and positions of slip surfaces) will be determined as indicated in the following paragraphs. Figures 2-4 and 2-5 are logic diagrams summarizing description of this variable.

Strike—Strike of the fault will be determined by random sampling of values from normal PDFs which take into account the most probable fault trends, as indicated by field evidence, for the two primary fault sets mapped by Scott and Bonk (1984) in the Yucca Mountain area (i.e., N25-40W for the northwest-trending set of faults, and N25E-N5W for the northeast set). These ranges for strike orientation will be represented in the PDFs such that 90 percent of the faults lie within these ranges, an approach which allows for consideration in the module of lower-probability faults having other orientations. In the PA codes to be used, 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 module to lie most probably between 115 and 130° for the northwest-trending set (i.e., N25-40W faults), and between 65 and 95° for the northeast-trending set (i.e., N25E-N5W faults).

Total Fault Trace Length and Intersection Length—Based on lengths of faults mapped by Scott and Bonk (1984) in the potential repository area, total fault trace length, l_t, may vary between 3 and 12 km for the northeast-trending fault set and between 2 and 10 km for the northwest set. Total fault trace length will be determined by random sampling of values from uniform PDFs, with the horizontal length of intersection of the fault with the repository, l_i, calculated by the software algorithm after total fault trace length is determined. Fault zones are centered on a midpoint designated by the (x,y) coordinates discussed under the fault zone location variable (Section 2.2.1) and extended from this midpoint equally in both directions along the strike direction of the fault based on total fault trace length, l_t. Faults which extend outside the 50×50-km simulation area are truncated at the boundary of that area. Many faults selected by the random sampling location process will not intersect the repository area. That is, intersection length can vary from zero to a maximum length dictated by the maximum dimension of the repository footprint in either a northwest or northeast direction parallel to the two primary fault sets. Therefore, l_{iNW} may vary between 0 and 2.4 km while l_{iNE} may vary between 0 and 3.8 km. It should be noted that the length of the northeast-trending Ghost Dance fault in the repository block is about 2.5 km based on the fault trace as shown on the geologic map of Scott and Bonk (1984). Fault traces longer than that are possible if the fault is positioned properly relative to the repository footprint. It is anticipated that the maximum fault intersection length possible will be one case considered for each of the two fault sets.

Dip—Dip angle (θ) of the fault will be determined by random sampling of values from normal PDFs which take into account the most probable dip ranges, as indicated by field evidence, for the two primary fault sets mapped by Scott and Bonk (1984) at Yucca Mountain (i.e., between 80NW and 80°NE for the northwest set and between 60W and 90° for the northeast set). These ranges in fault dip will be represented in the PDFs such that 90 percent of the faults have dips in these ranges, an approach which allows for consideration in the module of lower-probability faults having other dips. However, it is not considered very likely that low-angle faults either presently occur or will develop at the repository horizon level. The fault is analyzed at repository level rather than at the ground surface and there is assumed to be no variation in dip between the surface and the repository horizon. If steep (i.e, between

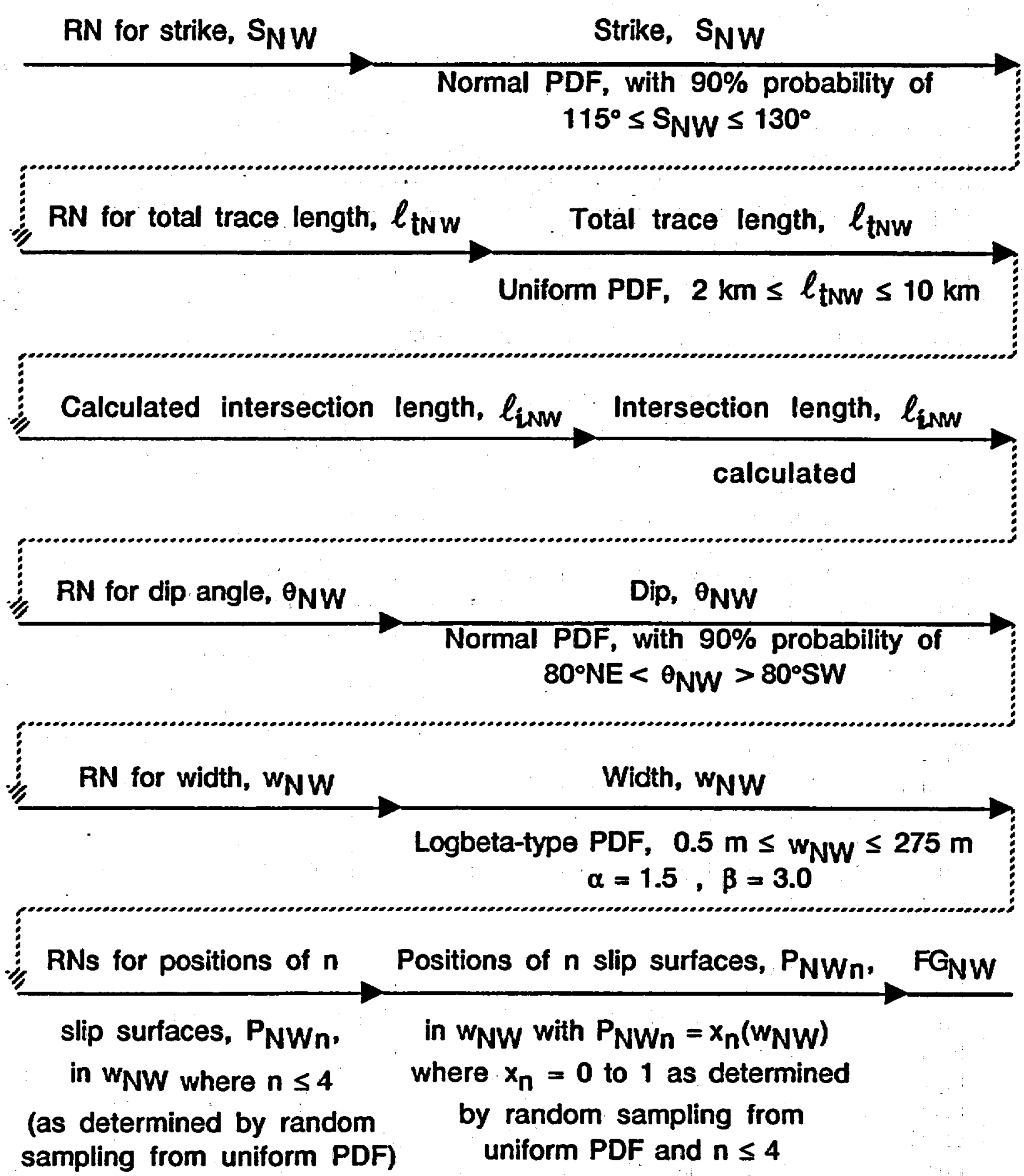


Figure 2-4. Logic diagram summarizing the fault zone geometry variable (FG_{NW}) for the NW fault set, where RN=Random Number and PDF=Probability Distribution Function

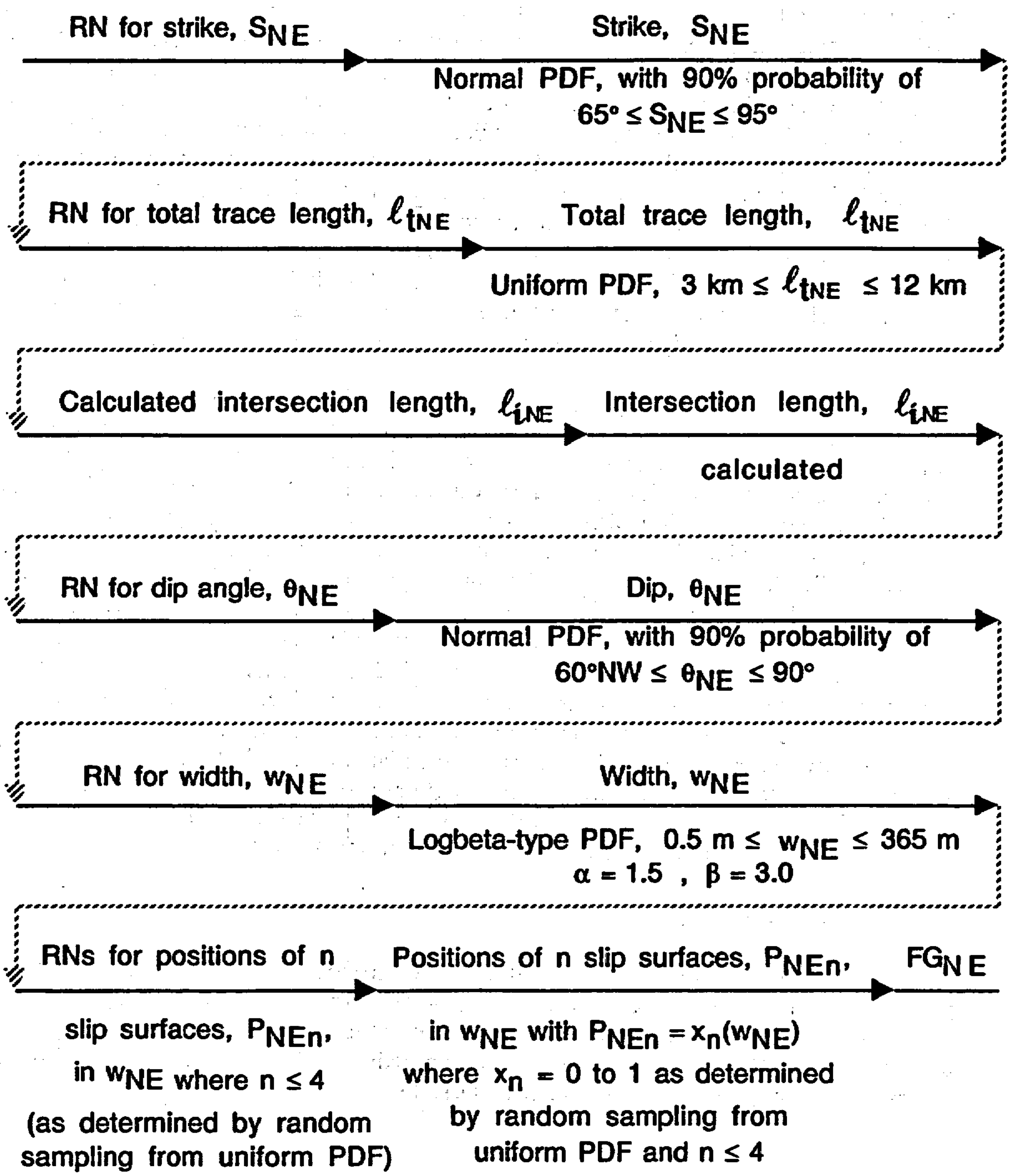


Figure 2-5. Logic diagram summarizing the fault zone geometry variable (FG_{NE}) for the NE fault set, where RN=Random Number and PDF=Probability Distribution Function

60 and 90°) dip angles of faults are considered, it appears reasonable to assume that the number of horizontally emplaced waste packages affected by fault displacement is relatively insensitive to variations in dip of the fault.

Width—Fault zone width, w, may be considered to vary up to at least the maximum observed to occur for the two primary fault sets. Therefore, w_{NW} may vary between 0.5 and 275 m, with the maximum being that reported for the Sundance fault by Spengler et al. (1994). Also, w_{NE} may vary between 0.5 and 365 m, with the maximum width being that reported by Spengler et al. (1994) for the Ghost Dance fault. Fault zone widths will be determined by sampling values from a logbeta-type PDF skewed toward the narrow fault zone widths but which still cover the possible width ranges for the two primary faults sets observed at Yucca Mountain. This type of PDF will be used since field data do not definitively indicate that fault zones of maximum width should be most numerous at Yucca Mountain. However, it is anticipated that the maximum width possible will be one case considered for each of the two fault sets. Width of the zone of faulting provides a measure of the width of the zone of secondary faulting effects, but these effects will not be considered directly in this version of the module. Both single and multiple slip surfaces within the fault zone will be selected and analyzed in initial runs of the module. Selection of locations of slip surfaces is described in the paragraph on *Positions of Slip Surfaces*.

Positions of Slip Surfaces—Both single and multiple slip surfaces will be modeled for considering partitioning of displacement (both largest credible per event and cumulative) in northwest and northeast-striking fault zones. Normal displacement will be assumed for the northeast fault set and strike-slip displacement for the northwest set in this version of the module. Positions of slip surfaces in the fault zones, P_{NWn} and P_{NEn}, will be determined by $P_{NWn}=x_n(w_{NW})$ and $P_{NEn}=x_n(w_{NE})$ where values of x_n between 0 and 1 will be selected by random sampling of uniform PDFs. Widths of the fault zones, w_{NW} and w_{NE}, will be determined as described in the paragraph on *Width*. The number of slip surfaces assumed possible, n, will be considered to vary from 1 to a maximum of 4, so that n=4 provides the upper limit on number of slip surfaces which may occur in a fault zone. 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 while conducting detailed field studies to define the complex nature of the Ghost Dance fault zone. Concentration of slip along a single surface is considered to be the most conservative case for assessing potential effects of fault displacement. It will be possible to compare effects of displacement along a single slip surface with effects from displacements along multiple slip planes which are randomly distributed (or systematically distributed, if specific spacing of the surfaces is provided as input) along the width of the fault zone.

2.2.4 Fault Activity

Whether a fault is classified as active or inactive will be addressed by assuming that the probability of movement on faults remaining to be encountered in the repository block is one during the next 10,000 yr. That is, both northeast- and northwest-trending faults are assumed potentially active in this time frame. For the analysis to proceed, an active fault is required. Figure 2-6 shows the logic diagram for description of the fault activity variable.

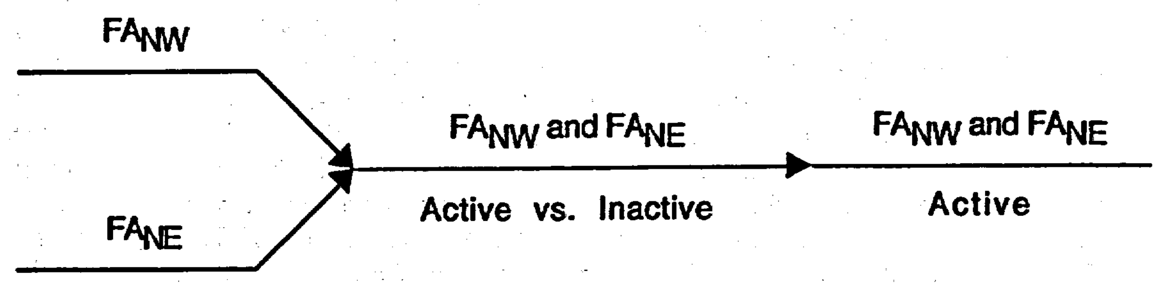


Figure 2-6. Logic diagram summarizing the fault activity variable (FA_{NW} and FA_{NE}) for NW and NE fault sets

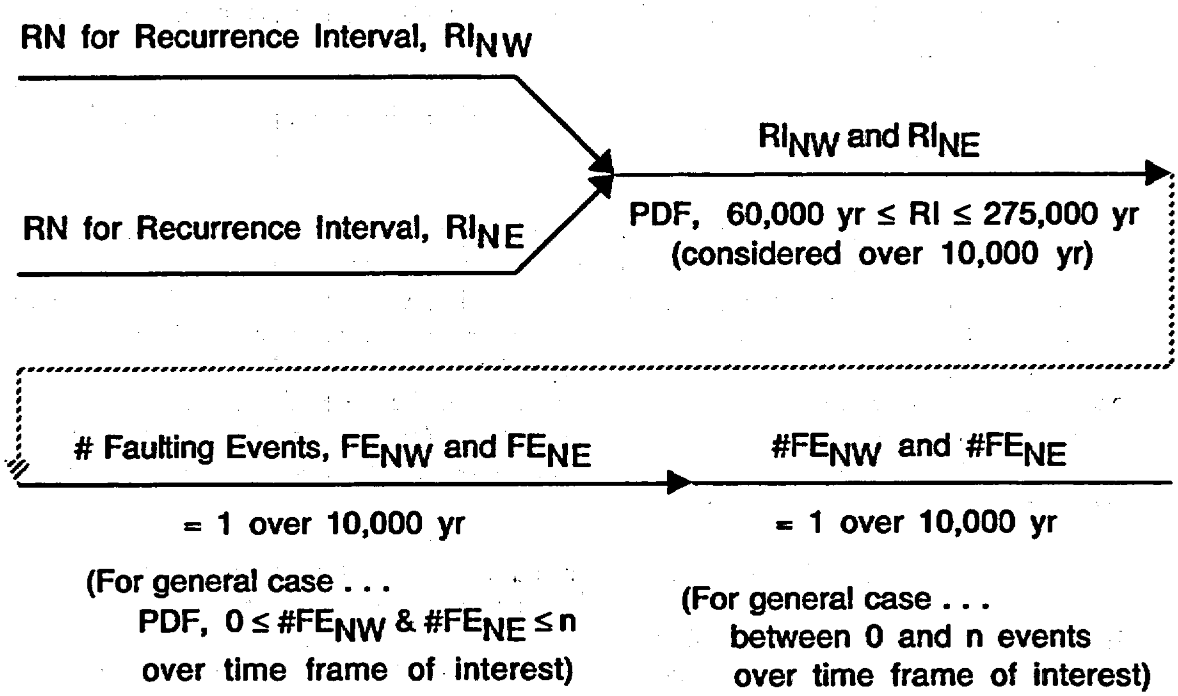


Figure 2-7. Logic diagram summarizing the number of largest credible displacement faulting events over 10,000 yr variable ($\#FE_{NW}$ and $\#FE_{NE}$) for NW and NE fault sets, where RN=Random Number and PDF=Probability Distribution Function

2.2.5 Number of Largest Credible Displacement Faulting Events Over 10,000 Yr

Number of faulting events possible for largest credible displacements will be determined by considering information on faulting recurrence intervals presented in the expert elicitation report prepared by EPRI (1993). Figure 2-7 illustrates the logic diagram for describing this variable. Lacking additional data, information on recurrence intervals presented for the Ghost Dance fault (by Whitney) in the EPRI (1993) report will be used for both northwest and northeast 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 repository block may have shorter recurrence intervals, since it is thought to provide a reasonable estimate for interval of recurrence of faulting in the repository block. Therefore, for the two primary fault sets observed at Yucca Mountain, recurrence intervals will 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.

In the general case, the number of possible events would be determined for the two primary fault sets observed at Yucca Mountain for the recurrence intervals drawn from the PDFs by considering another set of uniform PDFs for number of events possible over the chosen time frame (as indicated for the general case in Figure 2-7). However, for the time period of 10,000 yr, only a single largest credible displacement event is probable when the preceding recurrence intervals are assumed. Because it is not clear where in the recurrence sequence the faults at Yucca Mountain lie, this single event may occur at any time during the 10,000-yr period with different amounts of largest credible displacement possible for that single event.

2.2.6 Time of Occurrence of Largest Credible Displacement Faulting Events

Time of occurrence of largest credible displacement faulting events will be determined by random sampling from uniform PDFs for times ranging between 0 and 10,000 yr, taking into account the number of events possible based on recurrence interval for largest credible displacement events. Figure 2-8 illustrates logic diagrams for describing the timing variable for the first and subsequent largest credible displacement faulting events. In the specific case herein, only one event is possible but it may occur at any time within the 10,000-yr period. Hence, the time of this single first event is randomly selected between 0 and 10,000 yr [Figure 2-8(a)]. Amount of displacement will be determined (Section 2.2.7) and compared with the threshold displacement necessary for waste package disruption to ascertain whether disruption occurs.

For the general case, the logic could be extended to simulate multiple largest credible displacement faulting events by resampling both recurrence interval and times for subsequent events [Figure 2-8(b)]. Time for additional faulting events beyond the first would be measured from time of the previous event. A random number having a value between 0 and 1 would be used to determine the time of each successive event. This number would be multiplied by the recurrence interval to generate time of the next event, which would yield a time between 0 and the total recurrence interval. Time of the second (or later) event may fall within the time period of interest in the present simulation (i.e., 0 to 10,000 yr). If the event did fall within the 10,000-yr period, the amount of displacement would need to be determined (Section 2.2.7) and compared with the threshold displacement (as discussed for the first

Table 2-1. Recurrence intervals used in the FAULTING module for both northeast- and northwest-trending faults at Yucca Mountain. The intervals are derived from information on the northeast-trending Ghost Dance fault zone as presented in the elicitation report of EPRI (1993).

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)

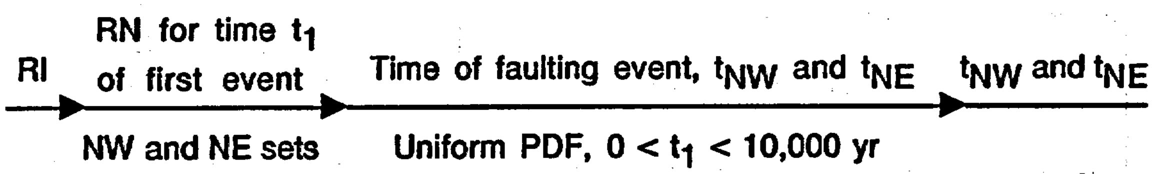
event case in the preceding paragraph) to ascertain whether it may lead to disruption of waste packages. If the time of the next event (second or later) were beyond the limit of the simulation, then there would be no additional events of interest. Given the recurrence intervals indicated by the field relationships (i.e., 60,000 to 275,000 yr), the majority of simulations should yield only one largest credible displacement event over a 10,000-yr time period.

2.2.7 Amount of Largest Credible Displacement per Faulting Event and Partitioning of Displacement Along Multiple Slip Surfaces

Amount of largest credible fault displacement per event for the northwest fault set will be determined by random sampling of values from PDFs defined by the values presented by Arabasz for the Pagany and Drill Hole Wash faults in the EPRI expert elicitation report (1993) as shown in Table 2-2. Figure 2-9 illustrates logic diagrams for describing this variable for the northwest-trending fault set and for partitioning of largest credible displacement along multiple slip surfaces within northwest-trending fault zones.

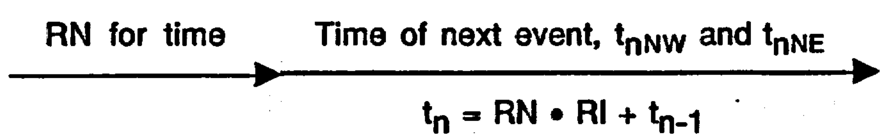
Amount of largest credible fault displacement per event for the northeast-trending fault set will be determined by random sampling of values from PDFs defined by the values presented by Whitney for the Ghost Dance fault in the EPRI expert elicitation report (1993) as shown in Table 2-3. Figure 2-10 illustrates logic diagrams for describing this variable for the northeast-trending fault set and for partitioning of largest credible displacement along multiple slip surfaces within northeast-trending fault zones. The maximum probable value is considered to be 45 cm for computation purposes since that is the highest probability value provided in the data (Electric Power Research Institute, 1993).

Whether the determined displacements occur along single or multiple slip surfaces in the fault zone, they are considered in the module to occur during a single faulting event. In the case of multiple



NOTE: At least one event assumed to occur over 10,000 yr.

(a)



NOTE: Probability of more than one event is sufficiently small that possibility of more than one event is neglected for a 10,000-yr time period.

(b)

Figure 2-8. Logic diagrams summarizing the time of occurrence of (a) first largest credible displacement faulting events variable (t_{NW} and t_{NE}), where RN=Random Number and PDF=Probability Distribution Function and (b) second (and later) largest credible displacement faulting events variable (t_{nNW} and t_{nNE}) for NW and NE fault sets

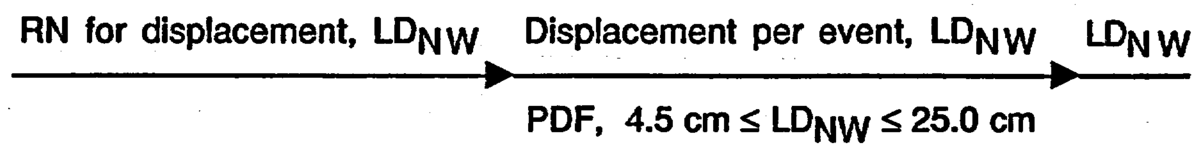
Table 2-2. Amount of largest credible displacement per faulting event used in the FAULTING module for northwest-trending faults at Yucca Mountain. The values are derived from information on the northwest-trending Pagany Wash and Drill Hole Wash faults as presented in the elicitation report of EPRI (1993).

Largest Credible Displacement (cm)	Estimated Cumulative Probability of Occurrence
4.5	(0.05)
9.0	(0.50)
18.0	(0.95)
25.0	(max)

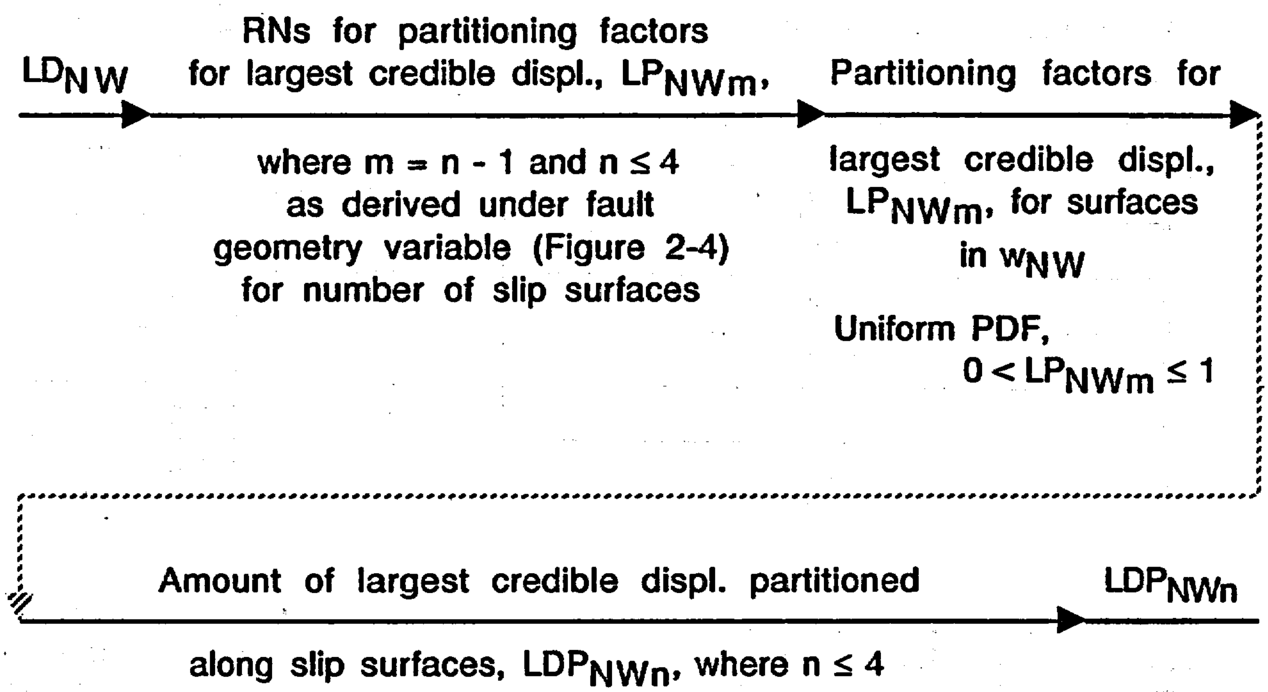
Table 2-3. Amount of largest credible displacement per faulting event used in the FAULTING module for northeast-trending faults at Yucca Mountain. The values are derived from information on the northeast-trending Ghost Dance fault as presented in the elicitation report of EPRI (1993).

Largest Credible Displacement (cm)	Estimated Cumulative Probability of Occurrence
6.0	(0.10)
12.0	(0.50)
20.0	(0.80)
30.0	(0.90)
45.0	(0.95)

slip surfaces, located as described under the discussion on *Positions of Slip Surfaces*, the total determined displacement is partitioned along n slip surfaces in the fault zone (where the value of n varies from 1 to a maximum of 4) by consideration of partitioning factors based on random sampling of uniform PDFs to allocate percentages of largest credible displacement along the surfaces. Lacking additional data, the information shown for amount of largest credible displacement per event for the specific faults indicated will be applied for analysis of unknown northwest- and northeast-trending fault sets. Even though major block-bounding faults outside the repository block may exhibit larger displacements per faulting event, this approach is being used since it is thought to represent a reasonable amount of largest credible displacement for a faulting event in the repository block based on displacements documented for the repository block faults in the field. A uniform PDF is not suggested for treating this variable, since it

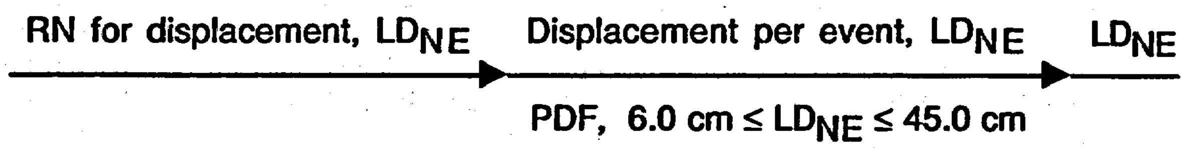


(a)

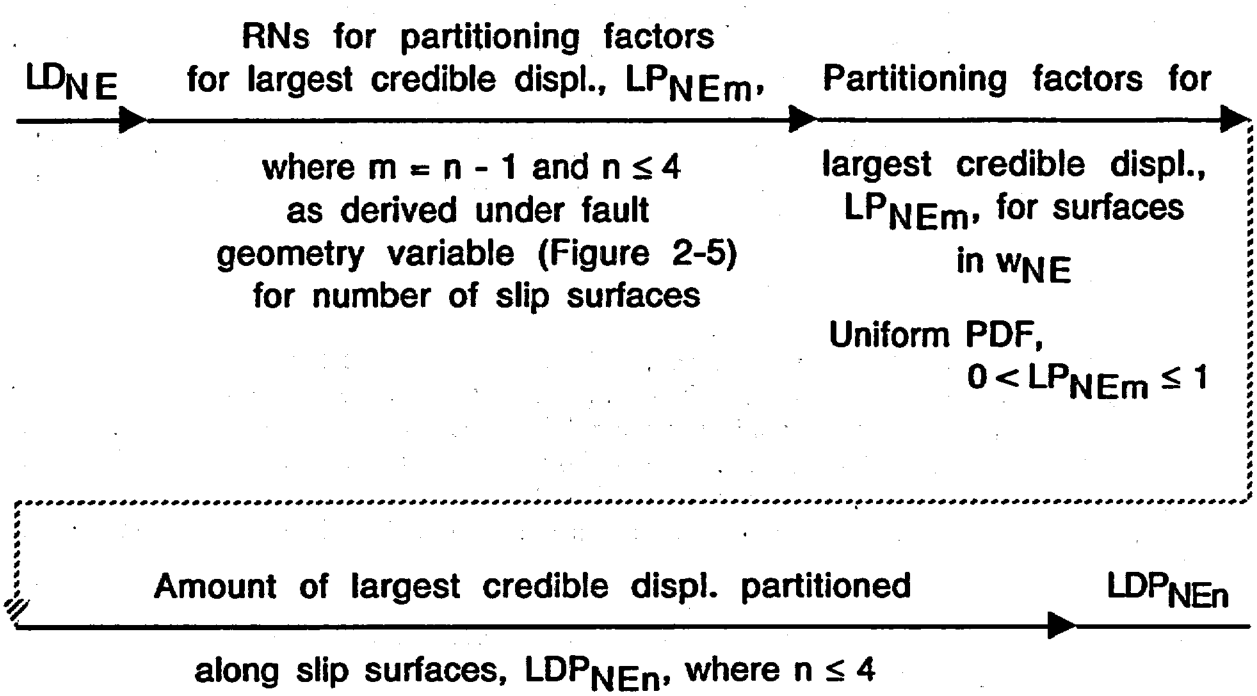


(b)

Figure 2-9. Logic diagrams summarizing (a) the amount of largest credible displacement per faulting event variable (LD_{NW}), where RN=Random Number and PDF=Probability Distribution Function and (b) partitioning of largest credible displacement along multiple slip surfaces variable (LDP_{NWn}), where $n \leq 4$ and $m = n - 1$, for the NW fault set



(a)



(b)

Figure 2-10. Logic diagrams summarizing (a) the amount of largest credible displacement per faulting event variable (LD_{NE}), where RN=Random Number and PDF=Probability Distribution Function and (b) partitioning of largest credible displacement along multiple slip surfaces variable (LDP_{NEn}), where $n \leq 4$ and $m = n - 1$, for the NE fault set

appears that such an approach would skew values toward the higher displacement end in a manner not suggested by the elicitation panel whose recommendations were presented by EPRI (1993). The displacement will be compared with the threshold displacement required for waste package disruption to determine if disruption occurs, and equated with timing as described in Section 2.2.6.

2.2.8 Amount of Cumulative Fault Displacement During 10,000 Yr and Partitioning of Displacement Along Multiple Slip Surfaces

Possible cumulative fault displacement will be determined by considering suggested slip rates over a 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 are 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 waste package disruption. (The threshold value is to be derived from waste package design data.) Slip rates will be selected by random sampling from PDFs defined by the slip rate values presented (by Arabasz) in the EPRI expert elicitation report (1993) as shown in Tables 2-4 and 2-5 for northwest- and northeast-trending fault sets, respectively. Figures 2-11 and 2-12 illustrate the logic diagrams for describing this variable and for partitioning of cumulative displacement along multiple slip surfaces for both northwest- and northeast-trending fault sets. Whether the determined cumulative displacements occur along single or multiple slip surfaces in a fault zone, they are considered to occur during a single faulting event. In the case of multiple slip surfaces, the determined cumulative slip is partitioned along n slip surfaces in the fault zone (where the value of n varies from 1 to a maximum of 4) by consideration of partitioning factors based on random sampling of uniform PDFs to allocate percentages of cumulative displacement along the surfaces.

Even though major block-bounding faults outside the repository block may exhibit higher slip rates, this approach is being used since it is thought to provide reasonable slip rates for cumulative fault displacements in the repository block.

2.2.9 Threshold Displacement

It is assumed that a minimum amount of displacement must be exceeded for faulting to disrupt waste packages. Based on discussions with mining and waste package engineers and rock mechanics specialists, it was determined that this minimum "threshold" displacement is difficult to quantify. Consequently, it was decided to model the threshold displacement as a random variable with a relatively large range of possible values so that sensitivity of predicted performance to the threshold displacement could be analyzed. The threshold displacement is based on a uniform PDF varying between 0.1 and 0.5 m.

2.2.10 Time Cumulative Fault Displacement Exceeds Threshold Displacement

The time that cumulative displacement exceeds a threshold displacement and results in waste package disruption can be readily calculated as threshold displacement divided by slip rate. Figure 2-13 illustrates the logic diagram for describing this variable. In this specific case, if that time is beyond

Table 2-4. Amount of cumulative fault displacement used in the FAULTING module for northwest-trending faults at Yucca Mountain. The values are derived from information on the northwest-trending Pagany Wash and Drill Hole Wash faults as presented in the elicitation report of EPRI (1993).

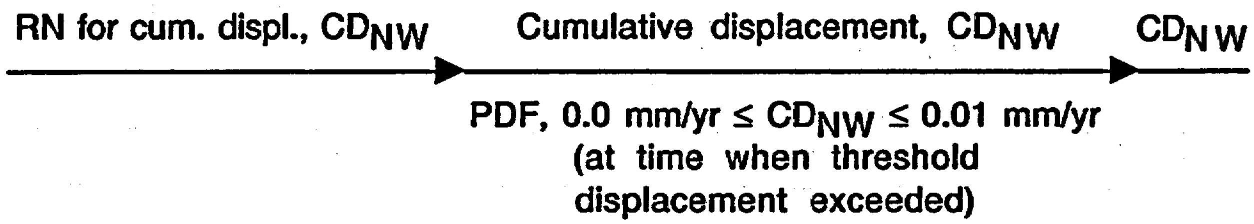
Slip Rate (mm/yr)	Estimated Cumulative Probability of Occurrence
0.0	(min)
0.00004	(0.05)
0.001	(0.50)
0.002	(0.95)
0.01	(max)

Table 2-5. Amount of cumulative fault displacement used in the FAULTING module for northeast-trending faults at Yucca Mountain. The values are derived from information on the northeast-trending Ghost Dance fault as presented in the elicitation report of EPRI (1993).

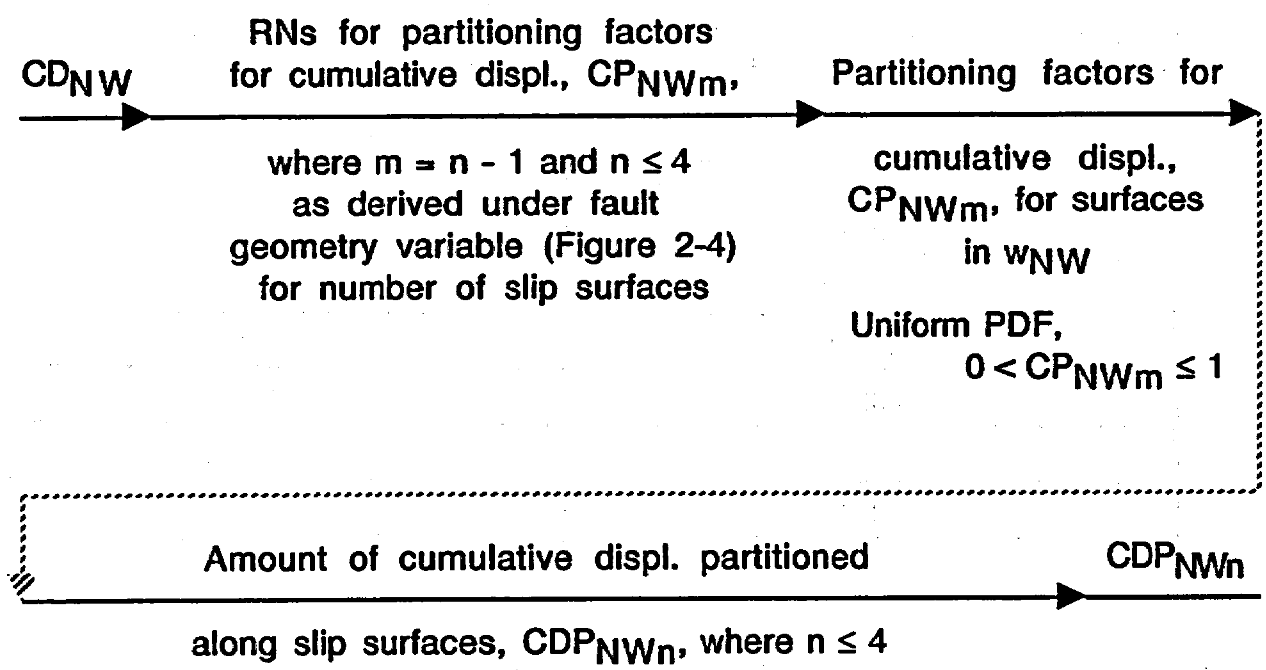
Slip Rate (mm/yr)	Estimated Cumulative Probability of Occurrence
0.00004	(min)
0.0004	(0.05)
0.0007	(0.50)
0.002	(0.95)
0.007	(max)

10,000 yr (e.g., as may be expected for slow slip rates), then cumulative displacement will not affect repository performance. If that time were less than 10,000 yr (e.g., for accelerated slip rates), then repository performance could be affected. The logic can be extended in application to time frames longer than 10,000 yr, should the need arise.

Cumulative displacement time should be compared with the largest credible event time (assuming both exceed the threshold displacement value and cause disruption) to determine the minimum time for waste package disruption. The minimum time is used to inform the SOurce TErm Code



(a)



(b)

Figure 2-11. Logic diagrams summarizing (a) the amount of cumulative displacement during 10,000 yr variable (CD_{NW}), where RN=Random Number and PDF=Probability Distribution Function and (b) partitioning of cumulative displacement along multiple slip surfaces variable (CDP_{NWn}), where $n \leq 4$ and $m=n-1$, for the NW fault set

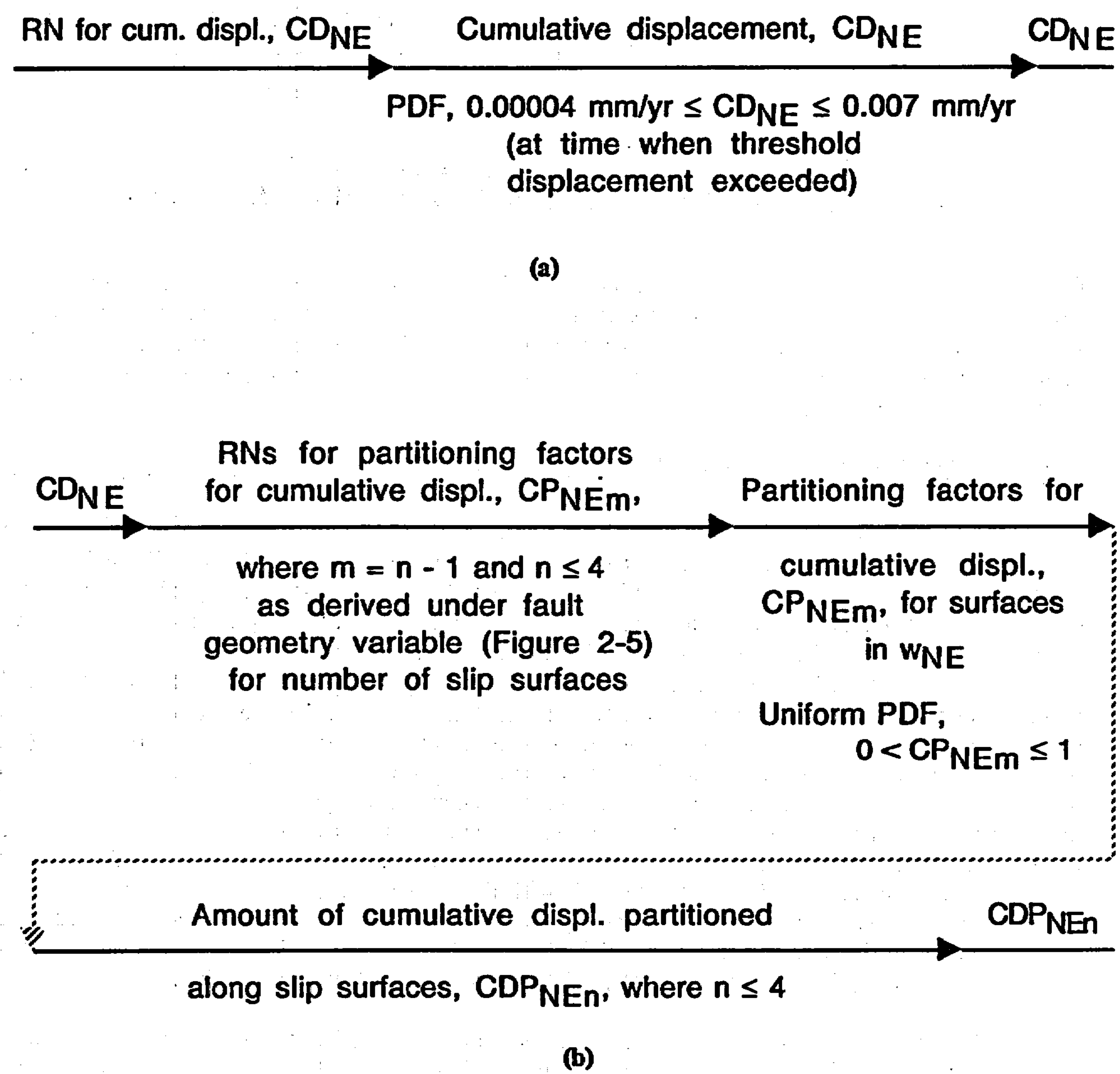


Figure 2-12. Logic diagrams summarizing (a) the amount of cumulative displacement during 10,000 yr variable (CD_{NE}), where RN=Random Number and PDF=Probability Distribution Function and (b) partitioning of cumulative displacement along multiple slip surfaces variable (CDP_{NEn}), where $n \leq 4$ and $m=n-1$, for the NE fault set

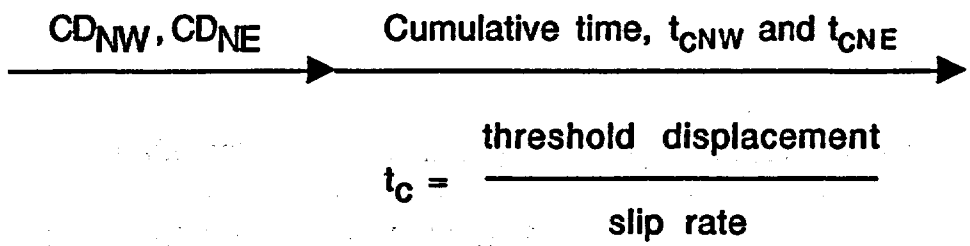


Figure 2-13. Logic diagram summarizing the time cumulative displacement exceeds threshold displacement variable (t_{CNW} and t_{CNE}) for NW and NE fault sets

(SOTEC) as described by Sagar et al. (1992), when fault-induced waste package failures occur (Figure 2-1). If neither the largest credible nor the cumulative slip events exceed the threshold, no fault-induced waste package failures happen. If fault displacement (either largest credible or cumulative) does induce waste package disruption, the number of affected waste packages will need to be calculated as generally discussed in Section 2.3.

2.3 GENERAL PROCEDURE FOR CONSEQUENCE ANALYSIS

The flow diagram of Figure 2-14 illustrates how the FAULTING consequence module fits into assessment of potential consequences of a faulting event in the repository block which induces waste package disruption and release of radionuclides. Numbers of drifts and waste packages intersected depend on fault geometry and repository design. Available radionuclide inventory depends on the time of occurrence of faulting. Description of a faulting event is based on geometric considerations for a fault lying within the 50×50-km simulation area surrounding the repository which is idealized as a finite line at the level of the repository. After description of the faulting event and determination of the earliest time that fault displacement exceeds the threshold displacement and produces waste package disruption (either by largest credible or cumulative displacement) through application of the FAULTING module, it is determined whether the earliest time of disruption is less than 10,000 yr. If the disruption occurs within this time period, number and locations of disrupted waste packages are determined and this information passed to SOTEC for calculation of radionuclide release. Given the center location of the fault, its strike orientation, and intersection length of the fault with the repository, along with repository layout, the number and locations of affected waste packages can be calculated. This calculation is performed in standard TPA utilities external to the FAULTING module because this information is also needed in scenarios for treating drilling (Freitas et al., 1994) and volcanism (Lin et al., 1993).

Table 2-6 summarizes the variables sampled in the FAULTING module and their respective distributions. Each variable is discussed in Section 2.2 of this report. These variables will be controlled by the TPA executive module to facilitate computation of overall performance using the Latin Hypercube Sampling procedure and sensitivity analyses.

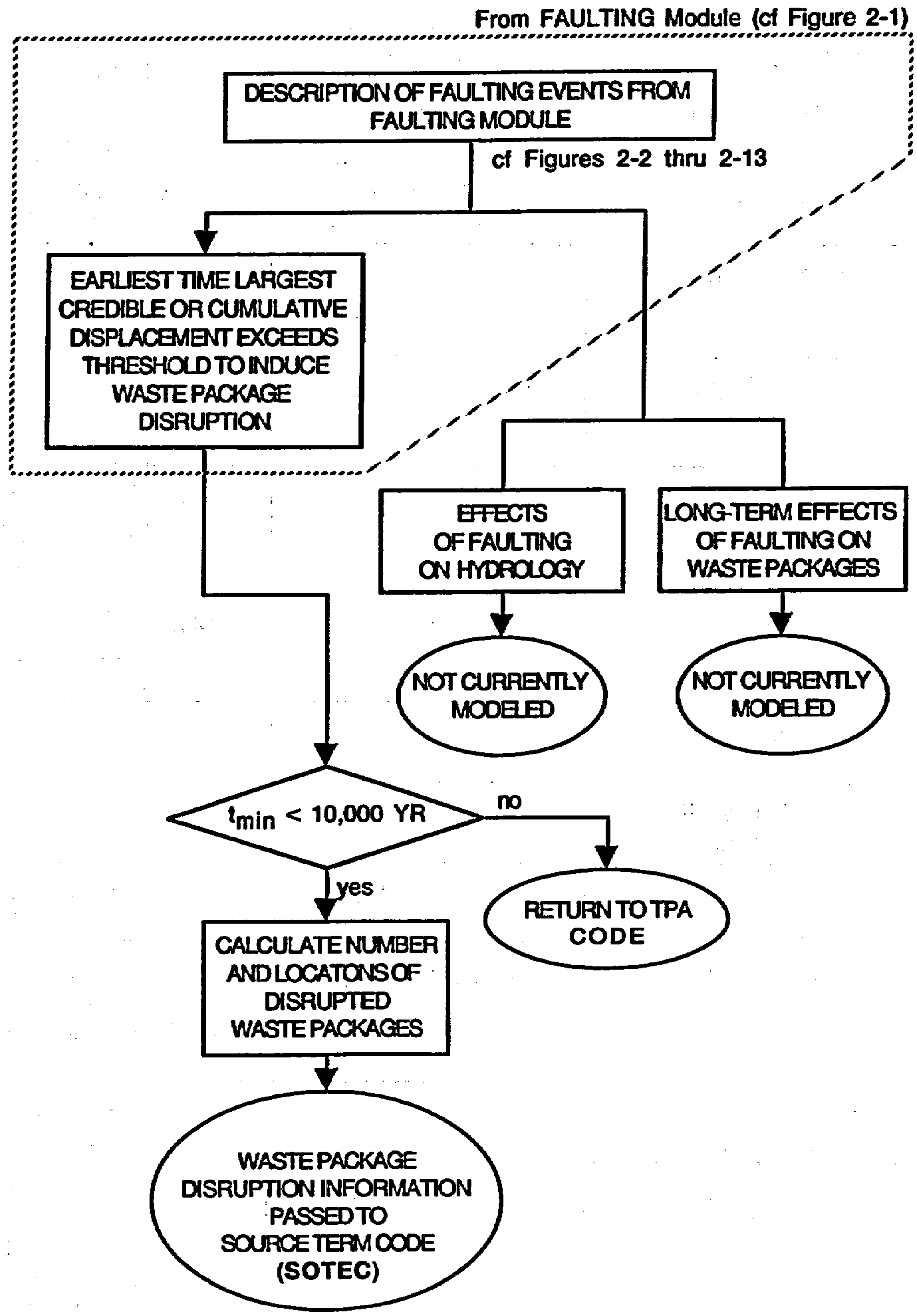


Figure 2-14. Flow diagram summarizing sequential steps in consequence analysis of faulting events for IPA Phase 3

Table 2-6. Variables sampled in the FAULTING module and their distributions

Variable Description	Symbol	Probability Distribution Function
Center of fault	Location x Location y	Uniform PDF $-25<x<25$ km Uniform PDF $-25<y<25$ km
Orientation	NW or NE	Uniform PDF 25% of time NW Uniform PDF 75% of time NE
Strike orientation	S_{NW} or S_{NE}	Normal PDF, 90% probability $115° \leq S_{NW} \leq 130°$ $65° \leq S_{NE} \leq 95°$
Trace length	ℓ_{tNW} or ℓ_{tNE}	Uniform PDF $2 \leq \ell_{tNW} \leq 10$ km $3 \leq \ell_{tNE} \leq 12$ km
Dip angle	θ_{NW} or θ_{NE}	Normal PDF, 90% probability 80° NE$<\theta_{NW}>$80° SW 60° NW$\leq \theta_{NE} \leq$90°
Fault zone width	W_{NW} or W_{NE}	Logbeta, PDF $\alpha=1.5$, $\beta=3.0$ $0.5\ m \leq W_{NW} \leq 275\ m$ $0.5\ m \leq W_{NE} \leq 365\ m$
Number of slip surfaces	n	Uniform probability $n=\{1,2,3,4\}$
Positions of slip surface	P_{NWn} or P_{NEn}	Uniform PDF over fault zone width
Recurrence interval	RI_{NW} and RI_{NE}	Uniform PDF $60{,}000 \leq RI \leq 275{,}000$ yr
Number of faulting events	$\#FE_{NW}$ and $\#FE_{NE}$	FE=1 Because time period of interest (10,000 yr) is short compared to recurrence intervals
Time of first largest credible event	t_1	Uniform PDF $0<t_1<10{,}000$ yr
Time of subsequent events	t_{nNW} and t_{nNE}	Uniform PDF over recurrence interval $t_{n-1}<t_n<RI+t_{n-1}$ (NOTE: The number of events determined by time period of interest, i.e., $t_n \leq 10{,}000$ yr. Because 10,000 yr is short and RI is long, only one event is simulated.)

Table 2-6 (Cont'd). Variables sampled in the FAULTING module and their distributions

Variable Description	Symbol	Probability Distribution Function
Amount of largest credible displacement	LD_{NW} or LD_{NE}	Uniform PDF $4.5 \leq LD_{NW} \leq 25.0$ cm $6.0 \leq LD_{NE} \leq 45.0$ cm
Largest displacement partitioned among slip surfaces	LDP_{NWn} or LDP_{NEn}	Uniform partitioning of LD along n slip surfaces
Amount of cumulative displacement	CD_{NW} or CD_{NE}	Uniform PDF $0.0 \leq CD_{NW} \leq 0.01$ mm/yr $0.00004 \leq CD_{NE} \leq 0.007$ mm/yr
Cumulative displacement rate partitioned for each slip surface	CDP_{NWn} or CDP_{NEn}	Uniform partitioning of CD along n slip surfaces
Threshold displacement for waste package failure	TD	Uniform PDF $0.1 < TC < 0.5$ m

3 FUTURE PLANS FOR MODULE DEVELOPMENT

The next immediate step will be coding of the variables presented in Section 2.2 of this report for implementing technical design of the FAULTING module and considering assessment of potential consequences of a faulting event in the repository block. Incorporation of new data will be undertaken as they become available from the DOE site characterization program and may alter numerical ranges of some variables used to describe faulting events.

After the module is designed, it should be possible to consider potential effects of faulting on hydrology (when data on fault zone hydrology become available) and potential long-term effects of fault displacement on waste package corrosion and weakening. It should also be possible to factor in seismic shaking effects by using fault length/earthquake magnitude relationships. Alternative tectonic models could be considered if it is deemed useful to take into account distributed/linked faulting and possible effects of different tectonic models on probability of occurrence of faulting events. Fault displacement distributed across multiple slip planes within a single fault zone can also be analyzed further. Slip tendency analysis (Morris et al., 1994; Ferrill et al., 1995) could be directly applied for determining three-dimensional orientations (i.e., strike and dip) of faults to be treated in the module. Use of this new analysis technique should make it possible to consider effects of frictional characteristics of faults (after such data are derived for the fault sets at Yucca Mountain) for ascertaining which fault orientations are most favorable for displacement in the present stress field.

4 SUMMARY

The FAULTING consequence module is being developed to generate a faulting event in a simulation area measuring 50×50 km centered around the potential repository at Yucca Mountain. Fault displacement is assumed to occur along a presently undiscovered, randomly located fault zone in the simulation area with strike direction of the zone being either northwest or northeast parallel to the fault trace orientations observed in the field at and near Yucca Mountain. The fault may or may not intersect the repository, depending on location of the fault in the simulation area, its orientation, and its total length relative to the position of the repository.

Variables for defining the fault zone are chosen randomly from ranges of values based on field data published in sources referenced in this report (i.e., Electric Power Research Institute, 1993; Scott and Bonk, 1984; Spengler et al., 1994). It is assumed the fault zones may possess attributes similar to those of the Ghost Dance and Sundance faults which have been mapped in the repository block by Spengler et al. (1994). The fault zone will have a randomly selected width, and offset within the zone will be considered along both single and multiple slip surfaces. Consequences of fault displacement depend on the length of intersection of the fault zone with the repository, waste package emplacement design, and the amount of displacement assigned to the faulting event. The procedure for assessing the potential for waste package-disrupting fault displacement in the repository block and the possible consequences of such displacement can be summarized as follows:

- Locate midpoint of the fault zone in the 50×50-km simulation area by random sampling to determine (x,y) coordinates of that point.
- Determine orientation of the fault trace, considering that faults with a northeast strike direction are assumed to occur 75 percent of the time and northwest-striking faults, 25 percent of the time, based on field observations.
- Determine geometry of fault zone (i.e., strike, total trace length, dip, width, and positions of slip surfaces) by random sampling and calculate length of fault intersection with the repository.
- Assuming an active fault and based on faulting recurrence intervals, determine number of largest credible displacement events over 10,000 yr by random sampling. (In this case, only a single event is modeled based on recurrence interval data for both northwest and northeast fault zones.)
- Select time and amount of a largest credible displacement by random sampling and determine whether this displacement results in waste package disruption by slip along either single or multiple slip surfaces.
- Select slip rate for the fault by random sampling, determine whether a threshold displacement value is exceeded and waste package disruption occurs as a result of cumulative slip along either single or multiple slip surfaces, and calculate the time at which cumulative slip exceeds the threshold and induces waste package disruption.

- Select earliest time for waste package disruption from either a largest credible displacement event or cumulative slip, if waste package disruption occurs.

- Communicate waste package disruption data (i.e., timing) to SOTEC of TPA code and conduct consequence analysis to determine radionuclide release, if canister disruption occurs as a result of either the largest credible displacement event or cumulative slip. (Consequence analysis will require input of data related to repository design.)

The technical specifications for a FAULTING module presented in this report will be coded for use in the NRC IPA Phase 3 analysis.

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